REPORT FOR DEPARTMENT FOR DIGITAL, CULTURE, MEDIA AND SPORT (DCMS)

ENSURING FUTURE WIRELESS CONNECTIVITY NEEDS ARE MET

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Contents

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Since producing this report, responsibility for digital infrastructure has moved to the Department for Science, Innovation and Technology (DSIT).

1 Executive summary

Wireless connectivity is becoming pervasive in the UK. Consumers, businesses and the public sector rely on the availability of different forms of wireless connectivity (mobile networks, Wi-Fi and a range of other solutions), where and when needed. UK businesses are using wireless connectivity as part of their digital-driven industry transformation. In industrial settings, wireless connectivity can be used to connect data via wireless sensor networks, to track objects, and to capture and transmit video images. 5G is the latest cellular wireless technology available in the UK market. It offers higher speeds and lower latency that support a range of advanced applications that could be transformative for UK businesses and industries. These advanced applications include controlling remote objects, and machine and vehicle automation.

Amidst this rapidly evolving landscape of new wireless technologies use cases, in November 2021 the Department for Digital, Culture, Media and Sport (DCMS) commissioned Analysys Mason, together with Oxera, to conduct this study to:

- investigate the wireless connectivity landscape, the wireless connectivity needed to support future use cases, and wireless solutions
- assess the extent to which the UK market will deliver cellular infrastructure[1] to meet future mobile traffic demand, and the juncture between cellular network investment being viable, and not viable
- identify demand-side and supply-side policies that could be used to stimulate the market or support investment to meet connectivity needs.

We used evidence captured from a literature review and a series of interviews with UK stakeholders to corroborate our assessments of the points above, and to validate our key modelling assumptions. Our main findings are summarised below.

Wireless applications that the UK market might need in future range from high-speed mobile data, video and smartphone applications, through to ultra-high definition (UHD) video, augmented and virtual reality (AR/VR) applications, and remote piloting of machinery and robotics.

The data speeds needed to support these future applications range from speeds similar to those delivered already by the cellular networks in the UK (around 20–30Mbit/s), through to 100Mbit/s and above. Highly interactive/immersive mobile AR/VR applications would also require much higher data rates and low latency, in the locations where these applications are consumed using mobile networks.

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[1] The 4G/5G networks provided by mobile network operators (MNOs).

Since the UK's MNOs are still expanding their 5G roll-out, speeds and network capabilities are expected to evolve with further roll-out.

We note that cellular networks in some of the best performing mobile markets worldwide are already providing data speeds above 100Mbit/s. Since higher downlink and uplink mobile speeds are needed in the context of meeting demand for more advanced wireless applications, without an improvement in mobile data speeds, the UK market might risk losing out on the advantages of these advanced services. However, given that some of the most advanced wireless applications are not yet available, there is still considerable uncertainty on the demand for these services and hence the level of mobile data speed that the UK market needs in future.

Cellular networks are operated in the UK by four national mobile MNOs.[2] A range of new local players are emerging, and private deployments of cellular technology (so-called private 5G networks) are also gaining traction.

All of the nationally available mobile spectrum in the UK is licensed to the four MNOs. Localised operators in the UK market either enter into arrangements to use the spectrum of one of the national MNOs, or access spectrum via the local access and shared access spectrum authorisations that Ofcom has put in place.

Shared access spectrum (in particular, in the 3800–4200MHz band) is also supporting the emergence of private cellular 4G/5G networks. These private networks can range in type and scale from dedicated, on-premises networks built for or by a single enterprise or industrial user, through to private networks using a combination of on-premises and public mobile network elements.

Network slicing, once available, will provide an alternative to building dedicated private 5G networks. The network-slicing concept has developed due to the evolution of 5G core networks to standalone (SA) network function virtualisation and cloud-based platforms. This evolution enables end-to-end network capacity to be split up and offered as a 'slice' to a particular user or use case. Network slicing will enable MNOs to provide new services that are use-case specific. These services could potentially have assured bandwidth, latency and/or reliability. 5G networks in the UK are expected to offer network slicing from approximately 2023.

Not all enterprise and business users will opt to use cellular technology, and some users will choose Wi-Fi as an alternative, especially where applications are not highly mobile.

UK consumers, businesses and the public sector can choose from a range of alternative wireless solutions instead of, or in combination with, cellular technology. Alternatives include various low-power wireless solutions, Wi-Fi and satellite

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[2] Three, VMO2, Vodafone and BTEE.

networks. The choice of solution might be made for cost reasons, because users have already invested in a particular form of wireless solution or because their network supplier has offered a particular type of solution. The role of Wi-Fi is well established in the UK. New forms that are emerging include Wi-Fi 6E and Wi-Fi 7 (in future). These can provide advanced applications in a range of settings, as an alternative to using a private cellular network, or a 5G network slice.

We developed a baseline model for future mobile coverage informed by evidence captured during the study, which indicates that speeds available in UK mobile networks today are on average less than 30Mbit/s. This model represents a hypothetical UK-wide macro mobile network using around 18 000 sites, with geographical/landmass coverage extending to 88% by 2024 and 90% by 2027. Capacity in this network is modelled on the basis of a typical UK MNO spectrum portfolio.[3]

The geographical distribution of the 18 000 sites in our network was calculated on the basis of how traffic (and thus population) is distributed across sites. Demand was distributed across the full portfolio of macro sites using a logarithmic curve. We did not model actual site locations, but we made assumptions about the geographical distribution of sites, following a traffic distribution curve.

A network deployment of this level will give rise to a varied level of service across the UK. On average, mobile users today might experience speeds of 27Mbit/s from a mobile network,[4] which can enable UHD video but is not sufficient for AR/VR (based on the published literature reviewed for this study). In a few areas (where approximately 15% of the UK live), speeds per active user reach greater than 50Mbit/s, enabling more advanced applications, including AR/VR. Given this 50Mbit/s service would not be available across a wide area, a user moving between different locations would not necessarily maintain this level of connection.

In our baseline model, network performance is estimated to increase primarily in suburban areas. This means that, by 2030, a 50Mbit/s service would be available in locations where 55% of the UK population live (again using assumptions on active users in a given location in the busy hour). To achieve this, we calculate that by 2030, 100% of urban and suburban macro sites and 56% of rural sites must have 3.5GHz spectrum added to the existing radio equipment. This equates to 3.5GHz spectrum roll-out extending to 93.8% of the UK population. This deployment is estimated to cost the modelled hypothetical operator GBP2.8 billion

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[3] Including low-band spectrum, spectrum in the 1800MHz, 2100MHz and 2600MHz bands for mixed 4G and 5G use, and spectrum in the 700MHz and 3.5GHz bands for 5G.

[4] Based on published average speed measurements for the UK market, as published at the time of producing this report.

(i.e. GBP312 million per annum) in nominal terms by 2030 (GBP2.1 billion in 2022 terms with a weighted average cost of capital of 8%).

Our modelling assumes some UK locations will not be covered by mobile sites by 2030 and hence total 'not-spots' will remain.[5] These locations represent the final percentage of UK geography that will not be covered beyond the footprint of the Shared Rural Network (SRN).[6]

We modelled three quality-of-coverage scenarios to investigate the additional costs of improved mobile quality of connection compared to the network capacity estimates from our baseline model. Scenarios were selected on the basis of improving consumer connectivity to a level of 50Mbit/s to UK locations within the modelled footprint of a UK mobile network (speed defined as that available to an active user, based on assumptions of the percentage of subscribers within a given location active in the busy hour), and to support increased levels of data traffic that could be generated by advanced industrial and business applications in future years.

Scenario 1 set a throughput threshold of 50Mbit/s per active user in the busy hour in UK locations within the footprint of our modelled mobile network (with user numbers per network based on mobile subscriber forecasts described in this report). Scenario 2 modelled an increase in enterprise traffic demand over public mobile networks. Scenario 3 modelled both 50Mbit/s to consumers plus increased enterprise demand. Our choice of scenarios was informed by:

- our baseline assessment of the average data speeds UK mobile networks might deliver by 2030, compared to the wireless connectivity needed for future use cases
- a comparison of the mobile network speeds delivered in other markets.

We chose a 50Mbit/s target for our modelling based on a combination of cost and demographic considerations for the UK market. These considerations reflect that the UK population is concentrated in urban areas and hence the costs of achieving wider geographical/landmass coverage must be weighed against the lower population density in non-urban locations.

- Scenario 1 requires a total of GBP3.3 billion investment per mobile network between now and 2030 (equivalent to an additional GBP51 million per annum, per operator, in nominal terms compared with the baseline). This additional investment includes a combination of capacity upgrading via adding more spectrum to existing

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[5] Not-spots are locations where there is no coverage available from any generation of mobile technology, from any network provider.

[6] As per current agreements between the UK government and MNOs, the SRN has an aggregate coverage target, using 4G technology, of 95% of the UK geography. Individual MNOs are targeted to achieve 90% geographical coverage.

sites, plus densification (adding what we call 'mini macro' sites in locations where capacity exceeds available capacity from the assumed spectrum portfolio).

- Scenario 2 results in GBP61 million in investment required per mobile network per annum between now and 2030, over and above our modelled baseline.
- Scenario 3 results in GBP124 million in investment required per mobile network per annum between now and 2030, over and above our modelled baseline.

We used illustrative analysis based on an assumption that a 5% nominal price increase for mobile consumers, sustained over the payback period, would be deemed acceptable. We conclude from our Scenario 1 modelling results that the additional investment to achieve a 50Mbit/s quality of connection across the UK should be viable in all urban and suburban areas, but not in all rural areas.

If we break down the additional average revenue per user (ARPU) requirement at a sub-national level, we estimate that the additional ARPU requirement per month would equate to GBP0.11 in urban locations, less than GBP0.01 in suburban locations, and GBP0.69 in rural locations. If the assumption of a 5% price increase is acceptable, this means that investment should be commercially viable in all urban and suburban areas. Considering rural areas by region, we find that a few rural areas[7] may not be commercially viable under a 5% national price increase. Assuming a 10% increase in price, only the Scotland rural region would remain unviable. In practice, there is no geographical pricing differentiation in the UK mobile market and hence any price changes would be at a national level.

Our assessment of the commercial viability of meeting increased enterprise/business traffic demand was based on: the increase in gross value added (GVA) that a business would experience by adopting advanced wireless technologies; and the share of this additional GVA that corresponds to the gross operating surplus (profits) of the business. We found that additional investment is viable in all urban and suburban locations other than the North East of England, but is not viable in rural locations.

If the value of the incremental expected benefits (business profits) is greater than the incremental revenue requirement for our hypothetical MNO to invest in a given area (over and above the baseline investment), then businesses should be willing to pay an amount that at least meets the revenue requirement. This is provided the businesses internalise all of the expected increase in profits in their willingness-to-pay assessment.

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[7] Modelled as rural locations within North East England, Yorkshire and the Humber, Wales, Northern Ireland and Scotland.

Using this approach, we find that the estimated increase in business profits exceeds the revenue required by MNOs from businesses located in all urban and suburban locations apart from North East suburban. This implies that investment could be commercially viable and go ahead in these areas. At the rural level, we find that no rural regional areas would be commercially viable, suggesting there is no commercial case for the modelled incremental cost of investing in those areas beyond the baseline model. However, the wider economic benefits to the areas (measured with reference to the total GVA uplift) does exceed the revenue requirement in some rural areas (East Midlands, West Midlands, East of England, South East and South West of England, in addition to North East suburban) and therefore in these areas there is likely to be a market failure.[8] If the government were to prioritise the targets set under Scenario 2, there should be support for intervention in these areas.

Our modelled Scenario 3 indicates that the business case for investing to serve both the enterprise demand and the 50Mbit/s per user may be more challenging and that the investment case is not commercially viable in 18 regional areas.[9] In nearly all (17) of these non-commercially viable areas, our analysis suggests there is a wider economic value to having both user and enterprise demand in that area, which indicates the likelihood of a market failure.[10] However, these results are highly responsive to assumptions on business willingness to pay, highlighting how sensitive the business case can be with respect to expected revenue.

A range of issues could affect the commercial viability of investing in additional public mobile network roll-out to meet future demand, including legal and structural barriers, demand-side uncertainties and various issues inhibiting the speed of roll-out. Policy interventions may be needed to address market failures and/or to support a pro-investment environment.

The investment challenge is greater:

- where the costs of investment are increased
- where there is greater uncertainty in the ability to commercialise the investment as a result of:

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[8] This refers to a failure of commercial roll-out to reach areas where the wider economic value of the investment exceeds the private cost of roll-out, yet this is not fully internalised in the private investment decision, nor captured in end users' willingness to pay.

[9] North East urban, North East suburban, North West urban, North West suburban, North West rural, Yorkshire urban, Yorkshire suburban, East Midlands urban, East Midlands rural, West Midlands urban, West Midlands rural, East urban, East suburban, East rural, South East rural, South West urban, South West rural, Scotland suburban.

[10] North West rural is the only area where it is not commercially viable, nor desirable from a wider economic benefits point of view, to meet Scenario 3 targets.

  - low willingness to pay
  - uncertainty related to willingness to pay
  - uncertainty related to regulation.

We identified a mix of issues that could hold back investment. Some areas may simply not be commercially viable. There may be other areas where, despite the benefits of roll-out exceeding the private costs and revenue requirements, commercial roll-out does not go ahead because this wider benefit is not internalised in the private investment decision, nor captured in users' willingness to pay. In other areas, even if the commercial case is viable for an MNO or an alternative network operator, other factors (as discussed in this report) may inhibit their ability to make the investment, or to do so without delay.[11]

Mobile operators have suggested that the costs of annual licence fees (ALFs) for spectrum affect their cashflow. Operators that fund investments out of free cashflow and operate within a capex envelope noted that ALFs impact investment. We found limited evidence of a direct link between ALF and investment in published literature. However, the scale of ALFs relative to the investment requirement from the baseline to our various scenarios is significant, and we estimate that ALFs exceed the annualised cost of meeting our Scenario 1, for the costs up to 2030.

We found that the annual average ALFs per operator of GBP93.14 million exceed our estimated annualised addition costs of meeting Scenario 1 (over the baseline) of GBP50.91 million. We also found that annual ALFs could cover 75% of the additional annual costs of meeting even the most expensive Scenario 3 nationally (GBP123.01 million). Notably, if the ALFs were put purely to funding rural coverage, this would be more than sufficient to cover the additional cost requirement in all rural areas, even under Scenario 3.

A simple discount or removal of ALFs, without obligations to reinvest the funds in network roll-out, may have a limited impact on investment. Policies aimed at ensuring these funds are redeployed towards investment would therefore be needed.

One approach would be to run a subsidy scheme funded by ALFs that operators can bid for to support their investment in those areas where a market failure has been defined. The subsidy programme would need to define the aim of the subsidy very clearly.[12] The subsidy price could be set by the operators through bids to meet a specific target in the intervention area.

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[11] Barriers comprise other impediments or frictions within the market that can hinder the deployment and/or adoption of advanced wireless services.

[12] For example, the programme may need to define what the intervention area is, and what the target quality of service is that must be achieved by the subsidised investment.

An alternative may be to offer ALF rebates, contingent on meeting certain investment requirements and quality-of-service targets in the intervention area. The overall rebate to any one operator may have to be set at the lowest of the ALFs paid by all operators, to avoid a situation where the size of the rebate offered to an operator is greater than the amount it pays in ALFs. The price of the subsidy would have to be set by government and be calculated and applied in a transparent manner.

Increased network sharing could generate cost-efficiency savings, with the cost savings increasing when active sharing is introduced.

Passive sharing refers to sharing of the physical base station site between at least two operators, while radio equipment is kept separate. Active sharing refers to sharing of active equipment between at least two operators. We analysed four different sharing scenarios, which varied depending on the type of network sharing (passive and active) and the geographical basis (urban, suburban, rural or national).

If only passive sharing is assumed on all new sites, the cost savings per MNO are relatively modest, namely 4% at the national level. Cost savings increase when active sharing is introduced, up to 9% at the national level. Our analysis only captures the effect of sharing on any new sites that our modelling predicts would be required to meet additional target quality-of-service levels, as well as costs of adding capacity to the most rural (SRN) sites. Published evidence might suggest higher cost savings being achieved from network sharing in some other markets.

While the results are illustrative in nature, they demonstrate an important mechanism through which network sharing can directly affect the economics of network deployment. Network sharing generates network cost savings which can support the investment case for deployment in a given area. Where network cost savings are achieved through network sharing, this would reduce the additional revenue requirement and corresponding ARPU uplift requirements.

The innovations and benefits that the most advanced 5G services offer could be lost if network slicing is not offered on a widespread basis. This could occur if restrictions imposed by net-neutrality rules lead to uncertainty on whether to invest in 5G-SA services.

Some MNOs interviewed for this study suggested that restrictions imposed by net-neutrality rules could inhibit or delay roll-out of new services via network slicing.

To provide an illustration of the benefits of advanced 5G services that could be at risk without commercialisation of network slicing, we used our modelling Scenarios 2 and 3 (advanced enterprise traffic) to consider the associated cumulative GVA uplift from those services. The modelled enterprise traffic has an associated cumulative GVA uplift of GBP2.6 billion up to 2030, in 2020 terms.[13] This may be significantly impacted if uncertainty on network slicing slows down the timing of realising these benefits or leads to them not being enabled at all.

Specific enterprise demands and use cases could still be served by dedicated, on-premises private networks or supplied by MNOs using private networks rather than public mobile networks. In the event that MNOs are unable to offer tailored services to enterprises through differentiated network slices using public mobile networks, not all of the potential benefits associated with tailored connectivity solutions will be lost, as MNOs or alternative operators could still offer these via dedicated private networks. However, alternative operators face their own challenges that we explore further below.

Guidance could be issued to provide more clarity and certainty as to what constitutes a specialised service under net-neutrality rules, whether network slicing can be assessed as such, and how any detriment to the general internet access service (IAS) as a result of network slicing would be assessed. Further guidance on traffic management rules and the ability to enter into commercial agreements could also be introduced. However, this could result in unintended consequences of discriminatory traffic management against the principles of the open internet.

Alternatively, a network slice could be defined as a specific category of service, distinct from a specialised service and an IAS, for which traffic management with commercial considerations would be allowed, subject to the terms being fair, reasonable and non-discriminatory (FRAND). Ofcom could publish further guidance on how such FRAND terms should be interpreted in relation to network slices (although as we note in this report, a change in legislation would be needed to do this).

We considered steps that could be taken to lower barriers to entry for alternative (non-national) network operators in the UK. We found that key issues are access to spectrum, roaming agreements with national MNOs and access to mobile network codes.

Alternative operators may be able to provide solutions that are not provided over the MNO wide-area public networks. For example:

- private networks to meet specific needs in defined localities, or
- neutral host solutions provided over shared or local access spectrum in areas where there may not be full coverage by all MNOs.

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[13] This is the GVA uplift estimated from Scenario 2, which focuses on enterprise traffic, and reflects the GVA uplift that may be experienced by the businesses that will be served by the hypothetical modelled MNO with 25% market share. The overall GVA uplift across all business in the area that take up advanced wireless connectivity services could be as high as GBP10.4 billion in 2020 terms.

Steps that could be taken to ensure lower barriers to entry for these alternative provides include the following:

- Ofcom should identify solutions that offer exclusive network identifiers in private networks, rather than requiring operators to use the ITU code, which is not suitable to enable roaming with other networks.

- In the absence of access-related obligations, national roaming will be subject to commercial agreements, and the terms of the agreement will be open to negotiations. Given roaming may be needed either for alternative providers or for providers of private networks to ensure uninterrupted coverage, or for alternative providers with their own spectrum to allow MNO customers to roam onto their network in not-spot areas, there may be merit in Ofcom investigating the issues associated with roaming agreements further and whether it considers amendments to MNO licences may be required to mandate access requirements. This is particularly relevant if there is evidence of specific agreements not being reached and/or there is a failure to offer fair and reasonable terms of access.

- Steps could be taken to improve the speed with which the shared access licensing regime operates, to remove factors that could be slowing down the roll-out of local solutions provided by alternative operators. Automating the application and approval process would help remove a number of the constraints that are currently adding extra time and frictions into the process.

Lowering barriers to deployment is still a relevant issue in the UK market despite legislative changes, and should be kept under review.

Deploying wireless infrastructure requires operators to co-ordinate with a range of stakeholders and comply with a range of planning rules and regulations. Barriers may arise where there are practical challenges to deploying infrastructure which add complexity and/or are overly burdensome or time consuming, particularly where legislation is not clear. Such barriers can impede network deployment, in terms of increasing transaction costs or reducing the speed of deployment.

Significant progress has been made to make legislative changes to remove a large number of the practical deployment barriers raised by stakeholders, particularly with recent updates to legislation on the permitted development rights (March 2022) and changes to the Electronic Communications Code (November 2021).

While the recent changes are positive, it will be some time before the impact of these changes can be determined. In order for these changes to be made quickly and taken into account and implemented in a consistent way, support should be provided for operators, councils, landlords and intermediaries to better understand the revisions and implement the changes. A collaborative approach with government, operators and landlords will be needed to ensure everyone is aware of the changes and that these adjustments are implemented and reflected across the board in a timely manner so the benefits of the changes can be realised.

2 Introduction

In October 2021, the Department for Digital, Culture, Media and Sport (DCMS) engaged Analysys Mason, together with Oxera, to conduct a wireless connectivity project. The project has been commissioned to provide analysis and modelling that will help to formulate policies aimed at stimulating the wireless connectivity market in the UK to meet future market needs (for consumers, the public sector, enterprise and industrial users) over the course of the next decade.

The UK government's goal from the wireless infrastructure strategy is ultimately to set out policy goals for the mobile and wireless market through the remainder of this decade, including target quality of connection needed across the market (or in specific locations/environments), reflecting evolution of demand for wireless connectivity, in particular driven by the more advanced use cases that 5G can deliver.

2.1 Aims of the project

The aims of the project have been to:

- Assess the level of wireless connectivity needed to support future use cases over the next decade, taking into account different types of user and use case characteristics (such as latency, speed and mobility).
- Explore choices of wireless solutions in different environments and address different types of user/use-case requirements (also reflecting whether higher levels of connectivity bring additional benefits to the user). This would include aspects such as the role of private networks, satellite, Wi-Fi and alternative providers (e.g. providers of cellular connectivity on a localised basis, neutral host infrastructure providers, internet companies and others).
- Model how far the market will go to deliver cellular infrastructure (4G/5G) to meet future connectivity needs at different points in the future, reflecting the drivers and constraints affecting the suppliers of cellular connectivity.
- Investigate how suppliers might view the juncture between connectivity that is commercially viable and connectivity that is not, and in so doing, identify potential market failures and barriers that might slow down or prevent suppliers investing in infrastructure.[14]

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[14] By market failures we mean specifically a failure of commercial roll-out to reach areas where the social value of the investment exceeds the private cost of roll-out, but this may not be fully internalised in the private investment decision such that the

- Identify and assess demand- and supply-side policies that might address these barriers and/or failures and stimulate the market to meet future connectivity requirements.

2.2 Approach to the study

Analysys Mason and Oxera have conducted this study through a combination of desk research, extensive literature reviews, and our own analysis, together with a purpose built model and inputs gathered during the course of the study through twelve one-to-one interviews with a selection of UK industry stakeholders.[15]

The methodology for the study was as follows:

- We initially gathered information through reviewing published literature combined with a series of interviews conducted with UK industry stakeholders, to corroborate our assessment and modelling of the level of wireless connectivity needed, demand-side and supply-side policies that might be relevant to our analysis, and assumptions on a baseline model of cellular infrastructure delivery in the UK.
- We then developed a cost model, to investigate the costs of cellular network roll-out under different scenarios of mobile data traffic demand, together with the additional revenues to cover scenarios of additional infrastructure investment compared to a baseline model.
- Alongside the cost model, we developed commercial viability calculations, to assess the juncture between viable and non-viable cellular investments.
- Using information gathered from our literature review and stakeholder interviews, together with modelling results, we shortlisted demand-side and supply-side policies, and conducted an assessment of different options.

The model and any information gathered through the stakeholder engagement have been provided separately to DCMS. Information provided from this stakeholder engagement has fed into and has helped to shape the analysis described in this study.

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level of network infrastructure investment that would maximise social value is not met. Barriers describe other impediments or frictions within the market that can hinder the deployment and/or adoption advanced wireless services.

[15] The companies interviewed were BTEE, Three, Vodafone, VMO2, Samsung, Ericsson, Hewlett Packard Enterprise, Meta, Telet, AQL, Dense Air and the Satellite Applications Catapult.

2.3 Structure of this report

The remainder of this document is laid out as follows:

- Section 3 describes wireless connectivity in the UK market and how the supply market might evolve
- Section 4 discusses demand for wireless connectivity in the UK market
- Section 5 presents the extent to which the market will deliver on cellular (4G/5G) wireless connectivity
- Section 6 provides an overview of key issues holding back investment and the policy options that might apply
- Section 7 discusses identifying and addressing market failure
- Section 8 provides an assessment of the key barriers and associated policy intervention options
- Section 9 discusses conclusions from the study, and recommendations for further work.

The report includes annexes containing supplementary material:

- Annex A describes the evidence we have captured from a literature review into the wireless connectivity requirements of different economic sectors in the UK market.

3 Wireless connectivity supply in the UK, and how this might evolve

Wireless connectivity of multiple different types is increasingly being used within homes and businesses.

Although many businesses, consumers and the public sector in the UK will have access to broadband services via a fixed network, there are benefits of using wireless connections compared to a wireline network in some settings, such as where it is different to scale or move fixed cabling. These example settings might include production lines in factories or manufacturing, where wireless connectivity reduces cable network requirements and provide flexibility to move and scale up productions. For consumers, wireless connectivity creates the ability to access applications on the move using smartphones, tablets and other connected devices and to remain connected to the same applications when moving between locations. In the public sector, wireless connectivity underpins many essential public services including in the transport and healthcare sectors.

Enterprises and industrial users are rapidly accelerating their digital transformation initiatives, potentially requiring highly flexible, secure and reliable wireless connectivity suited to delivering bespoke applications. 5G network slicing[16] will potentially enable customised services to be provided to those businesses and others who are demanding these, but delivering network slicing requires a core network technology capable of configuring demand-led slices. Delivering network slices using cellular technology requires further evolution of 5G solutions in the UK market beyond those currently being deployed. Alongside this, dedicated private cellular networks are emerging in the UK using spectrum that Ofcom has made available on a shared use basis. In addition, enterprises might choose to deploy other wireless solutions, chosen based on their specific needs, preferences and budget (with examples of the numerous forms of wireless connectivity used in UK market including Wi-Fi, low-power radio, satellite or various bespoke wireless systems).

This section of the report examines the supply of wireless connectivity in the UK market, including:

- the role of the four national mobile network operators (MNOs) in providing cellular connectivity across the UK population, and the solutions they are deploying – these are called ‘public mobile networks’

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[16] Network slicing refers to the segmentation of the 5G network into virtual, bespoke networks that can provide distinct properties and characteristics to specific customers and use cases without the need to build separate, physical networks.

- the evolving role of private cellular networks that some enterprises, businesses and industrial companies might choose for bespoke deployments within their own premises for the purposes of their own business needs
- the emerging/alternative providers in the UK cellular connectivity space in addition to the four national MNOs; we include here new, local, cellular-based providers, third-party wireless and neutral-host infrastructure providers
- non-4G/5G wireless connectivity solutions (such as short-range wireless technologies used in the Internet of Things (IoT)), satellite connectivity, and evolution of Wi-Fi.

The section also examines current opportunities, trends and challenges relating to alternative players in the wireless connectivity market, including localised.

3.1 National public (4G/5G) cellular networks

Public cellular services in the UK are provided by four MNOs nationally: Three, VMO2, Vodafone and BTEE. These MNOs provide mobile connectivity using spectrum licensed to them on an exclusive nationwide basis. Three MNOs (BTEE, VMO2 and Vodafone) provide 2G, 3G, 4G and 5G services. Three entered the UK market as a 3G operator and now offers 3G, 4G and 5G.

Data traffic carried by mobile networks has grown significantly in the 4G era, and is continuing to grow as operators evolve their networks to 5G, as discussed in the following section. The number of 2G/3G connections in the UK has declined rapidly in recent years, and the majority of mobile connections and traffic is currently carried on the MNOs' 4G networks. In December 2021, a joint statement published by DCMS and the UK MNOs stated that operators do not intend offering 2G and 3G services in the UK beyond 2033 at the latest, as a result of the government's objectives to expand the diversity of telecommunications supply chains, and support transition to 5G.[17] Individual operators are expected to announce their own 2G/3G switch-off dates driven by their customer needs; the expectation is that 3G networks might be switched off first, because some 2G services might be required in the UK market for longer than 3G services (such as legacy machine-to-machine applications using embedded 2G devices). This viewpoint on 3G networks being switched off sooner than 2G has been confirmed by some MNOs in interviews conducted for this project.

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[17] See https://www.gov.uk/government/news/a-joint-statement-on-the-sunsetting-of-2g-and-3g-networks-and-public-ambition-for-open-ran-rollout-as-part-of-the-telecoms-supply-chain-diversificatio

Frequency bands used in mobile networks are specified in the industry specifications prepared by the 3GPP.[18] MNOs in the UK are assigned to use spectrum in nine different bands harmonised by 3GPP for cellular use, although it is only in a sub-set of these bands in which all four MNOs hold spectrum:[19] 700MHz, 800MHz, 900MHz, 1400MHz, 1800MHz, 2100MHz, 2300MHz, 2600MHz and 3500MHz.

In Sections 3.1.1 to 3.1.4 below we discuss the spectrum holdings and technology evolution of the national MNOs in more detail, and highlight the potential implications of these spectrum holdings on the network evolution strategy of each MNO, and the level of cellular connectivity being provided by each.

3.1.1 Spectrum bands and their evolution through the generations of cellular technology

Successive generations of mobile technology (2G, 3G, 4G and now 5G) have been built upon new generations of radio technology, with each generation building on the foundations of the previous one but based on new radio and core network technology and bringing additional capabilities, capacity and support for new features. The additional capacity created through successive generations of mobile technologies has been enabled partly through improvements in spectral efficiency brought about through the new generations of technology, but also through additional spectrum being awarded in the UK for MNOs to use.

Whereas 2G and 3G networks in the UK used three frequency bands (900MHz, 1800MHz and 2100MHz), 4G and now 5G has added several new frequency bands into the mobile ecosystem. Mobile operators have refarmed spectrum originally used for 2G/3G services to 4G, as data traffic has grown on 4G networks. Refarming of 2G/3G spectrum to 4G is a process involving significant hardware changes and spectrum re-configuration, given that the technology used for 2G networks in the UK (GSM) utilises narrow, 200kHz-wide, channels. Successive cellular generations from 3G onwards have used wider, 5MHz or 10MHz channels, and 5G technology uses very wide contiguous spectrum, such as 100MHz. Migration in 4G spectrum deployment to support 5G are occurring in the UK market currently. This migration from 4G to 5G requires less hardware changes than 2G/3G to 4G refarming, since technologies such as dynamic spectrum sharing (DSS) are available enabling existing 4G spectrum to operate 5G and 4G radios simultaneously from base stations in the same wireless carrier.[20] The increased use

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[18] The 3rd Generation Partnership Project is the standards body responsible for developing the industry’s 5G specifications.

[19] In the other cases, the band is split between two or three rather than four MNOs.

[20] https://www.ericsson.com/en/news/2019/9/ericsson-spectrum-sharing

of software solutions will result in less hardware being used in mobile networks in future, facilitating more rapid reconfiguration and upgrades, and lowering costs.

As discussed in Section 4.1.1, the majority of UK mobile subscribers have now transitioned away from 2G/3G use to 4G and 5G devices, and the bulk of cellular traffic carried on the MNOs' networks is 4G/5G.

The frequency bands used by the MNOs and the total spectrum available per MNO is shown in Figure 3.1 below. All nationally available public mobile spectrum in the UK is licensed to the four national MNOs. This means any localised cellular operators either needs to enter into arrangements to use the spectrum of one of the national MNOs, or can access spectrum via the local access and/or shared access spectrum authorisations that Ofcom has put in place (i.e. in the 1800MHz band, 1781.7–1785MHz and 1876.7–1880MHz, the 2300MHz band, from 2390–2400MHz, 3800-4200MHz and/or 24.25–26.5GHz). The latter band is currently only available for low power, indoor use. In the 3800–4200MHz band, individual applications can apply to use only up to a maximum of 100MHz bandwidth per licensed location. Of these bands, the only band most widely supported in mobile devices is the 1800MHz band, although with a growing ecosystem of devices expected in the 3800–4200MHz band.

Spectrum assigned to each national MNO is shown in Figure 3.1 below. Organisations other than MNOs wishing to deploy 4G/5G solutions (e.g. local cellular providers, or private LTE/5G network deployers) either need to enter into an arrangement with one of the MNOs to use spectrum from the bands licensed to each MNO, or apply for a 'shared access licence' or a 'local access licence' which are the local licences now available upon request from Ofcom in several bands, as noted above.

Local network providers can apply to Ofcom for access to the spectrum licensed to the national MNOs in bands covered by the Mobile Trading Regulations, in locations where shared access is feasible (i.e. where the MNOs themselves are not deploying the spectrum). When Ofcom published its local licensing statement in 2019, the spectrum bands covered by the Mobile Trading Regulations was in the 800MHz, 900MHz, 1400MHz, 1800MHz, 1900MHz, 2100MHz, 2300MHz, 2600MHz and 3.4GHz bands.[21] Ofcom subsequently assigned two additional bands via auction to

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[21] See paragraph 2.10 of https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

MNOs, in the 700MHz band and 3600–3800MHz. We understand the 700MHz and 3600–3800MHz bands are now part of the Mobile Trading Regulations.[22]

Ofcom is understood to be preparing to authorise access to the 26GHz band for outdoor, mobile and fixed broadband (FBB) services. The 26GHz band is not included in the table of bands in Figure 3.1, but we anticipate that MNOs would be interested to use the 26GHz band for outdoor, and indoor, 5G services in addition to the bands already available to them.[23] Higher bands such as 26GHz are most suited to providing coverage within localised areas, which might be outdoor high-footfall areas, or indoors. Example locations where the 26GHz band might be deployed include stadiums, transport hubs and city centres. The bandwidth available in the 26GHz band (24.25–27.5GHz) provides multiple 100MHz channels suited to very-high-capacity 5G services. This bandwidth might be needed to enable high-quality AR/VR[24] applications, remote object manipulation and very-high-speed mobile broadband (MBB).

Figure 3.1: Frequency bands licensed to UK MNOs for nationwide use (MHz paired/unpaired[25]) [Source: Ofcom, 2022]

Frequency band (MHz)	BTEE	Vodafone	Three	VMO2
700 (paired and unpaired)	10MHz paired plus 20MHz unpaired	-	10MHz paired	10MHz paired
800 (paired)	5MHz paired	10MHz paired	5MHz paired	10MHz paired
900 (paired)	-	17.4MHz paired	-	17.4MHz paired
1400 (unpaired)	-	20MHz unpaired	20MHz unpaired	-

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[22] Ofcom's regulations state that local licences are available in all bands covered by the Mobile Trading Regulations (which now include the recently auctioned 700MHz and upper 3.5GHz bands). See https://www.ofcom.org.uk/__data/assets/pdf_file/0037/157888/local-access-licence-guidance.pdf and https://www.legislation.gov.uk/uksi/2011/1507/schedule

[23] https://www.ofcom.org.uk/__data/assets/pdf_file/0029/228836/protecting-passive-services-at-23.6-24-ghz-from-future-26-ghz-uses.pdf

[24] Augmented reality/virtual reality

[25] In the table, there is a mix of paired and unpaired spectrum shown in some bands. This is because 2G, 3G and 4G technologies have predominantly used paired spectrum whereas new 5G New Radio (NR) bands (e.g. 3.5GHz) predominately use unpaired. However, an unpaired variant of 4G technology can use the 2600MHz band, and the 1400MHz band is designated as supplementary downlink spectrum (i.e. spectrum used to provide additional downlink spectrum, deployed to be paired with uplink spectrum from another band).

Frequency band (MHz)	BTEE	Vodafone	Three	VMO2
1800 (paired)	45MHz paired	5.8MHz paired	15MHz paired	5.8MHz paired
2100 (paired and unpaired)[26]	20MHz paired plus 10MHz unpaired	14.8MHz paired	14.6MHz paired plus 5.4MHz unpaired	10MHz paired plus 5MHz unpaired
2300 (unpaired)	-			40MHz unpaired
2600 (paired and unpaired)	50MHz paired	20MHz paired plus 25MHz unpaired	-	25MHz unpaired
3500 (unpaired)	80MHz unpaired	90MHz unpaired	140MHz unpaired[27]	80MHz unpaired
Total	**130MHz (paired); 110MHz(unpaired)**	**68MHz (paired); 135MHz (unpaired)**	**44.6MHz (paired); 165.4MHz (unpaired)**	**53.2MHz (paired); 150MHz (unpaired)**

3.1.2 Public cellular coverage

While all MNOs provide close to 100% population coverage for mobile data services using earlier generations of cellular technology (2G, 3G and 4G), this is not the same as geographical coverage, which lags population coverage as a result of urban areas in the UK being highly populated.

The 5G coverage footprint does not yet match those of earlier generations and is still being rolled out. The 5G coverage footprint varies between MNOs depending on the spectrum each has deployed to date, and also reflecting, as indicated in the previous section, that spectrum portfolios vary between MNOs.

In the context of further 5G roll-out, a key evolution will be migration to 5G stand-alone networks, referred to as 5G-SA. The migration to SA is important as this will be the platform to enable end-to-end, cross-domain capability (referred to as network slicing).

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[26] Note that the 2100MHz unpaired spectrum has been licensed to MNOs but is not used.

[27] Three also holds spectrum from 3925–4009MHz, acquired from its merger with UK Broadband. This spectrum is not permitted under the current licence from Ofcom for mobile use and so can be deployed for fixed wireless only, see https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/mobile-wireless-broadband/below-5ghz

The question of how far MNOs will deliver coverage on a commercial basis is complicated by the different solutions coming under the '5G' name, such as 3.5GHz compared to low-band, transitioning of the various existing bands described in the table above, 5G non-standalone (5G-NSA) and 5G-SA, and so forth.

There are different types of deployment that MNOs might describe as '5G'. These are discussed below.

► *5G mid-band/3.5GHz*

- 5G coverage using 3.5GHz spectrum (also called 'mid-band 5G') provides the biggest capacity uplift and user experience improvement over 4G. This type of 5G deployment is the most expensive to roll out since it uses advanced antenna technology that in some cases requires either strengthening of existing sites, or building of entirely new sites, to accommodate the additional weight of equipment. This deployment is currently concentrated in urban locations in the UK.
- MNOs have referred to 'pure' 5G (a combination of 5G-SA (i.e. 5G core networks), together with 3.5GHz deployment) as being the combination of solutions that they believe is needed to deliver the bespoke uplink and downlink capacity, and low latency, needed by enterprise and industrial users.[28] This combination of 3.5GHz roll-out plus 5G-SA deployment is not yet available in the UK but MNOs have indicated that 5G-SA deployment will be available from 2023.

► *Sub-1GHz bands*

- 5G in 3.5GHz brings an indoor coverage challenge, since the deeper indoor coverage that can be provided by sub-1GHz bands cannot be provided using 3.5GHz frequencies. Sub-1GHz spectrum tends to be favoured by MNOs for coverage into harder-to-reach locations, including indoors. Three of the four UK MNOs have 700MHz spectrum, which is one of the frequency bands harmonised for 5G use at a European level. This spectrum provides potential for wider coverage, since the physical properties of spectrum below 1GHz are more suited to covering wider areas, and also for providing penetration into buildings (useful for indoor coverage).
- As well as, or instead of, using 700MHz, MNOs might transition 4G use from other sub-1GHz bands (such as 800MHz or 900MHz) in line with traffic demand.

► *Existing mobile bands used by previous generations of mobile technology*

- One way to transition 4G spectrum to 5G that will increase the availability of 5G to other parts of the UK not covered by mid-band 5G, is to transmit 5G signals

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[28] https://techblog.comsoc.org/2021/10/06/telefonica-deutschland-o2-pure-5g-with-dss-open-ran-and-5g-sa/

in the bands used for previous generations of mobile technology (such as 1800MHz, 2100MHz or 2600MHz). This can be done through using technologies such as dynamic spectrum sharing (DSS). Since this DSS technology is a software solution using existing radio hardware already deployed at base stations, it is cheaper to deploy than 5G with 3.5GHz. Operators are using this to extend 5G coverage in the lower frequency bands, but the performance delivered by DSS in these lower frequency bands is inferior to the performance that the 3.5GHz band can offer and may not be significantly better than what could be delivered by 4G on the same frequency band.

3.1.3 Policy interventions to date

Previous interventions in the UK mobile market have focused on cellular coverage in locations where the business case for MNOs to deploy has been challenging (such as areas of very low population density, typically rural and remote locations), and addressing practical barriers to deployment.

In urban locations, factors including pace of traffic growth and user demand have encouraged operators to invest in higher-performing networks in urban locations, but operators have not delivered ubiquitous coverage across the UK landmass with any generation of mobile technology.

Policy focus to date on rural and remote coverage reflects not only that the demand in these locations is more limited as a result of low population density, but that the cost of deploying a mobile site in a rural area can be considerably higher than in other areas of the UK due to challenges of building sites in remote locations, the distance from the base station site to the network (i.e. the backhaul network), access to power, and planning considerations.

One recent policy intervention has been to expand the 4G geographic/landmass coverage footprint via the Shared Rural Network (SRN). The estimates in Figure 3.2 below summarise the expected coverage footprint for 4G post SRN. A key distinction is that in the last locations to be covered shown in the right-hand side of Figure 3.2 below, policy intervention is being used to build out a single grid of sites for operators to jointly use, rather than operators building out site grids independently, which occurs in the more populated areas.

Figure 3.2: SRN (4G geographical) coverage forecast improvement [Source: Ofcom, SRN, Mobile UK, 2022]

Region	Coverage from all MNOs		Coverage from at least one MNO	
	Jan 2021	Forecast post SRN (Jan 2027)	Jan 2021	Forecast post SRN (Jan 2027)
Overall (UK)	69%	84%	91%	95%
England	84%	90%	97%	98%
Northern Ireland	79%	85%	97%	98%
Scotland	44%	74%	81%	91%
Wales	60%	80%	90%	95%

The estimates in Figure 3.3 below use data from the GSMA together with 5G.co.uk to estimate the level of 5G outdoor population coverage as of end 2021, noting this is 5G-NSA. The figures below do not indicate the 5G quality of connection in different locations but provide an estimate of the proportion of UK population within areas in which 5G coverage is available.

In Section 5 of this report, the level of outdoor 5G connectivity we expect the market to deliver over the remainder of this decade is discussed based on a model that we have developed for this study to estimate future roll-out. That section also describes our estimate what average quality of connection the market might deliver at different dates over the next decade.

Figure 3.3: 5G deployment by MNO [Source: 5G.co.uk; GSMAi, 2022]

MNO	5G mobile commercial launch	Locations with 5G major towns and cities (all locations)	5G mobile population coverage, Q4 2021[29]
EE	May 2019	82 [162]	36%
Vodafone	July 2019	44 [124]	34%
Three	February 2020	85 [300]	40%
VMO2	October 2020	75 [194]	24%

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[29] Note that Ofcom’s Connected Nations 2021 report (published in December 2021) estimates that 5G is available outdoors from at least one MNO at 42–57% of premises. See https://www.ofcom.org.uk/__data/assets/pdf_file/0035/229688/connected-nations-2021-uk.pdf

3.1.4 Further evolution of 5G

While the initial 5G services in the UK have been rolled out largely to meet capacity requirements for consumer MBB use, the mobile industry has defined and standardised a series of evolutionary steps to enable 5G networks to offer advanced services to enterprises and businesses. These new services will be significantly aided through deployment of 5G-SA architectures, to enable MNOs to tailor network slices to different user needs.

5G-SA uses new, cloud-based core network architecture (5G core, or 5GC) working alongside 5G new radio (NR) technology (deployed in mid-band, 3.5GHz spectrum that is already being rolled out at selected base stations across the UK, for 5G NSA). The 5G-NSA services available currently use 4G core networks to deliver 5G MBB, and/or 5G fixed-wireless access (FWA). A 5GC enables what the mobile industry refers to as ‘slicing’, which refers to tailoring the quality of network connection of ‘network slices’ to meet specific use-case requirements. Network slices might be used to deliver use cases with high quality of service or bespoke connectivity needs that consumer MBB services do not require (such as guaranteed, high bitrates either in the downlink or uplink direction, or both).

Literature refers to 5G-SA architecture enabling the ‘full’ implementation of 5G capabilities across the three use case areas defined in the industry’s specifications for 5G as developed by the Third Generation Partnership Project (3GPP). These three use case areas are widely referenced and summarised as follows:

- Enhanced MBB is the 5G version of mobile broadband services provided by 4G, widely used by consumers. Enhanced MBB (or 5G eMBB) is available in some locations of the UK now and allows users to download and stream video, use smartphone applications and browse the internet. If within a mid-band 5G coverage area, 5G eMBB should be faster than 4G MBB, and the additional capacity that mid-band 5G provides within networks will mean that more users can maintain a higher average speed of connection.

- Massive machine-type communication (mMTC) are 5G-based IoT services. 5G will potentially enable many more devices to be connected in a given location and (depending on network deployment), more demanding IoT applications (e.g. requiring higher throughput, or lower latency), can also be delivered.

- Ultra-reliable low-latency communication (URLLC) refers to the 5G use cases that are the most depending in terms of network performance, requiring very low latency and high reliability of connection. URLLC applications might include highly immersive AR/VR applications, robotics or connected and autonomous vehicles (CAV) if connected via a 5G network.

From a market demand perspective, current 5G -SA deployment targets the eMBB applications described above and hence adoption of 5G-NSA devices is largely in the consumer sector as users upgrade handsets from 4G, to 5G. There is limited evidence in the market currently (other than via 5G testbed and trials prototypes) of what network capabilities the more advanced solutions of 5G mMTC and URLLC might cater for in practice once commercially deployed, nor how network slicing might be orchestrated to meet these requirements via 5G-SA networks. Further clarity on what these more advanced solutions will deliver, and what pricing will apply for users to have access to these services, will be fundamental to understanding the demand for these services emerging in the future.

Although 5G-SA deployment, and the network slicing capability this introduces, is generally associated with delivering more advanced, enterprise and industrial use cases, a further benefit of 5G-SA to the consumer market is that it would enable MNOs to differentiate between 4G and 5G traffic (and hence, for example, tariff pricing can be more flexible, which might present several benefits).

Indications from UK MNOs is that 5G-SA services will be rolled out in the UK from 2023 (see Figure 3.4). In March 2022, Vodafone together with Ericsson announced a network slicing trial using 5G-SA networks.[30]

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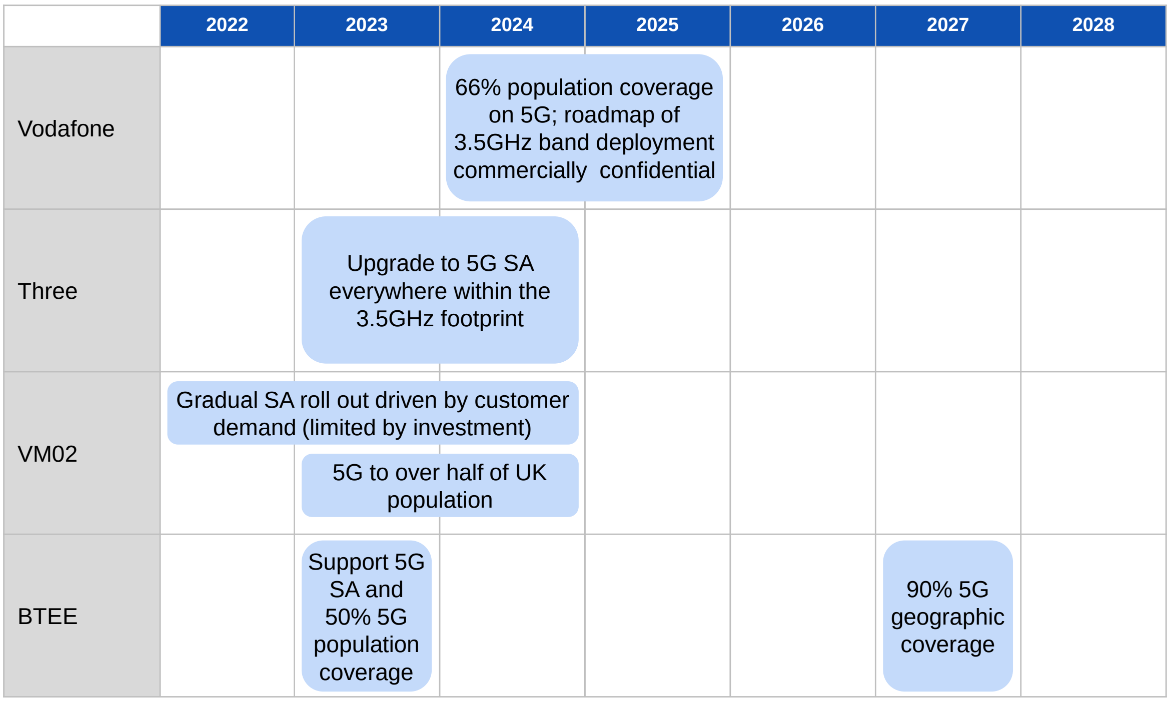
[30] https://www.ericsson.com/en/news/3/2022/ericsson-and-vodafone-create-uks-first-on-demand-5g-network-slice?msclkid=edcbbd0ea5d811eca4649d353270733c

Figure 3.4: 5G-SA roll-out [Source: Analysys Mason based on evidenced captured from stakeholder interviews, 2022][31]



	2022	2023	2024	2025	2026	2027	2028
Vodafone			66% population coverage on 5G; roadmap of 3.5GHz band deployment commercially confidential				
Three		Upgrade to 5G SA everywhere within the 3.5GHz footprint					
VM02	Gradual SA roll out driven by customer demand (limited by investment)	5G to over half of UK population					
BTEE		Support 5G SA and 50% 5G population coverage				90% 5G geographic coverage	

The implementation of bespoke network slices being configured by MNOs (or by users themselves) suggests a fundamental business model change for use of public mobile networks. Business-to-business (B2B) service capability will potentially sit alongside more traditional business-to-consumer (B2C) services that MNOs provide to MBB users. It is noted that in future MNOs may wish to differentiate pricing to some types of B2B user (e.g. enterprise and business) in response to the different quality of connections demanded by different users, and also possibly to vary prices based on other factors (e.g. relating to network congestion in different locations). There is a lack of clarity in the market currently on how this differentiated pricing might be applied, which reflects a mixture of technical and commercial challenges in implementing 5G-SA architectures. In the interviews conducted for this study, several challenges with 5G-SA roll-out, and associated pricing models, were raised:

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[31] The deployment ambitions presented here are based on either published statements or interview insights, and different operator ambitions do not necessarily align in terms of the years and technologies used in each target. Evidence has not yet been captured from VMO2 in this project as it did not respond to our initial interview request, however, at the time of producing this report, an interview is being scheduled. Published information can be found at https://news.virginmediao2.co.uk/building-5g-momentum-two-years-on-from-launch/

- The 5G-SA roaming landscape is still evolving (roaming services using 5G-NSA use the existing 4G core network roaming agreements that MNOs have entered into with counterparts in other markets). Data integrity and security using software solutions are two of the considerations relating to 5G-SA roaming.
- New models of wholesale billing might be required, but are not yet in place.
- 5G-SA roaming between different networks within the UK (e.g. roaming between different private 5G network domains, or from a private 5G network to an MNO's network) presents a further set of challenges relating to ensuring data integrity and security as well as quality of connection (e.g. maintaining a connection consistently across different operating environments).

The standards body responsible for developing the industry's 5G specifications, 3GPP, has designed the 5G core using what is referred to as a service-based architecture (SBA) and control/user plane separation (CUPS). This is so that core networks can be developed in a modular way and potentially enables operators to procure 'best-of-breed' core modules from different vendors. The 5GC will potentially also support seamless connection between multiple radio access technologies in future, such as between Wi-Fi and cellular, or satellite and cellular, as well as between different 5G deployment environments, such as between private 5G and a public 5G network. As described above, a mix of technical and commercial challenges are to be solved before different solutions will come together to offer a consistent user experience.[32]

Important architecture evolutions in parallel with 5G-SA are:

- Edge computing, which refers to distributed cloud computing that takes place in locations that are closer to users and sources of data than traditional cloud computing. Edge computing may take place on private or public premises: in the latter case, it can be delivered to customers as a (multi-tenant) service by public edge cloud providers.
- Network slicing, which, as already described, refers to the segmentation of the 5G network into virtual, bespoke networks that can provide distinct properties and characteristics to specific customers and use cases without the need to build separate, physical networks. These properties and characteristics may include differentiated security and quality-of-service features, performance capabilities and functionality. These functions can be selected and instantiated

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[32] There are different versions of 5GC implementation – some fixed–mobile operators might use a single core network supporting services across all their fixed and mobile traffic in a unified way. Mobile-only operators could use a single core network supporting services across public cellular and private cellular domains.

through software implementation referred to as a network slice selection function (NSSF).

The 5GC network (with the cloud-native core, NR (3.5GHz) and edge clouds) is thus expected to become the ‘services creation platform’ for the wireless connectivity that enterprise and industrial users will demand. The platform will be used to create separate network partitions (or slices) with unique network performance and latency characteristics to serve a particular use case or enterprise. A combination of networking technology innovations and other enablers in the transport network, such as segment routing and software-defined networking (SDN) will make end-to-end network slicing possible, but, as noted above, commercial implementation is still some way away (2023 at earliest in the UK).

Partnerships between different solutions providers might be needed to make end-to-end slicing possible – for example, cloud and internet providers, or hyperscalers providing public cloud services might work with MNOs, or with private 5G deployers, to run 5G applications and store 5G data. The role of hyperscalers is discussed in Section 3.4.

3.2 Private 4G/5G networks

A key trend gaining momentum in the UK market is that use cases requiring customisation of wireless connectivity to meet specific user demands (such as factory automation) are likely to be fulfilled through the deployment of private 5G networks.

The three main network deployment models for private LTE/5G networks have varying considerations in relation to costs and technical maturity:

- **Dedicated, on-premises networks:** This type of network is built specifically for the purpose of a single enterprise or industrial user. The network (comprising the radio access network (RAN) and core) as well as the edge computing assets are all privately owned and used internally by a single enterprise.[33] These networks are already emerging in the UK, and typically use private core deployments, in the absence of 5G-SA in public mobile networks. Some of these dedicated, on-premises networks are being provided by UK MNOs on behalf of enterprise or industrial users (using spectrum in the 3.8–4.2GHz band, available on a shared access basis).

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[33] https://www.analysysmason.com/research/content/articles/private-lte-5g-networks-rdme0-rma18-rma17/#:~:text=Private%20LTE%2F5G%20networks%20can,market%20is%20difficult%20to%20scale.

- **Hybrid networks:** A hybrid network can be built with a combination of public mobile network components and dedicated on-premises elements.[34] For example, a dedicated on-premises core network can work together with public radio network or public edge/public core to form a hybrid network with end-to-end slicing. This deployment model may be more capital cost-effective than the dedicated, on-premises network, and might be charged 'as a service', based on some form of service-level agreement, potentially with monthly charging. MNOs who we have interviewed as part of this study have mentioned that, in their view, clarity over whether net-neutrality regulations allow for private network pricing to be based on quality-of-service differentiation (rather than being a purely usage-based fee) represents one barrier to further investment by the MNOs into the hybrid private network approach.

- **Network slicing:** This approach becomes viable as operators migrate to using 5G-SA in combination with 3.5GHz deployment. It is similar to the hybrid approach above but would imply using existing macro or small cells within a public cellular network to provide the radio network (rather than deploying dedicated on-premises elements), together with the public edge/public core network from that MNO. It should be possible to slice together the public network capacity and dedicated on-premises elements in future, giving dynamic sharing between the bandwidth available (e.g. in the 3.5GHz band, together with 3.8–4.2GHz in the specific location of the user).

An alternative solution to using a private 4G/5G network might be to use Wi-Fi (see Section 3.5.1). A private network, using 4G/5G and/or Wi-Fi, might be provided by an MNO, a vendor, a third party enterprise solutions provider or by an alternative cellular network provider (see Section 3.3).

A combination of factors such as business need, cost and investment considerations and technology maturity are expected to dictate whether enterprise or industrial users will opt for dedicated on-premises private networks or a hybrid/network slicing strategy (or, might use a combination of both). Enterprise or industrial users who already deploy their own telecoms services might prefer a dedicated, on-premises solution simply due to preferring to build and operate their own networks. Being able to scale up private networks as more devices are added, or having use cases with connectivity requirements that are materially different than MBB traffic – such as applications requiring higher levels of uplink capacity - might also be a reason to choose this solution compared to using a public cellular network. This would particularly be true if the bespoke nature of applications that some enterprise and business customers might require suggest this deployment can be done more effectively within their own environment. The market is still nascent, but

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[34] Ibid.

there is strong potential for growth especially with growing adoption of complementary technologies such as edge computing/edge cloud, as noted above.

Analysys Mason's private 4G/5G network tracker reports on quarterly increases in private network deployments globally. From the most recent tracker (published November 2021), the highest number of publicly disclosed private LTE/5G network deployments are located in Western Europe (including the UK), with 103 deployments out of a total of 256 globally announced.[35]

The data from November 2021 suggests that the primary demand driver of private LTE/5G network is for smart factories, followed by mining sites and ports.[36] The data also suggests the majority of the publicly disclosed private LTE/5G networks deployed in the third quarter of 2021 were delivered by mobile equipment vendors. However, MNO participation in private network deployment is growing, and Analysys Mason's data suggests that MNOs are the main contractor in nearly a third of the private LTE/5G network deployments globally.[37] The third most common main contractor is specialist network providers, such as Edzcom (which was acquired by Cellnex in 2020). Alternative providers are discussed in Section 3.3.

Most private 5G deployments currently are of the dedicated, on-premises sort described above. Hybrid and network sliced variants are not expected to emerge at scale until 5G-SA networks are rolled out. It is noted that private cellular networks using 4G technology (i.e. LTE) have been available for some time. These private 4G networks also tend to be dedicated, on-premises deployments. A key reason for transitioning from 4G to 5G technology will be to support the lower latency connections that 5G radio operating in mid-band 5G spectrum can provide. Private 5G networks could hence cater for a diverse range of real-time applications requiring high reliability of connection that could not be fulfilled by LTE technologies, such as automated guided vehicles (AGVs), industrial robotic equipment and real-time asset tracking.

In our previous study for DCMS on 5G demand and the benefits of 5G, we identified several factors that might present barriers to adoption of 4G/5G private networks. A brief summary of these are as follows:

- **Cost and complexity**: Private LTE/5G networks may be more expensive to deploy relative to solutions using licence-exempt spectrum (e.g. Wi-Fi), due to potentially higher LTE/5G network component costs, as well as pricing models that MNOs and/or alternative providers might charge to provide dedicated end-

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[35] https://www.analysysmason.com/consulting-redirect/articles/private-networks-trends-rma17/

[36] Ibid.

[37] Ibid.

to-end slicing. Since cost is a barrier, we identified in the previous study that adoption might be limited to large enterprises that are willing to pay the high prices. Smaller enterprises will more likely be able to launch their own private LTE/5G networks in future as prices of components decline or as the hybrid deployment model becomes more mature.

- **Slow pace of change/cultural resistance**: Industries may be slow to react to changes in technology, especially where private network deployment may not be the most urgent investment required when undergoing digital transformation initiatives.
- **Immature business models**: The pricing models for private networks offered by means of a network-slicing deployment model are not yet clear. Pricing based on operational expenditure (opex) or software as a service (SaaS), such as those offered by the hybrid deployment approach, might appeal to some users. Other industries might prefer an upfront, capital-driven approach featuring dedicated, on-premises deployment. Fragmentation is therefore a risk.
- **Complexity and skills**: It is complex to deploy and manage a private LTE/5G network, which may hinder potential adopters. Specialised skills such as network design, deployment and system integration are required to set up a private network.

In addition, private LTE/5G networks have to operate on suitable available spectrum in the location of interest. This potentially gives rise to several questions such as scalability of solutions (e.g. a private provider wanting to use the same spectrum in multiple locations of the UK so to benefit from equipment economies of scale may not be able to do so if the same frequencies are not available in all locations of interest), and hoarding (e.g. the first-come, first-served approach to making spectrum available for local use might risk earlier competitors securing rights to use spectrum in given locations and then not actively using these assignments, to the detriment of later entrants). These issues are further explored in Section 8.

Ofcom was in the first wave of European national regulatory authorities (NRAs) to make spectrum available for private 5G deployment. One of the key bands that Ofcom has made available, 3800–4200MHz, now looks set to be adopted more widely in Europe. The European Commission’s Radio Spectrum Policy Group (RSPG) published an opinion in June 2021 recommending possible use of the 3800–4200MHz band for ‘local vertical applications’ (low/medium power), which is in line with what Ofcom has already implemented as part of its shared access licensing in the UK.[38] Ofcom has gone further than regulators in some other

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[38] https://rspg-spectrum.eu/wp-content/uploads/2021/06/RSPG21-024final_RSPG_Opinion_Additional_Spectrum_Needs.pdf

European countries and has made available four different bands under shared access licensing. In additional, local access licensing enables third parties to apply, via Ofcom, to use the spectrum of national MNOs in selected location(s) if the MNO is not deploying spectrum at that location.

The following is a summary of spectrum options for private network deployment in the UK:[39]

- Shared access licences are available in 1800MHz (1781.7–1785MHz paired with 1876.7–1880MHz), 2.3GHz, 3.8–4.2GHz and 26GHz on a first-come, first-served basis per location.
- There are two types of shared access licences
  - low-power licences issued per area
  - medium-power licences issued per base station.
- Shared access licences are available per 10MHz (up to 100MHz) in 3.8–4.2GHz, per 10MHz in 2.3GHz bands, and per 2×3.3MHz in the 1800MHz band.
- For the 26GHz band, 50, 100 or 200MHz channels can be applied for, but are for indoor use only.
- Local-access licences are available in any frequency band covered by the Mobile Trading Regulations, subject to availability, allowing access to spectrum unused by MNOs.
- Alternatively, private networks using Wi-Fi can operate within licence-exempt spectrum in the 2.4GHz, 5GHz or lower 6GHz bands.

3.3 Alternative providers of 4G/5G infrastructure

Private LTE/5G networks can be provided by several different types of suppliers: nationwide MNOs, as well as alternative providers (including equipment vendors, cloud companies and industrial network specialists). Alternative, non-nationwide cellular providers can also offer public mobile services, and may also offer 5G-based FWA as a broadband solution to homes or businesses. Telet and AQL are examples of these alternative providers, profiled in Section 3.3.1 and 3.3.2 below.

If intending to offer services directly to consumers or businesses, operators will need to be assigned a mobile network code (MNC) and mobile subscriber identity modules (SIMs). National roaming onto UK MNO network infrastructure might also be a

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[39] https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation

requirement, which is why some of the prominent alternative providers in the UK, such as Telet and AQL, have become members of the GSM Association (GSMA).

Although some alternative providers, such as Telet, aim to provide services directly to consumers, there are other alternative providers operating or intending to operate as neutral hosts for infrastructure, offering radio and/or core infrastructure hosting services to users provided by MNO and/or mobile virtual network operators (MVNOs). This results in a range of different types of alternative providers emerging in the UK market, as discussed below.

3.3.1 Telet

Telet is a UK company set up to improve mobile coverage in rural not-spots,[40] and to deliver wireless connectivity to enterprises. Telet is proposing to provide services in selected mobile not-spot locations, using shared access spectrum available from Ofcom in the 3.8–4.2GHz and 1800MHz bands.

Telet was originally set up to provide mobile coverage in a local mobile not-spot (Chalk Valley). Utilising shared access spectrum, Telet might offer 5G-based FWA as well as connectivity direct to mobile devices.

The operating model of the company was described as a multi-operator neutral host (MONH) model. The company installed small-cell radio infrastructure within not-spots under a shared access licence, and then entered into roaming agreements with UK MNOs so that users can roam onto a UK MNO network when outside of the coverage of the not-spot local network.

3.3.2 AQL

AQL is a UK-based, privately owned group of telecoms companies operating across the satellite, fixed and mobile space. In the fixed market, the company holds over 100 million telephone numbers in the UK, plus numbers outside of the UK. It is a fully licensed telecoms operator in the Isle of Man and owns a wireless network operated in the Isle of Man (BlueWave), which currently owns spectrum in the 3.5GHz band. AQL's website indicates that it was the "driving force behind establishing both IXLeeds, a fully independent internet exchange outside London, and the Isle of Man's first and only internet exchange, ManxIX".[41]

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[40] Ofcom defines 'mobile not-spots' as areas where people cannot access mobile services from any supplier. See https://www.ofcom.org.uk/__data/assets/pdf_file/0024/46158/not-spots.pdf

[41] https://aql.com/about/who-we-are/

The company holds ‘code powers’ (i.e. the right to install telecoms equipment) in several overseas markets (including small island nations such as the Isle of Man), for the purposes of providing internet peering and roaming connectivity. It is also active in the satellite space, providing connectivity for ground station infrastructure being built in the Isle of Man as part of the SpaceX/Starlink programme.

AQL’s role in the UK market can be described as a provider of data centres, network interconnection and enterprise data services (for example, SIMs for IoT connectivity, using several network technologies including cellular and also long range radio wide-area networks (LoRAWAN), which refers to various forms of wireless solution typically using licence-exempt spectrum in the UK (e.g. in the 868MHz band). AQL also deliver solutions to UK internet service providers (ISPs), which then provide B2C and B2B services to their end users.

In the context of 5G, AQL is aiming to offer 5G services to different economic sectors (its website mentions healthcare, education, defence, logistics and maritime as key sectors). Its GSMA membership status implies that it intends to make use of GSMA-defined roaming agreements with national MNOs to operate neutral host infrastructure, with end-to-end slicing through the deployment of a mobile 5G core network plus edge functionality (utilising its own existing distributed data centre and fixed interconnection solutions).

3.3.3 Third-party and neutral host infrastructure providers

Infrastructure providers include companies such as Cellnex Telecom, Dense Air, WHP Telecoms, BAI Communications and others. There are typically three types of environments in particular in which neutral host infrastructure providers are emerging with solutions for specific cellular coverage – indoors, in dense city locations, and for rural coverage. Additionally, companies such as Cellnex Telecom offer a tower portfolio across the UK market, which are widely used by UK MNOs.

A key difference between neutral host infrastructure and towers provision is that the neutral host provider plans the site and deploys the infrastructure needed to use the site (such as radio equipment and backhaul). MNOs then pay to use the infrastructure. This is different from MNOs paying to use third party towers such as those managed by Cellnex, since if paying to use a third-party tower, the MNO will typically install its own equipment at the site. Network upgrades when installed on a tower are MNO-led whereas the neutral host provider is responsible for network upgrades in a neutral-host infrastructure. This leads to some disadvantages for MNOs when using neutral host infrastructure since there is less flexibility to change/upgrade the infrastructure than if the MNO is installing its own equipment on a tower.

For neutral hosts to be successful, they need to play a role that is supportive of 4G/5G network roll-out amongst all the MNOs paying to use the infrastructure. The deployment must either reduce the cost of rolling out a solution compared to independent MNO deployments, or enable other benefits (such as more rapid deployment in a location that the MNO wishes to deploy) for it to be viable for the MNO to use. This might be achieved through:

- private investment in solutions for operators, which allow operators to achieve capital expenditure (capex) savings
- the use of more compact equipment/solutions that can be easily shared.

It might be beneficial for neutral host providers to offer services in the context of indoor small-cell infrastructure deployment, for example, where there is limited space for multiple separate deployments.

Another potential environment where there is a high level of capex associated with expanding cellular coverage is in rural areas. Operators may experience difficulty in extending independent coverage footprints in rural areas, and hence network sharing and/or use of a neutral host may be a solution. The SRN involves the deployment of base station infrastructure upon which MNOs can add their own radio equipment. A previous intervention by the Scottish government (4G infill) awarded a contract to infrastructure provider WHP Telecoms to deploy infrastructure for MNOs to use.

In the following subsections, we provide examples of the various infrastructure providers in the UK.

► *Dense Air*

Dense Air is a neutral host network in the UK that is involved in the DCMS 5G Testbed and Trials programme within the AutoAir project. The company is deploying its small-cell technology and network densification solutions at the Millbrook Proving Ground to support the development, testing and validation of connected and autonomous vehicles (CAVs).[42] The AutoAir project involves dense outdoor network deployment and creates a testing environment for future 5G networks using hyper-dense small cells in the UK.

Besides its involvement with the AutoAir project, Dense Air also utilises its small-cell technology for mobile network densification, rural broadband connectivity

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[42] https://denseair.net/autoair-c2i-2020-winner-uk-5g-test-bed/

extension and private networks. In December 2021, it was announced that Dense Air is being acquired by Sidewalk Infrastructure Partners.[43]

- ► *Cellnex Telecom*

Cellnex Telecom is one of the largest neutral hosts in the UK, and provides infrastructure as a service (IaaS) to operators. Services include distributed antenna systems (DAS) and small cells, telecoms infrastructure services and broadcasting networks, among others. Cellnex Telecom acquired the telecoms division of Arqiva in 2019, which included 7400 sites and marketing rights for a further 900 sites in the UK. The company now owns or controls approximately 9000 sites in the UK and has access to a widespread network of street-level assets for outdoor small cells and 5G deployments in urban areas.[44] Cellnex's strong portfolio of telecoms infrastructure has enabled it to form partnerships with all four UK MNOs, as well as many private businesses and emergency services users.

- ► *WHP Telecoms*

WHP Telecoms is the UK infrastructure provider selected by the Scottish government to fulfil the 4G-infill project in Scotland (in partnership with the Scottish government and Scottish Futures Trust). The programme provides funding to WHP Telecoms to install wireless masts (towers) in selected rural communities. WHP Telecoms is responsible for acquiring, designing and building each site, as well as connecting to power and backhaul (e.g. fibre). This builds upon the company's role in the wider UK market, where it provides site-sharing services to the mobile operator market as well as to ISPs and local providers.

In the 4G-infill project, WHP Telecoms is also responsible for negotiating the required leasing agreements with UK MNOs so that the MNOs can install radio equipment onto masts, and provide mobile services to consumers within not-spot locations.

- ► *BAI Communications*

BAI Communications is the company selected in August 2021 by Transport for London (TfL) to provide 4G- and 5G-enabled neutral host infrastructure in London Underground stations and tunnels. The contract is described as a 'concession to design, build and implement' a fixed and mobile network and to build an emergency services network, utilising assets within the TfL estate, such as fibre and site locations. The network is to be 4G and 5G ready (i.e. to enable UK MNOs to utilise the infrastructure to provide 4G/5G connectivity to consumers within underground

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[43] https://denseair.net/sidewalk-infrastructure-partners-will-acquire-5g-innovator-dense-air/

[44] Ibid.

stations), and also includes Wi-Fi and fibre in tunnels and in stations, for London Underground's own use and for use by emergency services.

3.4 The role of web hyperscalers in the UK mobile market

The term web hyperscalers, in the context of this study, refers to public cloud providers (PCPs) that provide public cloud infrastructure and related services, e.g. Amazon Web Services (AWS), Microsoft Azure, Google Cloud, IBM and others.

There is potential for hyperscalers to play a significant role in the development of 5G and wireless infrastructure not just in the UK but generally, as they are already involved in several key areas that will form part of 5G-SA deployments.

3.4.1 Cloud infrastructure

Cloud infrastructure is an important element of 5G mobile networks. As described earlier in this section, the 5G core network is also the first mobile network to be supported by cloud infrastructure. Both 5G-SA core and Open RAN require a cloud platform. Hyperscalers are interested in the opportunity to venture into these domains, where they could leverage their public cloud expertise to offer cloud solutions.

Hyperscalers provide two types of cloud infrastructure: public cloud (shared IaaS) and cloud technology stacks such as Google Anthos and Microsoft Azure that enterprises can run on their premises. The latter is of particular relevance to the deployment of private 5G networks for enterprise and industrial companies. If using shared access spectrum, enterprises and industrial companies could bypass MNOs entirely by working directly through web hyperscalers and existing system integrators.

There has been much discussion over whether telecoms operators are more inclined to use the infrastructure of PCPs to build their network rather than building their own network clouds. Forecasts suggest that PCPs will capture approximately 21% of all spending on network cloud stacks by 2026, as operators increasingly opt to build 5G cloud platforms using PCP cloud technology stacks.[45]

Meanwhile, discussions regarding cloud for Open RAN have started to gain traction in Europe. Vodafone, for instance, showcased connectivity based on open and interoperable standards during the G7 summit in Cornwall (UK) in June 2021.[46] Open RAN would also potentially allow operators to opt for cloud solutions from providers based in Europe, such as SUSE and Canonical, rather than US-dominated PCP cloud stack providers. This would reduce the total cost of

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[45] https://www.analysysmason.com/research/content/reports/cloud-infrastructure-forecast-rma16/

[46] https://www.analysysmason.com/about-us/news/newsletter/open-ran-tip-jul2021/

ownership and avoid supplier lock-ins,[47] further facilitating the roll-out of cloud infrastructure in Europe.

Future growth in edge computing will also require edge data-centre locations, and in this context operators currently possess more suitable locations than hyperscalers. As 5G networks continue to enable more applications to be accessed in future via mobile devices connecting to cloud-based applications (i.e. metaverse, referring to a network of three dimensional worlds, proposed by companies such as Meta), it may be in the best interest of PCPs to form partnerships with operators to co-develop cloud-based infrastructure.

3.4.2 Platform services

Hyperscalers are also providers of cloud-based software (e.g. IoT platforms, AI/analytics tools, and data management services). This may put hyperscalers in competition with MNOs and alternative providers for provision of some solutions, such as cloud-based solutions to enterprises and businesses. For example, AWS has launched a private 5G solution, which it is offering as a managed service.[48] MNOs are also offering managed services – for example, Vodafone is developing IoT platforms for business customers in which Vodafone is seeking to develop direct relationships with vertical industry app developers.[49]

However, hyperscalers may have some advantages over telecoms operators in the applications development area, as they potentially have more experience cultivating strong and expansive application development communities. These trends suggest that there could be incentives for MNOs and hyperscalers to co-operate on the provision of these services.

3.4.3 Hosting of mobile core network functions

Apart from edge cloud and platform services, hyperscalers may also play a role in the telecoms value chain with regard to opportunities to migrate to the cloud. In this area, hyperscalers seem likely to play an enabling role, as opposed to being in direct competition with 5G network providers that offer mobile connectivity directly to consumers.[50] Regardless, and as evidenced by the interviews conducted for this study, mobile operators will likely seek to retain control over their networks and

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[47] https://www.analysysmason.com/research/content/perspectives/open-ran-reality-rdns0-rma18/

[48] https://aws.amazon.com/private5g/

[49] https://www.irishtimes.com/business/technology/vodafone-introduces-new-iot-focused-app-development-platform-1.3934976

[50] https://www.analysysmason.com/research/content/articles/operator-hyperscaler-partnership-rdns0/

network quality when migrating to the cloud, in order to closely manage customer expectations, reduce churn and improve retention.

Currently, Microsoft Azure is the only hyperscaler that owns mobile network functions, following its acquisition of Affirmed Networks.[51] It provides technology stacks for private wireless networks, from on-premises edge computing in industrial premises to mobile network functions, and adopts a B2B strategy instead of marketing directly to consumers.

Hyperscalers are also investing directly in network roll-out to offer connectivity, though primarily in areas that are not covered by existing operators. This is more commonly seen in developing markets. Private LTE/5G networks are also a promising area for hyperscalers to develop infrastructure for in future.

Several partnerships between hyperscalers and operators have been set up to create mutual benefits for both types of stakeholders. Operators can leverage third-party cloud infrastructure, as well as cloud-based software from PCPs, to maximise their opportunity. Meanwhile, PCPs can make use of strategic operator locations to roll out their cloud stacks. Some examples of these types of partnerships include AWS wavelength with SK Telecom, Google Anthos with Vodafone, and Microsoft Azure with Telefónica.[52]

In order to play a larger role in the mobile market, hyperscalers will need to overcome a number of challenges. First, there is a need for hyperscalers to establish relationships with value chain partners (see Section 3.8). Second, hyperscalers will also have to grapple with the same concerns that telecoms operators typically have, such as achieving suitable returns on investment, understanding and generating demand for 5G and edge cloud, finding optimal edge locations for roll-out, and managing concerns regarding the regulatory requirement (e.g. net neutrality).

3.5 Alternative wireless solutions

There are a number of existing alternative wireless options to 4G/5G cellular, which might be particularly suited to specific coverage environments. These solutions are already widely used in the UK market and are expected to continue playing a role in the market.

4G/5G cellular solutions typically use licensed spectrum (or shared access spectrum, for private 4G/5G networks). The other main alternative wireless

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[51] https://blogs.microsoft.com/blog/2020/03/26/microsoft-announces-agreement-to-acquire-affirmed-networks-to-deliver-new-opportunities-for-a-global-5g-ecosystem

[52] https://www.analysysmason.com/research/content/videos/public-cloud-partners-summit-rma14/

solutions, such as Wi-Fi, typically use licence-exempt bands (e.g. in the UK, 2.4GHz or 5GHz, and the lower 6GHz band).

Alternative wireless solutions are described in Section 3.5.1 and 3.5.2 below.

3.5.1 Wi-Fi

Wi-Fi is primarily positioned in the UK market as a private wireless networking solution and has an extremely well-developed ecosystem. In the UK market context, Wi-Fi provides the main form of wireless 'last-drop' connectivity for many connected devices in homes, offices and industrial settings. Ongoing roll-out of fibre broadband in the UK has further expanded the use of Wi-Fi as the in-premises connection point for devices connecting to fibre broadband.

Wi-Fi technology has evolved since its original design from the initial standards designed to use the 2.4GHz band, to also using spectrum in the 5GHz band. The 5GHz band benefits from greater capacity/bandwidth, and ability to support additional, wider channels. IEEE802.11ax (also referred to as Wi-Fi 6) is the latest iteration of the Wi-Fi standard to reach commercialisation. It brings further new technology iterations such as higher-order modulation and multi-user MIMO[53] technology to increase data speeds, improve quality of service and better enable Wi-Fi technology to deliver use cases requiring stable quality of connection.[54]

Since most smartphones used in the UK market are Wi-Fi enabled, Wi-Fi is used extensively together with cellular network connectivity as well as forming the last drop for fibre connectivity to premises. Wi-Fi offloading is a common term used to describe the process of offloading mobile data traffic from 3G/4G networks onto Wi-Fi when a mobile device user is within range of a Wi-Fi hotspot. UK MNOs such as VMO2 have invested previously in 'public Wi-Fi' solutions, which are Wi-Fi access points installed in public places, for the purpose of offloading traffic from VMO2's 3G/4G networks.

Wi-Fi vendors are currently part of a global campaign seeking additional licence-exempt spectrum bands to be available globally for Wi-Fi expansion. The spectrum of interest is above the current 5GHz band (from 5925MHz up to 7125MHz).[55] This band forms part of a 6GHz fixed link band in the UK, as well as being allocated globally for satellite use. It also overlaps with spectrum included in 3GPP specifications for 5G new radio (3GPP band n96). Hence, mobile operators are also interested in using part of the 6GHz band (from 6425MHz), in public mobile networks.

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[53] Multiple-input and multiple-output.

[54] Such as presented by AR/VR use.

[55] For example, see https://www.ncta.com/positions/spectrum-wifi

In Europe, countries including the UK have confirmed that spectrum from 5925–6425MHz will become a licence-exempt band to accommodate future Wi-Fi systems. In other markets, such as the USA, the entire 6GHz band (5925–7125MHz) has been authorised for Wi-Fi use. The future use of the upper 6GHz band, from 6425–7125MHz, is under study in Europe ahead of the World Radiocommunications Conference in 2023 (WRC-23), in which future use of the band within ITU Region 1 (Europe, Africa and the Middle East) will be considered.

From the evidence gathered in the interviews conducted for this project (which we assume is also reflected in evidence that individual firms have submitted to DCMS), it can be concluded that there are polarised views on what the best use of the upper 6GHz band might be in the UK in the future.

The band is both attractive to:

- mobile operators for deployment in wide-area mobile environments in public mobile networks, mainly to provide capacity in areas where there will be the highest traffic loads (for example, wide-area MBB traffic concentrated in urban areas)
    - mobile operators show a preference for the upper 6GHz band being a licensed band, to support 5G expansion under similar conditions of use (e.g. ability to deploy on existing macro sites)
- Wi-Fi and/or low power radio proponents wanting to use the spectrum to provide the maximum number of channels (and the highest data speeds) available from technologies such as Wi-Fi 6G in localised environments
    - Wi-Fi proponents favour a licence-exempt approach as being suited to localised use, potentially similar to that in markets such as the USA where the entire 6GHz band has already been designated for unlicensed use.

The band might also be attractive for provision of additional capacity to meet the demand for bespoke enterprise solutions delivered using private cellular networks. These bespoke solutions would be similar to those that can be deployed via Ofcom’s shared use licensing in the 3.8–4.2GHz band in the UK.

It should be noted that Ofcom has recently made additional spectrum available for Wi-Fi in the lower 6GHz band. There is reportedly a limited supply of Wi-Fi 6 devices[56] and thus it is assumed the lower 6GHz band is as yet lightly used. It is hence challenging for policy makers to judge the future demand for Wi-Fi 6 and

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[56] For example, https://www.techspot.com/news/93302-analysts-manufactures-might-skip-over-wifi-6e-due.html

whether this future demand would require further additional spectrum in the upper 6GHz band, in addition to spectrum already available for Wi-Fi use.

The quality of a Wi-Fi connection can be considered in terms of the available throughput (affecting the average user experience), and the number of channels and total bandwidth available (affecting the peak speeds). Wi-Fi 6E (which is a Wi-Fi device capable of operating in the 6GHz band) uses wider bandwidth channels that offer higher throughput per channel. Hence a benefit of using Wi-Fi 6E is that both average and peak speeds might be improved for Wi-Fi applications in this band. The peak speed metric might be especially important for future AR/VR use cases for which a 'good' user experience will require a very-high-speed connection to improve the quality of immersion. Inconsistent throughputs will also affect user experience for future AR/VR applications and hence a benefit of having more spectrum for Wi-Fi would be so that throughputs are consistently higher per user. In both of the bands used by Wi-Fi in the UK today (2.4GHz and 5GHz) there are already significant, and growing, numbers of Wi-Fi devices. There is therefore a risk of localised congestion occurring, which would mean that consistently higher speeds cannot be guaranteed.

We understand that DCMS is considering future demand for spectrum in the UK in a separate study that is running concurrently to this one, and hence the purpose of this report is not to draw conclusions on future spectrum demand.

We note there is also a 60GHz version of Wi-Fi called IEEE802.11ay (sometimes referred to as 'WiGig'), which is likely to be relevant to commercial wireless deployments in some settings in the UK (WiGig forms part of technology solutions being trialled in DCMS's 5G Testbeds and Trials programme). Ofcom has already made regulatory changes to extend current licence exemption for short-range wireless systems from 57–66GHz up to 71GHz.[57]

3.5.2 Intelligent Transport Systems (ITS)

Intelligent Transport Systems (ITS) or co-operative ITS (C-ITS) refer to the low-power wireless systems that might be used to provide connectivity directly between vehicles, and between vehicles and roadside infrastructure. European policy promoted by the European Commission aims to make more use of C-ITS systems in the transport sector in Europe. C-ITS deployment will require vehicles to be equipped with low-power radios, designed to use the 5.9GHz spectrum band, which has been harmonised for this use in Europe. As well as communicating with other vehicles equipped with 5.9GHz radios, vehicles might also communicate with either roadside infrastructure (in the form of small wireless roadside units (RSU) that road

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[57] See https://www.ofcom.org.uk/consultations-and-statements/category-3/implementing-decisions-57-71-ghz-band

operators might deploy, also using the 5.9GHz band), and/or with cellular networks. If communicating with cellular networks, the connectivity would use the existing macro networks of MNOs, and would require vehicles to be equipped with cellular as well as 5.9GHz modems. The types of services that C-ITS might provide for vehicles include warning and assistance messages to vehicles on road conditions, roadworks, speed limits, incidents or other route-related information.

There are primarily two competing technologies that have been designed to provide C-ITS systems in Europe. One of these technologies is a Wi-Fi based technology called IEEE802.11p and the other is a cellular-based technology called cellular vehicle to everything (C-V2X). The current generation of C-ITS solutions are based on 4G (LTE) technology and the mobile industry is also defining a 5G-based V2X solution. Both LTE and IEEE802.11p technologies can be used in roadside units (the LTE-V2X solution has been adapted from standard LTE radio technology, to operate at low power, using the 5.9GHz band, whereas the IEEE802.11p technology was designed specifically to use this band). If using a cellular network to provide C-ITS messaging, the mobile industry refers to 'vehicle to network' (V2N) services. V2N services do not use 5.9GHz RSUs but instead use existing cellular networks to convey messages to vehicles.

Automated vehicle operation via 5G networks is one solution being tested in DCMS's 5G test bed and trials programme. Vehicles operating under the control of a network might be used in some enclosed environments – such as parking vehicles in a car park or in a production facility.

The IEE802.11p technology also has a future roadmap, to IEEE802.11bd, which is designed to supplement existing vehicle sensors, to support advanced driving applications including autonomy.

In the UK, the Department for Transport and Highways England (and counterparts in other UK nations) will be responsible for connected vehicles, and connected roadside, policy and implementation. Highways England's 'Strategic Road Network Initial Report' sets out recommendations for roadside technology roll-out up to 2025.[58] However, the government has recently announced pausing of 'Smart Motorways' roll-out, pending further analysis of additional measures to be implemented in these solutions.[59]

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[58] https://www.gov.uk/government/publications/highways-englands-strategic-road-network-initial-report

[59] https://www.gov.uk/government/news/smart-motorway-rollout-to-be-paused-as-government-responds-to-transport-committee-report

3.5.3 IoT and LPWA[60]

IoT refers to networks of devices equipped with different wireless technologies, sensors and software, to allow the exchange of data with other devices and systems over the internet.[61]

IoT requirements for different commercial and industrial enterprises are complex, diverse and specific to each use case, as described in Section 4.1.3. Wireless technologies such as Bluetooth and Wi-Fi are potential solutions for IoT applications in some environments. Bluetooth is typically limited to short-range applications ('personal area networks') and Wi-Fi is widely used in local area networks.[62] Both Bluetooth and Wi-Fi are low-power wireless solutions designed to operate using licence-exempt spectrum, which means that scaling these technologies up significantly (i.e. to form a wider national network) is not practical. As such, demand for wider-area IoT applications are usually met by existing wireless technologies that use licensed spectrum rather than licence-exempt spectrum (LPWA solutions). Included within the definition of LPWA are existing cellular-based IoT solutions such as narrowband IoT (NB-IoT), which operates as an overlay on 4G networks. Examples of different LPWA technologies are shown in Figure 3.5.

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[60] Low-power wide-area

[61] https://www.oracle.com/za/internet-of-things/what-is-iot/

[6262] https://behrtech.com/blog/what-is-lpwan-a-deep-dive-into-low-power-wide-area-networks/

Figure 3.5: A comparison of LPWA technologies [Source: Analysys Mason, 2022]

	NB-IoT	**LTE-M**[63]	**LoRa**	**Sigfox**	**Proprietary, e.g. Sensor Flexnet**
Spectrum	Licensed 700–900MHz, 1800MHz	Licensed 700–900MHz, 1800Mhz	Unlicensed 868MHz (in Europe)	Unlicensed 868MHz (in Europe)	Licensed (uses 410–430MHz spectrum in the UK, licensed to Arqiva)
Bandwidth	200kHz or shared with a 4G carrier	1.4MHz or shared with a 4G carrier	<500kHz	100kHz	25kHz
Coverage	<15km	<11km	<11km	<13km	<15km
Throughput	<150kbit/s	<1Mbit/s	<10kbit/s	<100 kbit/s	<100 kbit/s
Re-use of network	Re-uses LTE network	Re-uses LTE network	Re-uses elements of existing network (antennas, backhaul)	Re-uses cell sites, towers and backhaul	Re-uses cell sites, towers and backhaul
Standards body	3GPP	3GPP	Proprietary	Proprietary	Proprietary

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[63] Long-term evolution machine-type technologies

The introduction of 5G-based IoT connectivity may drive further increases in uptake of more advanced IoT solutions by enterprises and industry, driven by the high-throughput and low latency properties of 5G that may be suitable for more complex applications and use cases.[64] Some of the DCMS 5G Testbed and Trials projects, that are currently underway in the UK explore the use of 5G-based IoT for applications such as smart cities and autonomous transportation. For example, Vodafone is working with West Midlands 5G (WM5G) and GoMedia to improve tram safety and accessibility on the UK's first multi-city 5G testbed.[65] More sectors and use cases with high-bandwidth and low-latency requirements, such as CCTV cameras, autonomous transportation and smart buildings, will benefit from 5G IoT.

Many current low-bitrate IoT use cases (for example smart meters) only transmit small amounts of data periodically and may not require a 5G solution. For this reason, as well as cost considerations, existing LPWA solutions (including 4G-based ones) might continue to be preferred for these use cases for many more years to come.

In the UK, the government has also announced plans to introduce legislation to regulate the cyber security of certain consumer IoT devices, which would address potential security limitations that have historically been a barrier to take-up.[66]

In the following subsections, we describe the two main types of terrestrial LPWA networks, namely solutions using licensed spectrum and solutions using licence-exempt spectrum. We also briefly describe satellite IoT, which may provide an important solution for serving rural and remote locations.

Licensed LPWA networks

LPWA networks using licensed spectrum may provide a better quality of service than solutions using licence-exempt spectrum. The use of licensed spectrum also enables higher power transmission, which improves coverage. The main existing licensed cellular LPWA technologies are NB-IoT and LTE-M, which are both 3GPP standardised technologies.[67]

All of the MNOs in the UK have offered 2G-/3G-/4G-based machine-to-machine solutions for many years. More recently, Vodafone and VMO2 have started offering

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[64] https://www.bbvaopenmind.com/en/technology/digital-world/iot-and-5g-convergence/

[65] https://www.vodafone.co.uk/business/5g-for-business/5g-customer-stories/connected-trams

[66] https://www.gov.uk/government/publications/regulating-consumer-smart-product-cyber-security-government-response/government-response-to-the-call-for-views-on-consumer-connected-product-cyber-security-legislation#ministerial-foreword

[67] https://behrtech.com/blog/what-is-lpwan-a-deep-dive-into-low-power-wide-area-networks/

NB-IoT and LTE-M (both of these technologies use LTE frequency carriers, but involve hardware and software upgrades to be made at base stations):

- **Vodafone** launched its commercial NB-IoT network in 2018, making it the first MNO to offer commercial LPWA services. Nationwide roll-out is now complete: in July 2021, Vodafone stated that the network provides geographical coverage (both indoor and outdoor) of over 98% at a signal strength of –128dBm and 87% at a signal strength of –118dBm.[68] In other countries, such as the Netherlands and Germany, Vodafone Business is also rolling out LTE-M in addition to NB-IoT, although Vodafone has not announced this for the UK market. Both LTE-M and NB-IoT use LTE technology and hence would be termed a 4G service – the mobile industry also refers to NB-IoT and LTE-M "co-existing in the same network as other 5G-NR components".[69]

- **VMO2** launched an LTE-M network in 2020. Commercial services are now available. As of March 2022, its website states that (the eastern) half of the UK is currently covered, with "the rest of the national roll-out planned to complete in 2021".[70] As noted above, LTE-M uses 4G radio technology.

We understand that Three and BT are continuing to test licensed LPWA solutions:

- In 2019, **Three** announced that it was piloting an LPWA (LTE-M/NB-IoT) network as "the first step in a nationwide network roll-out that will support mass deployment of IoT devices". Its pilot network was set up at the Integrated Transport Electricity Gas Research Laboratory in Gateshead UK (InTEGReL). However, we are not aware of subsequent announcements from Three confirming commercial launch of LPWA technology or the extent of network deployment.[71]

- In 2020, **BT** launched an NB-IoT and artificial intelligence (AI) pilot with the UK water utility company Yorkshire Water. The smart water network was built to connect sensors in the water network in Northern England, and aims to improve the efficiency and effectiveness of monitoring water quality and network conditions.[72]

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[68] https://newscentre.vodafone.co.uk/press-release/iot-coverage-98-percent-of-uk/

[69] For example, https://www.ericsson.com/en/reports-and-papers/nb-iot-and-lte-m-in-the-context-of-5g-industry-white-paper

[70] https://www.o2.co.uk/business/solutions/iot/lte-m

[71] The lab is a collaboration between Northern Gas Networks, Newcastle University, Northern Powergrid, Northumbrian Water and Siemens. See https://www.threemediacentre.co.uk/content/three-uk-strengthens-internet-of-things-with-low-power-wide-area-capability/

[72] https://www.yorkshirewater.com/news-media/innovation/

Solutions using licence-exempt spectrum

Other LPWA technologies include solutions such as long range wireless, or LoRa (also called LoRa wide-area networks, or LoRaWAN) and Sigfox. These solutions can use licence-expect spectrum, such as 868MHz in the UK. A specific long-range wireless solution designed for machine to machine use is deployed in the UK by Arqiva, using licensed spectrum in the 400MHz band, and used to provide wide-area connectivity for smart meter communications hubs (CH) in parts of the UK. In other parts of the UK, CH WAN connectivity is via the 2G/3G networks of VMO2.

The sole Sigfox network operator in the UK is WNDUK, which has deployed more than 1500 Sigfox base stations in the UK, and offered network coverage to over 83% of the UK population and 54% of the UK landmass as of 2021, [73] based on Ofcom reported data. In early 2022, it has been reported that the Sigfox company has filed for bankruptcy protection in its home market of France. How this is affecting the WNDUK roll-out is not known.[74]

LoRa wide-area networks (LoRaWAN) are a range of alternative solutions provided through public or private deployments. The public LoRaWAN is an open-source network that allows users to connect devices to existing gateways (base stations). Private LoRaWAN operates on a subscription basis, offering managed carrier-grade services with guaranteed availability.[75]

The Things Network (TTN) is a leading provider of public LoRaWAN in the UK, with approximately 950 gateways nationwide, serving about 100 communities.[76] Similarly, there are a number of private LoRaWAN providers in the UK such as Commns365, Connexion and The Things Industries, among others. Ofcom estimates that private networks have at least 580 gateways and are serving approximately 37 000 devices combined as of 2021.[77] The Scottish government has also appointed North, a specialist expert in IoT, to design, deliver and maintain the nation's LPWA network, offering IoT

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[73] https://www.ofcom.org.uk/__data/assets/pdf_file/0035/229688/connected-nations-2021-uk.pdf

[74] https://www.datacenterdynamics.com/en/news/iot-startup-sigfox-files-for-bankruptcy/

[75] https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2020

[76] https://www.ofcom.org.uk/__data/assets/pdf_file/0035/229688/connected-nations-2021-uk.pdf

[77] Ibid.

connectivity to 1.4 million people in Scotland.[78] North adopted LoRa wide-area technology for both public and private network deployment.[79]

Satellite IoT

Satellite technology is transitioning to become an important link in the IoT value chain, particularly in rural areas.[80] Eutelsat, for example, offers three satellite IoT products to complement terrestrial coverage:[81] IoT FIRST, IoT MOVE and ELO.[82]

Eutelsat uses its existing geosynchronous Earth orbit (GEO) satellites to offer IoT FIRST and IoT MOVE. These products provide low-bandwidth IP connectivity services for fixed and mobile assets respectively. Both are offered through Eutelsat's existing channels as a satellite service provider.[83] However, due to the high cost of terminals, IoT FIRST and IoT MOVE may only appeal to a more narrow market base, including sectors such as retail and banking, energy and utilities, infrastructure and construction.[84] Satellite IoT service providers will need to overcome the challenge of generating sufficient demand to offset relatively low revenue per connection in the IoT business.

Eutelsat is also launching a constellation of low-Earth orbit (LEO) nanosatellites, called ELO, that would be compatible with existing terrestrial LPWA standards, meaning connections with existing LPWA terminals would only require minimal design changes.[85] ELO was launched in a strategic partnership with Sigfox. Sigfox integrated the global coverage offered by ELO into its range of IoT connectivity services.[86]

Small satellite constellations may present an obstacle due to signal transmission delays, and satellite providers may need to launch a larger fleet of satellites to offer a more seamless IoT connectivity experience. The role of satellite in the connectivity market is further described in Section 3.7, after considering various aspects of future mobile connectivity in Section 3.6.

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[78] https://north.tech/solutions/internet-of-things/

[79] https://www.analysysmason.com/research/content/data-set/lpwa-networks-index-rdme0/

[80] https://data.gsmaintelligence.com/research/research/research-2021/radar-connectivity-from-the-sky

[81] https://www.analysysmason.com/research/content/articles/eutelsat-iot-offer-rdme0/

[82] Information from Eutelsat official website, December 2021

[83] https://www.analysysmason.com/research/content/articles/eutelsat-iot-offer-rdme0/

[84] Information from Eutelsat official website, December 2021

[85] https://www.analysysmason.com/research/content/articles/eutelsat-iot-offer-rdme0/

[86] Information from Eutelsat official website, December 2021

3.6 Future mobile connectivity by 2030 – 6G

While more established areas of wide-area demand for cellular connectivity can be estimated via data traffic forecasts such as those presented in Section 4, there is a larger degree of uncertainty over future demand, in particular future traffic from new uses of cellular networks as the market evolves towards 6G.

The fact that 5G is also evolving is in parallel with research into 6G, and there is a possibility that more spectrum bands potentially suited to future mobile (5G/6G) will be decided on internationally at WRC-23 and subsequently at WRC-27. These additional bands will create possibilities for further coverage and/or capacity expansion, depending on the bands in question.

The UK forms part of ITU Region 1 and for Region 1, the bands under discussion for possible future mobile use at WRC-23 are in the UHF range (specifically the 600MHz band) and the upper 6GHz band (6425–7125MHz). Some stakeholders commented on a need for more sub-1GHz spectrum in the UK market in our interviews with them for this project, and the 600MHz band would facilitate this. There are conflicting demands for access to the upper 6GHz band as this band is part of specifications for both licensed mobile use (i.e. via 3GPP specifications) and Wi-Fi 6 (see Section 3.5.1). The upper 6GHz band is currently extensively used in the UK for fixed links, and there are international satellite allocations including earth stations located within Europe that are subject to interference protection requirements.

For future generations of mobile technology, current research points to higher bands than the ones standardised for 5G being considered for future use, in addition to bands already used in cellular networks today (if not at WRC-23, then spectrum for 6G use might potentially be discussed in the context of agenda items for discussion at WRC-27). These future spectrum options might include bands that are currently largely unallocated for commercial use (such as bands around 100GHz and upwards, referred to as sub-terahertz and terahertz ranges[87]). Sub-terahertz and terahertz ranges have fundamentally different characteristics to the frequency bands used in cellular networks today, which will affect future architectures. Communication over these frequencies can only occur over very short ranges due to higher path loss. This means there would be a need for much denser infrastructure compared to architectures currently used in macro cellular networks. The use of denser infrastructure brings about several key challenges, such as mobility management, cost, and contiguous coverage. Possible

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[87] 'Sub-terahertz' and 'terahertz' refer to spectrum bands in the 90GHz to 300GHz range (http://www.brave-beyond5g.com/index.php/sub-thz/). The characteristics of these frequencies mean that new technologies and materials are needed – these are the subject of current research.

ideas include moving to user-centric, ‘no-cell’ architectures.[88] However, these would mainly be suited to operating within localised deployments as opposed to wider areas.

Academic research is currently focusing on establishing a better understanding of the capabilities and limitations of these frequencies so as to determine potential use cases, network architectures and solution designs. Notwithstanding that research is at an early stage, the significant differences between sub-terahertz/terahertz frequencies and those used in cellular networks today suggests 6G is unlikely to be defined by the ability to use the sub-terahertz/terahertz ranges alone. To ensure an ordered evolution from 4G/5G, future 6G technologies would also need to operate in bands used by cellular networks today.

In early 2020, Ofcom consulted on making frequencies available in bands above 100GHz. Based on consultation responses, Ofcom decided to introduce a flexible access (shared use) licence in several bands. Sub-terahertz spectrum has also been made available for mobile use in the USA. The Federal Communications Commission (FCC) has chosen to offer relatively long-term (ten-year) experimental licences, issued on a locally licensed, first-come, first-served basis, but with several portions designated specifically for unlicensed use.

3.7 Satellite connectivity

As terrestrial mobile technologies such as cellular and Wi-Fi are continually evolving, so too are satellite networks.

Satellite connectivity is used extensively within broadcasting (broadcast satellite), within fixed telecoms networks (fixed satellite services) and for connectivity to devices (mobile satellite).

Mobile satellite technologies have evolved continuously throughout the last three decades since the first generation of low-Earth orbit (LEO) satellite solutions emerged in the late 1990s. The current technology is much more powerful in terms of data throughput and ability to achieve low latency, allowing information to be transmitted with significantly shorter delays. Compared to the original generation of satellites in geostationary orbit (GEO), high-throughput satellites (HTS) and very-high-throughput satellites (VHTS) now exist today, adopting new technologies such as spotbeam technology to improve spectrum re-use. This allows VHTS for example to bring far higher capacity closer to where the user need resides.[89]

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[88] For example, see https://zero5g.com/wp-content/uploads/2021/11/6GIEEEACCESS.pdf

[89] http://interactive.satellitetoday.com/via/january-2020/vhts-soaring-to-unprecedented-heights/

As satellite technology continues to evolve over the remainder of this decade, there could be greater use of satellite technologies for connectivity direct to devices (either to IoT devices, or direct to mobile handsets). These hybrid terrestrial-satellite handsets do not currently exist for consumer use but specifications are part of 3GPP's Release 17 specifications, which would imply that devices might become available after 2025. The extent to which satellite would be used for direct-to-device connectivity in the UK market specifically remains unclear, given the terrestrial network footprint across much of the UK. Uptake would also depend on the price of a hybrid terrestrial-satellite device and its affordability relative to existing terrestrial-only mobile devices.

There may be a role for satellite connectivity in rural locations, to provide broadband connectivity, wide-area wireless coverage (e.g. for tracking of goods being driven across the UK), as well as for other forms of IoT connectivity. Particular satellite IoT connectivity applications might include:

- those in which the device is located outside of terrestrial coverage
    - for example, agricultural use cases such as tracking of cattle, or forestry use cases, or gas/oil pipelines, or utility grid locations in remote areas
- where the device requires wide-area connectivity due to being transported across the UK and hence are moving in and out of cellular coverage
    - for example, transportation of heavy machinery or other high-value goods tracking requiring continuous connectivity.

3.7.1 Recent developments in satellite connectivity

There are a number of drivers for recent advances in global satellite connectivity, including those listed below.

Developments in small sat technology

Reduction in costs of launching and building the satellites due to technological breakthroughs in the past two decades is a key driver for developments in the 'small sat' space. Companies have successfully developed vertically integrated vehicle production lines, which increase production efficiency and vehicle reliability. Technology developments have also effectively increased the re-usability of rockets to further decrease launch costs. This would open up the playing field for more satellite service providers as the barrier of entry is lowered. Some new satellite companies may be targeting coverage in rural parts of UK. In the interviews conducted for this project, some stakeholders mentioned the possibility of using future satellite constellations for rural connectivity. A concern expressed was whether there will be sufficient capacity from these satellite networks specifically over the parts of the UK where connectivity is needed (since satellites have a regional or global footprint, the capacity available over the UK at a given point in time depends on the constellation design).

Use of satellite connectivity for IoT

The increasing footprint of terrestrial IoT connectivity has enabled many more unexplored applications for enterprises and consumers to emerge. However, with terrestrial infrastructure not available in in sparsely populated areas, this results in a lack of connectivity for IoT consumers, not just for those permanently located in rural areas, but also for those companies operating IoT systems that might travel into uncovered areas (such as goods vehicle tracking). This is an opportunity where satellite IoT connectivity might improve the terrestrial IoT footprint, and make it more resilient (e.g. by acting as a back-up route).[90]

Hybrid terrestrial-satellite networks

The standards body that creates standards for mobile technology (3GPP) is also creating standards to facilitate satellite network element compatibility with the protocols used in mobile specifications. There are several versions of hybrid terrestrial-satellite connectivity emerging in the market, either using spectrum allocated for mobile satellite services in a terrestrial component, or using spectrum allocated to the mobile service in the satellite payload. The potential of these hybrid systems in the UK market context is not yet clear.

Government policies aimed at ensuring broadband availability for all

Governments internationally are seeking to address the digital divide and widen digital connectivity to all, meaning satellite services may become increasingly relevant to support network roll-out in rural areas where terrestrial networks are unable to reach. Satellite is typically considered as a fixed broadband substitute and can be used to provide backhaul connection for cellular sites in rural areas; to use a satellite network to communicate directly to a mobile device would require a new form of hybrid terrestrial-satellite device that might emerge based on the latest 3GPP Release 17 specifications, as mentioned above.

3.7.2 Areas of collaboration between the mobile and satellite industries

Technology and market developments such as those discussed above suggest greater collaboration and integration between terrestrial and satellite connectivity in

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[90] https://data.gsmaintelligence.com/research/research/research-2021/radar-connectivity-from-the-sky

future. In such an integration, it will most likely be the case that satellite connectivity provides solutions at the edges of cellular connectivity, which could drive the development of further rural infrastructure in the UK. Release 17 of the 3GPP 5G specifications includes satellite integration, which might enable satellite companies seeking to provide direct-to-mobile device satellite services to do so via a standardised 5G device.

Some of the other areas of collaboration between the mobile and satellite industries include:[91]

- **Mobile backhauling:** The increase in terrestrial cellular sites drives the need for mobile backhauling, and satellite backhaul forms a solution, especially in rural areas where laying fibre is not an option and/or is too expensive.
- **Trunking, cloud and data centre:** 5G networks rely on enabling applications such as edge computing, which is driving the demand for satellite connectivity from distributed data centres and for potential cloud customers in remote locations.
- **IoT:** Cellular IoT connectivity, together with satellite IoT connectivity, could provide UK-wide, resilient IoT connectivity for the use cases requiring a full geographical footprint (as noted above).
- **Military/government:** Military/government investment in communications, surveillance and intelligence capabilities is also driving further satellite industry development, and in this context satellites may be able to provide additional resilience in support of terrestrial network infrastructure.
- **Aviation:** while the Covid-19 pandemic has dampened the short-term growth of in-flight connectivity, there may still be stronger long-term potential as the number of planes fitted for in-flight connectivity continue to increase.[92]

There is a rising number of entrants into the satellite market over the last decade, including ViaSat, Telesat, Kuiper (by Amazon). It is important to note that only a small number of companies have successfully launched LEO satellite constellations. The two companies with substantial LEO satellites are OneWeb and SpaceX. Details of these companies are briefly summarised below. As part of the summary, we also provide examples of other satellite companies that may play a role in the wireless connectivity market in the UK, namely Freedomsat, We Konnect and AST SpaceMobile.

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[91] Satellite Services: To Infinity and Beyond – Volume 1, Barclays Equity Research 2021.

[92] Ibid.

OneWeb

- The UK government and the Bharti Group acquired OneWeb in October 2020[93] and OneWeb currently has its headquarters in the UK.
- OneWeb has launched 218 satellites into LEO as of May 2021, with an additional 430 satellites to be launched by 2022.[94] The company plans to offer global coverage in 2022,[95] and is currently targeting business customers instead of retailing directly to end consumers.
- The company offers connectivity solutions for four major business sectors: enterprise, government, maritime and aviation.
- OneWeb operates a wholesale model. Several B2B verticals have expressed interest in satellite services for IoT connectivity, including:
  - public sector and government
  - manufacturing: consumer electronics and electrical
  - healthcare
  - retail and hospitality
  - manufacturing: automotive and transport equipment
  - utilities
  - transportation and warehousing.

Starlink (SpaceX)

- Starlink is a satellite broadband service provider developed by the private space company, SpaceX.
- Starlink has launched 1800 LEO satellites as of September 2021, with aims to have launched 12 000 satellites by late 2026.[96]
- The company currently offers high-speed broadband connections to consumers. Starlink's beta product has about 100 000 customers, but the prices are at the higher end of the spectrum.

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[93] https://www.gov.uk/government/news/uk-government-secures-satellite-network-oneweb

[94] https://data.gsmaintelligence.com/research/research/research-2021/radar-connectivity-from-the-sky

[95] Information from OneWeb official website, November 2021

[96] https://www.ispreview.co.uk/index.php/2021/09/starlinks-leo-satellite-broadband-service-to-exit-beta-in-october.html

- Unlike other satellite providers that operate on a B2B basis, Starlink is reportedly operating with a direct-to-consumer model (i.e. direct to mobile device and retailing directly to consumers).
- Starlink's ground station in the Isle of Man recently came online in 2020, expanding its network capacity to enable more connections.[97]

Freedomsat

- Freedomsat offers unlimited 4G broadband packages to its home and business customers by using the VMO2 and Vodafone mast networks for maximum 4G coverage in the UK.
- Apart from 4G broadband, the company also offers a selection of satellite internet packages for homes and businesses that are not covered by fibre or ADSL broadband connections (see Figure 3.6 below).[98]

Figure 3.6: Freedom satellite internet packages [Source: Freedomsat, 2022]

	Home 10 package	Home 30 package	Home 75 package
Data (extra data option)	10GB or 20GB)	30GB or 60GB	75GB or 150GB
Download speed (extra speed option)	15Mbit/s or 30Mbit/s		
Upload speed (extra speed option)	3Mbit/s 6Mbit/s		
Price / month (12-month contract)	GBP25–40	GBP45–80	GBP105–150

We Konnect

- We Konnect uses GEO VHS by Eutelsat to provide internet access in 16 countries in Europe (including the UK) and North Africa. The company offers a selection of broadband packages to customers anywhere in the UK (see Figure 3.7 below).[99]

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[97] https://www.businessinsider.co.za/spacex-elon-musk-starlink-satellite-base-isle-of-man-uk-2021-8

[98] Information from Freedomsat official website, 2021.

[99] Information from We Konnect official website, 2021.

Figure 3.7: We Konnect satellite internet packages [Source: We Konnect, 2022]

	Easy package	Zen package	Max 120 package
Average speed	22Mbit/s	37Mbit/s	75Mbit/s
Priority data/month	20GB	60GB	120GB
Video streaming	SD-quality	HD-quality	Full HD quality
Price/month	GBP29.99	GBP44.99	GBP69.99

AST SpaceMobile

- AST SpaceMobile is the first space-based cellular broadband network for mobile phones. The company has plans to offer cellular broadband coverage in the 49 largest countries in the equatorial regions.[100]
- The company plans to launch the prototype satellite, BlueWalker 3, with SpaceX in late 2022 for its cellular broadband network.[101] An additional 170 LEO satellites will follow in 2023.[102]
- AST SpaceMobile announced a strategic partnership with Vodafone in 2020 to enable both companies to potentially reach 1.6 billion people across the globe through the new satellite constellation.[103]
- The revenue model of AST SpaceMobile is still not entirely clear, but it is most likely to be operating through a wholesale model with Vodafone to test and deploy the new network.

3.8 Implications of technology advances on future market structure and mobile value chains

As described in Section 3.1–3.7, a range of technology advances may result in changes in supply structure (the value chain) in the mobile market over the remainder of this decade. Some of the key trends described in this section include new network and service possibilities, emerging alternative players, and changes

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[100] https://www.vodafone.com/news/press-release/vodafone-and-ast-spacemobile-unveil-launch-plans-space-based-mobile-network-initially-reaching-16

[101] https://www.satellitetoday.com/launch/2021/07/30/ast-spacemobile-to-launch-demo-satellite-with-spacex/

[102] https://www.business-live.co.uk/technology/500m-plan-satellite-calls-todays-20702481

[103] https://www.vodafone.com/news/press-release/vodafone-and-ast-spacemobile-unveil-launch-plans-space-based-mobile-network-initially-reaching-16

to equipment hardware and software in the national cellular networks giving rise to new partnerships between industry players.

3.8.1 Network function virtualisation (NFV) creates flexibility and opens up the value chain

NFV refers to 'virtualising' network functions by migrating from proprietary hardware to software applications running on commercial off-the-shelf hardware.

It not only potentially opens up the equipment supply value chain to a range of other suppliers and creates additional deployment flexibility though software configuration, but also creates the possibility of alternative infrastructure providers, such as neutral hosts, offering flexible solutions. Open RAN, in particular, is a broader movement that aims to increase supply chain diversity, allowing multiple vendors to provide equipment and software. These changes may shift supply away from large traditional vendors, and also enhances the role of third-party systems integrators. If Open RAN proves to be less costly to deploy than traditional RAN, this might also provide a flexible platform for provision of connectivity in hard-to-reach rural locations. Open RAN might also be used in private 5G deployments (e.g. to provide dedicated radio sites for specific economic sectors), where greater vendor diversity could allow for more service differentiation and more choice for private network owners.

3.8.2 Cloud-based infrastructure presents opportunities for hyperscalers

A natural evolution of NFV is that the software elements of network functions are run on cloud-based (i.e. internet) platforms and related infrastructure. As network functions start to be run on cloud-type platforms and infrastructure, it provides an opportunity for hyperscalers (PCPs) that offer IaaS to enter the mobile value chain. PCPs will not necessarily host network functions on their infrastructure, but can offer their cloud stack technology to run functions at MNOs' on-premises locations, or on-premises locations of different economic sectors of 5G user (e.g. industrial, ports, airports).

3.8.3 Network slicing allows MNOs to provide new use-case services at scale across their networks

It is the evolution of 5G core networks to standalone, NFV and cloud-based platforms that creates the concept of dividing up end-to-end network capacity (from core to RAN) and assigning a 'slice' of that capacity to a particular use case, end user or application, with assured bandwidth, latency and reliability characteristics. Network slicing allows MNOs to provide new use-case services to specific industry verticals (e.g. healthcare, automotive and manufacturing). Importantly, this capability would be present in MNO networks only within the footprint of 5G-SA coverage (which we understand would be within the 3.5GHz coverage footprint).

3.8.4 Edge clouds enable MNOs to host edge computing services

A further evolution from cloud-based 5G core networks is the processing of containerised application functions at large numbers of edge locations, bringing computing power closer to the end user and enabling low-latency and high-reliability services. Edge clouds provide an opportunity for MNOs to leverage their site locations and existing backhaul connectivity arrangements to host edge computing services. Server providers (e.g. Dell and HPE) may become more important in the mobile value chain through provision of 'bare metal clouds' (akin to cloud infrastructure, without the virtualisation layer).

3.8.5 MNOs may face competition from alternative access network connections

A range of wireless technologies could be used to provide wireless connectivity to address some use cases in some environments, depending on user choices and need. These alternative technologies to conventional MNO-provided cellular connectivity include various technologies such as LEO satellites, Wi-Fi 6, and private networks using shared access spectrum. MNOs also face new forms of competition, potentially from new types of players, who might be offering services via these alternative access network connections. Whether these changes can create new partnership and revenue opportunities for MNOs is not well-evidenced currently.

3.8.6 Supply chain diversity policies may mean that MNOs partner with new suppliers as well as existing ones

DCMS's '5G supply chain diversification strategy' intends to diversify the telecoms supply market for reasons of resilience as well as competition.[104] At the heart of the strategy is the ambition to attract new suppliers into the UK market, as well as to accelerate open-interface Open RAN solutions. In July 2021, DCMS announced an open competition, called 'Future RAN', to unlock the potential of Open RAN. The competition will provide GBP30 million of UK funding to projects that support the goals of the diversification strategy.[105]

It is expected that by 2030, the RAN infrastructure used by UK MNOs, and in private 4G/5G deployments, will be different to today's infrastructure, and that additional vendors will supply equipment. Open RAN, together with the other trends identified

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[104] https://www.gov.uk/government/publications/5g-supply-chain-diversification-strategy/5g-supply-chain-diversification-strategy

[105] https://www.gov.uk/guidance/future-ran-diversifying-the-5g-supply-chain

above, also suggest that there could be more providers of networks, either working together with the four national MNOs or acting as competitors.

This could potentially lead to additional diversification, but also to more fragmentation within the mobile value chain. We note that Ofcom is currently conducting a strategy review into the mobile market, to consider how the market might evolve, and how this evolution might impact regulation of the mobile market.[106]

We can envisage several ways in which the mobile value chain might evolve over the next decade. The subsection below provides a brief illustration of alternative options for mobile value chain evolution.

3.8.7 Mobile value chain evolution

Transition of 5G core networks to utilise cloud platforms is expected to enable MNOs to provide virtual private networks via slicing, as well as providing evolved public MBB, IoT and FWA services over a wide area of the UK. However, alternative providers, cloud providers and satellite companies are also offering solutions. The ‘cloudification’ of the public mobile networks is expected to result in an increasing role for alternative players, and in new partnerships that supply wireless connectivity. By the end of this decade, we may therefore see a significantly more diverse supply picture in the UK market.

The UK MNOs have thus far largely controlled the mobile value chain, and have provided wide-area cellular connectivity between end-user devices, core networks and the internet, as shown in Figure 3.8 below.

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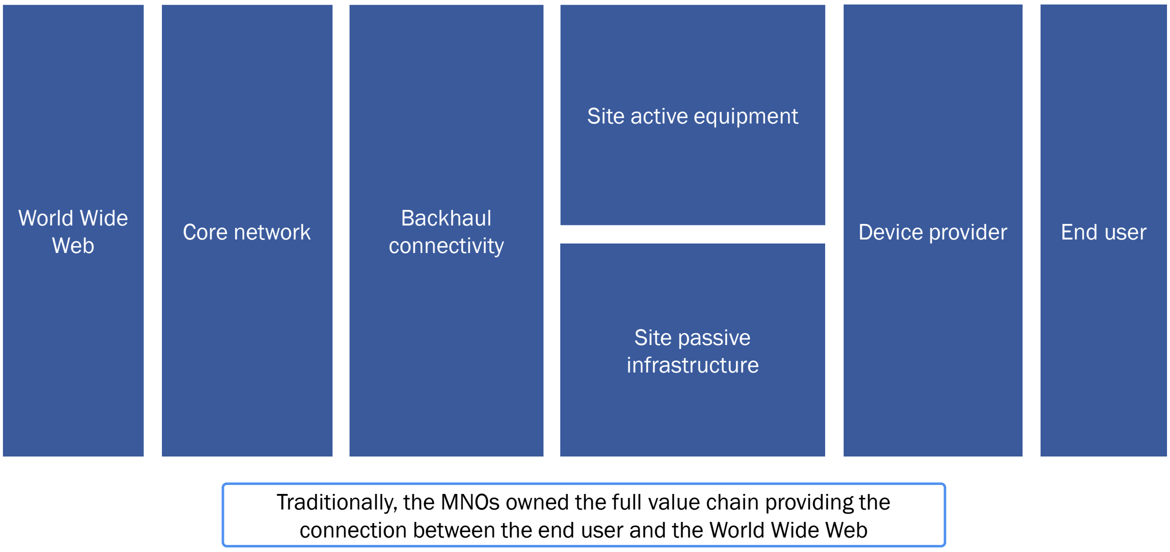
[106] https://www.ofcom.org.uk/phones-telecoms-and-internet/information-for-industry/policy/mobile-strategy

Figure 3.8: Reference value chain in the UK (mobile market in 2021) [Source: Analysys Mason, 2022]



Traditionally, the MNOs owned the full value chain providing the connection between the end user and the World Wide Web

We are already witnessing changes in cellular network ownership: MNOs are divesting towers/sites infrastructure to third-party infrastructure companies. In the UK, there are longstanding RAN-sharing agreements between the MNOs, which means that RAN infrastructures are shared to a high degree between Vodafone and VMO2. Passive infrastructure sharing also occurs between BTEE and Three.

'Cloudification', as discussed in this subsection, raises the prospect of increasing parts of cellular networks being driven by software and hosted in the cloud. Separation of the software and hardware functions at the RAN means that some RAN functions could be based in the cloud. This would give greater deployment flexibility to MNOs, including for the provisioning of private 5G deployments alongside public network capacity.

This cloud-based network functionality may give an opportunity for PCPs/hyperscalers to provide the infrastructure that supports core network and RAN software functionality. Additionally, PCPs might also provide private networks direct to enterprises – the recent AWS announcement relating to 'AWS Private 5G' would make it easier for enterprises to set up private networks. AWS delivers small-cell radio units, 5G core and RAN software, and the SIMs required to set up a private 5G network and connect devices. AWS's solution automates the set-up and deployment of the network, which it states can be scaled 'on demand'.[107] This is illustrated in Figure 3.9 below.

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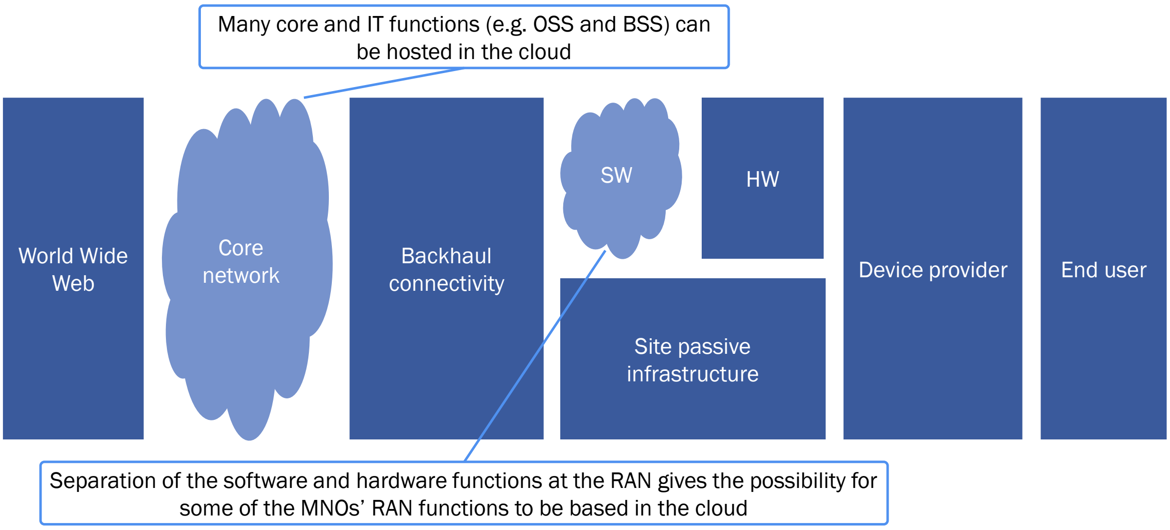
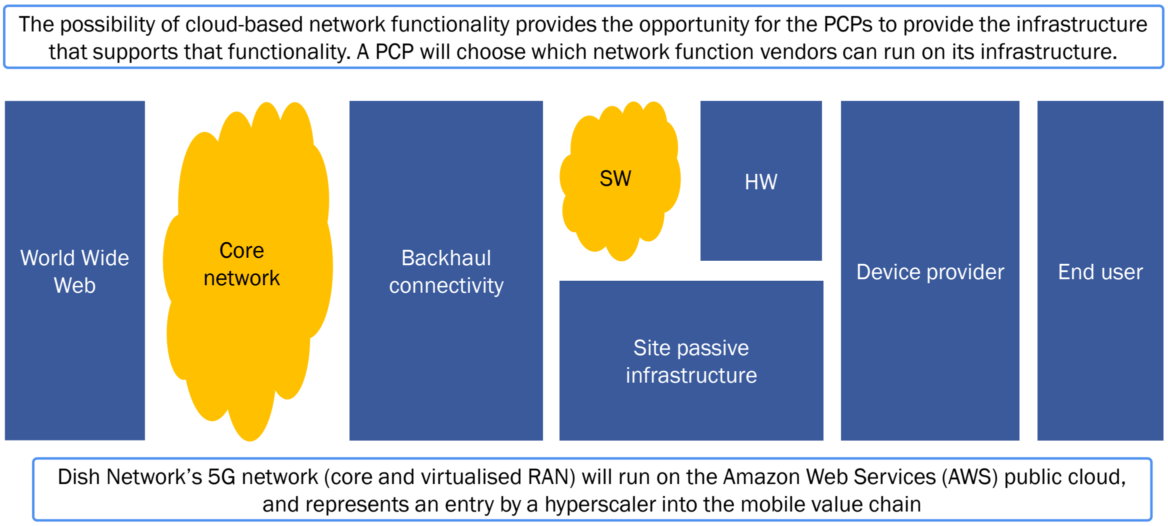
[107] Private 5G Mobile Networks – AWS Private 5G – Amazon Web Services

Figure 3.9: Move to software-based and cloud native functions [Source: Analysys Mason, 2022][108]


Many core and IT functions (e.g. OSS and BSS) can be hosted in the cloud

Separation of the software and hardware functions at the RAN gives the possibility for some of the MNOs' RAN functions to be based in the cloud

Figure 3.10: Role of hyperscalers [Source: Analysys Mason, 2022]


The possibility of cloud-based network functionality provides the opportunity for the PCPs to provide the infrastructure that supports that functionality. A PCP will choose which network function vendors can run on its infrastructure.

Dish Network's 5G network (core and virtualised RAN) will run on the Amazon Web Services (AWS) public cloud, and represents an entry by a hyperscaler into the mobile value chain

The demand for low-latency connectivity for some of the use cases described in Section 4.2.2 means that having storage and computation capabilities closer to where users are located will become increasingly important. This is prompting a migration from centralised to distributed edge cloud provision. Distributed data centres (i.e. data centres away from the London hubs) is a key trend. The MNOs may be well positioned to offer low-latency applications due to their existing access to numerous site locations and associated backhaul, however PCPs/hyperscalers will also see opportunities from this shift to a distributed edge cloud model.

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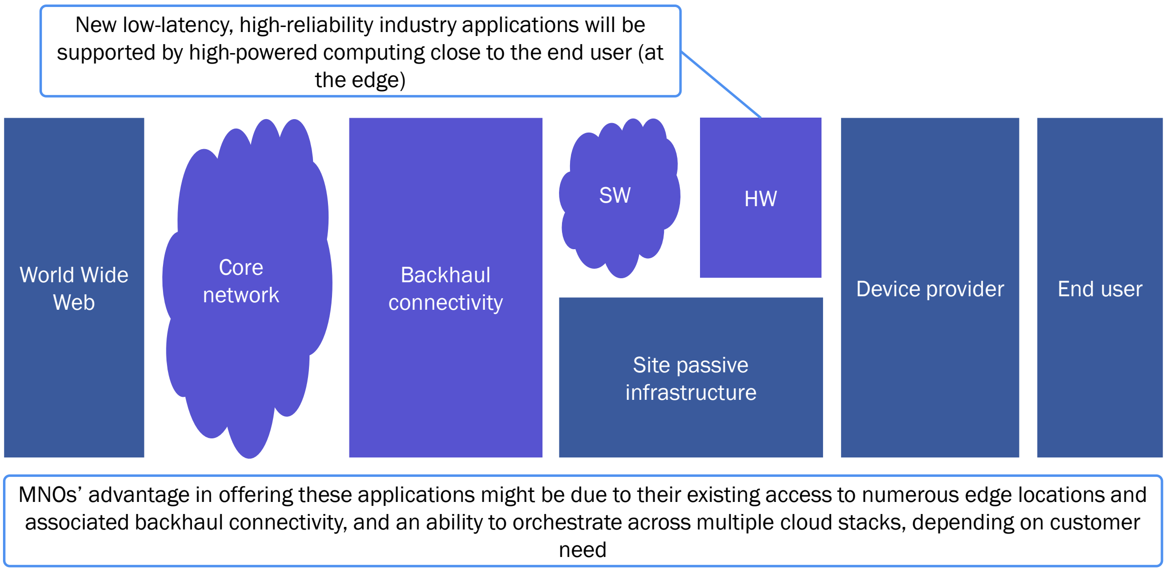
[108] OSS = operations support system; BSS = business support system; SW = software; HW = hardware

Figure 3.11: MNOs offering edge-native services [Source: Analysys Mason, 2022]

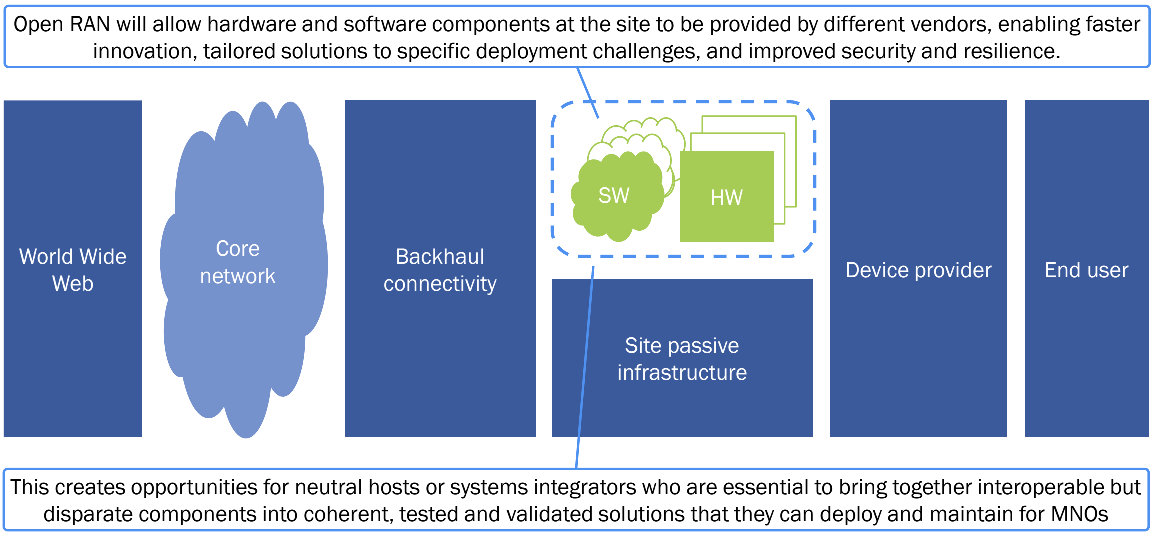


New low-latency, high-reliability industry applications will be supported by high-powered computing close to the end user (at the edge)

MNOs' advantage in offering these applications might be due to their existing access to numerous edge locations and associated backhaul connectivity, and an ability to orchestrate across multiple cloud stacks, depending on customer need

MNOs and vendors that have been interviewed for this project have all variously referred to Open RAN initiatives as unlocking new opportunities, but also creating challenges (e.g. due to re-procurement, migration and integration costs, also associated with high-risk vendor removal in the MNO networks). Open RAN may also support alternative neutral host models, such as those described in Section 3.3.

Figure 3.12: Open RAN, neutral hosts and system integrators [Source: Analysys Mason, 2022]



Open RAN will allow hardware and software components at the site to be provided by different vendors, enabling faster innovation, tailored solutions to specific deployment challenges, and improved security and resilience.

This creates opportunities for neutral hosts or systems integrators who are essential to bring together interoperable but disparate components into coherent, tested and validated solutions that they can deploy and maintain for MNOs

Finally, alternative wireless technologies, both terrestrial technology (e.g. Wi-Fi, LoRaWAN) and satellite technology (e.g. LEO satellites) will continue to play a role in providing wireless connectivity in some environments. We expect LEO satellites to be relevant both for remote connectivity and to provide resilience/alternative routing to terrestrial networks operating across the UK. Wi-Fi already has a significant role in UK homes, businesses and in some industrial settings. Wi-Fi could be used in outdoor industrial settings, such as ports, as well as indoors.

4 Demand for wireless connectivity in the UK, and how this might evolve

This section discusses demand for different types of wireless connectivity in the UK across different categories of consumer use, and use across different economic sectors. The section considers how this demand is expected to evolve over time, and how different user needs might vary in terms of wireless connectivity capabilities such as speed of connection, latency, coverage, security and other features.

Within this section we refer to published forecasts of wireless data traffic, and mobile connections, which are available through Analysys Mason's subscription research programmes.[109] Within this project, we have added to published forecasts with our own assumptions, specifically on connections and wireless traffic up to 2030, and on specific needs relevant to business and economic sectors in the UK market.

4.1 Evolution of demand from existing use cases

We broadly consider the evolving need for wireless connectivity across:

- smartphones and other consumer devices (Section 4.1.1)
- wireless connectivity into the home, i.e. 5G-based FWA (Section 4.1.2)
- IoT (Section 4.1.3)
- other specific needs relevant to different business/economic sectors in the UK market (Section 4.1.4).

Section 4.1.4 provides a comparison and summary of wireless data traffic across the different categories of user. Wireless traffic forecasts are based on those published by Analysys Mason Research.

4.1.1 Wireless connectivity to smartphones and other consumer devices

This subsection considers mobile handset devices (i.e. smartphones[110]) as well as other portable consumer wireless broadband devices such as laptops, PCs, netbooks, tablets and e-readers.

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[109] https://www.analysysmason.com/what-we-do/practices/research/

[110] Mobile handsets include both smartphones and basic handsets. However, the traffic generated by basic handsets is negligible, and in this report we therefore use the terms 'smartphone' and 'handset' interchangeably. The vast majority of handsets in the UK are smartphones (currently over 90%, expected to increase to over 95% in the next few years), and traffic per handset is minimal for basic handsets.

The wireless connectivity needs of these devices are currently primarily served by cellular and Wi-Fi technologies. However, other technologies also play a role (e.g. Bluetooth is used for the provision of relatively low bitrate wireless connectivity over short distances).

Trends in smartphone data traffic, and data traffic from other consumer devices are considered in turn below. We provide traffic forecasts for both cellular and Wi-Fi.

Data traffic over cellular networks

► *Mobile handsets and smartphones*

The total number of mobile handset connections in the UK is not anticipated to change significantly over the coming decade, given the maturity of the UK mobile market (with many subscribers using multiple devices).

As can be seen in Figure 4.1 below, the majority of handset connections in the UK are currently using 4G networks, and the proportion of legacy 2G and 3G handsets used by UK consumers is rapidly declining, as users migrate to 4G, or 4G/5G, devices.[111] Internationally, it is noted that 2G/3G use is higher than it is in the UK in some other markets, and so there is a consideration for MNOs that visitors to the UK may still use 2G/3G handsets and therefore require legacy 2G/3G connectivity to be available. This consideration is not further explored in this report but will be a consideration for MNOs when considering transitioning away from legacy 2G/3G networks in line with the UK government’s statement on the sunsetting of these networks.

As discussed in Section 3.1, 5G mobile services were launched commercially by each of the UK MNOs in 2019–20 and MNOs are in the process of rolling out their 5G networks. The proportion of 5G handsets is growing as devices penetrate the market; 5G handsets are expected to overtake 4G by 2025, based on estimates published by Analysys Mason Research.

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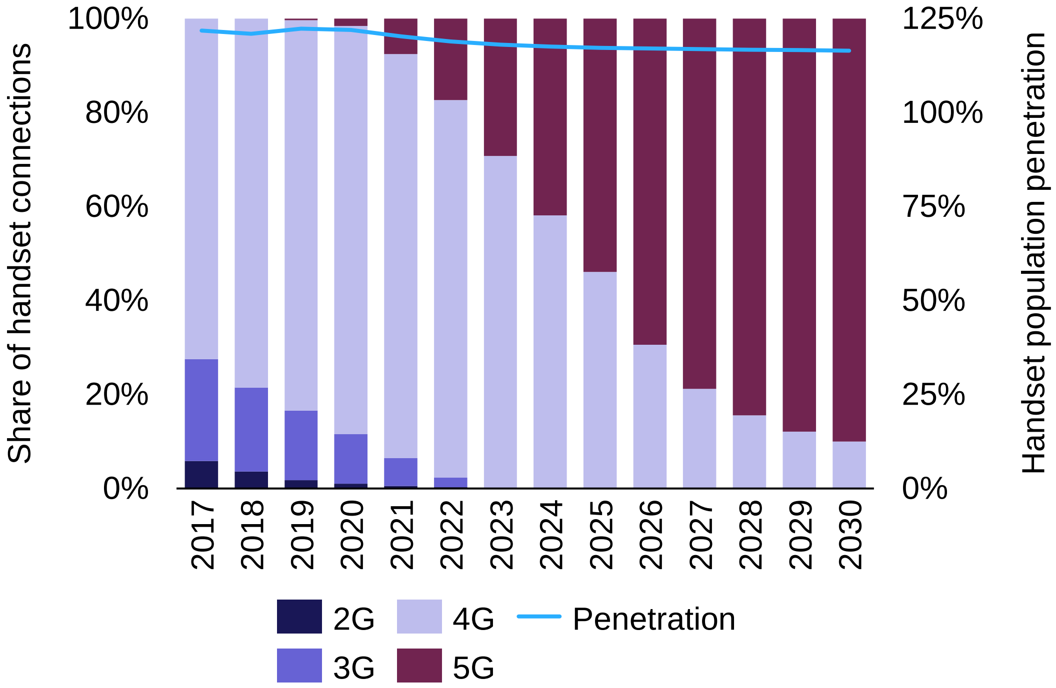
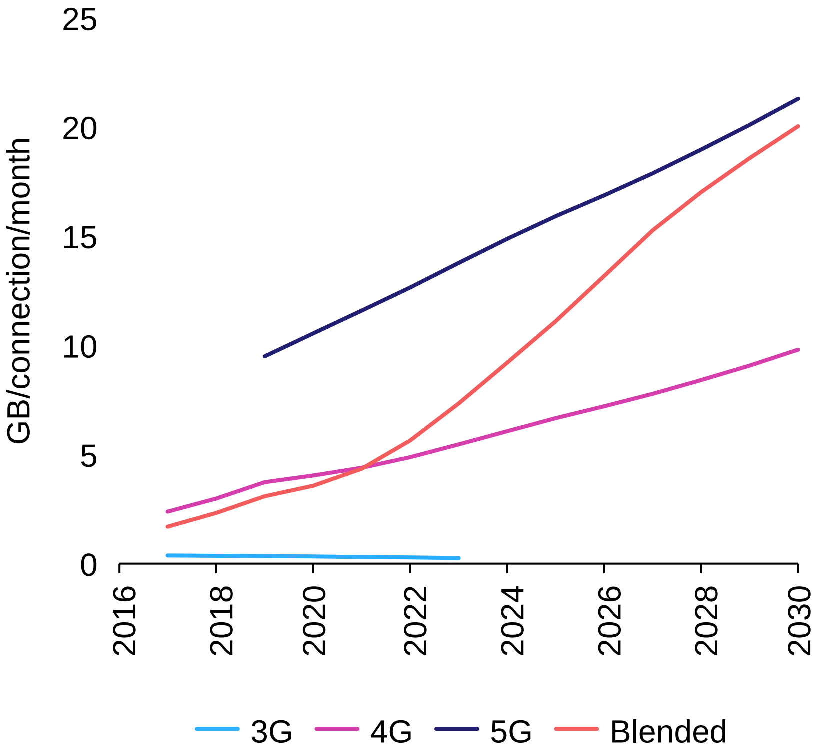
[111] MNOs in the UK are expected to switch off their 3G networks in the coming years; 2G networks may be maintained for longer, but the proportion of handsets that use 2G is already negligible. The remaining 2G users are predominantly machine-to-machine devices, which have a longer equipment life than mobile handsets, and can be difficult to replace before they reach end of life (due to being in hard-to-reach locations, or embedded into other devices).

Figure 4.1: Handset connections and penetration [Source: Analysys Mason Research, 2022]



Total combined cellular data traffic per handset connection in the UK was approximately 3.6GB per connection per month in 2020 (around 4GB for 4G, and 10GB – 2.5 times higher – for 5G). According to the published forecasts of Analysys Mason Research, this figure is forecast to grow to 19GB/month by 2030 (with year-on-year growth declining over the decade to around 5% by 2030).

Figure 4.2: Cellular traffic per handset [Source: Analysys Mason Research, 2022]



The forecast of the levels of 5G traffic in the UK compared to 4G upon which the modelling described in this report is based is shown in Figure 4.3 below. Our forecast is based on total 5G data traffic generated by consumer handsets overtaking 4G in 2024, reflecting an increasing portion of consumers upgrading devices from 4G to 5G. As shown, the growth rate in cellular handset traffic dropped in 2020 as a consequence of the Covid-19 pandemic. This does not mean there was a fall in mobile traffic, but only that the growth rate reduced. The reasoning for this is that in the Analysys Mason Research forecast, there is an assumption of lower out-of-home and out-of-office usage of mobile devices for the year 2020. There is an assumption of a higher Wi-Fi share of traffic when at home during that year (there was also a small increase in fibre broadband take-up in 2020 among previously mobile-only households). Year-on-year growth is expected to increase sharply over the next few years, before following a declining trend over the rest of the decade.

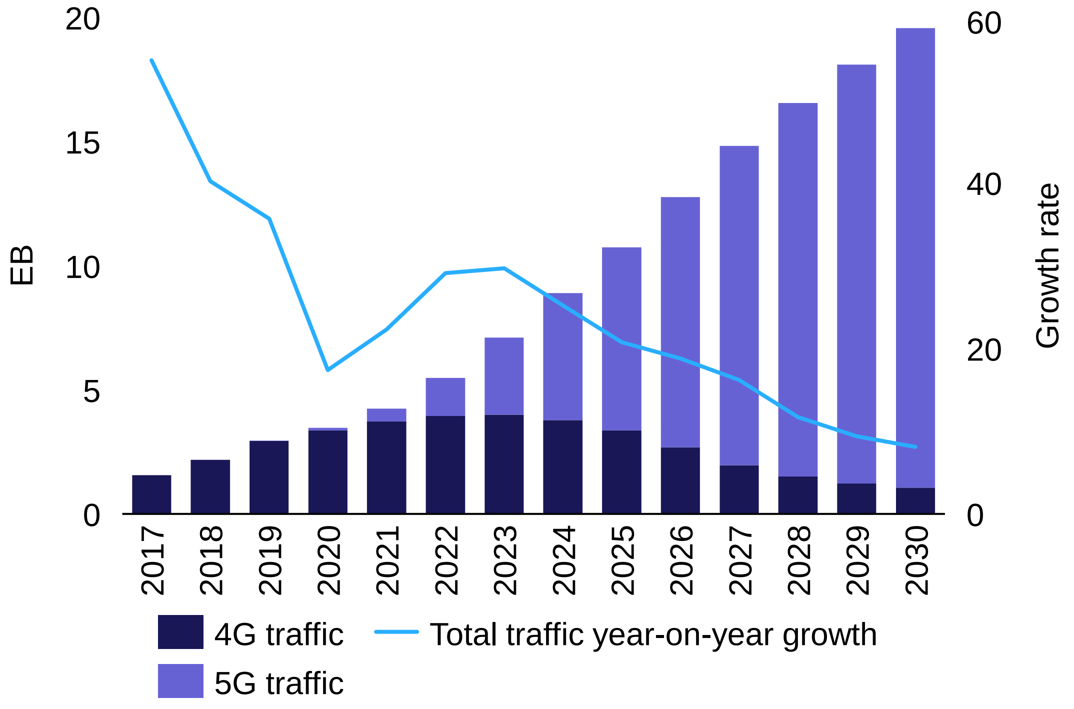
The growth rates shown here are lower than some other estimates, such as recently published by Ofcom in its discussion paper on meeting future demand for mobile data. Ofcom's scenarios are as following:

- Low growth: 25% increase per annum to 2030, 20% increase per annum between 2030 and 2035.

- Medium growth: 40% sustained increase per annum to 2035.
- High growth: 55% increase per annum to 2030, and 60% increase per annum between 2030 and 2035.

The forecasts published by Analysys Mason Research are less optimistic than Ofcom's scenarios. Key considerations are that UK mobile data usage is currently lower than other leading countries (and hence there would need to be significant shift in UK mobile consumption for mobile data usage per subscriber in the UK to be comparable with the highest international indicators) and that fixed broadband penetration is comparatively high in the UK, with the UK's fixed data usage amongst the highest in the world. There might also be considerations on higher rates of fixed–mobile convergence (FMC) informing Ofcom's forecasts. The forecast from Analysys Mason Research on FMC for the UK market is that while the UK has been experiencing increased take-up of FMC SIMs, leading FMC markets in Europe (such as the Netherlands, Spain or France) are still well ahead in this regard.

Figure 4.3: Total 4G and 5G handset traffic [Source: Analysys Mason Research, 2022][112]



► *Other devices (e.g. laptops and tablets)*

As smartphones increasingly provide the functionality needed by users, the number of active connections to the cellular network from other mobile consumer wireless

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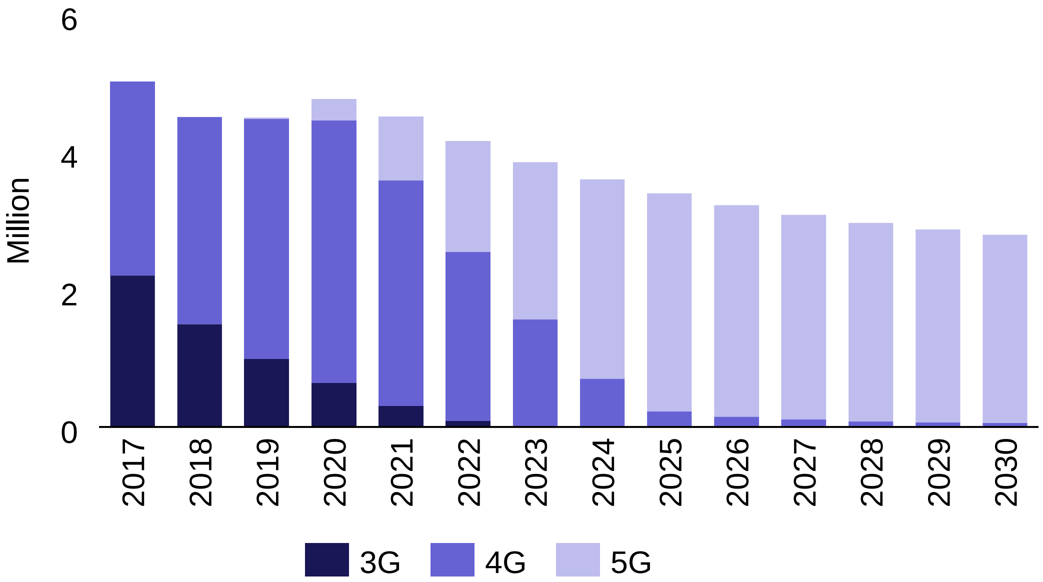
[112] EB = exabyte

broadband devices typically used today (such as laptops, PCs, netbooks, tablets and e-readers) is expected to decline over the coming years. As shown in a forecast from Analysys Mason Research in Figure 4.4 below, the number of such devices is forecast to decrease to around 3 million in 2030. These forecasts refer to current device types only and do not reflect future devices (e.g. AR/VR headsets) that might use a cellular network. By comparison, Ofcom has acknowledged in its mobile spectrum demand paper that its higher growth scenarios assume new applications emerging.[113]

Figure 4.4: Number of other MBB devices [Source: Analysys Mason Research, 2022]



While cellular traffic per connection is higher for wireless broadband devices other than smartphones, the absolute number of other devices on the cellular network is significantly lower (and declining, as noted above). As a consequence, total cellular traffic from other devices is small compared to that from handsets, as shown in Figure 4.5 below.

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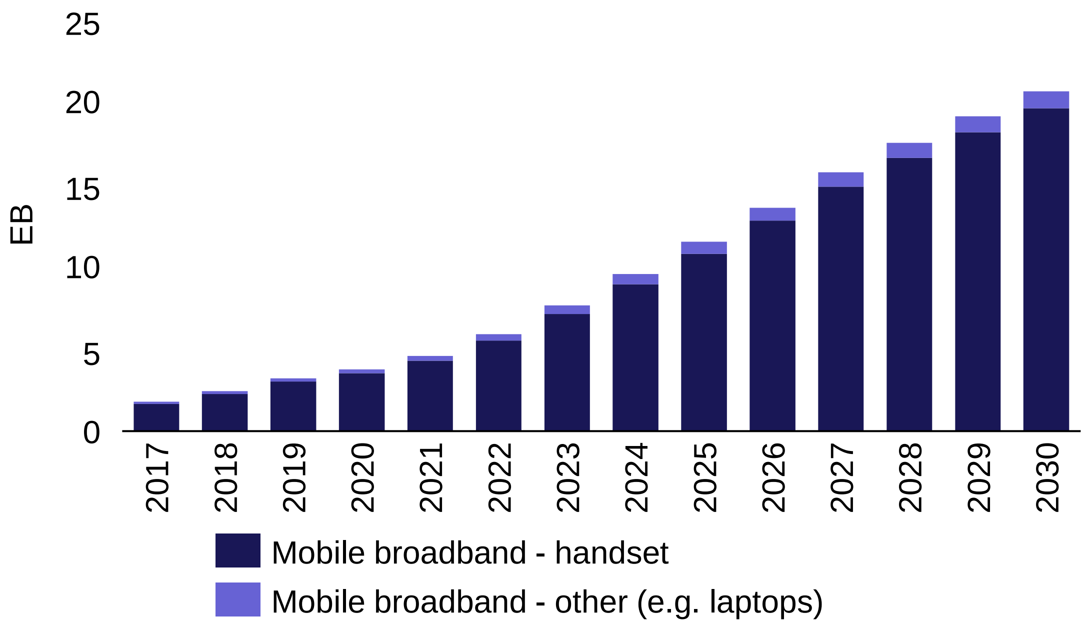
[113] https://www.ofcom.org.uk/consultations-and-statements/category-3/discussion-paper-meeting-future-demand-for-mobile-data

Figure 4.5: Cellular traffic from mobile handsets and from other MBB devices [Source: Analysys Mason Research, 2022]



Data traffic over Wi-Fi

Fibre connectivity is increasingly being adopted by homeowners and businesses, and the government and private sector have invested heavily in fibre networks in the UK. Use of Wi-Fi is correspondingly growing as the main indoor solution for wireless connectivity. Wi-Fi connects multiple devices within homes/buildings that receive internet connectivity via fibre or other high-speed FBB connections.[114] MNOs are increasingly offering cheaper mobile packages (e.g. unlimited data), which might act as a disincentive for users to shift to using Wi-Fi in the home. However, the high FBB take-up in the UK means users can receive a good service from fixed or mobile (in premises within the coverage areas of both technologies). Fixed-to-mobile substitution is low in the UK market and hence the strong FBB penetration is what drives Analysys Mason's Wi-Fi forecasts.

As such, Wi-Fi plays a key role in delivering in-home connectivity for various consumer uses and devices beyond just internet connectivity/handsets. For example, Wi-Fi connectivity includes wireless routers for TV viewing/catch-up services, wireless hubs for heating systems and wireless security systems in buildings, among others.

The Wi-Fi standards have evolved to Wi-Fi 6 and Wi-Fi 6E, which offer a better quality of service than their predecessors. Wi-Fi 6E, which was commercialised in

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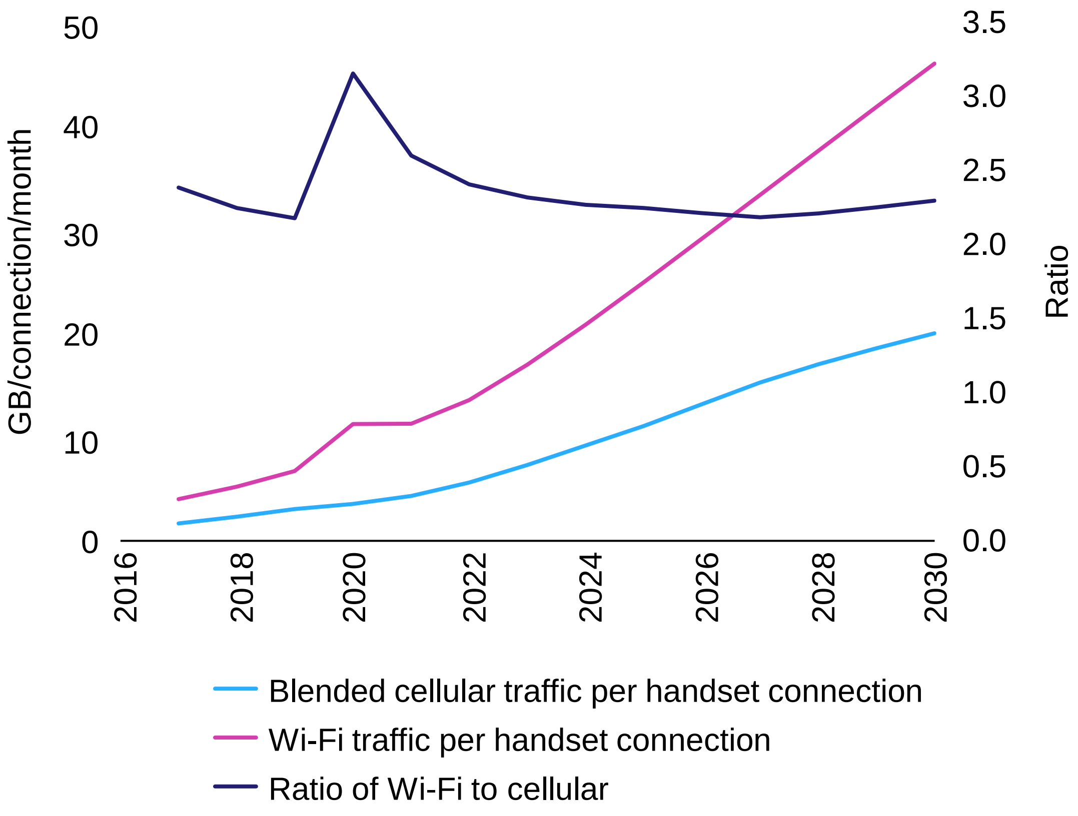
[114] Wi-Fi often provides the 'last-drop' connectivity for many connected devices in homes, offices, industrial settings (e.g. factories) and in public-service locations.

devices in 2021, adds a large block of new spectrum in the lower 6GHz band in the UK that will deliver on the promise of gigabit speeds. As a consequence, we do not expect 5G to offer major performance advantages over Wi-Fi for general private usage in an indoor context. Section 3.5.1 provides details on the evolution of Wi-Fi.

- ► *Traffic over Wi-Fi via mobile handsets and smartphones*

Over the past few years, smartphones in the UK have generated around 2.5 times as much traffic over Wi-Fi as over cellular. We expect this ratio to be approximately maintained as Wi-Fi usage grows alongside cellular. Note that in 2020, Wi-Fi handset traffic spiked as a consequence of the Covid-19 pandemic and the ratio grew to over 3, as shown in Figure 4.6 below.

Figure 4.6: Cellular versus Wi-Fi traffic per handset [Source: Analysys Mason Research, 2022]



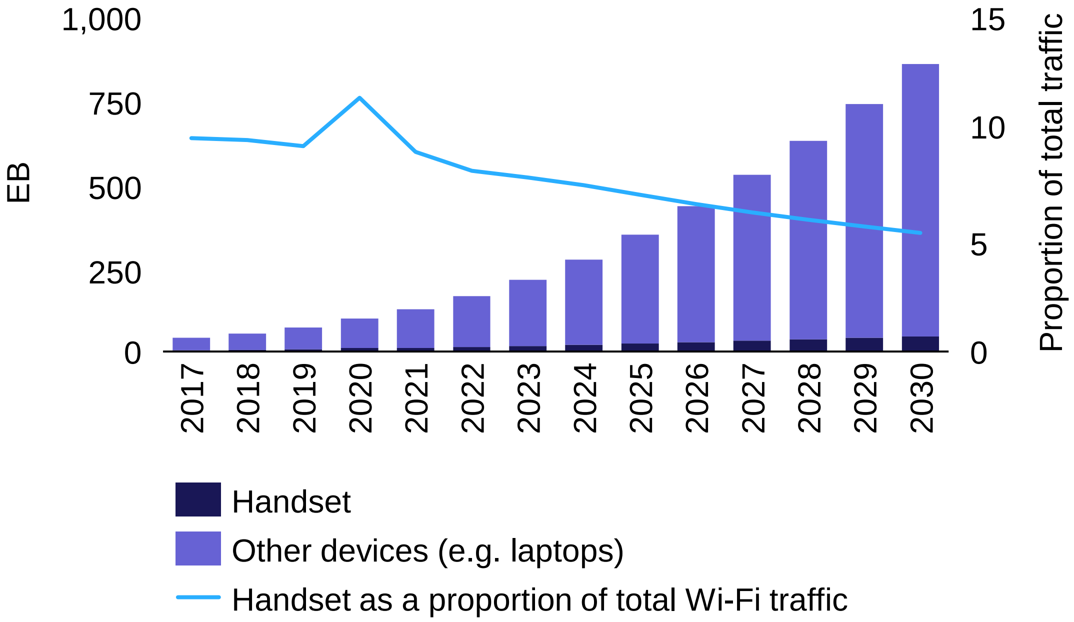
- ► *Wi-Fi traffic over other devices (e.g. tables and smartphones)*

Only a small portion of other (i.e. non-smartphone) mobile consumer wireless broadband devices (such as laptops and tablets) have an embedded SIM and connect to a cellular network and so many of these devices only operate wirelessly over Wi-Fi.

As described in Section 3.5.1, use of Wi-Fi is extremely well established as the main indoor solution that provides wireless connectivity to multiple devices within homes. Use of Wi-Fi to provide, for example, wireless routers for TV viewing/catch-up services or laptop connectivity for high-bandwidth applications (like video streaming) are increasing the Wi-Fi traffic generated by non-handset devices. Trends such as increased working from home and data-hungry future use cases (such as consumer VR/AR) will accelerate this.

As shown in Figure 4.7 below, other devices generate far more Wi-Fi traffic than handsets. Currently around 9% of total Wi-Fi traffic is generated by handsets, and this is forecast to decline to around 5% in 2030. (Note that the proportion spiked in 2020 as a consequence of the Covid-19 pandemic.)

Figure 4.7: Wi-Fi traffic from handsets versus other devices [Source: Analysys Mason Research, 2022]



4.1.2 FWA

FWA refers to wireless transmission technology that delivers connectivity from a wireless base station to distributed fixed points located on domestic premises and/or other buildings. It serves principally as an alternative to wired FBB.[115] FWA has evolved from using largely proprietary wireless technology, to 4G-based FWA and now 5G-based FWA. 4G and 5G FWA can either use the same network infrastructure as used by the MNOs to carry MBB traffic (assuming that the

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[115] This excludes MBB devices that enable seamless handover, and other mobile devices such as Mi-Fi devices. These are included in Section 3.1.

geographical footprints for FWA and MBB overlap) or alternatively FWA could be deployed as separate networks/infrastructure.

Historically, the uptake of FWA in the UK has been limited to only a few tens of thousands of customers. The greater speeds enabled by 5G operating at higher frequency bands (3.5GHz, and potentially 26GHz in the future) may allow 5G FWA to be more competitive with next-generation access (NGA) FBB solutions. 5G FWA may offer a lower-cost or more rapid solution than fibre for operators to deploy in rural areas. There may also be demand for a service which is perceived as simpler than fixed solutions (i.e. a ‘plug-and-play’ solution with no engineer installation visit required).

Currently, the main FWA provider in the UK is the MNO Three. It offers 4G and 5G ‘Home Broadband’ services. Three’s 5G service is limited by its 3.5GHz coverage footprint (which is being rolled out in the densest areas first – see Section 3.1 for details). Three’s FWA customer base grew sharply in 2020 following the introduction of its 5G FWA service, which is currently advertised as offering unlimited data packages with average download speeds of 100Mbit/s. Other MNOs may choose to offer 5G FWA services in the future, and there is also a potential role for alternative providers using unlicensed/shared spectrum in the 3.8–4.2GHz and 26GHz bands (see Section 3.2).[116]

Nevertheless, given the expected level of coverage and competition from gigabit-capable FBB in the UK in future,[117] we do not anticipate substantial levels of fixed-to-FWA substitution. As shown in Figure 4.8 below, in our baseline forecast, 5G FWA connections reach around 1 million in 2030 (less than 4% of total FBB connections).

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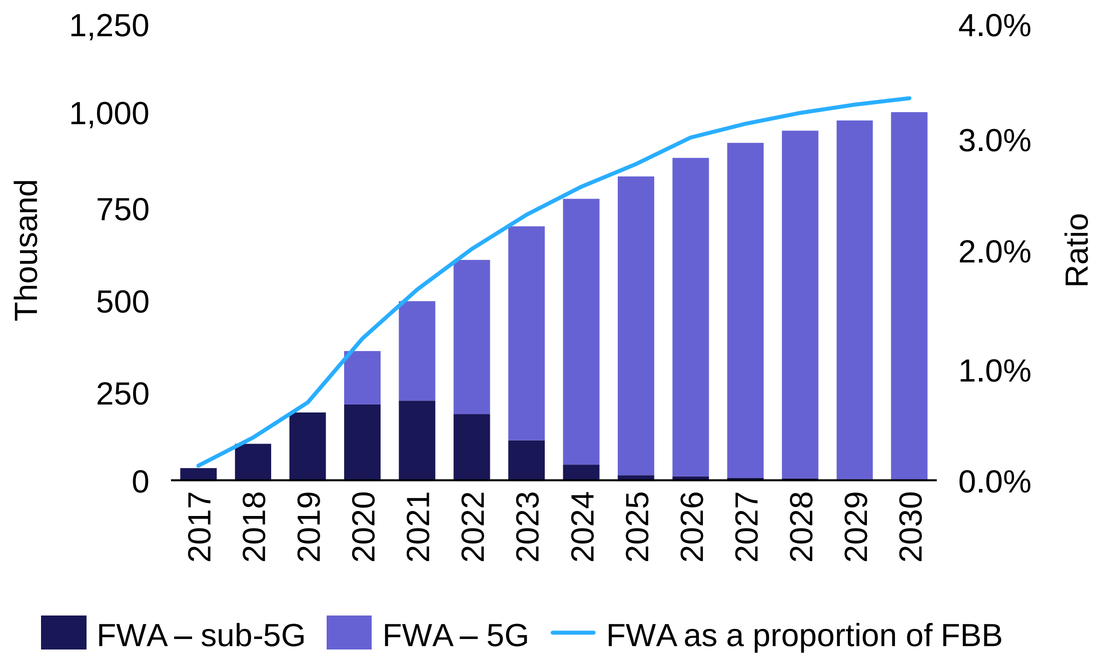
[116] The 5725–5850MHz band is also available in the UK for FWA services on a light-licensed basis with dynamic frequency selection (DFS) and transmit power control (TPC) requirements. Ofcom’s wireless telegraphy register shows that around 70 players have been issued 5.8GHz FWA licences, including wireless internet service providers (WISPs), businesses and research institutions.

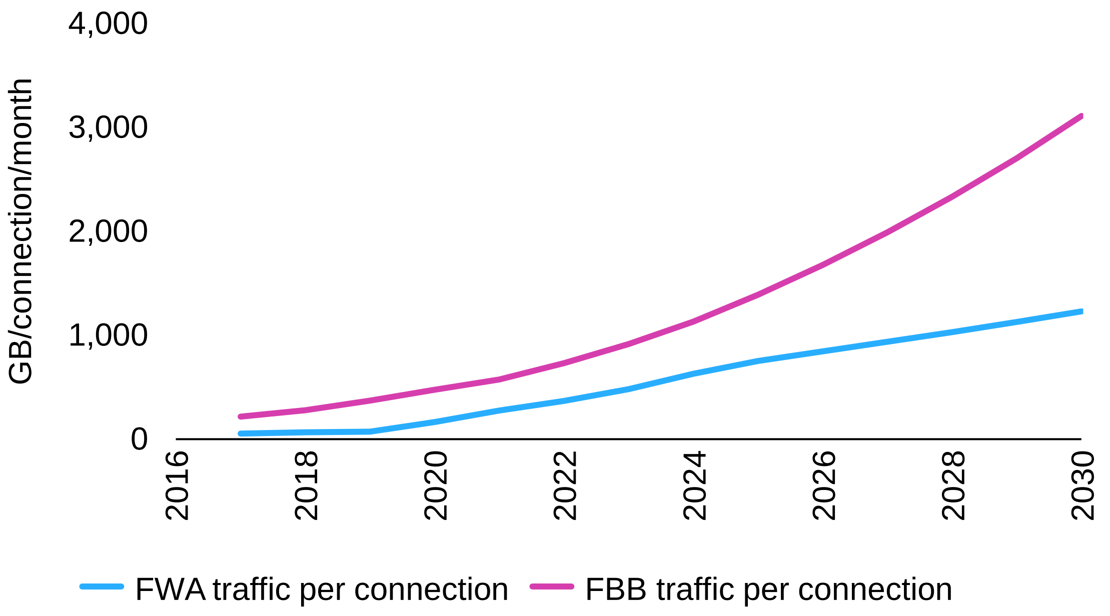
[117] By 2026, we expect nearly 80% of premises in the UK to be covered by fibre to the premises (FTTP).

Figure 4.8: FWA connections [Source: Analysys Mason Research, 2022]



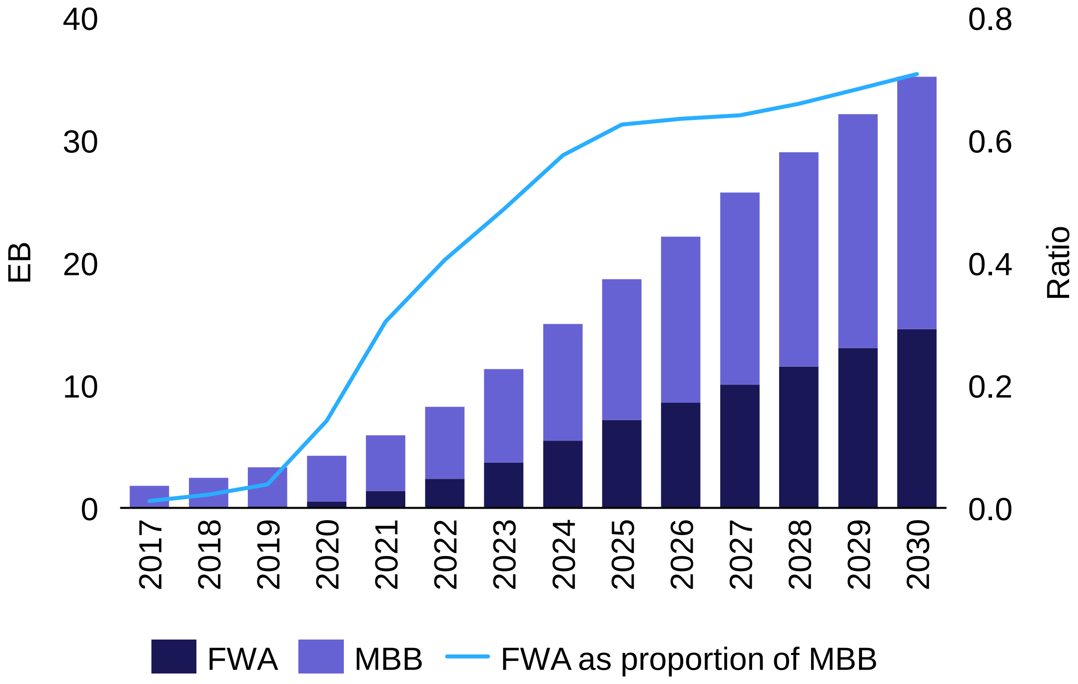
As shown in Figure 4.9 below, our forecast is that FWA traffic per connection is around 40–50% of the FBB average across the period 2017–22. Thereafter the FBB traffic per connection rises more steeply than the FWA traffic.

Figure 4.9: Traffic per FWA connection per month [Source: Analysys Mason, 2022]



Total cellular FWA traffic is forecast in Figure 4.10 below, and compared against total MBB cellular traffic (i.e. traffic from smartphones and other MBB devices). While the number of FWA connections is much lower than MBB, the traffic per connection is much higher. As can be seen, FWA traffic is forecast to reach around 70% of MBB traffic in 2030.

Figure 4.10: Total cellular traffic – FWA versus MBB (handsets and other devices) [Source: Analysys Mason, 2022]



4.1.3 Wireless connectivity for IoT

As well as connecting consumer devices, mobile networks, and/or Wi-Fi, can be used to provide wireless connectivity for numerous forms of IoT devices. IoT describes the network of physical objects – 'things' – which refers to devices that are embedded with sensors, software and other technologies and which connect with each other for the purpose of connecting and exchanging data with devices and systems over the internet.[118]

IoT connectivity is used for a large variety of use cases, from cattle tracking to connected smoke alarms to vehicle monitoring. We also include connections between connected and autonomous vehicles (CAVs) in the automotive category below, although MBB-type connectivity to consumer devices used within vehicles would be included in our handsets and smartphones estimate provided above.

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[118] Definition provided by Oracle, a global IoT player.

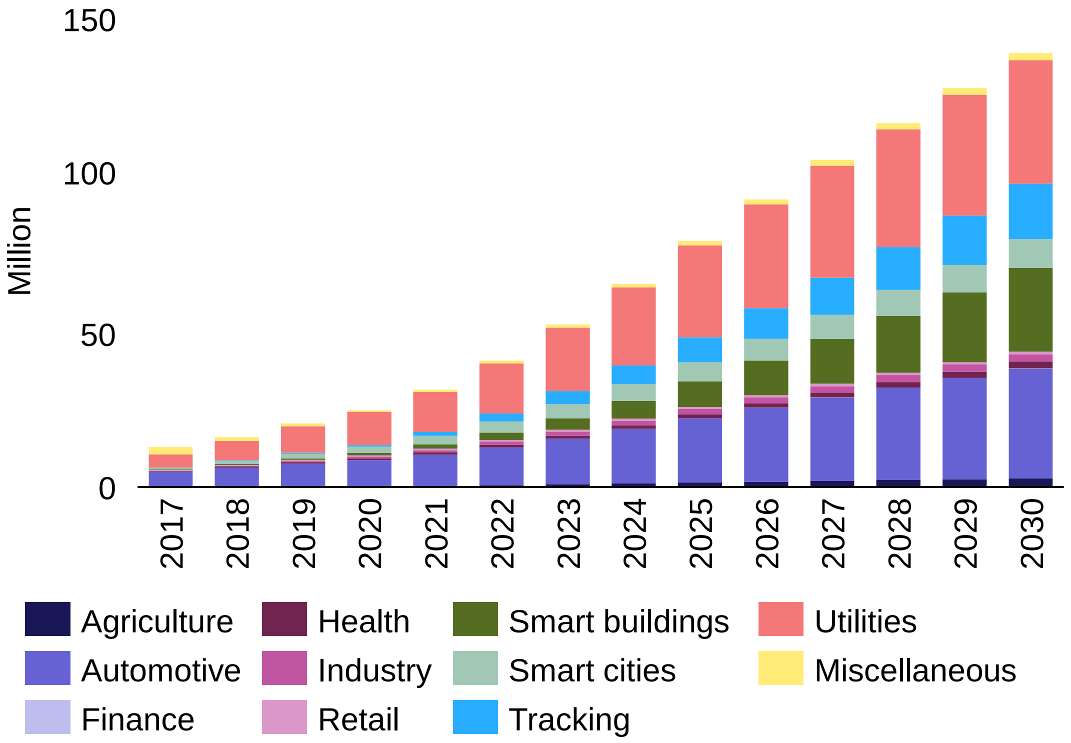
Wireless IoT use cases that are captured in forecasts published by Analysys Mason Research are shown in Figure 4.11 below.

Figure 4.11: Wireless use cases in Analysys Mason Research wide-area IoT forecasts [Source: Analysys Mason Research, 2022]

Sector	Use case
Agriculture	Cattle, forest, irrigation
Automotive	Fleet heavy goods vehicle (HGV), fleet light commercial vehicle (LCV), embedded, aftermarket
Finance	ATMs
Health	Chronic remote patient monitoring (RPM), acute RPM, personal emergency response systems, or PERS
Industry	Heavy equipment, gas/oil pipelines, machine tools, warehouse management
Retail	In store, roadside, temporary, transit hub, public venue signage, vending machines
Smart building	Security alarms, security cameras, smoke alarms, white goods
Smart cities	CCTV, parking, streetlights, waste bins
IoT tracking	Bicycles, people, cylinders, high-value assets, pets, skips
Utilities	Electric, dual-fuel meters, gas and water meters, water pipelines, smart grid
Miscellaneous	Other applications included in the forecasts that are not dedicated to any of the categories above

Figure 4.12 shows a forecast of the number of wireless IoT connections by sector in the UK to 2030. For each use case, forecasts have been developed by Analysys Mason Research using a combination of public data, interviews with IoT stakeholders and Analysys Mason modelling assumptions.

Figure 4.12: Wireless IoT connections, by sector [Source: Analysys Mason, 2022]



Total wireless IoT connections in the UK are forecast to increase from around 25 million in 2020 to around 140 million in 2030. Automotive and utilities are the largest sectors by connections (together accounting for over 50% of all wireless IoT connections by 2030). The automotive industry is expected to see a huge shift in the next decade.

The evolution of connected vehicles will utilise wireless connectivity both within the vehicles, and potentially between vehicles and the roadside. Wireless connectivity within the vehicle (e.g. to smartphones or other devices) is classed as smartphone data traffic, described previously. The IoT portion of the automotive use case demand refers to messaging sent to vehicles via a mobile network (for example, to provide speed advisory advice, roadworks warnings or other route updates). CAV and the infrastructure options underpinning these is discussed in Section 3.5.2.

IoT usage in the utilities sector is also expected to see significant changes in the next ten years, driven by transformation of the energy grid to reflect real-time monitoring and related developments. The resulting technological changes are expected to include distributed grid, grid control automation and distributed energy storage. It is worth noting that the connections forecast developed by Analysys Mason Research mainly covers more traditional IoT use cases that already exist today. The connections forecast currently do not include more advanced use cases that are expected to emerge in the utilities sector (such as remote expert applications using AR/VR, UHD video imaging of assets, drones inspection).

Thus, the data requirements for smart grids in future might be somewhat higher than our forecasts, and there will be demand from utility companies to utilise advanced services via mobile devices such as UHD video and AR/VR, for their own business needs. However, it is not yet clear how such requirements will be delivered – whether via a public cellular network, using private cellular networks or possibly via a dedicated utility-sector network using a frequency band set aside for this specific use, such as exist in some other European markets using spectrum in the 410–430MHz or 450–470MHz band.[119]

Public sector users in the UK, such as those in the health sector, are expected to generate relatively higher IoT traffic loads, due to the higher data rates of use cases such as remote patient monitoring (RPM).

Figure 4.13 below shows a forecast published by Analysys Mason Research of the number of wireless IoT connections in the UK, split by technology. Further details of the other IoT technologies indicated below are provided in Section 3.5.2.

To reflect the demand for future IoT applications that are not captured in the forecasts below (which are abstracted based on current IoT use cases), we have developed modelling scenarios (presented in Section 5.2.3) that illustrate the additional cellular infrastructure needed to reflect increasing data traffic levels either driven by increased consumer use, increased use of advanced IoT applications (referred to as enterprise traffic) or both.

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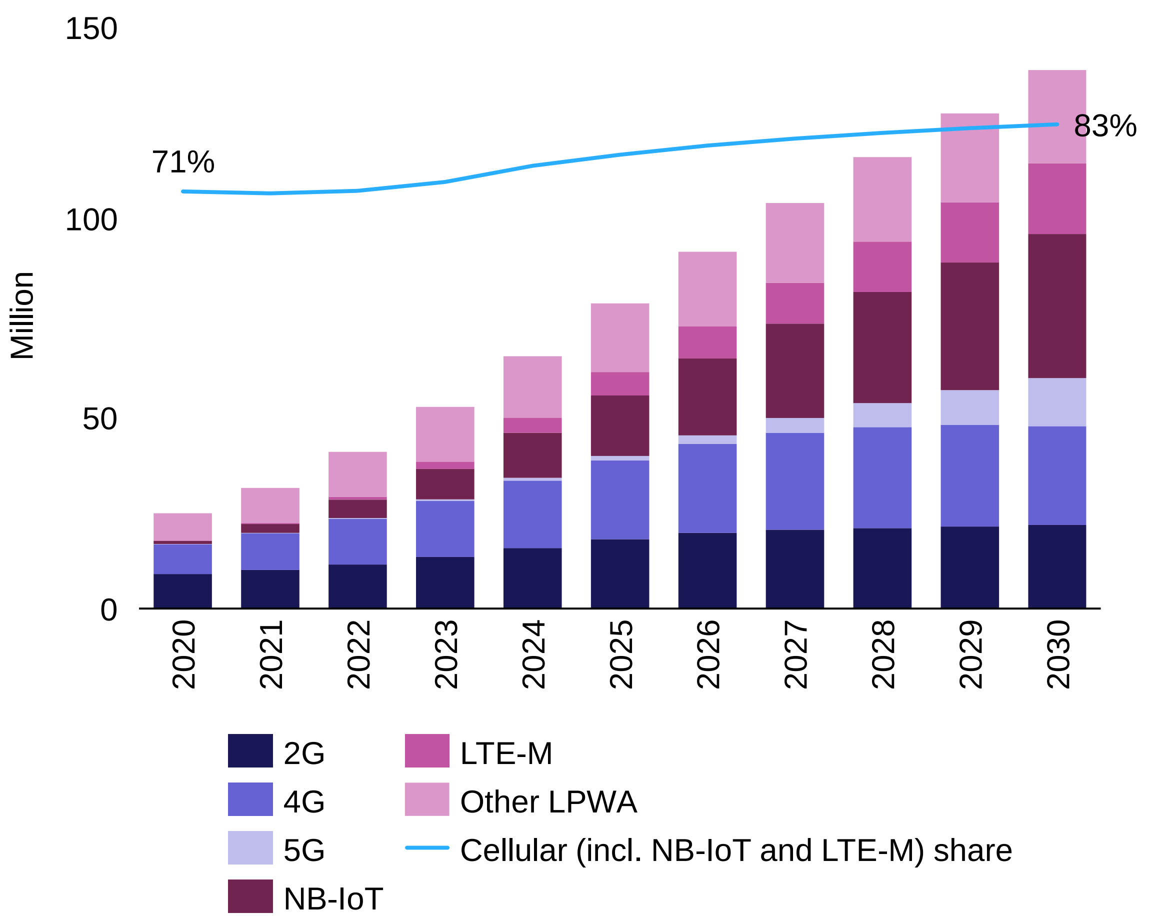
[119] For example, see https://eutc.org/media/2021/07/2021-04-EUTC-Response-to-Dutch-450-MHz-consultation-2021-1.pdf

Figure 4.13: Wireless IoT connections by technology [Source: Analysys Mason Research, 2022]

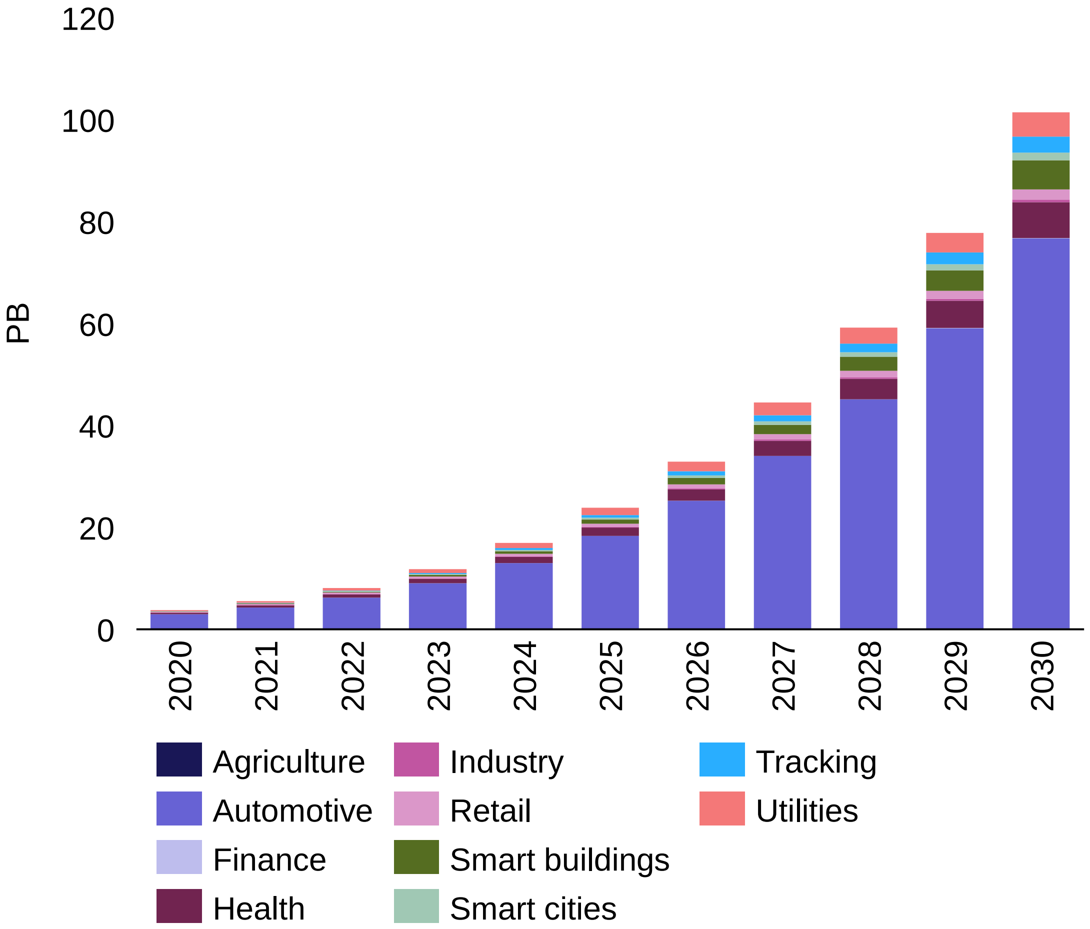


As indicated in the above forecast, IoT connections are currently split (relatively evenly) between 2G, 4G and other LPWA, but by the end of the decade and beyond, there will be a rapidly increasing portion of lower-bitrate IoT connections using 4G and higher-bitrate connections using 5G. In particular, NB-IoT and LTE-M connections are expected to grow significantly in future as network capabilities are rolled out more extensively. NB-IoT and LTE-M networks are 4G-based and discussed in Section 3.5.2.

The forecasts above suggest most IoT connections requiring wide-area connection, such as in the utilities, tracking, smart city, smart building, agricultural and industrial sectors might continue to use 4G-based technologies, namely NB-IoT, LTE-M, or other LPWA technologies, by the end of this decade. This reflects that 4G technology capabilities will be sufficient for these applications given the relatively low bitrates needed (e.g. for sensor/tracking-type applications, as described in Annex A).

Compared to other traffic categories (e.g. MBB, FWA), the traffic per IoT device (LPWA or non-LPWA) is typically far lower (particularly so as IoT devices tend to transmit smaller data packets intermittently). The total traffic load generated on cellular networks by wide-area IoT connections (shown in Figure 4.14 below) is therefore a small fraction (<1%) of cellular traffic generated by smartphones and other consumer devices. The assumption that wide-area IoT connections only represent a very small fraction of total traffic load assumes a year-on-year growth rate in the traffic per IoT connection of 20%.

Figure 4.14: IoT devices traffic forecast [Source: Analysys Mason Research, 2022]



4.1.4 Comparison of traffic from different categories of user

In this subsection, we summarise and compare the cellular and Wi-Fi traffic demands of the different user categories discussed in the previous subsections, based on Analysys Mason's current forecasts.

For the reasons provided above, we have excluded sector-specific traffic generated in localised areas with requirements relating to very high throughput or quality of service. We have also excluded sector-specific traffic carried on some of the UK mobile networks, such as the mobile traffic from emergency services users of the Emergency Services Network (ESN)).

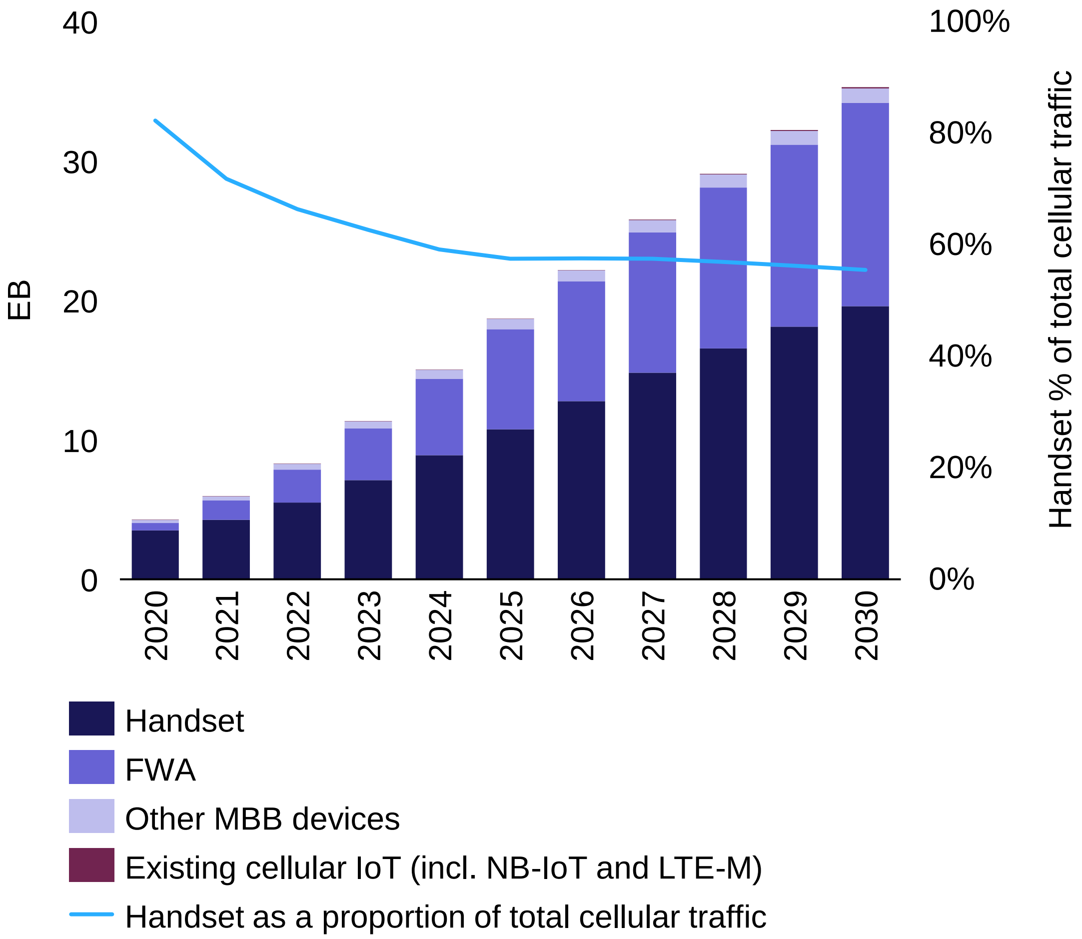
Traffic carried over public cellular networks

Figure 4.15 below shows a forecast of total traffic carried over public cellular networks. We include traffic generated by four different types of user/device:

- handsets (smartphones)
- other MBB devices (e.g. tablets, laptops) either connected directly to a mobile network or via a FWA connection using a cellular network
- wide-area IoT devices for existing use cases.

Traffic shown is based on published connection forecasts from Analysys Mason Research. The forecast includes traffic generated by FWA connections over mobile networks, but excludes any traffic for advanced IoT enterprise use cases. Section 4.2.3 below describes these limitations, as well as mechanics built into the quantitative model developed for this project that allows illustrative traffic forecasts for these use cases to drive public network capacity assumptions in the model.

Figure 4.15: Public cellular network traffic [Source: Analysys Mason, 2022]



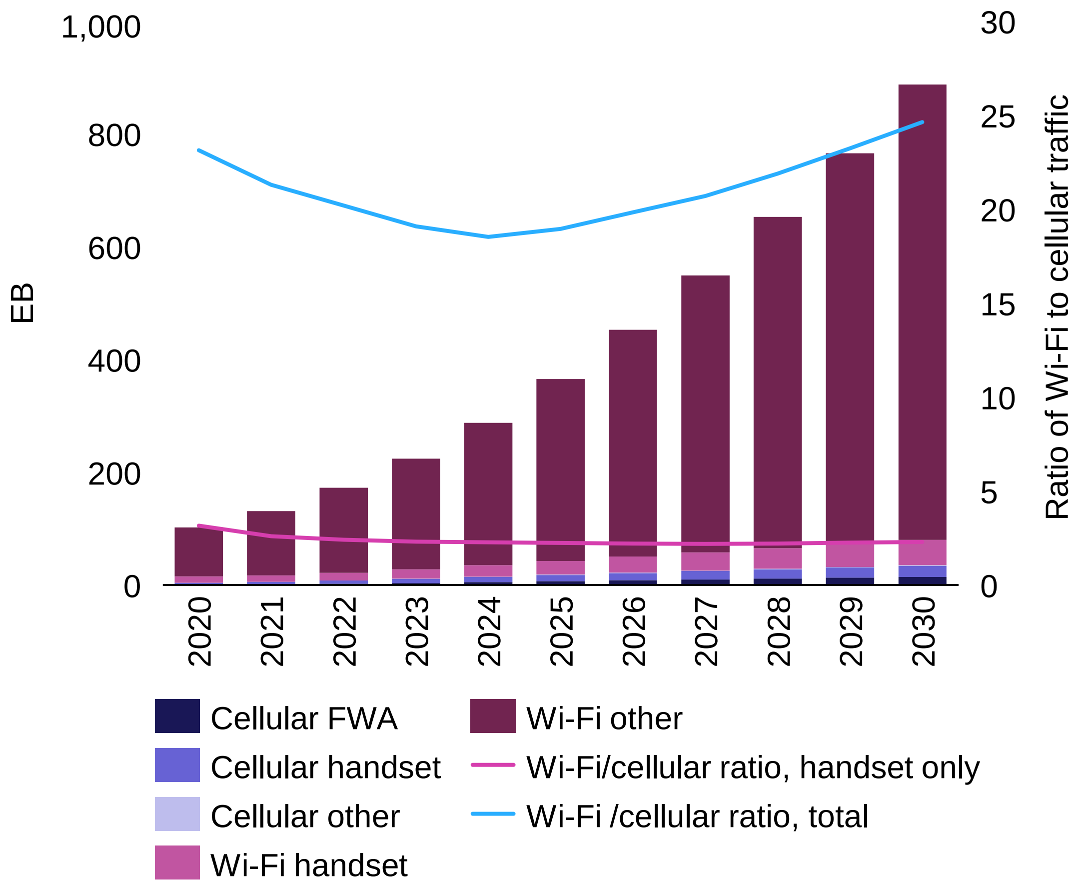
Traffic over public mobile networks generated by laptops, tables and IoT devices makes up only a few per cent of the total traffic load. This reflects that laptops and tablets are more often connected using Wi-Fi in the UK (either connected via a fixed/fibre connection, or via FWA). IoT traffic currently excludes the more advanced IoT use cases, explored further in Section 4.2.

Cellular networks are likely to continue to be dominated by handset (smartphone) traffic. In our baseline forecast, we assume that FWA connections grow to around 1 million by 2030. While this is a small fraction of smartphone connections, the traffic per connection is much higher for FWA than smartphones. Handset traffic is forecast to be around 55% of total cellular traffic in 2030.

Public cellular traffic versus Wi-Fi traffic

Estimates from Analysys Mason Research are that around 90% of total consumer Wi-Fi traffic is currently generated by non-handset devices, such as tablets and laptops. This is forecast to increase to around 95% in 2030. As shown in Figure 4.16 below, consumer Wi-Fi traffic exceeds total cellular traffic by a factor of around 25. This ratio is forecast to decrease slightly over the coming years with the growth of cellular FWA traffic outstripping Wi-Fi.

Figure 4.16: Public cellular traffic versus Wi-Fi traffic [Source: Analysys Mason, 2022]



4.2 Future enterprise/IoT demand

In addition to demand for wireless connectivity from consumer devices, for FWA and to connect current types of IoT devices, individual economic sectors within the UK will have their own specific wireless connectivity requirements, based on the individual processes and applications used within each organisation. This demand will include more advanced IoT use cases, not reflected in the forecasts above.

The pace of digital transformation within UK industries is giving rise to new types of wireless connectivity demand, to connect industrial equipment wirelessly using secure, resilient links. Some of these industrial applications have previously used tethered (i.e. wired) connections, but wireless connection allows significantly more flexibility for machinery to be moved and to operate over wider areas. These more demanding IoT use cases might potentially use 5G networks in future. In the next section, we discuss what underpins future demand, in terms of sectors of use, and the relevant use cases.

4.2.1 Definition of sectors/use cases

In our previous study for DCMS on ‘Realising the benefits of 5G’[120] we identified nine economic sectors broken down into subsectors, each with different connectivity requirements.

For the purposes of the present study, we have revised the list to aggregate into 7 sectors and 15 subsectors, as shown in Figure 4.17. Each subsector has specific wireless connectivity requirements unique to that subsector. The wireless connectivity requirements for these sectors have been captured through the literature review conducted for this study, which is described in Annex A.

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[120] The study conducted recently by Analysys Mason and Cambridge Econometrics (2021).

Figure 4.17: Economic sectors and subsectors [Source: Analysys Mason, 2022]

Sector	Subsector
1. Media and entertainment	1.a. Media creation
	1.b. Venues and events
2. Public services	2.a. Health and social care
	2.b. Education
	2.c. Emergency services
3. Energy and utilities	3.a. Energy and utilities – smart grid
	3.b. Energy and utilities – site operations
4. Rural industries	4.a. Agriculture, forestry and fishing
5. Smart urban	5.a. Smart cities
	5.b. Construction
6. Transport	6.a. Road
	6.b. Rail
	6.c. Air
	6.d. Ports
7. Manufacturing	7.a. Smart factories and warehousing

We have revised the categories of use case identified in the previous study's literature review in order to avoid double-counting the MBB-only demands that are already captured in the data forecasts described in Sections 4.1.1 and 4.1.2 (there is some overlap with the IoT forecasts described in Section 4.1.3). This leads us to define eight distinct categories of use case requiring wireless connectivity:

- AR/VR
- Ultra-high definition (UHD) video
- Sensor networks
- Remote machine manipulation
- Robotics
- Drones
- Smart tracking
- Connected and autonomous vehicles (CAV).

Based on the literature review conducted for the previous study, and additional research conducted within this study, we have identified the use-case categories that are likely to be most relevant to each subsector. These are summarised in Section 4.2.2 below. A detailed breakdown is provided in Annex A.

4.2.2 Connectivity requirements per sector

We have conducted a literature review to gather evidence to support determination of the specific connectivity requirements per economic sector. These specific connectivity requirements might include bespoke requirements that different sectors, and businesses within sectors, will have in terms of capacity, latency coverage and other operational considerations (such as a need for end-to-end security and network resilience). We began by looking at the generic requirements per device for each use case, and then any specific variations by sector.

Our findings on the applications enabled through different levels of wireless quality of connection is are detailed in Annex A.

We then compare the use-case requirements per economic sector against the characteristics of various technologies, as a way to arrive at an indication of the potential technologies that might be a good match to deliver different use cases that might be needed by different sectors of the industry.

Figure 4.18: Comparison of wireless technology performance characteristics [Source: Analysys Mason, 2022]

Technology	Capacity	Latency	Coverage
4G	~100Mbit/s	20–30ms	Local plus contiguous wide area
5G (mid band)	Up to ~1Gbit/s	<10ms	Local plus contiguous wide area
5G (mmWave[121])	Up to ~3Gbit/s	<2ms	Local, non-contiguous over wide areas
Wi-Fi 5	~200Mbit/s	~30ms	Local
Wi-Fi 6	500–2000Mbit/s	~20ms	Local
Satellite (GEO)	~20Mbit/s (current) ~100Mbit/s (next generation)	~250ms	Wide area
Satellite (LEO)	500–1000Mbit/s (claimed)	~25–35ms	Wide area

The requirements are generally presented as being the estimated requirement based on literature available at the current time. However, it is worth noting the following:

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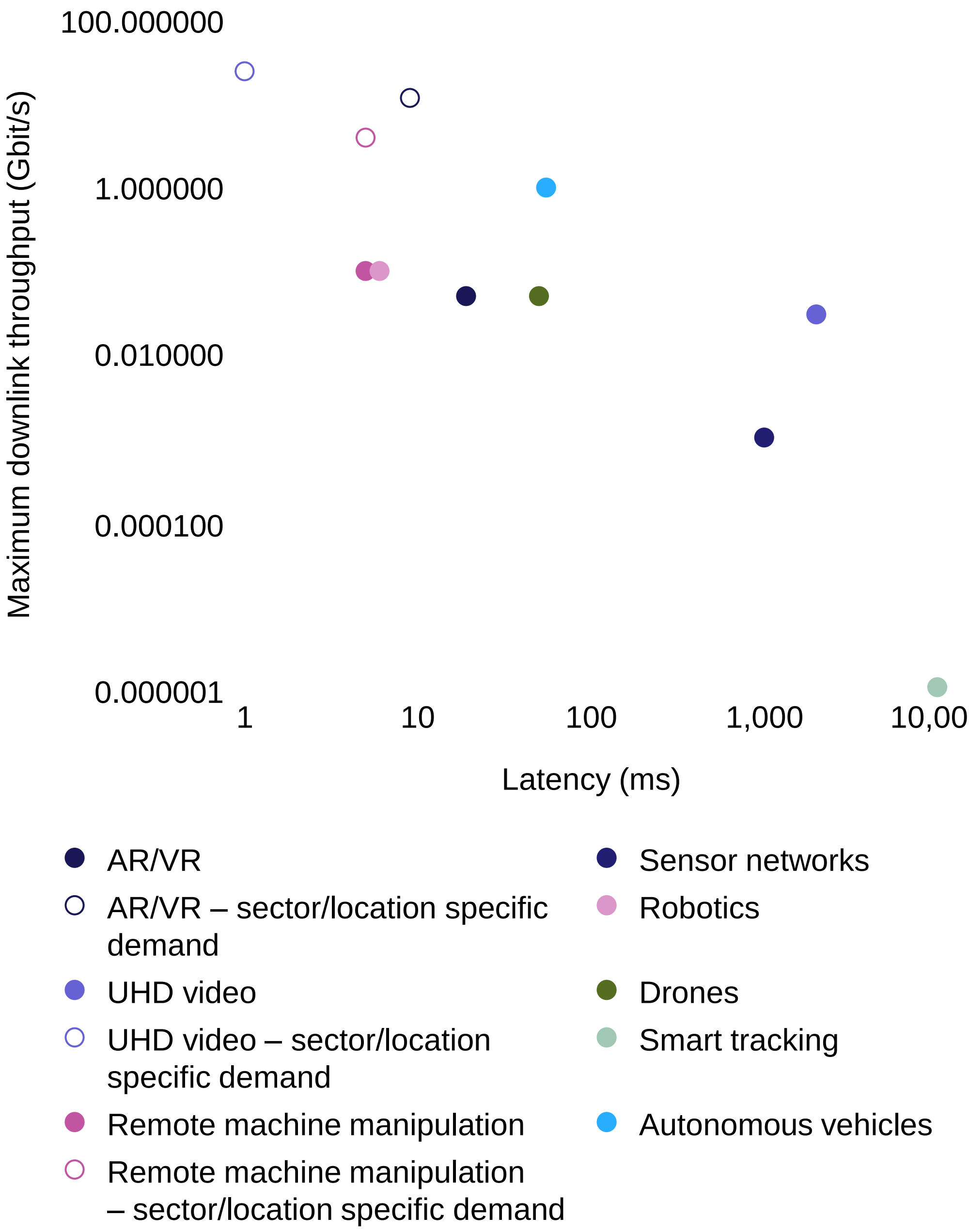
[121] Millimetre wave, which in the 5G context refers to selected bands above 24.25GHz (e.g. the 26GHz band), will allow very-high-capacity, low-latency applications to be delivered within a local area (cell sizes are reportedly up to a several km radius, depending on cell loading and environment); see https://www.ericsson.com/en/press-releases/2020/9/ericsson-qualcomm-and-u.s.-cellular-achieve-extended-range-5g-data-call-over-mmwave.

- Some future use-case requirements rely on data speeds and/or functionality not currently implemented within initial 5G deployments. For example, some requirements are based on 3GPP Release 17 specifications, which are not yet finalised, and hence would not be expected to be commercially achievable before around 2025 at the earliest, as described in Annex A.
- Many use cases will evolve over time, which might increase efficiency of data consumption (e.g. increasing video resolution), but could also increase the data throughput and/or latency requirements (e.g. increasing autonomy in vehicles).
- For use cases that are not currently commercially available in specific sectors (e.g. AR/VR in emergency services), the requirements capture the range across other similar present-day use cases, any information on prototypes/trials and, if known, the potential future sector-specific requirements.
- The allocation of potential technologies to use cases are indicative, based on speculated performance requirements of various sector use cases, and potential performance characteristics of various technologies. Ultimately, the main technologies used to serve each sector use case will also depend on technology choices made by different types of providers (e.g. MNOs, others) and how well positioned different providers are in serving the different use cases.

Based on literature we have reviewed, many future use cases have requirements that would present similar requirements for mobile networks (e.g. in terms of the required speed of connection) across different sectors of use. The throughput requirements vary more between the type of use than between the sector of use. As such, a MNO providing wide-area coverage with sufficient throughput and low latency would enable to address multiple use cases across various sectors of use. Where some sectors or users require specific forms of connection – for example, more uplink capacity, or contiguous coverage indoors and outdoors – MNOs may find that these capabilities cannot be delivered using a public mobile network that is dimensioned for downlink-oriented consumer traffic. Hence, other solutions, such as a private cellular network, might provide bespoke solutions.

Some sectors of enterprise or public sector use have specific connectivity requirements applying to any telecommunications connection they use, such as in terms of resilience, or data security. The sectors for which additional requirements (such as network resilience) may apply are those sectors operating critical national infrastructures – for example, Emergency Services, energy and utilities and transport. Addressing the future connectivity needs of these sectors via public mobile networks would require additional infrastructure – for example, additional resilience would need to be built into the MNO's network plus specific solutions for power back-up and data security. Typically, these additional investments would be funded by the public sector or enterprise user. An example of the additional investments needed to meet specific sector requirements in the UK is the Emergency Services Network (ESN), using BTEE's mobile network, funded via the Home Office.

Figure 4.19: General connectivity requirements and sector-/location-specific connectivity requirements for use cases [Source: Analysys Mason, 2022]



4.2.3 Uncertainties in demand evolution, supply options and relevance to public cellular networks

As discussed in Section 4.2.2, there is a wide range of connectivity requirements across the different economic sectors.

Many of the use cases have requirements that go beyond what the public cellular networks are able to provide currently, and it is not clear the extent to which these requirements will be met in future. We would expect the traffic for these use cases to be served by dedicated infrastructure (whether provided by the public cellular operators or alternative providers; see Section 3). Use cases in this category generally have highly localised and high-capacity demand (media creation, venues and events, health and social care, energy/utilities – site operation, education, construction, air, ports and smart factories and warehousing).

For wide-area, lower-bitrate IoT use cases, demand is captured in the IoT traffic forecast in Section 4.1.3 (this is primarily demand for wireless sensor networks, wireless surveillance and smart tracking). These forecasts reflect that some lower bitrate IoT demand might be met using alternative wireless technologies.[122]

There are also various spectrum bands dedicated to short-range wireless use, which will provide localised wireless connectivity for specific types of use as an alternative to using a wide-area network. This includes the 5.9GHz band, assigned for use by low-power vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity for use in Intelligent Transport Systems (ITS) in the UK, although not yet deployed. The V2V and V2I applications that might use the 5.9GHz band refer to 'basic safety' applications for road safety and traffic efficiency.[123] These applications are a subset of the vast range of sensing and connectivity requirements a fully autonomous vehicle will have in future. For autonomous driving, future technologies such as 5G-based vehicle to everything (5G-V2X, or NR-V2X) are anticipated to be used. These solutions are not yet commercially available,[124] but prototypes of the sorts of solutions envisaged for automated driving are being tested as part of the 5G Testbeds and Trials programme.

This leaves a handful of wide-area use cases that may have additional demand for public cellular connectivity beyond connectivity already provisioned through existing contracts and solutions:

- Emergency services (future applications beyond those being deployed as part of the ESN). Such future applications, if not already captured by the ESN, might

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[122] There are existing, large-scale contracts in place for IoT connectivity in the UK. These include the Arqiva-delivered wide-area networking solution using 412–414 or 422–424MHz spectrum, used by smart meters in the north of England and Scotland, and a 2G/3G smart-meter wide-area network contract with VMO2 for south and central Great Britain.

[123] Examples include roadworks warnings, emergency vehicle approach warnings, speed limit warnings, described in more detail here: https://www.car-2-car.org/about-c-its/.

[124] They are part of 3GPP Release 17 specifications, which are currently being finalised.

include use of AR/VR, UHD video, sensor networks, remote machine manipulation, robotics and drones.

- Energy/utilities (specifically more demanding, higher-bitrate smart grid applications, including AR/VR-assisted operations (e.g. remote expert and visualisations of remote environments, UHD video and drone inspection).
- Rural industries (AR/VR, remote machine operation, drones).
- Smart cities (sensor networks, AR/VR, drones).
- Road (contiguous MBB connectivity to vehicles, for infotainment/data updates via public mobile networks). CAVs would additionally use sensors and vehicle-to-vehicle connectivity, and may also utilise vehicle to infrastructure using roadside units using 5.9GHz spectrum, if these are implemented in the UK, as discussed in Section 3.5.2.

Given the significant amount of uncertainty surrounding future sector-specific demand for advanced use cases, and choices over how these might be delivered (i.e. dedicated on-premises/network slicing/hybrid) for each sector or use case, currently available forecasts of IoT traffic tend to only cover wide-area demand for existing use cases, but not more advanced ones.

In Section 5, we describe the model developed for this study to investigate future supply of cellular infrastructure in the UK, which includes scenarios of higher traffic demand reflecting the uncertainties described here. The baseline model we have developed is based on deployment that has been announced by operators together with future deployment plans that were indicated by selected operators during the interviews conducted for this study. We refer to this as the model ‘baseline’. There are various factors that will affect operators’ roll-out rates in practice, and hence we have made assumptions on the rate of roll-out in the baseline based on the information that operators provided during the interviews conducted for this study.

In this model, scenarios are included to generate alternative indicative forecasts of demand for additional advanced use case traffic, beyond the data traffic include in the more near term traffic forecasts described above. The future data scenarios presented in the model are illustrative at present due to a lack of evidence but can be refined over time as more information becomes available on demand for more advanced applications, and how these will be paid for.

The model also includes mechanics to:

- allocate a proportion of this advanced use case traffic demand to public mobile networks delivered via network slicing (versus privately deployed on-premises networks)

- illustrate a situation where MNOs deploy additional capacity to ‘pre-emptively’ meet some of this demand to be served using network slicing, and what this means for the quality of connection in local areas for consumers.

By assuming a portion of advanced use case traffic demand is met through network slicing on public networks, we are aiming to reflect the fact that there might be connectivity benefits for consumers if MNOs pre-emptively upgrade network capacity to serve business traffic in given locations (i.e. spill-over benefits to consumers, from deployment of capacity to meet business connectivity needs using public networks). It is noted that business or enterprise traffic served by cellular sites deployed within the enterprise or business premises might not be useable by other mobile users, if the network is configured as a private network. Hence, there would be no spill-over benefits to the local area in terms of improved coverage.

Figure 4.20 shows how an illustrative forecast of advanced use case traffic can be split by supply option (public or private) and the extent to which MNOs might deploy public network capacity for these advanced use cases pre-emptively.

Figure 4.20: Illustrative enterprise traffic forecast by estimated supply method [Source: Analysys Mason, 2022]

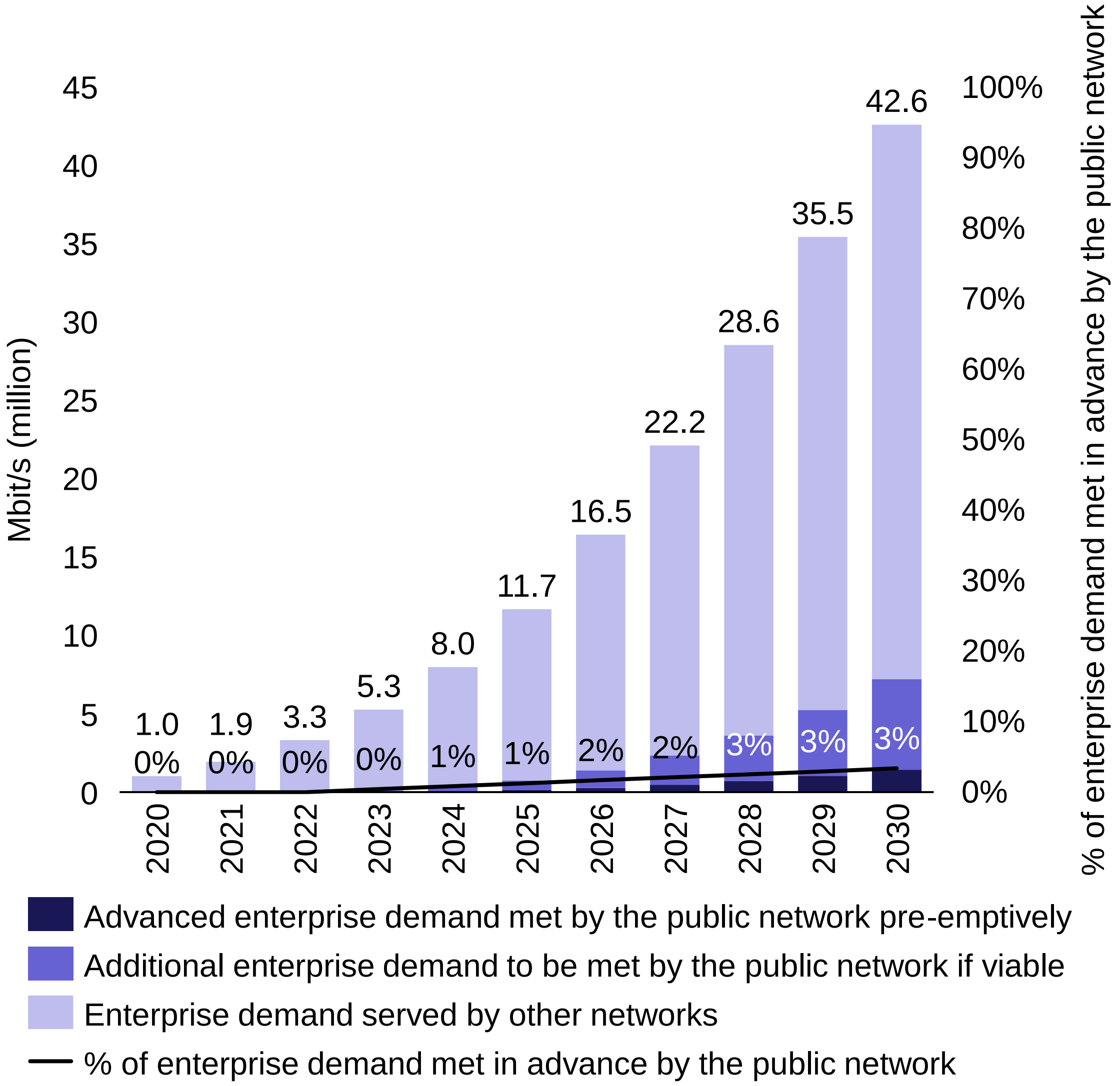
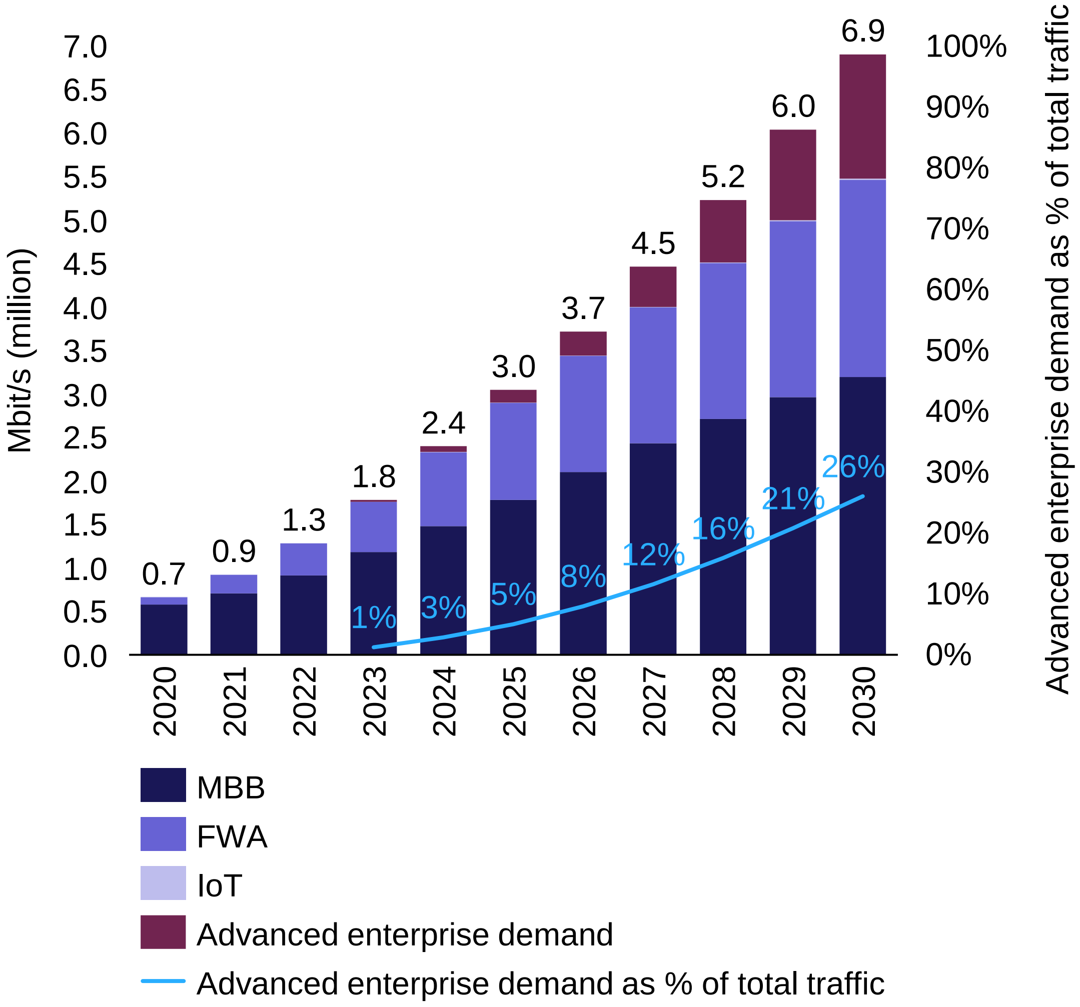


Figure 4.21 shows how the resulting allocation of advanced enterprise demand can be added to other traffic demand categories in order to drive the expected future coverage in the model baseline for a hypothetical operator.

Figure 4.21: Forecast of baseline traffic to be served by the hypothetical operator, including advanced enterprise demand that is 'pre-emptively' met [Source: Analysys Mason, 2022]



In Section 5, the traffic forecast shown in Figure 4.21 is used to predict deployment of additional capacity on existing sites, as well as new sites, for a hypothetical operator in the UK. The traffic forecast would represent the extent to which deployment can be expected to take place based on current market dynamics, as well as announced plans, which would be referred to as the baseline deployment. Several scenarios are then considered and higher quality-of-coverage levels are targeted (e.g. widespread availability of higher average download speeds per active user/remaining advanced enterprise demand that MNOs do not 'pre-emptively' meet). For each of these scenarios, the difference in the cost of deployment between those higher targets and the baseline deployment are then calculated.

4.3 Spill-over benefits to public mobile connectivity from investment in private networks

Previous studies have expanded on the socioeconomic benefits of enterprise and private cellular networks,[125,126] in the form of productivity improvements for businesses that deploy these private networks, as well as benefits to downstream consumers of services. As we have discussed in Section 3.2, public MNOs might provide private cellular networks in the UK (either using public mobile infrastructure, via network slicing, or by deploying additional dedicated infrastructure). Other third party providers might deploy private cellular networks too, bypassing public mobile networks completely (e.g. if the private cellular network uses spectrum available via Ofcom’s shared access licensing, and this network is directly connected to backhaul and to a private cloud, without using a public network). However, if MNOs serve enterprise traffic, either using their public mobile network infrastructure entirely or through a hybrid approach whereby some private infrastructure works alongside some public network capacity, then there could be spill-over benefits to consumers, if MNOs were to upgrade the public mobile infrastructure to serve enterprise traffic.

There would be limited direct impact on local levels of public mobile connectivity if private networks are deployed entirely on the premises (without deployment of any elements that would be shared with public mobile traffic). Current indications described in Section 3.2 are that on-premises dedicated deployment is a common model for private networks currently. If these networks remain private and on-premise, any network capacity upgrades would not generally be available to public users. Hence there is limited spill-over effect to local levels of public mobile connectivity albeit that local economies will benefit from enterprise and businesses being more productive if adopting advanced wireless use cases via private networks.

However, if MNOs serve enterprise traffic via their public mobile networks (e.g. with network slicing), and if the MNO makes upgrades to network capacity to serve enterprise traffic demand, then there could be spill-over benefits to consumers from excess capacity available in those locations where upgrades would occur. To illustrate what these spill-over benefits might mean for local areas, we examine the distribution of average download speeds obtained by the population in 2030 as a result of Scenario 2 of our modelling. Figure 4.22 shows that introducing enterprise demand reduces the speed that consumers will achieve relative to the baseline. This is because the excess capacity that would result in higher speeds in the

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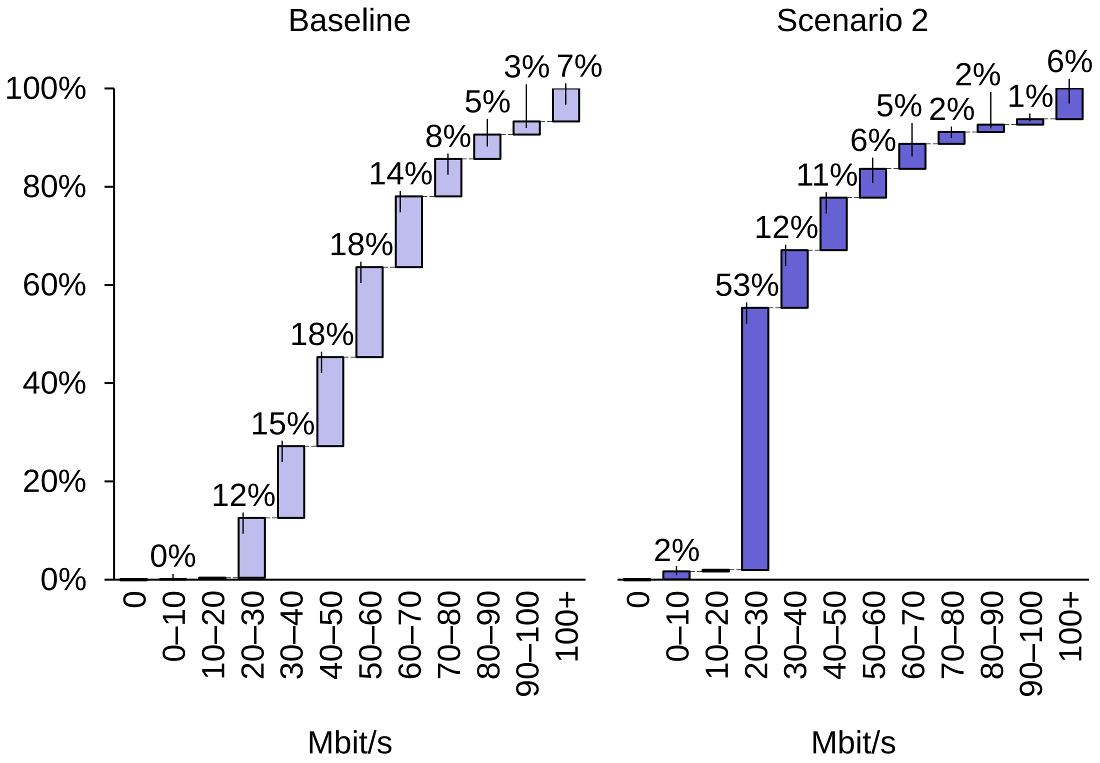
[125] See https://www.analysysmason.com/contentassets/3716b071d2f647c9a9e57e56900b4f66/analysys-mason---status-costs-and-benefits-of-5g-26ghz-deployments-in-europe.pdf

[126] See https://www.gsma.com/spectrum/wp-content/uploads/2019/10/mmWave-5G-benefits.pdf

baseline is used to meet enterprise demand, reducing the capacity available to consumers, and thus reducing the speeds they can achieve. There are a handful of locations where introducing enterprise demand triggers deployment of spectrum that results in a greater excess capacity meaning speeds are improved (when looking at each grid square it can be seen that 5% of the population has improved speeds in Scenario 2 relative to the baseline), but this vastly outweighed by the remaining population’s reduced speeds.

Figure 4.22: Percentage of population with the following average speed per active user by the end of 2030 according to the baseline and Scenario 2 [Source: Analysys Mason, 2022]



Private network investment could also result in additional spill-over effects for consumers. For instance, private networks offer a near-term opportunity for 5G-SA deployment to be tested, ahead of MNOs migrating to 5G-SA in a few years from now.

Private networks might also offer a near-term proving ground for the Open RAN ecosystem, ahead of this technology being adopted more widely in the macro mobile networks. Given that Open RAN architectures are still immature, ‘first generation’ solutions are being tested outside of urban areas, which will be the most demanding environments on the Open RAN platform due to highly variable traffic loads. Vodafone UK had planned to start Open RAN deployment in rural areas before moving to urban areas later on.[127] Private networks offer another environment for near-term, Open RAN infrastructure (since enterprise networks have more predictable traffic loads and are geographically constrained). These Open RAN solutions for private networks could be deployed in the near term, whereas we might not expect widespread use of Open RAN in macro networks until after 2025. Once deployed in public networks, Open RAN architectures could result in deployment cost savings, with some of these savings potentially passed onto consumers in the form of better service availability. However, such benefits might not necessarily be felt locally in the short to medium term. The benefits are more likely to impact public networks in a general way by accelerating the path to future developments.

4.4 Other environments with potential gaps in supply

4.4.1 Indoor locations

Although outdoor macro cells deployed by MNOs are dimensioned to carry indoor traffic, the macro network is typically insufficient to meet all end users' quality-of-service expectations for in-building connectivity. Achieving indoor coverage via outdoor macro cells might become more problematic using mid-band 5G spectrum, since the propagation characteristics of high-frequency bands result in more limited ability to penetrate physical objects such as walls and windows, compared to lower bands.

MNOs generally favour use of sub-1GHz bands to meet quality-of-service expectations for in-building connectivity via outdoor macro cells. However, the bandwidth available in bands below 1GHz is more limited than in the high-frequency bands, and the latest 5G antenna technologies (i.e. massive MIMO) are not designed for these bands. This means that sub-1GHz spectrum can become congested in locations with high traffic load, degrading the in-building quality-of service.

Enterprises and industrial users needing a consistent quality-of-service within their premises might look to use tailored solutions, either procured from an MNO, from an equipment vendor or another third party (e.g. PCP).

The main technologies used to provide indoor coverage include private Wi-Fi, indoor small (cellular) cells, DAS/in-building solutions (IBS), and in some cases mobile repeaters. Private cellular networks using the 26GHz band in the UK would be a further alternative, and we note that Ofcom has recently consulted on availability of the upper 6GHz band for enterprise and industrial use, indoors.

A comparison of these indoor coverage solutions are provided in Figure 4.23.

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[127] See https://www.vodafone.com/news/corporate-and-financial/vodafone-europe-first-commercial-open-ran-network

Figure 4.23: Comparison of indoor coverage solutions [Source: Analysys Mason, 2022]

Technology	**Number of users (more users is more suitable)**	**Cost of deployment (lower cost is more suitable)**	**User experience (‘higher’ experience is more suitable)**	**Location viability – residence (‘higher’ viability is more suitable)**	**Location viability - enterprise (‘higher’ viability is more suitable)**
Private Wi-Fi	Low	Low	Low	Very high	High
Small cells	Medium	Medium	Medium	Medium	High
DAS/IBS	High	Very high	High	Very low	High
Mobile repeaters	Low	Low	Low	High	Low
Private cellular network	Medium	High / very high	High / very high	-	High

Historically, private Wi-Fi has been the primary solution for indoor coverage, and it is deeply entrenched in many residential and commercial settings. However, there are several limitations to Wi-Fi, particularly around co-ordination and consistency, that mean it could partially be displaced by another solution. Voice calling is one such limitation: Wi-Fi calling is offered by all UK MNOs (although not necessarily available for all devices and tariffs[128]), but it is not always a seamless experience, as it sometimes requires phone reboots. It also requires voice over internet protocol (VoIP) applications that not everyone has, leaving parts of the population to still rely on traditional voice. The handover from Wi-Fi networks to cellular networks during a data session or call is not usually seamless either. Additionally, while connecting to familiar Wi-Fi networks (at home or in the office) is easy, in new locations, such as shopping centres, it is less convenient and may come with additional security concerns. There may also be interference issues due to the use of unlicensed spectrum.

In spite of these limitations, Wi-Fi is unlikely to be significantly displaced in many residential and commercial settings due to the low cost of deployment and high location viability. In the case of handsets, however, the cellular share of traffic has been growing (see Figure 4.24). This growth has been driven by lower data tariffs that make consumers less incentivised to switch over to Wi-Fi at home. This is a trend that was reversed in 2020 because of the impact of the Covid-19 pandemic, but that is expected to return as the pandemic subsides, though flattening out in the long run as fixed

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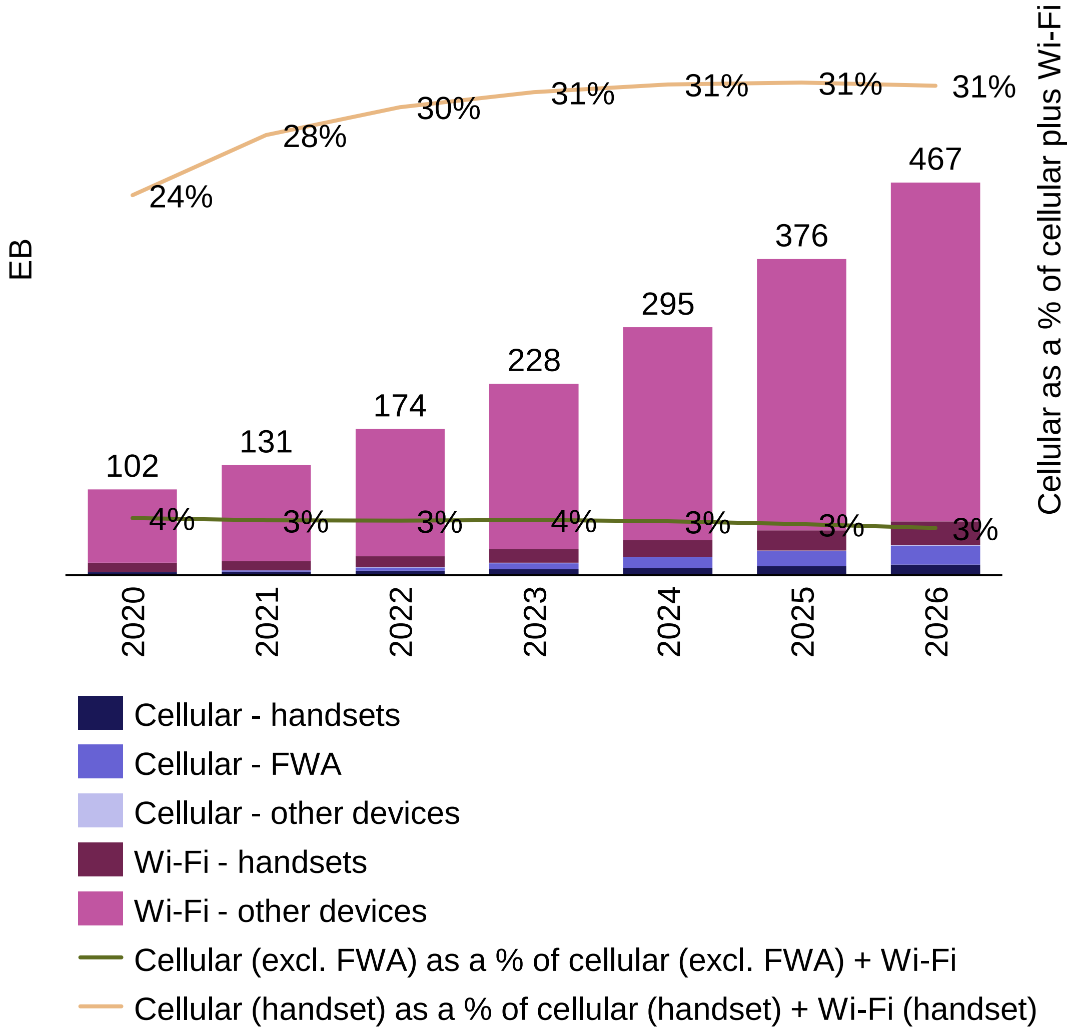
[128] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

broadband continues to improve. In a 2021 study, Ofcom found that customers using Three's network used a higher proportion of data over mobile compared with Wi-Fi than customers using other networks, which it said "may be driven by higher take-up of high and unlimited data tariffs among Three customers".[129]

Figure 4.24: Forecast of cellular and Wi-Fi data traffic in the UK [Source: Analysys Mason, 2022]



Additionally, Wi-Fi 6 offers a better quality of service than predecessors. Wi-Fi 6E, commercialised in 2021, adds new spectrum to deliver on the promise of gigabit fixed access, and is unlikely to be inferior to 5G for general public and private use within localised settings. It also appears unlikely that public cellular (namely 5G) will replace Wi-Fi in enterprise office settings. The fundamental openness and low cost

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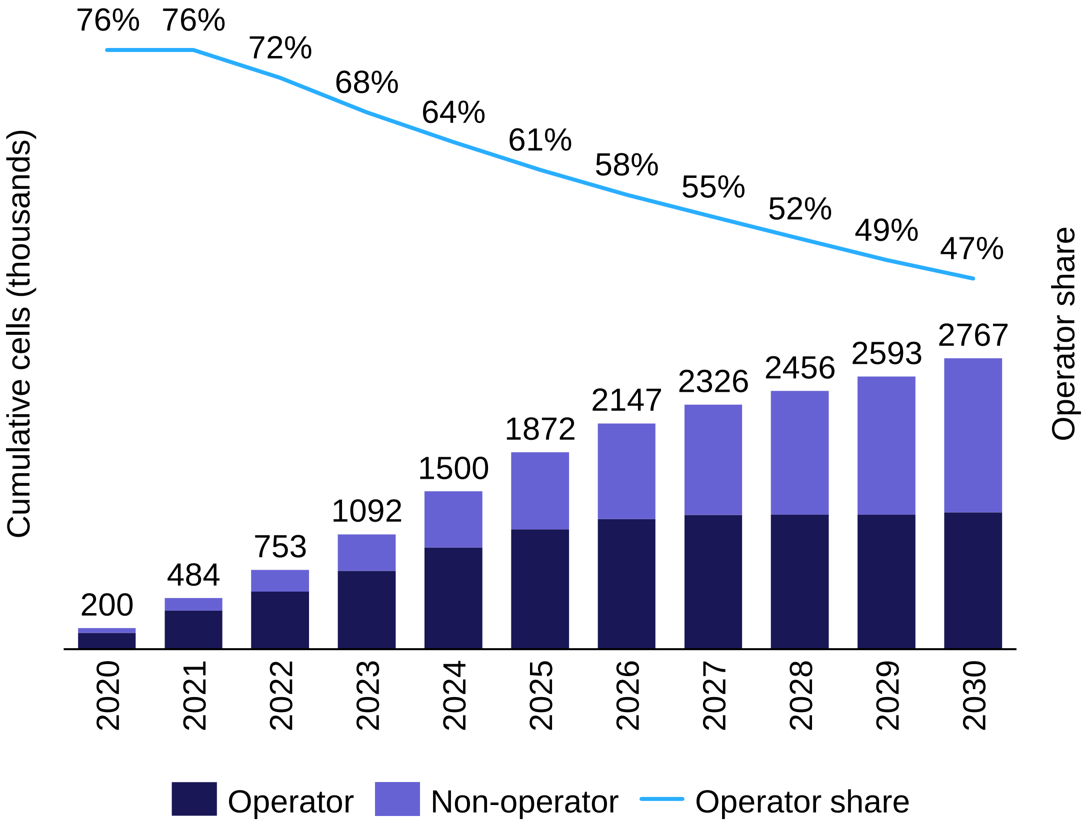
[129] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

of Wi-Fi offers a major disincentive to migrate; however, there may be more opportunity for 5G in more specialised industrial settings. Future in-building deployment could increasingly take place through indoor small cells, with non-operator deployments playing a growing role (for example, see Figure 4.25). It should be noted that the indoor small-cell market is still at a nascent stage and might not reach its forecast potential.

Figure 4.25: Forecast of indoor small cells in use in Europe [Source: Analysys Mason Research, Analysys Mason, 2020]



The indoor small-cell value chain could also move more towards a ‘landlord pays’ model, where landlords pay neutral hosts to provide infrastructure and deploy networks using MNO spectrum. In such a scenario, indoor small cells would increasingly be deployed by non-operator neutral host entities over time.

In general, improvements in the supply of indoor coverage are likely to be location specific, and may depend on the building owner’s willingness to pay for better connectivity. In the UK, supply of indoor solutions will likely focus on commercial and high-footfall buildings such as large shopping centres, stadiums, stations and shared working spaces. There may be a supply-side benefit to MNOs providing cellular indoor solutions in some of these locations; retaining ‘control’ of subscribers can be beneficial (e.g. in venues such as shopping centres or sports arenas where customer data could be valuable) and may outweigh the cost.

In the UK, there are a number of companies that provide indoor connectivity solutions to venue owners. These include companies that offer Wi-Fi infrastructure and services to commercial venues, such as WiFi Spark, Glide Group and Telent-Sky, for example. Other companies that have thus far offered DAS solutions, such as Wireless Infrastructure Group, Shared Access, Boost Pro and Virtua, among others, might also increasingly offer indoor small-cell-based solutions if demand for such solutions grows in future.

MNOs are currently focused on enhancing outdoor macro networks and are less likely to spend significant amounts on improved indoor coverage. Models that allow other providers to become increasingly involved in the provision of better indoor coverage, through the use of neutral host models, may be the solution that improves indoor coverage in more locations. However, ongoing network enhancements by MNOs are expected to result in some improvements to indoor mobile coverage.

The increased deployment of 700MHz spectrum on sites is expected to improve indoor mobile coverage by increasing capacity on outdoor base stations. In locations with high traffic loads, the network would not be able to support devices at the edge, such as those that require in-building penetration to reach. The use of 700MHz spectrum would increase capacity in the outer area of the cell, which would improve indoor coverage to a degree. MNOs can also be expected to use 26GHz spectrum as well as small cells in specific areas where indoor coverage is deemed to be important.

Early research on 5G early adopters and consumer expectations suggest that customers rate indoor coverage as an important feature and expect consistency between outdoor and indoor quality of coverage with 5G. Some early adopters of 5G have also claimed decreased Wi-Fi usage after making the switch from 4G to 5G.[130] These findings, if applicable to wider populations, could suggest that, in the context of 5G deployment, mobile operators should place more emphasis on indoor coverage compared to 4G deployment in the past.

There are however, reasons to question the extent to which indoor coverage would end up being a key competitive priority for operators. The view of early adopters may not represent broader customer preferences. Further, although some customers have started to use 5G instead of Wi-Fi, it is likely that a majority of mobile users will still rely on indoor Wi-Fi for use cases such as video streaming, given the better performance (currently and in the future) of fixed broadband compared to mobile solutions, even if MNOs were to make a strong push to improve indoor mobile coverage.

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[130] See https://www.ericsson.com/en/reports-and-papers/consumerlab/reports/five-ways-to-a-better-5g

Customer preferences and behaviours should continue to be tracked through primary research initiatives such as surveys in order to explore:

- customer expectations of 5G performance indoors relative to outdoors
    - the customers surveyed should cover a larger segment of the user base than just early adopters
- preferences regarding Wi-Fi substitution
- likelihood of churning from existing mobile providers if 5G indoor mobile coverage does not meet expectations.

The effectiveness of recent efforts in the UK to improve indoor mobile coverage should also be monitored. For example, in 2021, Ofcom developed proposals on boosting indoor mobile signals using mobile phone repeaters and measures to improve information about these repeaters available to consumers.[131]

Overall, indoor mobile coverage with 5G is expected to improve compared to 4G. It is, however, not expected to be displaced by indoor Wi-Fi due to how entrenched the technology is, ongoing improvements to it, as well as the stronger performance characteristics of fixed networks relative to mobile networks. In commercial venues, venue owners are expected to pay for better indoor connectivity over time should they find a benefit to doing so. Residential users are expected to continue using Wi-Fi, although some users may replace Wi-Fi with 5G due to the added convenience of not having to switch technologies when moving from outdoor to indoor settings. Wider use of mobile phone repeaters, as promoted by Ofcom, can also help to improve indoor mobile performance.

While indoor mobile coverage is unlikely to match outdoor mobile coverage, it is likely that most consumers would be able to receive decent connectivity on mobile devices indoors by continuing to use indoor Wi-Fi, mobile phone repeaters, or by connecting to indoor solutions in commercial or high-footfall venues. The consumers that appear most at risk of not being able to receive good connectivity in indoor settings could be segments of the population that have lower income or are less tech-savvy and that might not have the same fixed broadband, indoor Wi-Fi, or mobile phone repeater alternatives that a majority of the country would have access to. If indoor mobile coverage is subsequently identified as a policy priority, policy makers could also require MNOs to report indoor coverage based on more stringent measures than were used for 4G, and any subsequent release of low-band spectrum can also involve indoor coverage obligations.

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[131] See https://www.ofcom.org.uk/consultations-and-statements/category-1/mobile-phone-repeaters-extended-range

In Section 5 of this report, we describe a theoretical composite model that models the level of coverage provided by a public cellular network outdoors only. In order to model actual indoor coverage, it would be necessary to have data on the specific locations of base stations and buildings, such as the data used by Ofcom in collaboration with operators to generate a granular database tracking indoor 4G coverage (less granular versions of which are published as part of the Connected Nations reports). While we observe as noted above that indoor coverage is unlikely to match outdoor coverage, the additional network deployment costs and challenges to deliver consistent indoor coverage from mobile networks is not considered in a quantitative manner in this model.

4.4.2 Road and rail

We have used the baseline model to assess how coverage along major transport routes within the UK changes over time. The results are illustrative of the level of coverage that might be available in the locations where major transport routes are situated.[132] The analysis is not therefore representative of the quality of connection that would be guaranteed along rail routes or roads. This is because public mobile infrastructure in the UK is not usually deployed trackside or directly on motorways, but typically uses base station masts located on nearby land. This is for practical reasons and because mobile networks are primarily designed to provide population coverage.

Figure 4.26 and Figure 4.27 show the GIS data on major roads (in England) and rail routes (in Great Britain) that we used in this analysis.[133]

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[132] To do this, we have used our baseline assessment of coverage to UK population located within a 10km×10km square grid.

[133] Although there is GIS data available on roads in the UK, the data includes major and minor roads and hence is does not correspond to key transport corridors. This dataset was chosen as it most closely correlated with DCMS's focus of interest, as described to us, on key transport corridors.

Figure 4.26: Major roads in England [Source: ONS, Analysys Mason, 2022]

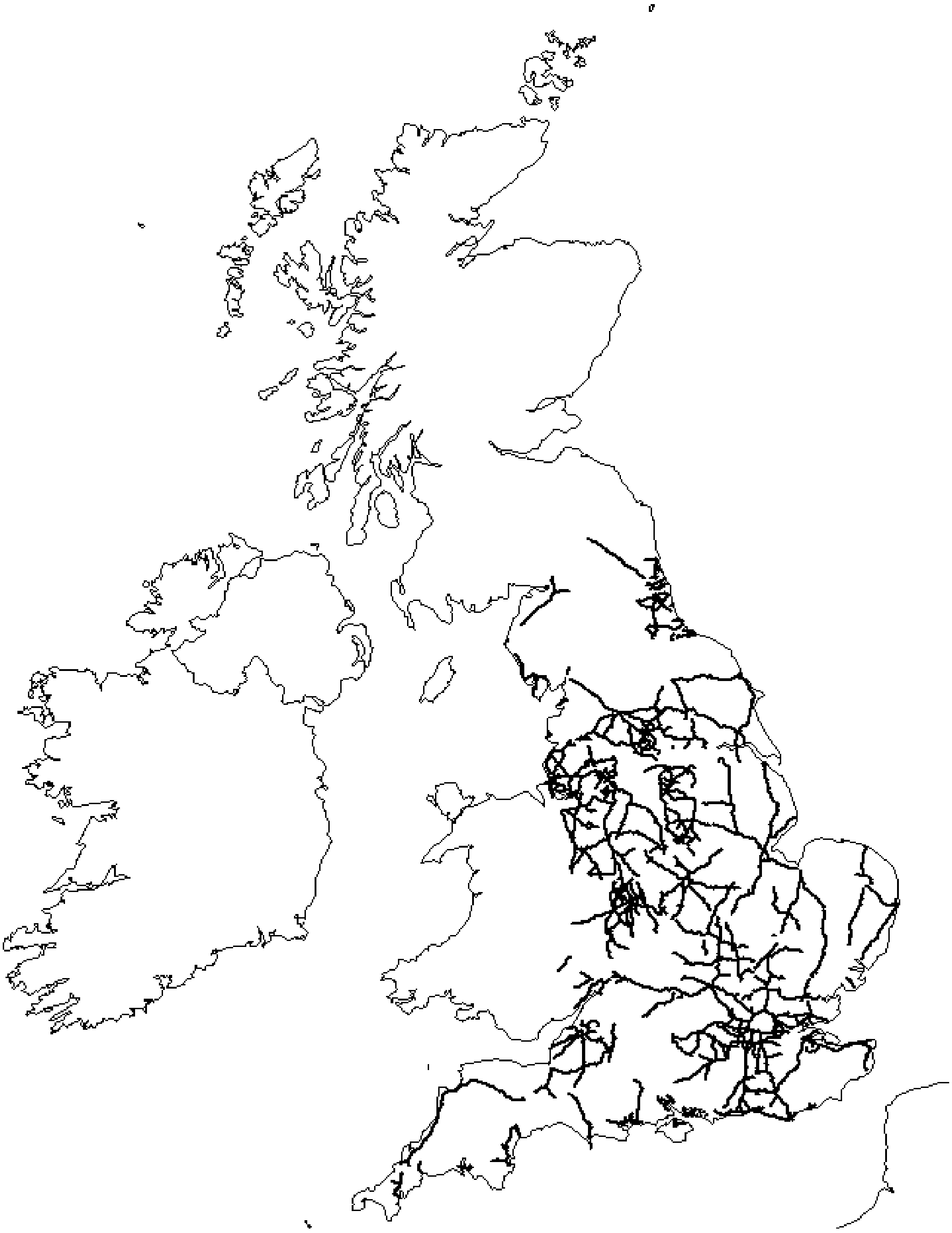


Figure 4.27: Railways in Great Britain [Source: Eurographics, Analysys Mason, 2022]

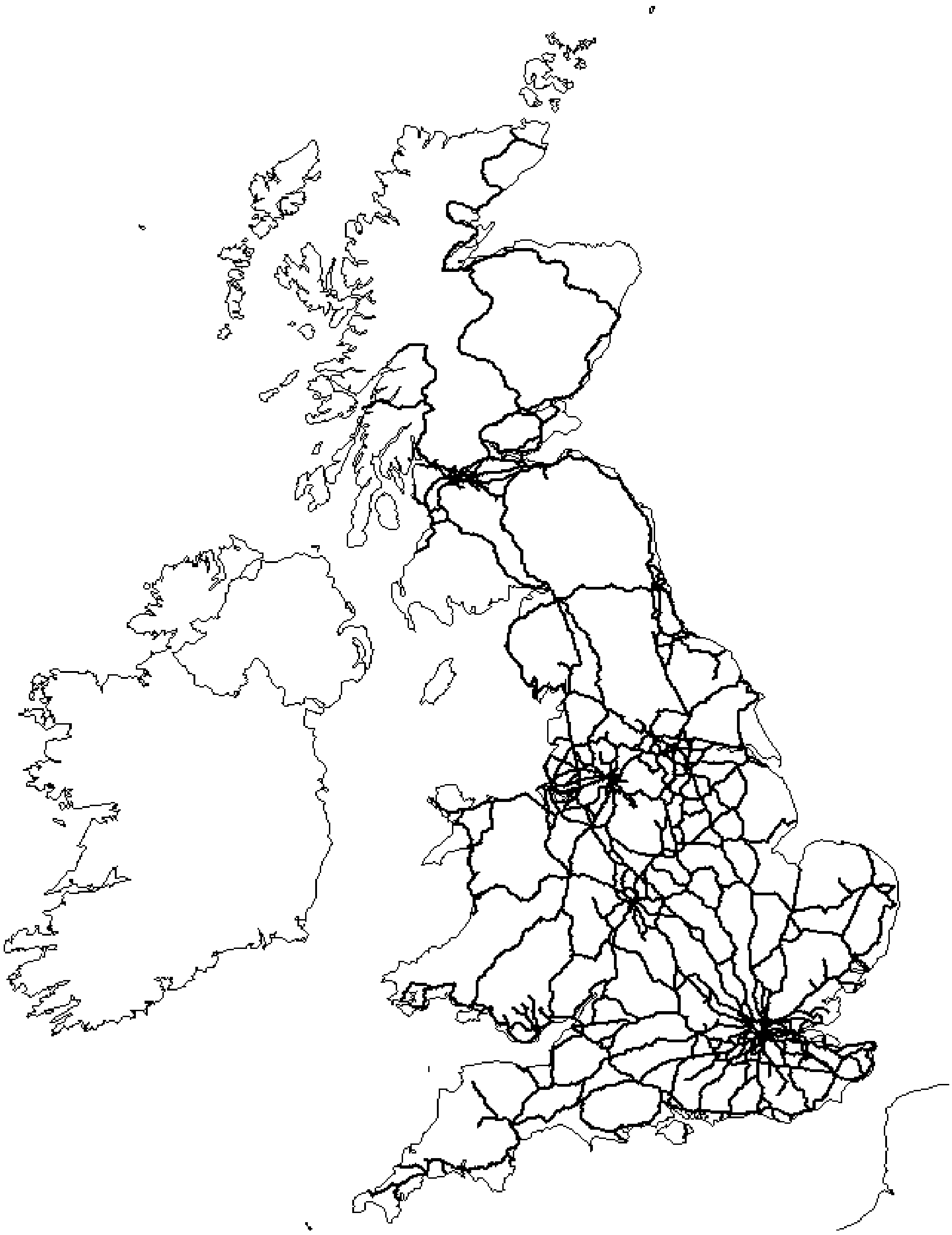


Figure 4.28 shows what our baseline model would suggest is the current distribution of quality of coverage of major roads in our model's grid squares. Quality of coverage is presented in terms of the average speed per active user in the corresponding grid squares in our model. Hence, it does not necessarily represent

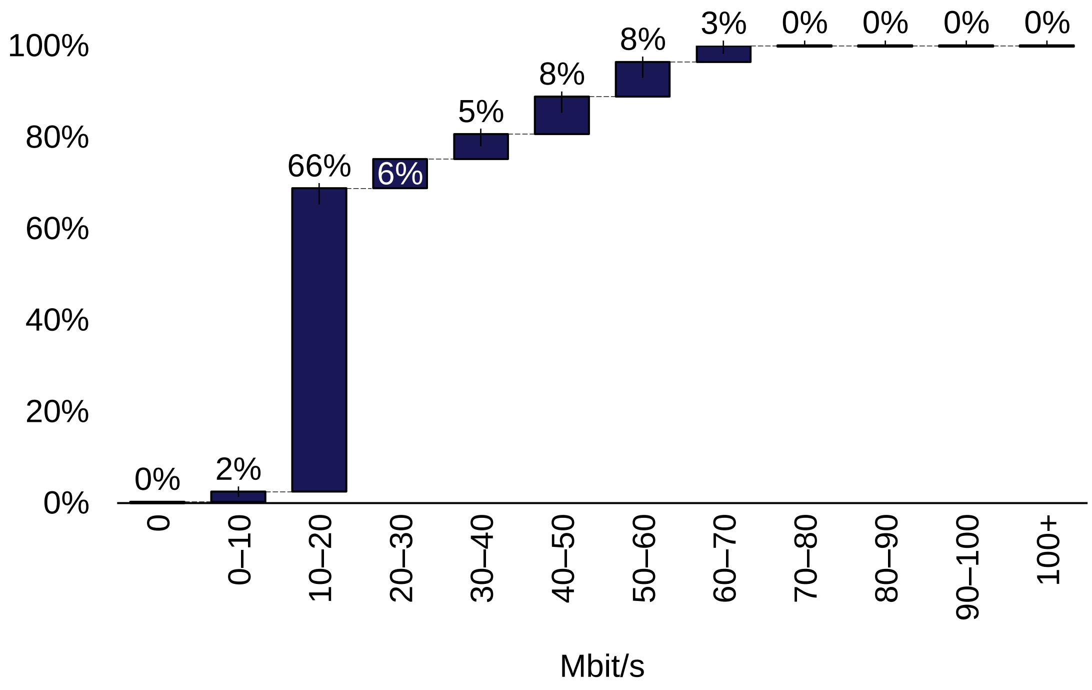
the average speed that a user within a vehicle on a road would receive **consistently** when driving along the road.

Figure 4.29 shows the corresponding distribution in 2030, as a result of the market roll-out of the baseline. From these two figures, it can be seen that by 2030:

- the percentage of roads with coverage greater than 30Mbit/s[134] has increased from 25% to 91%
- all major roads have some level of coverage by 2030
- 13% of roads have coverage of greater than 100Mbit/s by 2030.

It is noted that the average speed a user experiences on a road, as well as in any environment, depends on the network loading at a given time of day, and hence will vary between different times of day and different loading assumptions. Our baseline model makes assumptions on the data traffic demand by 2030, as implied by number of network users and data consumption per user. A higher or lower data consumption by users in a given location would therefore impact the average speed that other users receive.

Figure 4.28: Percentage of major roads in grid squares in England with the following average speed per active user by the end of 2021 [Source: Analysys Mason, 2022]



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[134] As indicated earlier in this report, this speed is sufficient to enable UHD video on the move.

Figure 4.29: Percentage of major roads in grid squares in England with the following average speed per active user in 2030, according to the baseline [Source: Analysys Mason, 2022]

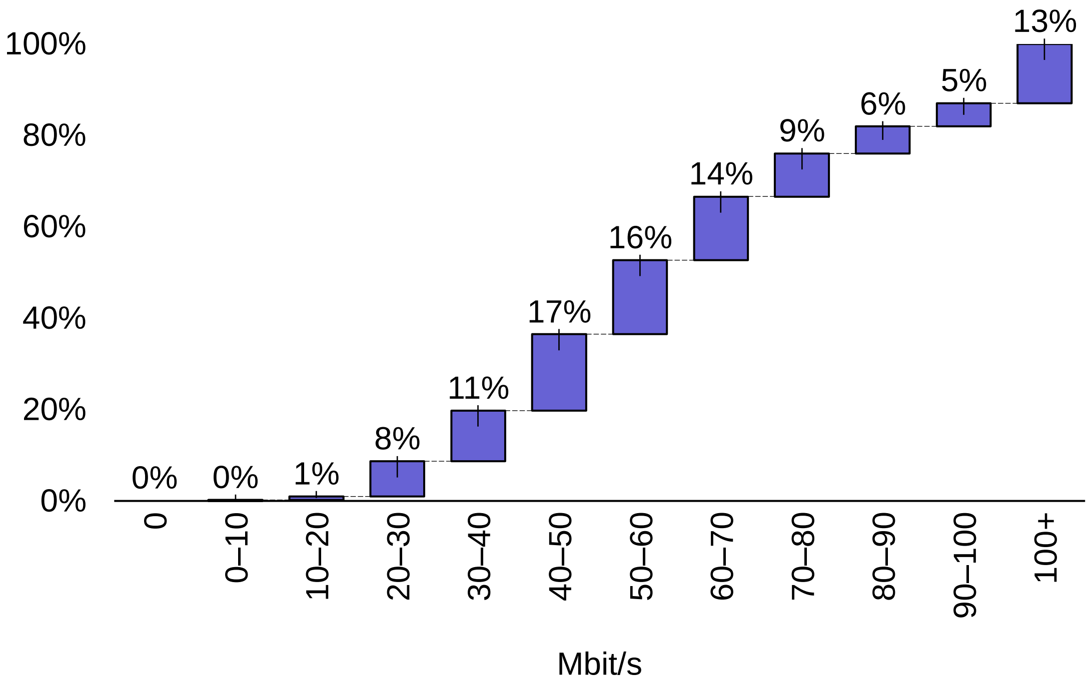


Figure 4.30 shows the current distribution of quality of coverage of rail routes in our baseline model's grid squares. Quality of coverage is presented in terms of the average speed per active user available in the corresponding grid squares in our model. As noted earlier in this section, the average speed estimate is not indicative of this speed being available consistently across all roads and there will be variability in coverage levels due to macro site placement, network loading, location and speed of the vehicle.

Figure 4.31 shows the corresponding distribution in 2030. From these two figures, it can be seen that by 2030:

- the percentage of railways with coverage greater than 30Mbit/s (enabling UHD video on the move) has increased from 19% to 82%
- 12% of railways have coverage of greater than 100Mbit/s by 2030.

However, according to the baseline, our estimate is 1% of railway routes, primarily in Scotland, are in geographical locations that will remain without mobile coverage by 2030.

Figure 4.30: Percentage of railway in grid squares in Great Britain with the following average speed per active user by the end of 2021 [Source: Analysys Mason, 2022]

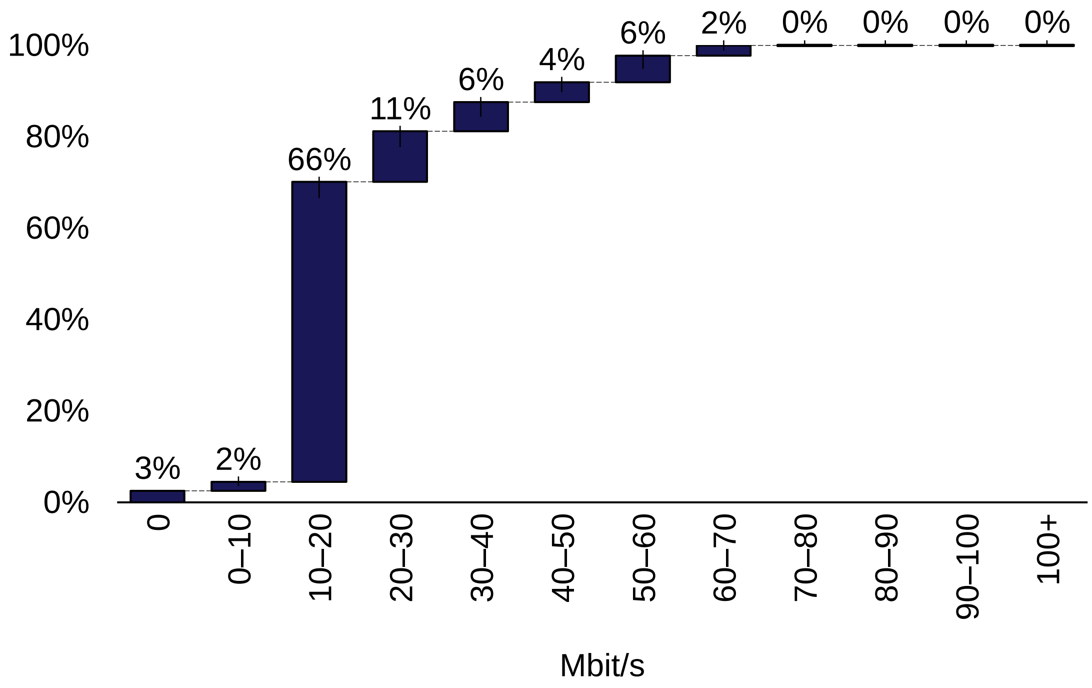
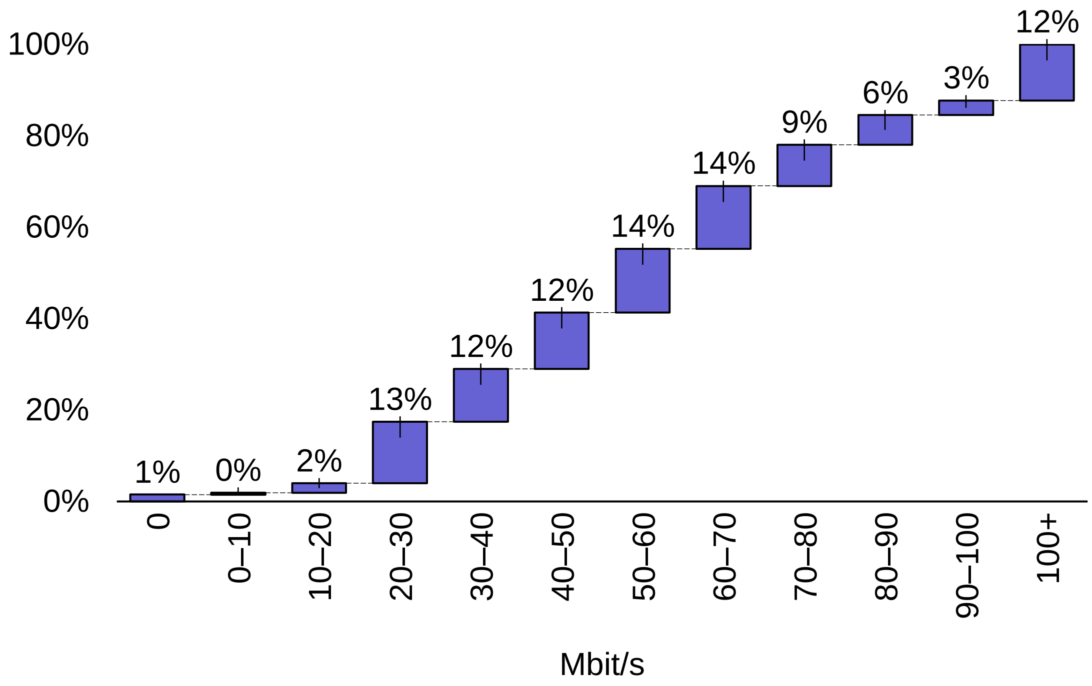


Figure 4.31: Percentage of railway in grid squares in Great Britain with the following average speed per active user in 2030, according to the baseline [Source: Analysys Mason, 2022]



4.5 Implications of future demand on how far the market will deliver cellular connectivity

The discussions presented in the subsections above indicate that there is considerable uncertainty on the nature of future demand for public mobile network capacity.

In terms of what connectivity future users and use cases need, better network quality will be needed if some future use cases are to be delivered using public mobile networks, Network quality can be defined and measured in different ways and the definition of what is considered as ‘good’ coverage depends in the use case and environment. Peak, average and minimum network speeds are often referred to in different literature, and network coverage needs to be distinguished between what a user can expect to receive if using a device outdoors, compared to indoors, where in-building penetration factors need to be considered.

Additionally, quality of user experience is becoming increasingly important for some applications (e.g. video or AR/VR). However, the quality of the user experience depends not only on the network capabilities of the network itself in terms of coverage and speed, but also the type of device being used and the location of the user relative to the nearest base station site. It is noted that network throughput (which is one determinant of user experience) will vary between different times of the day, as well as between different user locations, and at different times of the day. A further factor to consider is that the application providers themselves (e.g. the providers of commonly used social media platforms) might scale video quality down in response to network loading. This is a decision taken by the application providers, independently of the network providers themselves. For example, the quality of Netflix streaming services was scaled down during recent lockdown periods due to the level of demand.[135]

There is also a relationship between quality of coverage that different users might demand, compared to the willingness to pay for this quality, which is not yet well understood for 5G. Given that 5G services are still being developed in the UK, the early indicators of 5G demand do not provide a solid basis from which to estimate what the long-term demand for 5G will eventually be. This is because 5G networks do not yet provide the full range of services that 5G technology promises to deliver. The most significant advances in 5G, such as the ability to support many more device connections with very low latency and high reliability, will not occur until more advanced 5G technologies (within networks, and in devices) become available. The 5G services deployed initially in the UK are driving demand mainly for consumer-

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[135] https://www.independent.co.uk/life-style/gadgets-and-tech/news/coronavirus-netflix-streaming-quality-internet-down-a9412771.html

based MBB applications, with demand based largely on consumers who are opting to replace 4G smartphones with 4G/5G smartphones.

The quantity of demand for the most advanced 5G services – requiring very low latency, and high reliability – is not currently known, being a function of network quality, price and willingness to pay, and the alternative choices available to different users. A clearer picture of this demand for the most advanced services that 5G might deliver in future is not likely to emerge until the current 5G-NSA network architectures have evolved to being standalone and hence the characteristics of more advanced deployments, in terms of their capability and price, become clearer (which, based on evidence captured for this study, will be 2023 at earliest from some of the UK MNOs; see Figure 3.4).

As described previously in this section, there are a range of alternative wireless technologies that some users might continue to find sufficient in some environments. Therefore, the demand that will develop over the remainder of this decade for further cellular connectivity, and 5G specifically, is difficult to estimate, depending on individual preferences and choices of solutions, as well as factors such as price and willingness to pay. In its specification for this study, DCMS was interested to understand if an integrated model, bringing together demand and supply for different wireless solutions in an interactive way, could be developed. During the course of this project, the challenges in developing such a model led us to conclude that an interactive model would not provide a meaningful way to accurately assess how the supply of cellular connectivity will evolve (primarily due to the range of assumptions needed, with high levels of uncertainty). Evidence captured from interviews conducted during this study also indicate that the approach used by the industry to model to what extent cellular connectivity will be delivered (in terms of speed, and coverage) is based largely on forecasts of data traffic, mobile subscribers/connections growth and penetration of different solutions (e.g. 5G penetration as a portion of the total cellular market). In the next section of this report, we describe the model that we have developed in this project to provide DCMS with a better understanding of how far the market will go to deliver future wireless connectivity under different scenarios of market development, to inform future policy thinking.

5 Modelling approach and results

This section presents our approach to a quantitative model that uses future mobile data traffic demand inputs and geographical demographic data to generate different deployment forecasts (additional spectrum bands on sites, new sites) and associated costs (capex and opex). The model is based on a hypothetical MNO in the UK market, not representative of any individual MNO in the market. The purpose of the model is to illustrate how far public mobile infrastructure will be rolled out across the UK market over the remainder of this decade, and the network costs involved in delivering this roll-out.

Based on the assumptions described in this section, we gauge what this roll-out might imply for the average download speeds that might be available to users across the UK. We then consider how the model can be used to indicate the scale of additional investment to deliver certain levels of future connectivity – informed by our analysis of use-case requirements for consumers and businesses, and the network speeds these would imply. We use the model to estimate the gap in investment between:

- what we model that the market will deliver
- what might be needed to meet different future targets for quality of coverage.

5.1 Modelling approach and current limitations

5.1.1 Analytical approach

The model is built at a geographically granular level. The UK landmass is split into grid squares that have sides that are 10km in length, and calculations are then performed for each grid square. This level of granularity allows the potential reach of outdoor coverage and gaps to be visualised. A cost model allows the added cost required to meet those gaps to be estimated.

Our approach defines a ‘gap’ as the difference between what the hypothetical operator would be expected to deploy in future based on current market dynamics and trends (a baseline deployment), and what it would be expected to deploy to meet a higher quality-of-coverage target (referred to as the scenarios). This target would be an aspirational target of the level of connection quality that might be needed in the UK market in future, for consumers and/or for businesses.

The modelled hypothetical operator network does not exactly represent the network deployments of any one MNO that operates in the UK market today. We have deliberately modelled at a hypothetical level to avoid complexities relating to the different UK MNOs' varying network strategies, spectrum portfolios, customer bases and data packages. In the hypothetical roll-out, we have instead defined a representative spectrum holding and existing footprint for the hypothetical operator that is broadly based on actual operator data.

Establishing a baseline deployment

The extent to which operators will deliver connectivity is difficult to estimate. In practice, there are various factors other than demand for services that affect operators' roll-out rates, such as planning issues and capex restrictions. There might also be locations that MNOs will prioritise, for instance to provide coverage continuity with existing deployments, as well as coverage of transport links.

MNOs will generally deploy additional capacity when and where it is commercially viable. Commercial viability is determined by revenue compared to cost. If MNOs do not provide sufficient capacity in their networks, then performance will degrade and customers may potentially chose to switch to using another network. In the mobile industry, this is referred to as 'churn'. There are various reasons why a user would choose to switch to another network, such as price, network performance and customer service. To monitor network performance, MNOs will typically monitor the traffic load on all the sites in their networks together with other metrics. When a site reaches a certain level of congestion, the model assumes the MNO will want to deploy a new spectrum carrier to provide more capacity and hence to avoid capacity being degraded at that location, which would affect the network experience of its customers and therefore give rise to risks that may affect its market share.[136] This modelling approach is one that Analysys Mason uses regularly in projects where we work with MNOs, in the UK and in markets around the world. We are confident that this approach is one that mobile operators will recognise as an industry-standard method of modelling the costs of mobile network roll-out under different scenarios of traffic load.

In this model, we first assume a particular level of existing capacity for each site in the hypothetical operator network, assuming a site configuration (i.e. spectrum deployed at each site) that is representative of the UK market. After that, we mechanically drive a baseline deployment using traffic forecasts as an input. Once the busy-hour traffic load exceeds the amount of capacity available on a site, additional spectrum carriers will need to be deployed. Once all carriers available have been deployed, then a new site will be added.

The resulting addition of spectrum carriers and sites is calibrated based on announced plans of actual operators and insights gained during interviews

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[136] For example, if a customer was able to receive better quality from another provider and hence might choose to move to another supplier at the end of its subscription period.

conducted for this study. The traffic forecasts that are mechanically used to drive the baseline deployment include the following components:

- Traffic forecasts for existing use cases (see Section 4.1 for details)
    - MBB traffic: derived from published Analysys Mason Research forecasts, extrapolated over the modelling period for this model, which corresponds to an increase from 5.6GB per connection per month in 2022 to 20GB per connection per month in 2030
    - FWA traffic: also derived from published Analysys Mason Research forecasts
    - wide-area IoT traffic for existing use cases: from Analysys Mason Research connection forecasts, together with Analysys Mason assumptions on estimated traffic per connection.
- Traffic forecasts for new advanced enterprise use cases (see Section 4.2 for details)
    - advanced enterprise traffic that is 'pre-emptively' met by MNOs: high-level assumptions that cannot be supported with published evidence at present, but which we have estimated based on the best information available to us at this time, based on our internal research.

A summary of the resulting traffic forecasts is shown in Figure 4.21.

Defining scenarios involving higher quality-of-coverage levels

Once the baseline deployment has been established, several further scenarios are defined. These scenarios each involve a deployment resulting in a higher quality of coverage than the baseline (see Figure 5.1).

Figure 5.1: Overview of modelling scenarios [Source: Analysys Mason, 2022]

Scenario	Description
Scenario 1: 50Mbit/s per active user	This scenario models the additional infrastructure costs of meeting a connection target of a minimum MBB downlink speed of 50Mbit/s per active user in regions of the UK where according to the baseline the market would not deliver this.[137] As described in Section 4.2 and Annex A, this would enable consumer use of emerging applications that might become more widely used in future, such as AR/VR in addition to UHD video. The reasons for choosing

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[137] Defining a higher downlink speed per active customer target will result in a higher level of MBB capacity deployed. To users, this improves experience by allowing users to have a better probability of gaining a higher-speed connection.

Scenario	Description
	50Mbit/s for the target consumer speed are described in Section 5.2.2.
Scenario 2: Enterprise traffic	This scenario models the additional infrastructure costs of serving an increased portion of enterprise traffic (e.g. such as traffic generated by more advanced IoT applications using a 5G connection over public network, using network slicing. This scenario built from high-level assumptions on: • data traffic demand per business (estimated to be 1Gbit/s for businesses with fewer than 10 employees, 5Gbit/s for businesses with 10–49 employees and 10Gbit/s for businesses with more than 50 employees). Our illustrative estimate is that this could enable simultaneous operation of 10, 50 and 100 robots or remotely operated machines respectively • percentage of businesses taking up advanced wireless connectivity using cellular technology (i.e. public plus private) by 2030. These assumptions[138] equate to 0.1% of businesses with fewer than 10 employees, 3.5% of businesses with 10–49 employees and 10% of businesses with more than 50 employees, which amounts to just under 27 000 businesses across the UK by 2030, based on our estimates using the latest datasets available from the Office of National Statistics (ONS) • portion of the above users that will utilise a public mobile network for these advanced services as opposed to choosing to deploy a private cellular solution, or choosing another solution entirely (such as Wi-Fi). Our estimates assume the portion of users utilising public mobile networks could be 50% of businesses with fewer than 10 employees, 25% of businesses with 10–49 employees and 10% of businesses with more than 50 employees, which equates to 1482 business in 2030. This is in line with an assumption that larger firms might be better placed with the expertise needed to procure a private cellular solution whereas smaller businesses might choose from available public network options in their location, without having the detailed in-house capability needed to plan for a private network deployment. • the growth in number of businesses taking up public cellular networks over time

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[138] Assumptions are based on a previous study conducted by Analysys Mason together with Cambridge Econometrics, on realising the benefits of 5G

Scenario	Description
	• ONS data on how many businesses are located in districts, counties and unitary authorities across the UK.
Scenario 3: 50Mbit/s per active user plus enterprise traffic	This scenario combines the two previous scenarios.

For each scenario, the cost of additional deployment beyond the baseline to reach those higher quality-of-coverage targets is calculated, representing the added cost needed in order to reach better connectivity compared to what a hypothetical operator in the market would do based on current market dynamics, trends and announcements.

Generating and interpreting cost estimates

Once the additional cost to achieve a higher quality-of-coverage level is calculated, the model then estimates the annual revenue required for that additional deployment to be considered commercially viable. The commercial viability is illustrative and based on the additional revenue an operator would need, estimated over a 12-year period, assuming a discount rate of 8%. The 12-year period was chosen as being indicative of a typical active radio equipment lifecycle.

It is important to note that this revenue is not the revenue that an MNO should expect from the additional deployment but is the *additional revenue* that an MNO would need to achieve to cover the additional costs, based on the assumed discount rate and payback period, for the additional deployment to be made on a commercial basis.

Once the annual additional revenue needed has been calculated, this revenue can then be normalised in alternative ways to get a sense of whether the additional revenue needed might realistically be achieved or not. When considering the viability of deployment to meet future consumer demand, we model viability of investment in in a given location as the required annual additional revenues that MNOs would need to achieve from consumers, divided by the number of mobile connections we have modelled in that location, giving a required revenue uplift per consumer/user. Then we assume if the required revenue uplift is small compared to the amount the user is already paying (using UK mobile average revenue per user (ARPU), as shown in Figure 5.13), then this additional revenue might be realistically achieved.

For scenarios addressing demand for advanced enterprise services using cellular networks, we have considered that the required revenue needed by an MNO from these services to make the investment viable could be compared to the share of the expected uplift in the direct benefit to business in the form of increase profits (Gross operating surplus), which can be calculated as a share of gross value added (GVA) as explained further in Section 7.

The wider economic benefits that could be generated by businesses adopting the new services is represented by the expected uplift in GVA (including all components of GVA). The GVA impact estimates are taken from a previous study conducted by Analysys Mason and Cambridge Econometrics for DCMS, on realising the benefits of 5G. The previous study presented two scenarios – 5G as a general-purpose technology, and 5G as an advanced digital technology. The model baseline deployment described above is based upon an incremental 5G deployment, similar to the 'advanced digital technology' scenario of the previous study. Scenario 3 (50Mbit/s per user plus enterprise traffic is similar to the 'general-purpose technology' scenario of the previous study. Hence, we consider the incremental GVA uplift (of the portion of businesses that adopt 5G technology and use a public mobile service) as being the difference between the advanced digital technology and the general purpose technology from the previous study.

We discuss the interpretation of the model results with respect to commercial viability of the investment and the identification of market failures in more detail in Section 7.

5.2 Modelling results

The model begins by calculating the theoretical roll-out plan of the hypothetical MNO based on the traffic forecast in Figure 4.21. It predicts that by 2030 the MNO will deploy 700MHz on 93% of sites and 3500MHz on 71% of sites, in order to support a peak throughput of 6.88 million Mbit/s (see Figure 5.2 and Figure 5.3).

Figure 5.2: 700MHz footprint in 2021 and in 2030 in the baseline [Source: Analysys Mason, 2022]

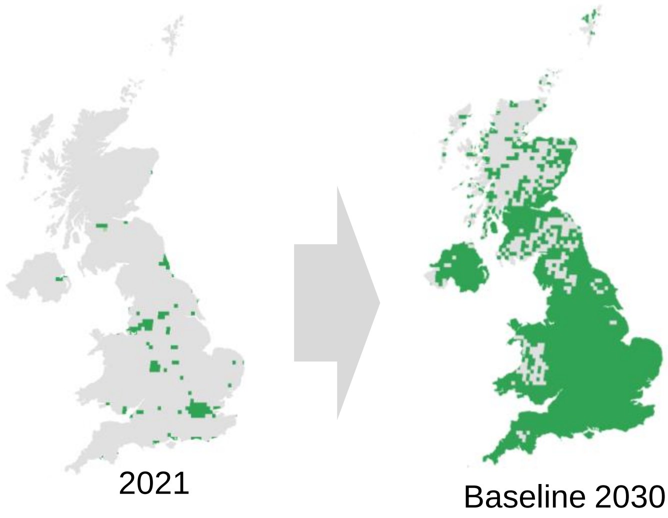
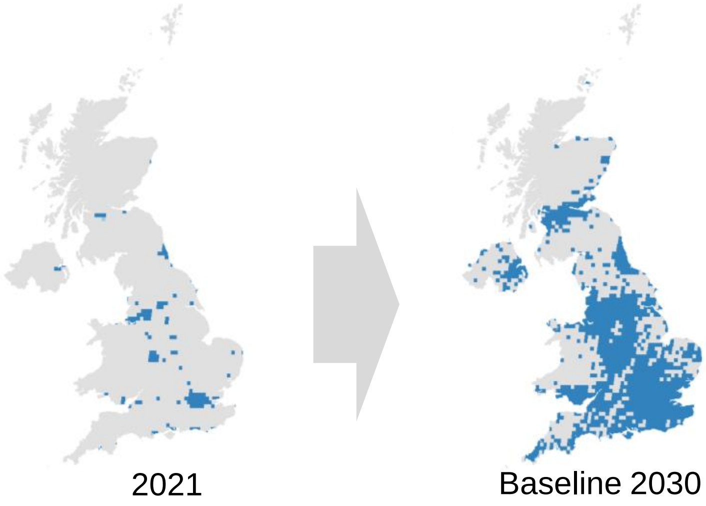


Figure 5.3: 3500MHz footprint in 2021 and in 2030 in the baseline [Source: Analysys Mason, 2022]



This modelled deployment is predicted to cost a nominal GBP2.8 billion (for one hypothetical MNO in the UK market) by 2030 (i.e. GBP311 million per annum).

A network deployment of this level will give rise to a varied level of service across the UK. On average, users today can experience speeds of 27Mbit/s, which would enable UHD video.[139] On that basis we can determine the average number of active users during the busy hour, and estimate how the speeds achievable by active users vary by location and over time (Figure 5.4). In a handful of areas, speeds per active user reach greater than 50Mbit/s, which enables video-controlled drones and decent quality AR/VR. Figure 5.5 shows that this level of service would be available to 15% of the population,[140] however, this 50Mbit/s service would not be delivered consistently over a wide area, and hence a user moving between different locations would not maintain a consistent connection.

In the baseline, network performance is estimated to increase in primarily suburban areas over the remainder of this decade up to 2030. This means that a higher number of people can use drones and AR/VR over the public cellular network. We estimate by 2030, a 50Mbit/s service would be available to 55% of the UK population.

In the baseline, our modelling assumes some UK locations (shown in black in Figure 5.4) will not be covered by mobile sites by 2030. These locations represent the final percentage of UK geography that will not be covered beyond the SRN

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[139] See Figure 2.3 in https://www.ofcom.org.uk/__data/assets/pdf_file/0028/231877/mobile-strategy-plum-report.pdf

[140] Note that the model assumes that if a band is deployed on all sites within a specific region then the all the population and area within the region gets coverage.

footprint.[141] In other locations, our model suggests an uplift in user experience between now and 2030. However, according to the baseline roll-out we have modelled (based on evidence provided by MNOs for this study on their intended roll-outs) significant areas of the UK look likely to remain at a 20–30Mbit/s level per user, although according to Figure 5.6 only 12% of the population lives in these areas. As noted above, this is not sufficient to maintain a good AR/VR connection, for example. This throughput level is also comparable to what can be provided using 4G, meaning that users receiving 20–30Mbit/s via a 5G network may not distinguish any step change in quality of connection compared to using a 4G network. The implication of that might be that users are not willing to pay more for a 5G service; conversely, MNOs will not be able to monetise the 5G investment since users do not see any difference compared to having access to a 4G connection.

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[141] As per current agreements between the UK government and MNOs, the SRN has an aggregate coverage target, using 4G technology, of 95% of the UK geography. Individual MNOs are targeted to achieve 90% geographical coverage.

Figure 5.4: Average downlink speed per active user (Mbit/s) in 10km×10km grid squares across the UK in 2021 and 2030, according to the baseline [Source: Analysys Mason, 2022]

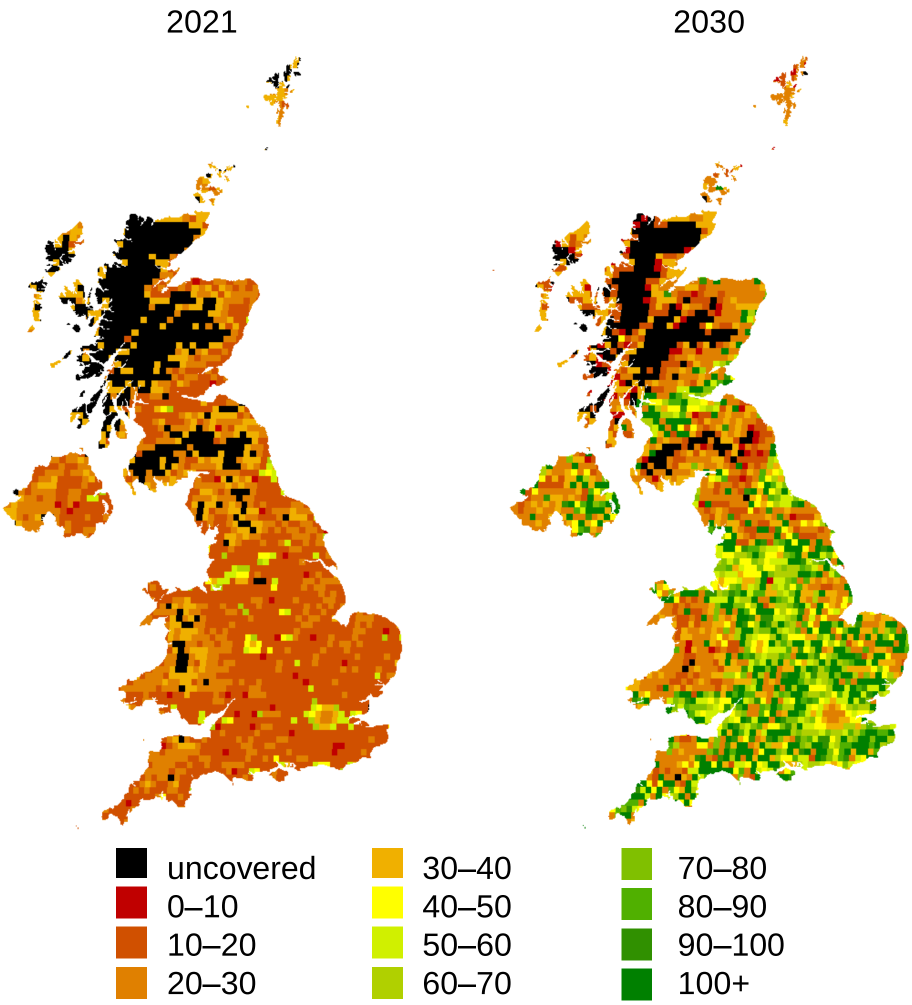


Figure 5.5: Percentage of population with the following average speed per active user by the end of 2021 [Source: Analysys Mason, 2022]

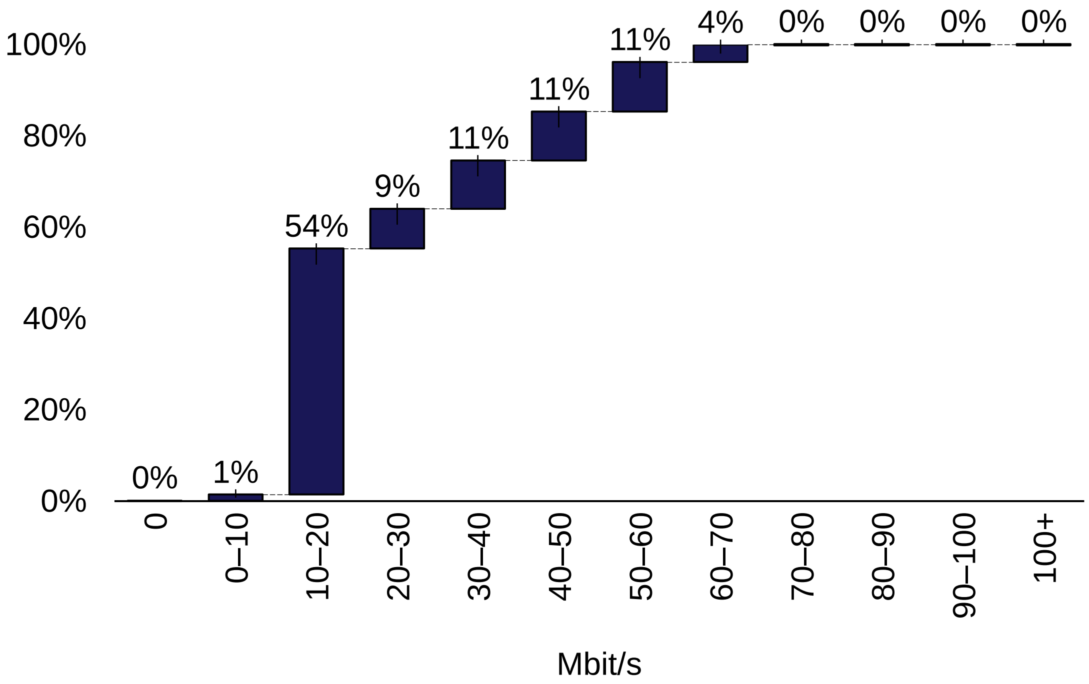
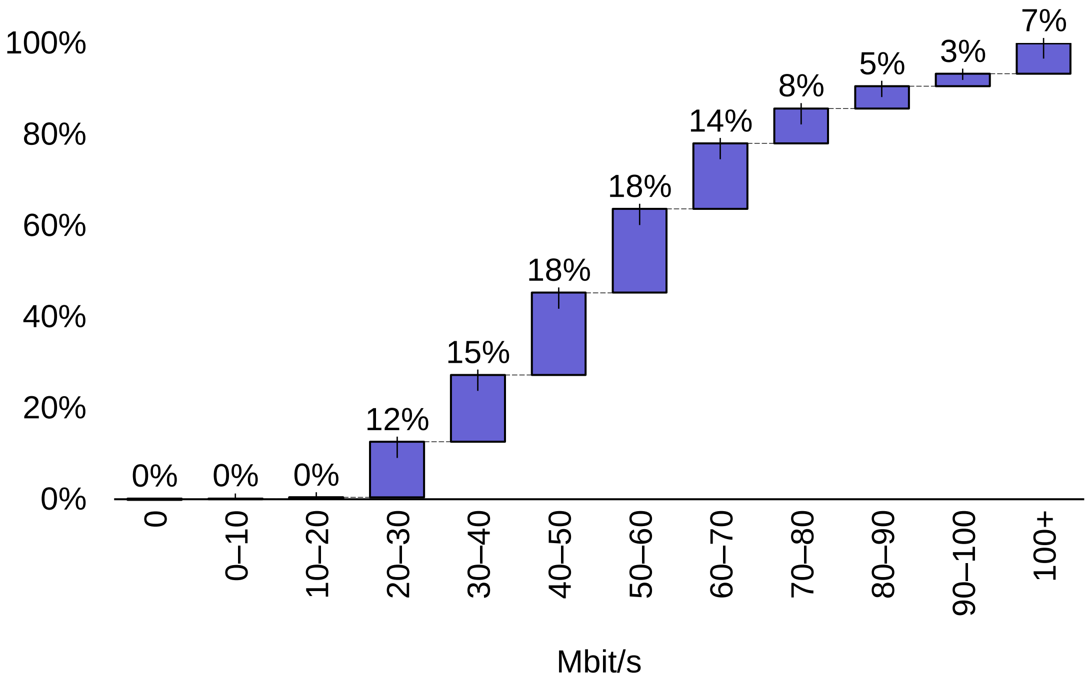


Figure 5.6: Percentage of population with the following average speed per active user by the end of 2030 [Source: Analysys Mason, 2022]



The three different scenarios are applied on top of this baseline. Figure 5.7 shows the level of 700MHz 5G deployment required in order to satisfy each of the scenarios. Similarly, Figure 5.8 shows how much further the 3.5GHz footprint will extend in each scenario. In both of these figures, it can be seen that in each scenario the 5G footprint extends into uncovered rural areas, but also densifies in suburban regions. In Figure 5.8, an assumption of MNOs serving enterprise traffic via the public network deployment results in significantly more rural sites needing to be upgraded to mid-band 5G via the 3.5GHz band, as well as indicating regions where a purely population-driven roll-out may not provide sufficient capacity to meet business demands.

Figure 5.7: 700MHz footprint in 2021, and footprint in 2030 in each scenario [Source: Analysys Mason, 2022]

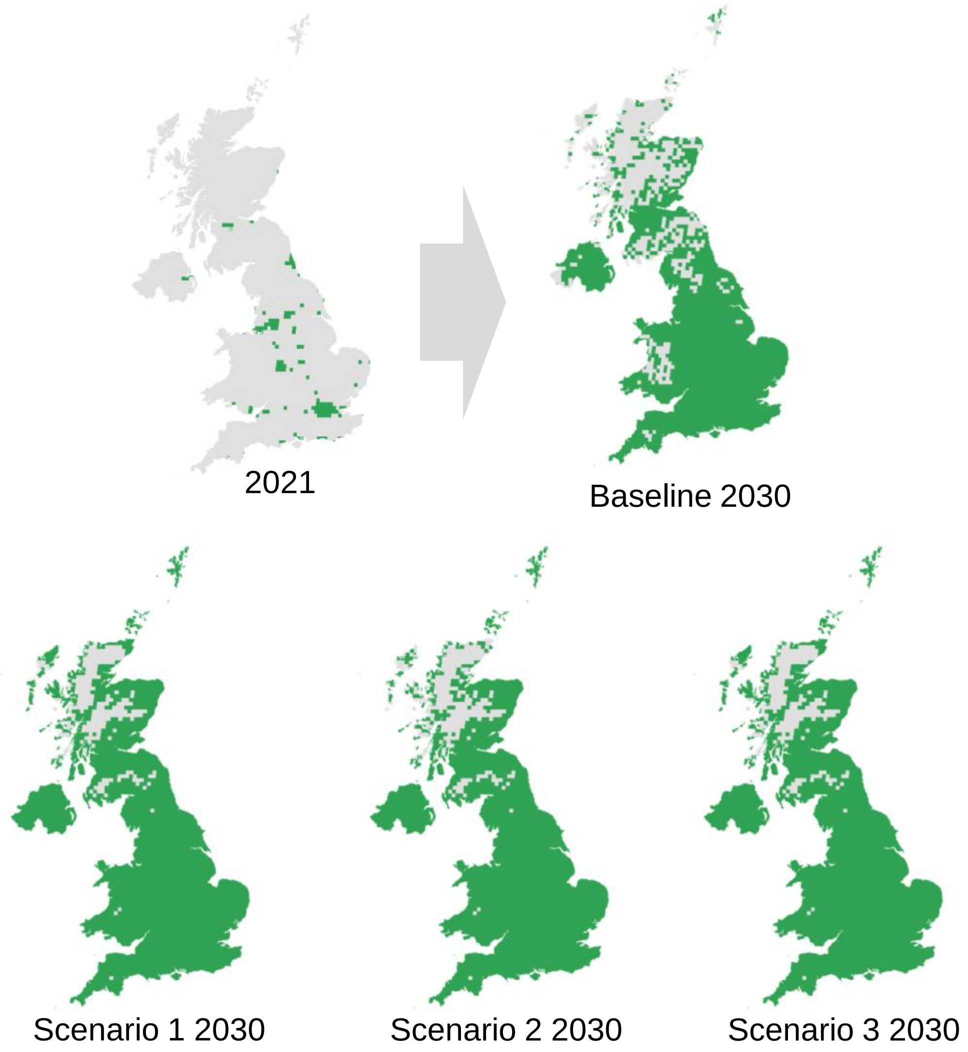
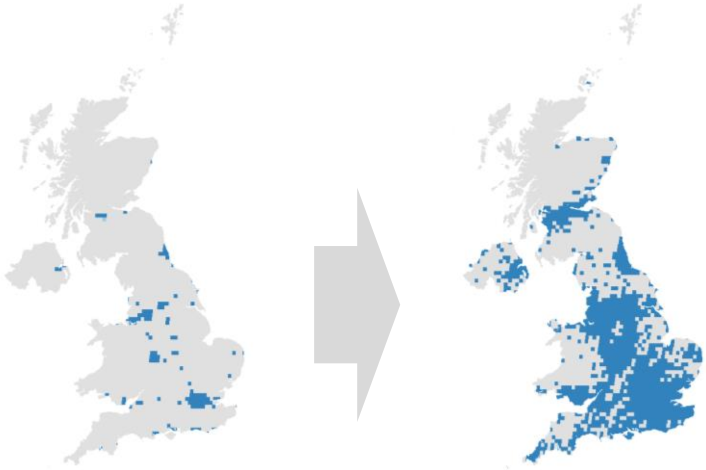


Figure 5.8: 3500MHz footprint in 2021, and footprint in 2030 in each scenario [Source: Analysys Mason, 2022]



2021 Baseline 2030

Scenario 1 2030 Scenario 2 2030 Scenario 3 2030

The costs required for each scenario relative to the baseline are shown in Figure 5.9. Scenario 1 (50Mbit/s to all users, consistent with the network capacity a consumer might need to consume, for example, future AR/VR applications) costs the least, at an additional GBP51 million per annum, over the period of the model from the present time until 2030.

Figure 5.9 also shows that at a national level, Scenario 3 (50Mbit/s to all users plus a higher level of advanced services demand from enterprise and business) costs more than the combined cost of Scenarios 1 and 2. This is because many of the sites already have all available spectrum bands deployed and in order to meet the combined demand, new sites need to be built. Building new sites is more expensive than the initial capacity increase accrued through adding spectrum bands. However, Figure 5.10 shows that this is not the case in all areas. In rural geotypes, there is a cost saving when deploying to meet both consumer and enterprise traffic compared to the cost of deploying to meet one or the other, which could be passed onto the consumers or businesses.

Figure 5.9: Nominal additional cost associated with each scenario per annum in 2022–30, and the gap between Scenarios 1 and 2, and Scenario 3 [Source: Analysys Mason, 2022]

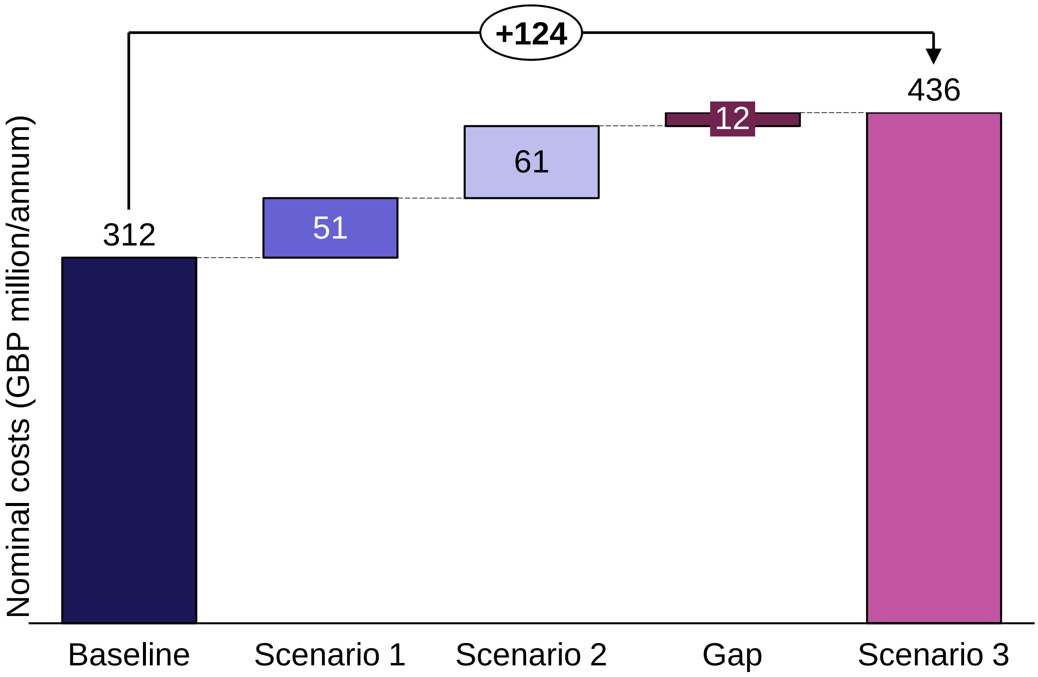
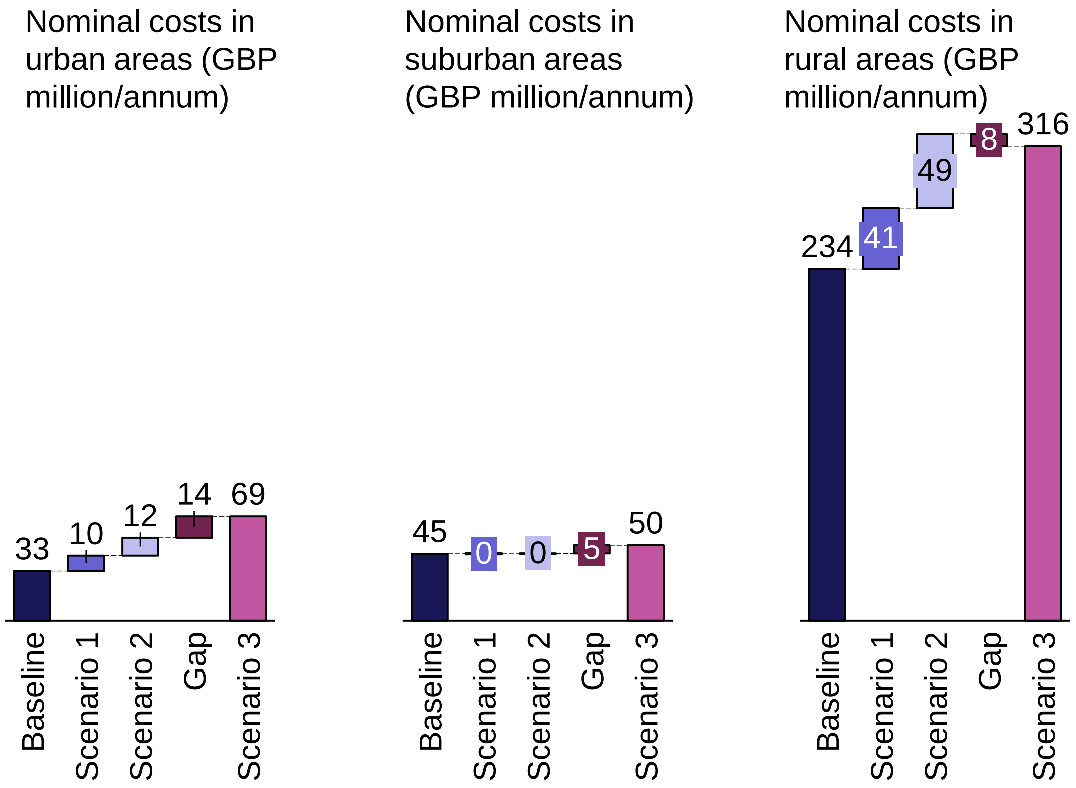


Figure 5.10: Nominal additional cost associated with each scenario per annum in 2022–30, and the gap between Scenarios 1 and 2, and Scenario 3 by geotype [Source: Analysys Mason, 2022]



To consider whether MNOs will make these investments, we use the measures described earlier in this section, i.e. additional ARPU per consumer, or revenue per business, compared to a GVA uplift estimate for businesses using higher levels of connectivity.

Figure 5.11 shows that on average across all rural areas, the cost saved by deploying to meet both consumer and enterprise demand in Scenario 3 could reduce the revenue required over the modelled 12-year period by up to GBP8 million per annum. However, when looking at the revenue required across the whole of the UK (Figure 5.12), the reduced revenue requirement in rural areas is outweighed by an increased revenue requirement in urban and suburban areas. We discuss the viability of these revenue requirements and means of reducing the additional infrastructure costs in Section 7.1.

Figure 5.11: Nominal additional revenue required per annum over the payback period in rural areas per scenario [Source: Analysys Mason, 2022]

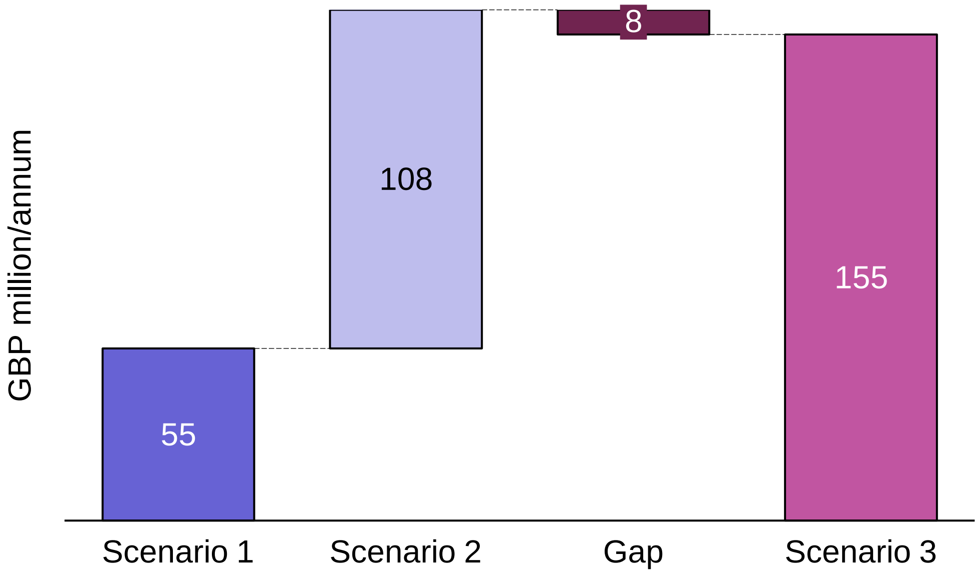
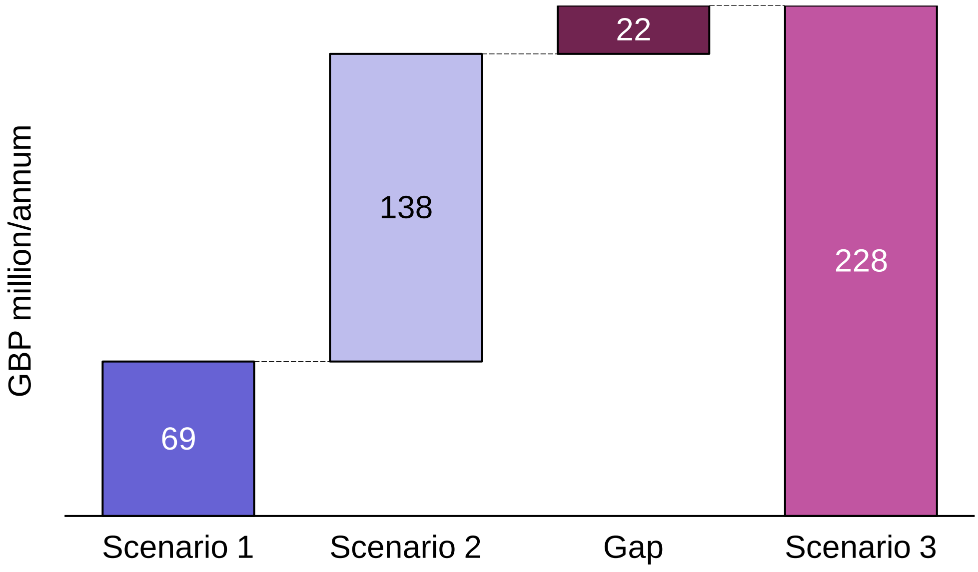
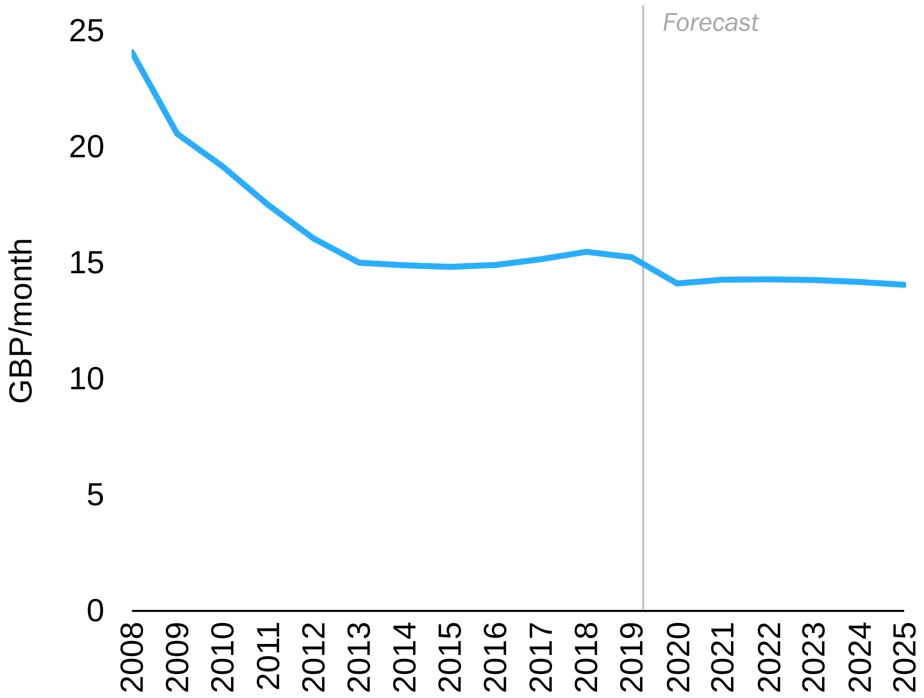


Figure 5.12: Nominal additional revenue required per annum over the payback period UK wide per scenario [Source: Analysys Mason, 2022]



The GBP69 million additional revenue required UK wide per annum for Scenario 1 equates to an additional GBP3 per consumer per annum, equivalent to an ARPU uplift of GBP0.28 per month. For reference, Figure 5.11 shows the historical UK ARPU trends, and Analysys Mason's forecast for the UK up to 2026. The uplift of GBP0.28 corresponds to approximately 2% of current total ARPU. The GBP137 million additional revenue required for Scenario 2 equates to GBP92 647 per annum per business adopting a public mobile solution. This amount is calculated from the portion of total UK businesses we assume will adopt advanced 5G connectivity using a public mobile network, noting our model assumes many businesses will either choose to deploy a private cellular network from a third-party supplier or may use Wi-Fi.[142] The size of the additional business revenue that the model estimates that MNOs will need to recover the additional cost of infrastructure to meet advanced use cases is indicative of the significant additional requirements these advanced use cases create in terms of the capacity needed in a cellular network.

Figure 5.13: Evolution of mobile ARPU in the UK [Source: Analysys Mason, 2022]



Detailed results on the final deployment of sites and spectrum, the costs associated with achieving that deployment and the revenue required for the deployment to be commercially viable are further discussed in Sections 5.2.1 and 5.2.2 below.

5.2.1 Model baseline results

Based on the traffic forecast in Figure 4.21, we predict that by 2030 the hypothetical MNO will build an additional 53 densification sites and significantly extend the current 5G footprint (as shown in Figure 5.7 and Figure 5.8), in order to provide the required capacity. The current and expected final level of deployment of each

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[142] Our high-level estimate of the upfront (capital) cost of installing a private cellular network is that this might range from GBP200 000 to GBP800 000, depending on the size of the network. Running costs might be around 10% of the capital cost.

spectrum band is shown in Figure 5.14, with regional and geotype variations shown in Figure 5.15 and in Figure 5.16 respectively.

Figure 5.14: Current level of deployment, and expected final deployment levels UK wide in the baseline [Source: Analysys Mason, 2022]

Band	Current deployment level (number and % of current sites)	Current population coverage	Expected final deployment level (number and % of final sites)	Expected final population coverage
700MHz	2708 (15%)	41.70%	17000 (93%)	99.17%
800MHz	18 050 (100%)	99.91%	18339 (100%)	99.98%
900MHz	18 050 (100%)	99.91%	18341 (100%)	99.98%
1800MHz	18 050 (100%)	99.91%	18208 (99%)	99.94%
2100MHz	12 625 (70%)	93.37%	16202 (88%)	98.54%
2600MHz	9025 (50%)	82.49%	15104 (82%)	97.33%
3500MHz	2708 (15%)	41.70%	13006 (71%)	93.78%

The 26GHz band is not included in our model, however this band might be used by national MNOs or local providers to provide capacity where there is a requirement for high speeds and/or very high capacity. To justify the investment of adding 26GHz capability to base stations, there would either need to be cost saving advantages to MNOs to meet future traffic demand, or a commercial benefit to MNOs (e.g. to improve the quality of their network in specific locations). This commercial benefit of having better capacity in key network locations may result in a market share advantage to that operator, if that operator’s network performs better than other networks, or would avoid loss of market share through churn, which could occur if one operator’s network is performing worse than others in a given location.[143]

Currently, Ofcom only permits indoor use of the 26GHz band. If Ofcom follows other European regulators in making 26GHz available for outdoor use, this band might be used to provide additional capacity in outdoor, as well as indoor, environments. The 26GHz band also has flexibility to vary the uplink/downlink capacity at a local level, and thus could be useful in providing capacity for industrial networks where there is a high uplink traffic need.

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[143] For example, a market share advantage could be gained from winning a higher portion of net user additions to its network, due to customers who churn from other providers. Conversely, investment in infrastructure can avoid loss of market share by ensuring that the operator’s network is performing no worse than other networks in that location.

Figure 5.15: Expected final deployment level by region in the baseline [Source: Analysys Mason, 2022]

Region	Peak throughput by 2030 (Gbit/s)	Infill sites	Expected final deployment level (number and % of final sites)							Supported throughput by 2030 (Gbit/s)	Throughput not met by 2030 (Gbit/s)[144]
			700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2600 MHz	3500 MHz		
North East	265	-	574 (90%)	638 (100%)	638 (100%)	638 (100%)	543 (85%)	519 (81%)	459 (72%)	472	-
North West	709	-	1400 (95%)	1470 (100%)	1470 (100%)	1470 (100%)	1335 (91%)	1285 (87%)	1206 (82%)	1228	-
Yorkshire and the Humber	568	2	1357 (96%)	1419 (100%)	1419 (100%)	1419 (100%)	1313 (93%)	1218 (86%)	1060 (75%)	1071	-
East Midlands	559	-	1537 (99%)	1552 (100%)	1552 (100%)	1552 (100%)	1524 (98%)	1426 (92%)	1157 (75%)	1069	-
West Midlands	576	-	1385 (100%)	1385 (100%)	1385 (100%)	1385 (100%)	1343 (97%)	1246 (90%)	1118 (81%)	1084	-
East	689	-	1861 (100%)	1862 (100%)	1862 (100%)	1862 (100%)	1847 (99%)	1779 (96%)	1494 (80%)	1324	-
London	678	51	684 (100%)	684 (100%)	684 (100%)	684 (100%)	684 (100%)	684 (100%)	684 (100%)	832	-
South East	1061	-	2295 (100%)	2295 (100%)	2295 (100%)	2295 (100%)	2295 (100%)	2295 (100%)	2193 (96%)	1993	-
South West	618	-	2044 (99%)	2068 (100%)	2068 (100%)	2068 (100%)	1977 (96%)	1819 (88%)	1440 (70%)	1258	-

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[144] Note that this value is the sum of shortfalls in grid squares with insufficient capacity to meet demand. Other grid squares may have excess capacity and could support higher throughputs, and hence peak, supported and shortfall throughput columns are not additive.

Region	Peak through-put by 2030 (Gbit/s)	Infill sites	Expected final deployment level (number and % of final sites)							Supported through-put by 2030 (Gbit/s)	Through-put not met by 2030 (Gbit/s)[144]
			700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2600 MHz	3500 MHz		
Wales	344	-	1180 (85%)	1392 (100%)	1392 (100%)	1390 (100%)	1003 (72%)	869 (62%)	718 (52%)	674	-
Scotland	581	-	1768 (69%)	2579 (100%)	2578 (100%)	2447 (95%)	1539 (60%)	1307 (51%)	1010 (39%)	1054	-
Northern Ireland	232	-	914 (91%)	999 (100%)	999 (100%)	999 (100%)	802 (80%)	659 (66%)	467 (47%)	432	-
UK-wide[145]	6881	53	17000 (93%)	18339 (100%)	18341 (100%)	18208 (99%)	16202 (88%)	15104 (82%)	13006 (71%)	12 491	-

Figure 5.16: Expected final deployment level by geotype in the baseline [Source: Analysys Mason, 2022]

Region	Peak through-put by 2030 (Gbit/s)	Infill sites	Expected final deployment level (number and % of final sites)							Supported through-put by 2030 (Gbit/s)	Through-put not met by 2030 (Gbit/s)[146]
			700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2600 MHz	3500 MHz		
Urban	3060	51	4038 (100%)	4038 (100%)	4038 (100%)	4038 (100%)	4038 (100%)	4038 (100%)	4038 (100%)	4908	-

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[145] Note that numbers may not sum exactly due to rounding.

[146] Note that this value is the sum of shortfalls in grid squares with insufficient capacity to meet demand. Other grid squares may have excess capacity and could support higher throughputs, and hence peak, supported and shortfall throughput columns are not additive.

Region	Peak throughput by 2030 (Gbit/s)	Infill sites	Expected final deployment level (number and % of final sites)							Supported throughput by 2030 (Gbit/s)	Throughput not met by 2030 (Gbit/s)[146]
			700 MHz	800 MHz	900 MHz	1800 MHz	2100 MHz	2600 MHz	3500 MHz		
Suburban	1122	-	2104 (100%)	2104 (100%)	2104 (100%)	2104 (100%)	2104 (100%)	2104 (100%)	2104 (100%)	2276	-
Rural	2699	2	10858 (89%)	12197 (100%)	12198 (100%)	12066 (99%)	10060 (82%)	8962 (73%)	6864 (56%)	5307	-
UK-wide[147]	6881	53	17000 (93%)	18339 (100%)	18341 (100%)	18208 (99%)	16202 (88%)	15104 (82%)	13006 (71%)	12 491	-

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[147] Note that numbers may not sum exactly due to rounding.

Our modelling estimates this baseline deployment will cost the hypothetical MNO a total nominal cost of GBP2.8 billion by 2030 (GBP2.1 billion in 2022 terms, with a weighted average cost of capital (WACC) of 8%). Capex makes up the majority of the total cost, and is mostly incurred in the period 2024–26, after which point opex begins to account for a much larger proportion of total annual cost (see Figure 5.17). Costs by region and geotype are provided in Figure 5.18 and Figure 5.19 below.

Figure 5.17: Nominal capex and opex for 2022–30 in the baseline [Source: Analysys Mason, 2022]

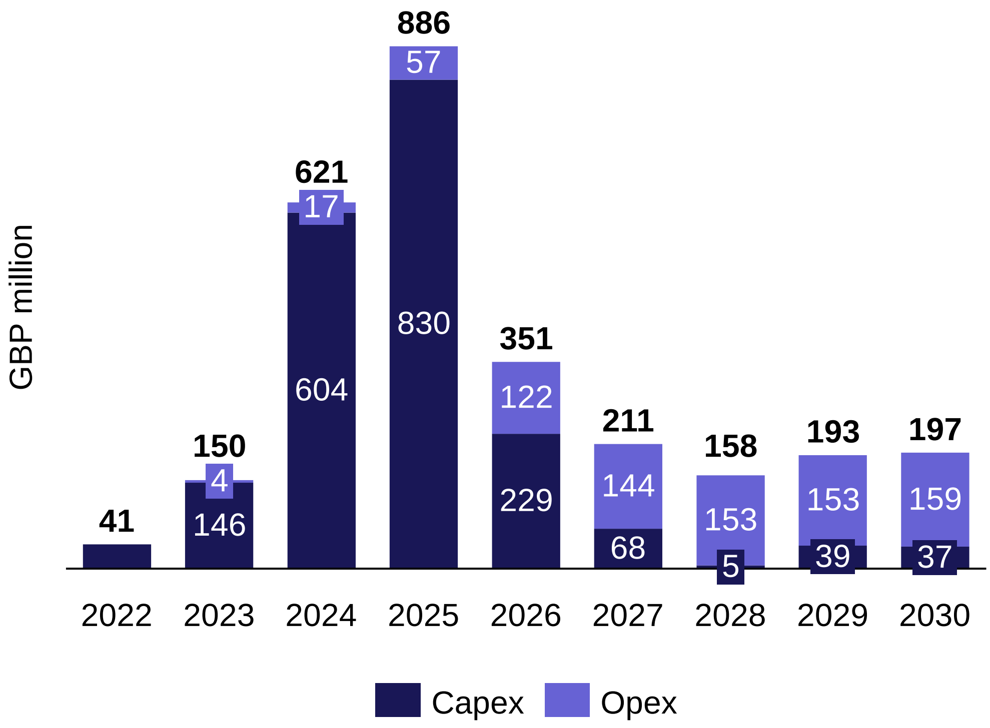

Figure 5.18: Regional costs for the baseline [Source: Analysys Mason, 2022]

	Nominal costs for 2022–30 (GBP million)			Present value of costs for 2022–30 in 2022 terms, WACC = 8% (GBP million)		
Region	**Opex**	**Capex**	**Total**	**Opex**	**Capex**	**Total**
North East	26	65	91	17	53	70
North West	53	145	198	34	118	152
Yorkshire and the Humber	58	158	215	37	127	164
East Midlands	74	182	256	47	146	194
West Midlands	55	145	200	35	116	151

	Nominal costs for 2022–30 (GBP million)			Present value of costs for 2022–30 in 2022 terms, WACC = 8% (GBP million)		
Region	**Opex**	**Capex**	**Total**	**Opex**	**Capex**	**Total**
East	95	234	330	61	190	251
London	2	14	16	1	11	12
South East	110	292	402	71	238	310
South West	102	242	344	65	194	260
Wales	56	143	200	36	112	149
Scotland	137	278	415	90	230	320
Northern Ireland	41	99	140	26	77	103
UK-wide[148]	809	1998	2807	523	1612	2136

Figure 5.19: Costs per geotype for the baseline [Source: Analysys Mason, 2022]

	Nominal costs for 2022–30 (GBP million)			Present value of costs for 2022–30 in 2022 terms, WACC = 8% (GBP million)		
Geotype	**Opex**	**Capex**	**Total**	**Opex**	**Capex**	**Total**
Urban	56	243	299	37	200	237
Suburban	73	328	402	46	259	306
Rural	680	1427	2107	440	1153	1593
UK-wide[149]	809	1998	2807	523	1612	2136

5.2.2 Defining quality-of-coverage scenarios

As described in Figure 5.1, three key quality-of-coverage scenarios have been modelled as part of this study. The choice of scenarios has been informed by:

- Our baseline assessment of the capacity and average data speeds that UK mobile networks might deliver in some locations by 2030, as indicated in Figure 5.6.
- Assessment of the level of wireless connectivity needed to support future use cases, as indicated in Figure 4.19.

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[148] Note that numbers may not sum exactly due to rounding.

[149] Note that numbers may not sum exactly due to rounding.

- How the UK's mobile network speeds compare with mobile speeds in other markets, which is described below.

First, we note that forward-looking studies are positive about the case for upgrading to faster broadband connections of all types, including via wireless, with a key reason for this being that faster connection speeds enable businesses to be more productive and competitive. For example, strong claims for the impact of high-speed broadband access on international competitiveness, as well as social cohesion, are made in previous studies investigating the impact of superfast fixed broadband in the UK market.[150] Literature also links increasing wireless and MBB penetration with innovation and competitiveness. Internationally, it is clear that MBB speeds are changing, with average MBB downlink data speeds in leading markets worldwide now well above 100Mbit/s (peaking at over 1Gbit/s).

In addition, network provision will support the development of digital skills (those needed to work in emerging sectors) and also aid existing firms to become more competitive in an increasingly digital world. Spreading access to higher-speed mobile services to more areas will thus underpin economic competitiveness and hence the presence of high-speed broadband networks, including mobile, are associated with superior economic performance in published literature.[151]

We note that there is a relationship between achieving a higher quality of mobile connection, and the consumption of mobile services in future, in that better-performing mobile networks might drive an increase in the average mobile data usage. Significant increases in average data usage per user could degrade the quality of connection in busy locations, absent of further investment in capacity to meet future demand.

The data traffic forecasts published by Analysys Mason Research assume an average (smartphone) mobile data usage in the UK that is lower than countries elsewhere in Europe. We note that a recent report published by Ofcom in relation to its mobile strategy review refers to international comparators on mobile network performance and usage, indicating Finland as a market where mobile data usage is significantly higher than in the UK. One reason given in that report for the high

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[150] For example, https://www.semanticscholar.org/paper/Costs-and-benefits-of-superfast-broadband-in-the-UK-Dini-Milne/c7542d7e995f29ce3a91dfe444659871350e3bbd and https://www.bt.com/bt-plc/assets/documents/about-bt/bt-uk-and-worldwide/bt-in-the-uk-and-ireland/research-and-reports/the-impact-of-high-speed-broadband-for-communities.pdf

[151] See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/257006/UK_Broadband_Impact_Study_-_Impact_Report_-_Nov_2013_-_Final.pdf

level of mobile data usage in Finland is higher levels of fixed–mobile substitution.[152] In the UK, fixed broadband penetration is high, and fixed data usage is also very high. Thus, the high fixed penetration in the UK tends to limit mobile traffic volumes and growth compared to countries with lower fixed network penetration or higher fixed–mobile substitution. The high fixed penetration in the UK is one reason why users opt for Wi-Fi at home for data connection (regardless of the unlimited mobile data pricing offers of MNOs). Thus, the growth in mobile usage per UK user seems likely to be constrained in future by continued high penetration of fixed networks.

Notwithstanding the difference in characteristics between the UK market and some of the other markets where 4G/5G data speeds are far higher than in the UK, it is clear from published estimates that the UK's mobile data speeds fall some way below international comparators. As shown below, UK mobile networks (excluding BTEE) have been measured to deliver data rates of 20Mbit/s or less in measured locations. A recent report prepared on behalf of Ofcom also refers to UK mobile downlink speeds (excluding BTEE) being 27Mbit/s.[153]

Given that the UK's download speeds trail the speeds in some other markets, achieving a very high download speed target (say 100Mbit/s) would require a significant further investment in infrastructure given the gap between this high target and what is available currently. A 50Mbit/s connectivity target would require less additional investment, as we show in our modelling results.

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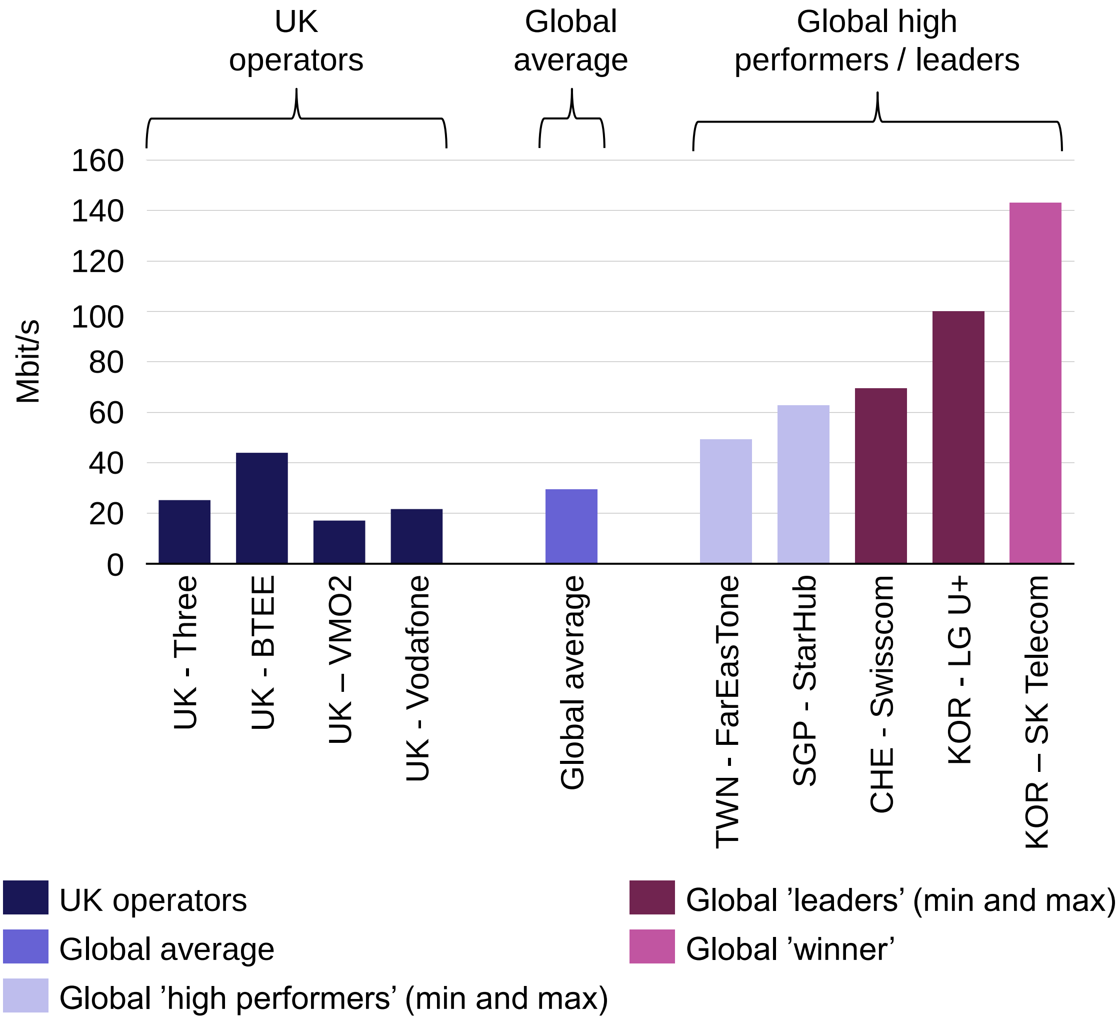
[152] For example, Section 2.4.2 in https://www.ofcom.org.uk/__data/assets/pdf_file/0028/231877/mobile-strategy-plum-report.pdf

[153] See Figure 2.3 in https://www.ofcom.org.uk/__data/assets/pdf_file/0028/231877/mobile-strategy-plum-report.pdf

Figure 5.20: Data from Opensignal on average download speeds[154] *[Source: Opensignal, published figures for second half of 2021]*[155]



5.2.3 Quality-of-coverage scenario results

We assessed three scenarios – a 50Mbit/s per active user scenario, a scenario in which mobile networks deliver additional amounts of business/enterprise traffic and

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[154] The Opensignal description of metrics in its reports refers to download speed experience as measuring the average downlink speed experienced by Opensignal users (the figures quoted are overall network figures, not specific to 5G, published at the time of conducting the analysis for this report, in the second half of 2021).

[155] From the Opensignal United Kingdom Mobile Network Experience Report September 2021, available at https://www.opensignal.com/reports/2021/09/uk/mobile-network-experience, and the Opensignal Global Mobile Network Experience Awards 2022 report, that uses data from the second half of 2021, available at https://www.opensignal.com/sites/opensignal-com/files/data/reports/pdf-only/data-2022-02/opensignalglobalmobilenetworkexperiencefebruary2022_3.pdf

a scenario in which networks deliver both 50Mbit/s per active user plus additional business/enterprise traffic.

Scenario 1: 50Mbit/s per active user

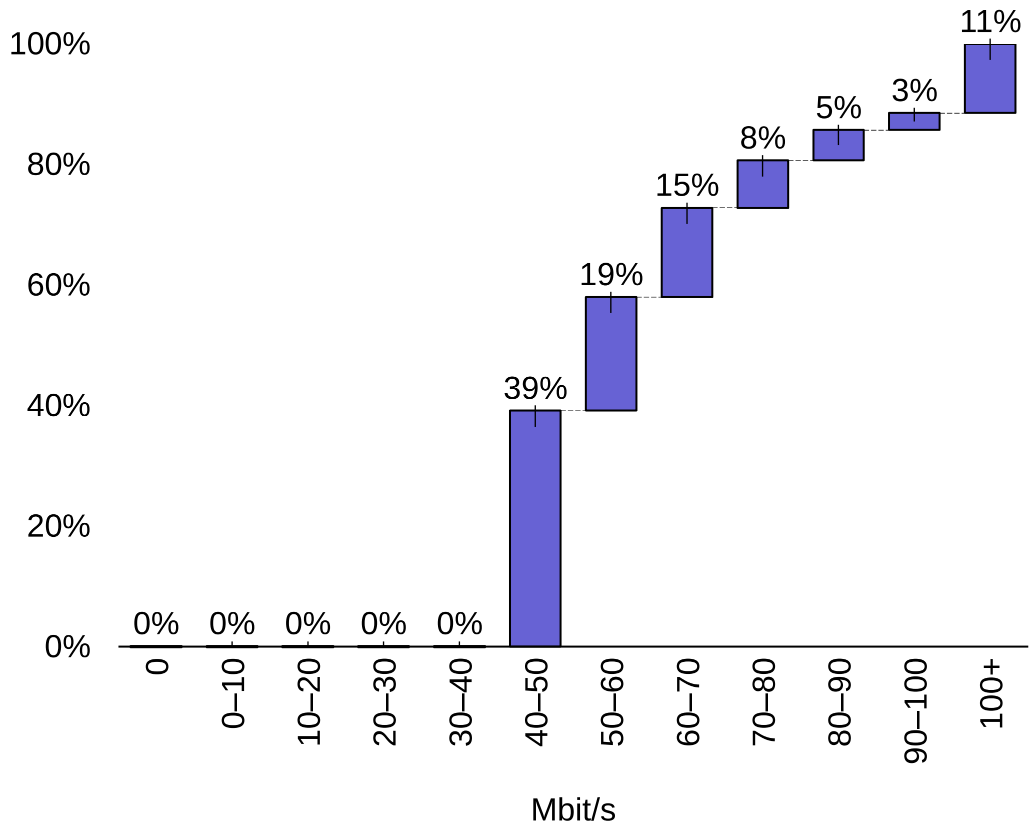
In Scenario 1, an average download speed of 50Mbit/s per active user has been defined as a target quality-of-connection threshold.

In order to achieve a minimum speed of 50Mbit/s per active user by 2030 in all locations where the baseline identifies this quality of connection not being met, the market would not provide this quality-of-service level (see the average downlink speeds lower than 50Mbit/s represented by the red, orange and yellow grid squares in Figure 5.4). The network needs to support a peak throughput of 11 600Gbit/s, which requires 701 infill sites in total and a much larger 5G footprint.

Results show that, compared to the baseline, Scenario 1 requires the MNO to deploy all available sub-1GHz, 1800MHz and 2100MHz spectrum on 100% of sites, 2600MHz on 98% of sites and mid-band 5G (3.5GHz on 90% of sites). Population coverage of the 3.5GHz coverage increases from just under 42% in the baseline in 2021, to 98.5% in Scenario 1. Of the 702 infill sites needed, nearly 430 are in London, with the remainder distributed across the UK. Split by geotype, 661 additional sites fall in urban locations of the UK and 40 in rural.

These deployments will not only result in 100% of the population achieving average download speeds of greater than 50Mbit/s, but in order to meet the target in some areas, the spectrum deployment will result in excess capacity, increasing speeds above the 50Mbit/s target. According to this scenario, by 2030 11% of the population will experience speeds greater than 100Mbit/s (see Figure 5.21).

Figure 5.21: Percentage of population with the following average download speed per active user by the end of 2030 according to Scenario 1 [Source: Analysys Mason, 2022]



The deployments required to meet the minimum 50Mbit/s per active user scenario (Scenario 1) are estimated to cost a nominal GBP3.3 billion by 2030 (GBP2.5 billion in 2022 terms when discounted at a WACC of 8%). Figure 5.22 and Figure 5.23 show breakdowns of cost by region and geotype. Note that when adding additional capacity requirements, the deployment priority of sites can change. In the 50Mbit/s scenario, certain suburban sites are upgraded later than they would be in the baseline in exchange for earlier upgrade of more constrained urban and rural sites, hence the opex for suburban locations in Scenario 1 is lower than for the baseline.

Figure 5.22: Additional costs per annum, in nominal terms, by region for 2022–30 in Scenario 1 [Source: Analysys Mason, 2022]

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Region	**Opex**	**Capex**	**Total**
North East	0.40	1.32	1.72
North West	0.81	2.73	3.54
Yorkshire and the Humber	0.53	2.27	2.79

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Region	**Opex**	**Capex**	**Total**
East Midlands	0.38	2.12	2.49
West Midlands	0.19	1.64	1.83
East	0.28	1.99	2.27
London	0.92	5.58	6.50
South East	0.22	1.40	1.62
South West	0.49	3.20	3.69
Wales	1.45	4.24	5.69
Scotland	4.07	11.13	15.20
Northern Ireland	0.73	2.85	3.58
UK-wide[156]	10.46	40.45	50.91

Figure 5.23: Additional costs per annum, in nominal terms, by geotype for 2022–30 in Scenario 1 [Source: Analysys Mason, 2022]

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Geotype	**Opex**	**Capex**	**Total**
Urban	1.27	8.89	10.16
Suburban	-	-	-
Rural	9.20	31.56	40.75
UK-wide[157]	10.46	40.45	50.91

In order for the additional deployment to be commercially viable for the hypothetical operator, we require the cost to be recovered within a 12-year payback period after it is incurred, with a WACC of 8%. In this scenario, an additional annual revenue of GBP69 million in nominal terms is required over the payback period in order for the additional deployments to be commercially viable. When distributed across the network's users, this equates to an ARPU uplift of GBP0.28 per month. The required additional annual nominal revenue and ARPU uplift required for the different regions and geotypes to achieve 50Mbit/s per active user are provided in Figure 5.24 and Figure 5.25 respectively.

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[156] Note that numbers may not sum exactly due to rounding.

[157] Note that numbers may not sum exactly due to rounding.

Figure 5.24: Additional revenue requirements by region for Scenario 1 [Source: Analysys Mason, 2022]

Region	Additional revenue required over the payback period (GBP million per annum in nominal terms)	ARPU uplift (GBP/ month/user)
North East	2.41	0.25
North West	4.66	0.17
Yorkshire and the Humber	3.68	0.18
East Midlands	3.06	0.16
West Midlands	2.36	0.11
East	2.77	0.13
London	8.90	0.26
South East	2.16	0.06
South West	4.55	0.22
Wales	7.66	0.64
Scotland	22.39	1.11
Northern Ireland	4.64	0.63
UK-wide[158]	69.24	0.28

Figure 5.25: Additional revenue requirements by geotype for Scenario 1 [Source: Analysys Mason, 2022]

Geotype	Additional revenue required over the payback period (GBP million per annum in nominal terms)	ARPU uplift (GBP/ month/user)
Urban	14.24	0.11
Suburban	-	-
Rural	55.00	0.69
UK-wide[159]	69.24	0.28

If the target minimum average speed per user was increased, the cost required for Scenario 2 would increase too (see Figure 5.26). The increase would be exponential, however the restriction on number of densification sites means that there is a limit to the amount that can be invested in order to improve speeds, and in the region of 60–10Mbit/s the cost curve looks linear. However, the percentage

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[158] Note that numbers may not sum exactly due to rounding.

[159] Note that numbers may not sum exactly due to rounding.

of throughput that would not be served increases at the higher end of the speed curve, indicating that MNOs would either need access to additional spectrum beyond that currently available, or more significant use of smaller cell overlays would be needed (which our model does not consider). Figure 5.27 shows how the revenue requirement and ARPU increases as a result of increasing the average speed target per active user.

Figure 5.26: Annualised nominal additional costs for 2020–30 if the target minimum average speed per active user was varied in Scenario 1 [Source: Analysys Mason, 2022]

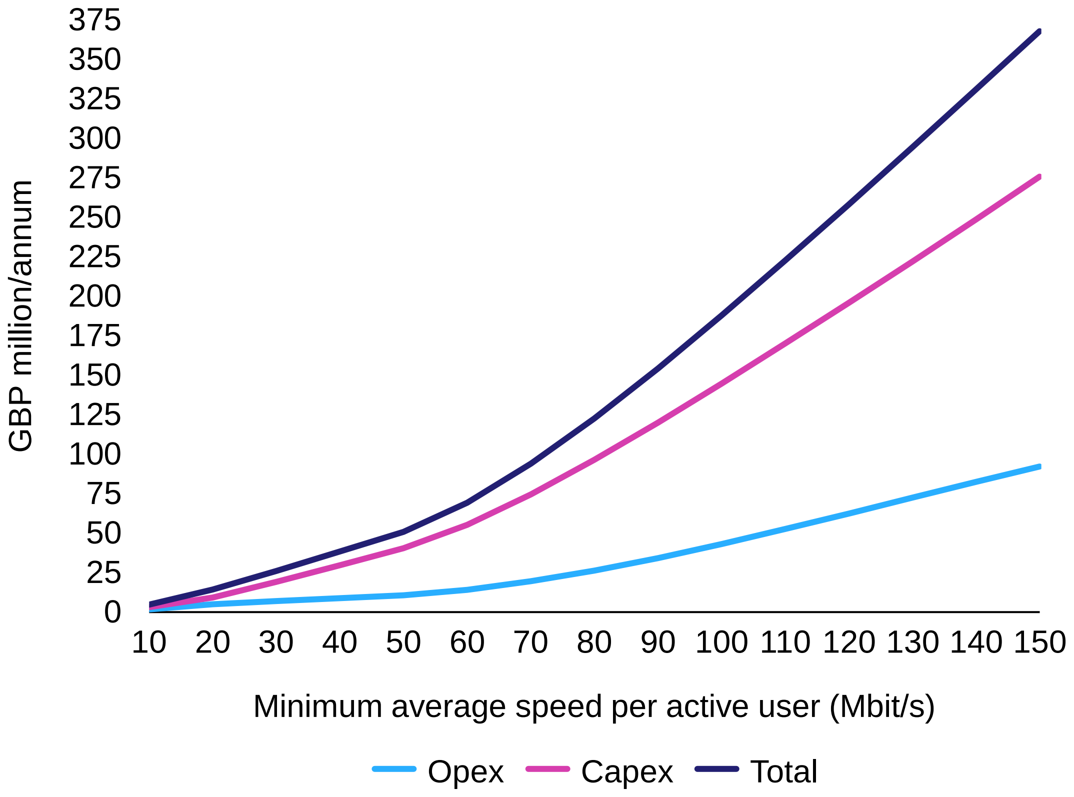
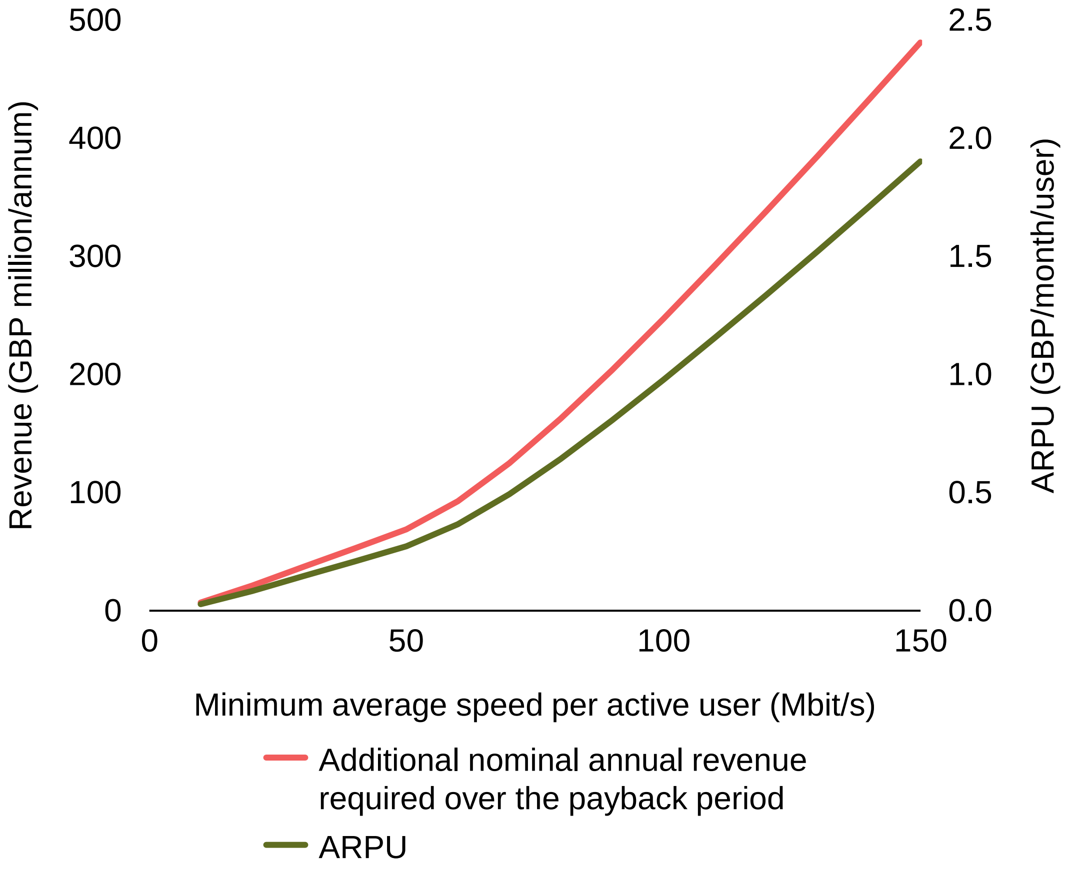


Figure 5.27: Annualised nominal revenue required over the payback period, and corresponding ARPU, if the target minimum average speed per active user was varied in Scenario 1 [Source: Analysys Mason, 2022]



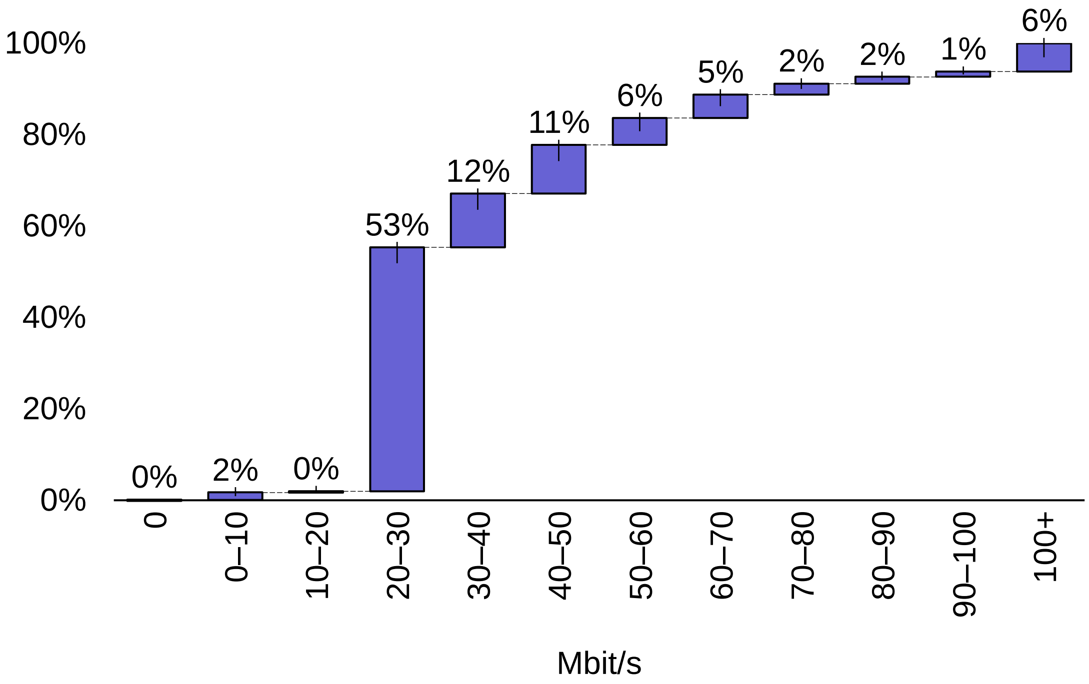
Scenario 2: Enterprise traffic

The results obtained from Scenario 2 (enterprise traffic) are illustrative on the basis of high-level assumptions that we have made on advanced enterprise (IoT-type) traffic demand to build up a traffic forecast. Using our inputs, the model calculates that in order for the public network to meet the forecast traffic, an additional 1460 densification sites are required, and 92% of final sites will have all the available spectrum deployed (corresponding to 98.66% population coverage). However, there is unmet demand in this scenario (throughput in the busy hour would need to increase by a further 56Gbit/s in some locations, which is beyond the capacity our model allows based on existing spectrum and site densification assumptions). This limit on site densification is in line with our standard modelling practice, reflecting densification issues in practice such as availability of sites, space and feasibility of densifying in some locations. Meeting this excess demand would require a small-cell overlay to be added to macro networks, or additional spectrum to be available to the MNOs.

Modelling results for Scenario 2 indicate that the MNO would need to deploy all sub-1GHz spectrum and 1800MHz on 100% of sites, 2100MHz on 96% of sites, 2600MHz on 94% of sites and 3.5GHz on 92% of sites. Nearly 1500 densification sites are predicted to be required, of which 606 are in London.

These deployments will result in consumer speeds decreasing relative to the baseline as excess capacity is used to meet enterprise demand rather than provide higher consumer speeds. 78% of the population will experience speeds below 50Mbit/s (see Figure 5.28).

Figure 5.28: Percentage of population with the following average download speed per active user by the end of 2030 according to Scenario 2 [Source: Analysys Mason, 2022]



The model calculates the nominal cost of the deployments required in order to meet the estimated enterprise traffic demand together with the forecast wide-area traffic by 2030 as GBP3.4 billion (GBP2.5 billion in in 2022 terms with a WACC of 8%). When compared with the baseline where the market pre-emptively deploys to meet 20% of the enterprise traffic, an additional annualised nominal cost of GBP61 million is required for each year from 2022 to 2030 in order for the market to serve the remaining 80% of enterprise traffic. Figure 5.29 and Figure 5.30 show the additional costs broken down into opex and capex by region and geotype respectively.

Figure 5.29: Additional costs per annum, in nominal terms, by region for 2022–30 in Scenario 2 [Source: Analysys Mason, 2022]

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Region	**Opex**[160]	**Capex**	**Total**
North East	0.58	2.03	2.62
North West	0.05	4.63	4.69
Yorkshire and the Humber	0.31	4.07	4.37
East Midlands	-0.14	3.18	3.04
West Midlands	0.41	3.07	3.48
East	-0.18	3.12	2.94
London	1.18	8.07	9.25
South East	-1.95	3.28	1.34
South West	1.49	4.51	5.99
Wales	1.55	4.53	6.08
Scotland	2.67	9.74	12.41
Northern Ireland	1.76	3.46	5.23
UK-wide[161]	7.74	53.69	61.43

Figure 5.30: Additional costs per annum, in nominal terms, by geotype for 2022–30 in Scenario 2 [Source: Analysys Mason, 2022]

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Geotype	**Opex**[162]	**Capex**	**Total**
Urban	0.13	11.83	11.96
Suburban	-0.10	0.35	0.25
Rural	7.71	41.51	49.22
UK-wide[163]	7.74	53.69	61.43

In order for the additional deployment required to meet the additional 80% of the enterprise traffic to be commercially viable for the hypothetical operator, an additional annual revenue of GBP137 million in nominal terms is required over the payback period. When distributed across the number of businesses modelled to

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[160] Note the negative values result from deployments being delayed relative to the baseline, resulting in less opex accrual.

[161] Note that numbers may not sum exactly due to rounding.

[162] Note the negative values result from deployments being delayed relative to the baseline, resulting in less opex accrual.

[163] Note that numbers may not sum exactly due to rounding.

use the hypothetical MNO’s network (1482, as indicated in Figure 5.1), this corresponds to an ARPU of GBP7721 per month. Over the payback period this will add up to GBP1261 million, 49% of the GBP2579 million GVA uplift expected as a result of the additional connectivity over the same period. The required additional annual nominal revenue, ARPU uplift and cumulative revenue required for the different regions and geotypes that serve the illustrative enterprise demand are provided in Figure 5.31 and Figure 5.32 respectively.

Figure 5.31: Additional revenue requirements by region for Scenario 2 [Source: Analysys Mason, 2022]

Region	Additional revenue required over the payback period (GBP million per annum in nominal terms)	ARPU (GBP/month/ business)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative revenue as a percentage of cumulative GVA uplift
North East	4.78	8751	58	44	77%
North West	12.71	7033	226	115	51%
Yorkshire and the Humber	11.97	8860	143	110	77%
East Midlands	9.33	7044	228	86	38%
West Midlands	7.80	5381	178	72	40%
East	10.08	6404	215	92	43%
London	13.18	4707	611	121	20%
South East	12.98	4937	399	116	29%
South West	11.99	7558	191	112	59%
Wales	11.86	15 372	90	110	122%
Scotland	23.06	16 210	184	212	115%
Northern Ireland	7.53	14 533	58	71	123%
UK-wide[164]	137.27	7721	2579	1261	49%

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[164] Note that numbers may not sum exactly due to rounding.

Figure 5.32: Additional revenue requirements by geotype for Scenario 2 [Source: Analysys Mason, 2022]

Geotype	Additional revenue required over the payback period (GBP million per annum in nominal terms)	ARPU uplift (GBP/month/ business)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative revenue as a percentage of cumulative GVA uplift
Urban	24.87	3140	1288	224	17%
Suburban	4.71	2384	292	43	15%
Rural	107.70	13 656	998	994	100%
UK-wide[165]	137.27	7721	2579	1261	49%

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[165] Note that numbers may not sum exactly due to rounding.

Scenario 3: Enterprise traffic plus 50Mbit/s per user

Scenario 3 combines a target of meeting enterprise traffic and a minimum of 50Mbit/s per active consumer user. This means that 4097 new infill sites will need to be built by 2030 and 94% of sites will have all the available spectrum deployed (covering 99.85% of the population). However, there is unmet capacity in the busy hour such that the busy-hour throughput would need to increase by 156Gbit/s, primarily in urban regions. As for Scenario 2, this is due to the model placing an upper bound on the number of densification sites that can theoretically be deployed.

Under Scenario 3, the MNO would deploy sub-1GHz and 1800MHz spectrum on 100% of sites, 2100MHz and 2600MHz on 94% of sites and 3.5GHz on 99% of sites.[166]

These deployments will only result in 98% of the population achieving average download speeds of greater than 50Mbit/s, or some of the business demand will go unmet due to the limit on densification sites explained above. Additionally, as in Scenario 2, consumer speeds are lower than they are in the absence of additional enterprise traffic (Scenario 1) due to surplus capacity being used to meet enterprise demand rather than increase consumer speeds (see Figure 5.33).

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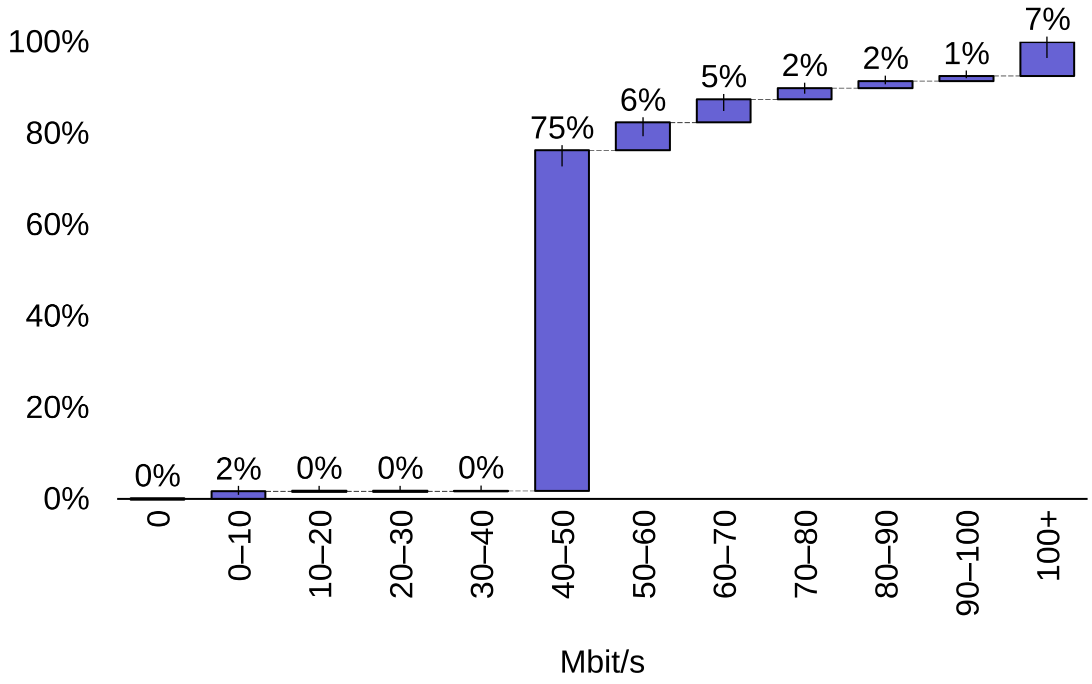
[166] Note that 3500MHz is deployed on more sites than 800MHz, 2100MHz and 2600MHz despite being last in the carrier order because it is deployed on densification sites whereas the other bands are not.

Figure 5.33: Percentage of population with the following average download speed per active user by the end of 2030 according to Scenario 3 [Source: Analysys Mason, 2022]



The deployments required are estimated to cost a nominal GBP3.9 billion by 2030 (GBP2.9 billion in 2022 terms when discounted at a WACC of 8%). When compared with the baseline, the additional deployments associated with achieving 50Mbit/s per active user in addition to serving existing wide-area traffic and the specified enterprise traffic will cost an average nominal GBP124 million for each year from 2022 to 2030. Breakdowns of cost by region and geotype are provided in Figure 5.34 and Figure 5.35 respectively.

Figure 5.34: Additional costs per annum, in nominal terms, by region for 2022–30 in Scenario 3 [Source: Analysys Mason, 2022]

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Region	**Opex**	**Capex**	**Total**
North East	0.98	3.69	4.67
North West	1.18	10.92	12.09
Yorkshire and the Humber	1.04	7.59	8.63
East Midlands	0.49	6.85	7.34
West Midlands	1.12	7.10	8.23
East	0.64	7.05	7.69
London	1.78	14.01	15.79
South East	–0.25	11.42	11.17

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Region	**Opex**	**Capex**	**Total**
South West	1.95	7.17	9.13
Wales	2.10	7.73	9.82
Scotland	4.51	18.34	22.85
Northern Ireland	1.98	4.62	6.61
UK-wide[167]	17.51	106.50	124.01

Figure 5.35: Additional costs per annum, in nominal terms, by geotype for 2022–30 in Scenario 3 [Source: Analysys Mason, 2022]

	Additional costs for 2022–30 (GBP million per annum in nominal terms)		
Geotype	**Opex**	**Capex**	**Total**
Urban	2.10	34.18	36.27
Suburban	1.59	4.04	5.63
Rural	13.82	68.29	82.11
UK-wide[168]	17.51	106.50	124.01

In order for the additional deployment to be commercially viable for the hypothetical operator, an additional annual revenue of GBP228 million in nominal terms is required over the payback period. This will likely be provided by some combination of consumers and businesses, however the decision of how the MNO will apportion the cost to users cannot be estimated. At most, if all the cost was apportioned to one user type, consumers would need to pay a maximum additional ARPU of GBP0.91 per month, or businesses would have to pay GBP12 836 per month, which cumulatively, over the payback period, would correspond to 77% of the cumulative GVA uplift over the same period. The regional and geotype variations are shown in Figure 5.36 and Figure 5.37 respectively.

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[167] Note that numbers may not sum exactly due to rounding.

[168] Note that numbers may not sum exactly due to rounding.

Figure 5.36: Additional revenue requirements by region for Scenario 3 [Source: Analysys Mason, 2022]

Region	Additional revenue required over the payback period (GBP million per annum in nominal terms)	ARPU uplift (GBP/month/user)	ARPU (GBP/month/business)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative revenue as percentage of cumulative GVA uplift
North East	7.64	0.80	13 986	69	71	103%
North West	23.57	0.88	13 045	251	215	85%
Yorkshire and the Humber	18.17	0.90	13 453	171	167	98%
East Midlands	15.93	0.82	12 024	236	146	62%
West Midlands	14.84	0.67	10 236	196	136	69%
East	17.18	0.78	10 916	220	158	72%
London	22.77	0.67	8131	623	208	33%
South East	27.63	0.77	10 512	419	251	60%
South West	16.68	0.80	10 515	206	155	75%
Wales	17.13	1.44	22 202	95	158	167%
Scotland	37.36	1.86	26 266	188	344	183%
Northern Ireland	9.31	1.27	17 969	58	87	151%
UK-wide[169]	228.22	0.91	12 836	2730	2095	77%

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[169] Note that numbers may not sum exactly due to rounding.

Figure 5.37: Additional revenue requirements by geotype for Scenario 3 [Source: Analysys Mason, 2022]

Geotype	Additional revenue required over the payback period (GBP million per annum in nominal terms)	ARPU uplift (GBP/month/ user)	ARPU uplift (GBP/month/ business)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative revenue as percentage of cumulative GVA uplift
Urban	60.95	0.46	7696	1438	550	38%
Suburban	12.45	0.34	6308	292	116	40%
Rural	154.82	1.94	19 631	1000	1429	143%
UK-wide[170]	228.22	0.91	12 836	2730	2095	77%

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[170] Note that numbers may not sum exactly due to rounding.

5.2.4 Limitations of the current model and future considerations

It is worth noting that this modelling approach deploys additional capacity on an assumed existing grid of sites, but does not deploy coverage into entirely new geographical areas in the UK not already covered by existing network plans (noting that these plans include 4G capacity provision via SRN sites).[171] Network expansion (i.e. new SRN sites) is treated in the model through a defined roll-out process which is not traffic driven. As such, the model assumes any latent demand in non-commercially viable areas is not served, since there is no existing mobile network site grid in these locations. Likewise, in some of our modelling scenarios, the modelling assumes some future traffic cannot be met in some busy locations using existing spectrum, due to insufficient capacity (taking account of assumptions on network densification). This unmet traffic demand would require additional spectrum to be available to meet demand in those locations, which is beyond the bands currently available for public mobile network use.

The modelling assumes capacity is deployed to meet busy-hour traffic load. However, this is not necessarily the same as meeting all demands for the network performance that users want (e.g. peak user speeds, quality of connection/reliability, guarantee of connectivity indoors).

Our calculation of average user speed is based on an estimate of the concurrent number of users that might be accessing the network in a given location at a given time. In practice, average speeds will vary at different times of the day depending on traffic loading (i.e. depending on how many other users are accessing the network simultaneously in the same location, how close the user is to the base station and the data load that those other users are placing on the network). Other factors such as type of device and location of the user (e.g. within premises, or moving around outdoors) and the way that networks allocate traffic to users will also impact the average speeds that a user receives.

Other limitations of the current model assumptions mainly lie in the lack of evidence and uncertainty in the following areas:

- the extent to which the emergence of future new use cases will drive future mobile network traffic requirements (noting that alternatives to using public mobile networks include use of Wi-Fi, private cellular networks or alternative hot-spot/not-spot solution providers)

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[171] Because this model involves a single theoretical composite footprint, it would not be able to identify partial not-spots that would require actual site locations and detailed radio planning data for each network. Without this data, detailed nuances of coverage will not be brought out in this model.

- how far MNOs will ‘pre-emptively’ deploy capacity for advanced enterprise use cases, in a market environment in which both demand and willingness to pay for advanced 5G services is not yet established.

As use cases become more proven in terms of demand, and devices capable of delivering these advanced use cases become available, model inputs should be refined, either by incorporating new published forecasts of advanced data traffic, or making more informed assumptions on demand as case studies of specific deployments become available.

6 Overview of key issues that could impact the investment decision

The modelling exercise described in Section 5 has shown there is a gap between:

- **the baseline model** – what the hypothetical MNO could be expected to roll out in terms of improvements and upgrades to its public cellular networks in response to their customer demand, and
- **a number of different targets** that could be envisioned for a minimum level of quality of service and coverage that it would be desirable and/or necessary for the UK market to have available.

Where a gap has been identified, the additional costs associated with the incremental investment to meet the target, and the associated revenue requirement to support the commercial viability of such investments, are calculated.

The extent to which the market will deliver on closing the gap will depend on whether there is a positive, commercial case for investment for the MNOs (with regard to public mobile networks) and whether there may be scope for alternative operators in the market to supplement the provision of services, or provide infill coverage in areas that MNOs may not reach.

Ultimately, the business case for investment in wireless infrastructure in a particular area depends primarily on the cost of providing coverage relative to the revenue that can be earned over the lifetime of the investment. This view is supported by responses in the stakeholder interviews conducted as part of this research, where it was explained that costs, rate of return and profitability were the most important factors that MNOs take into account when considering where to roll out.[172] Specifically, a core principle of corporate finance is that an investment should be made where the expected internal rate or return on the investment (internal rate of return (IRR)) is higher than the project-specific cost of capital.[173]

Therefore, the investment case, and the likelihood of private investment being sufficient to meet the target quality of service, will be disadvantaged where there are issues that could lead to increasing the costs of investment, or introduce

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[172] Based on a stakeholder interview for this study.

[173] In its mobile markets discussion paper, Ofcom also highlighted that investment decisions are primarily based on expected future returns (for example on the basis of expected net present value of expected IRR on the investment). Ofcom (2022), ‘Ofcom’s future approach to mobile markets – a discussion paper’, 9 February 2022, paragraph 6.12.

uncertainty in the ability to commercialise the investment and obtain the required revenue. Generally speaking, the investment challenge is greater:

- where the costs of investment are increased, for example due to the need to densify the network and provide significant additional capacity through site upgrades or new sites (e.g. in urban areas) or due to lower population density (e.g. in rural areas) or due to the additional administrative and regulatory costs over and above the capex needed for investment in new equipment and sites; and
- where there is greater uncertainty in the ability to commercialise the investment as a result of:
  - low willingness to pay, because there is limited demand in that area for advanced wireless connectivity services
  - uncertainty in willingness to pay, due to a lack of understanding of potential use cases or potential benefits
  - uncertainty in regulation (such as if net-neutrality rules might impact the ability to commercialise certain 5G features, such as network slicing).

Below, we provide an overview of the main issues identified that may be impeding investment in advanced wireless connectivity in the UK. This is based on a review of evidence in the public domain as conducted through previous studies for DCMS[174] and a series of stakeholder interviews carried out with UK MNOs, other wireless providers, internet companies and vendors, for this project. The key issues identified are summarised in Figure 6.1. In the following sections, we consider these issues in more detail.

Specifically we consider the conditions under which there would be a clear case for intervention in the form of public funding (such as a subsidy), to address the issues around ‘uneconomic deployment areas’, through an assessment of commercial viability, the identification of market failures,[175] and consider if issues around investment case uncertainty can also be resolved. We also consider those cases where, even in the absence of government intervention to address such market

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[174] Analysys Mason and Cambridge Econometrics (2021), ‘Realising the Benefits of 5G’, August 2021.

[175] In the context of this report, a market failure refers to a failure of commercial roll-out to reach areas where the wider economic value of the investment exceeds the private cost of roll-out, because these wider economic benefits may not be fully internalised in the private investment decision, nor captured in end-users’ willingness to pay.

failures, there may be other ‘barriers’[176] that could be removed to ensure that private investment could go as far as possible, prior to the need for public intervention:

- In Section 7, we consider whether the additional investment requirements to meet different quality-of-service targets could be met by increased revenue from users or businesses, identifying those areas that may be commercially viable (or not) under each of the three scenarios considered. We also consider the conditions that would be needed to identify a market failure in cases where operators will not roll out to specific areas even where the wider economic benefits from doing so exceed the costs of investment. These are areas where government intervention may be needed in future.
- In Section 8, we discuss the main barriers to investment that were raised in the stakeholder interviews and consider different policy options to address those barriers.

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[176] Barriers describe other impediments or frictions within the market that can hinder the deployment and/or adoption of advanced wireless services.

Figure 6.1: Overview of key issues identified [Source: Oxera, 2022]

Investment case uncertainty and uneconomic deployment areas

- Uncertainty over willingness to pay for 5G solutions
- Deployment in many hard-to-reach, rural areas may not be commercially viable
- This scale of uneconomic deployment areas could increase given the cost of deploying 5G infrastructure

Regulatory and policy environment

- Policy interventions adding to the costs faced by operators:
- ORAN technology targets and targets for vendor diversification / high risk vendor removal add costs
- Cost of ALFs hampers investment
- Investment spread too thinly across market players (market structure)
- Current net neutrality rules create uncertainty over ability to price 5G based on differentiated service levels

Barriers faced by alternative operators

- Spectrum-related barriers: difficulties and limitations with the shared access and local access licencing regime
- Need to strike roaming agreements with MNOs to enable roaming
- Inability to obtain mobile network codes

Practical deployment barriers

- Difficulty obtaining approval of planning permission, and inconsistency in the application of planning rules by Local Authorities
- Challenges with negotiating rentals with landowners

7 Assessing commercial viability of the investment requirement and identifying scope for market failures

MNOs typically find it attractive to upgrade network coverage in more populated geographical areas, such as cities, due to the economics of density which support the investment case. Stakeholder interviews suggested roll-out of 5G networks would be prioritised in the most commercially attractive areas. For example, one MNO said it would prioritise busier areas where demand is higher. It added that its initial roll-out of 5G was in urban areas, where the new spectrum available for 5G use (especially the mid-band 5G spectrum, around 3.5GHz) would provide additional capacity to meet traffic demand.[177] This is consistent with investment theory which states that investment decisions are primarily based on expected future returns, specifically in cases where the IRR exceeds the WACC.

During the interviews, multiple stakeholders noted that 5G coverage in rural areas would be unlikely to be commercially viable and that government intervention would be needed to fill this gap.[178]

Before considering the types of intervention that could address underserved areas, it is necessary to identify areas where there could be a market failure. These are areas which are (a) unlikely to be commercially viable because the expected willingness to pay by users of the network is unlikely to exceed the cost of investment and associated revenue requirement; but (b) could experience broader economic benefits which do exceed the cost of the investment.

The modelling results indicate the additional revenue that an MNO would need to achieve in order to cover the costs of meeting a quality-of-service target over the baseline roll-out, based on the assumed discount rate and payback period. The annual additional revenue needed for commercial viability has been reported as an ARPU uplift across all end users served by an MNO, which can give a sense of whether the additional revenue needed might be realistically achieved or not. Based on assessment at a granular level, in areas where the willingness to pay for enhanced quality of service is greater than or equal to the additional revenue requirement, the investment will in theory be commercially viable and likely to go ahead. Conversely, where the willingness to pay is less than the additional revenue requirement, then there will not be a viable commercial case for investment.

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[177] Based on a stakeholder interview for this study.

[178] Based on a stakeholder interview for this study.

However, there is an important distinction between what users should in theory be willing to pay for a given level of quality of service if they take into account all of the expected benefits, and what they are actually willing to pay. Market failure could occur where:

- there is information asymmetry or uncertainty regarding the value of a given level of quality of service or use case
- there are wider economic and social benefits that are not internalised by either end users or operators in their investment and purchase decisions.

A market failure provides justification for intervention. It is defined as those cases where the wider economic benefits are greater than the costs of the investment, but these benefits are not fully reflected in in the willingness to pay of the beneficiaries, making the investment commercially unviable.

As discussed in Section 6, it is important to note that if an investment is not commercially viable in a given area, it does not **necessarily** mean that there is an economic market failure. In cases where the expected wider economic benefits are not sufficient to cover the costs of the investment, there is unlikely be a case for further intervention unless further evidence of wider social benefits can be provided. A fuller consideration of economic and social benefits could also examine the environmental costs associated with roll-out of 5G into rural, and in particular very remote, areas.

Below, we summarise the key results under each of the modelling scenarios.[179] We consider the implications of the results for where investment may or may not be commercially viable, and what evidence would be required to conclude that there is a market failure that would justify intervention.

7.1 Scenario 1 – Consumer traffic only

For Scenario 1, we undertake a high-level assessment of where the investment may be considered commercially viable or not, and therefore which areas may see the target of 50Mbit/s met in the absence of government intervention.

In making this assessment, the analysis focuses on assessing whether an MNO would be able to meet the required revenue target to cover the cost of investment, with a focus on estimates of the willingness to pay by end users.

The analysis does not explicitly consider other reasons that may be driving investment decisions in a competitive market, such as competitive dynamics and the desire to deliver additional connectivity to avoid loss of customers. While we recognise that this

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[179] As discussed in Section 5, the three scenarios are Scenario 1 (50Mbit/s per active user), Scenario 2 (enterprise traffic) and Scenario 3 (50Mbit/s per active user plus enterprise traffic).

may be an important factor driving investment (and note that Ofcom has commented on this in its recent discussion paper[180]) it is not possible to assess how that will play out precisely, in particular, for assessing decisions to invest beyond the baseline model. In this regard, we note that the results of our baseline model are based on what the MNOs have committed to rolling out, and is already likely to include some degree of assessment of competitive dynamics and the optimal response. It is possible that competitive dynamics may drive investment decisions beyond the results of our baseline model but there will be a limit to how far this dynamic will drive investment before the focus shifts to an economic assessment of the cost of the investment compared against the incremental revenue that can be obtained from that investment. It was also confirmed in the stakeholder interviews that the prospect of customer revenues (whether individual or business) and profits is one of the key drivers of investment decisions (as noted above).

Focusing on whether the revenue requirement in different areas will be met, it is important to note that any increases in price for users will be implemented at a national level, given there is no scope for geographical differential pricing of mobile services in the UK market. The decision to invest in a particular area will therefore be based on an assessment of what price increase could feasibly be achieved at a national level. The assessment will then consider whether the price increase, multiplied by the number of users in a given area, would be sufficient to cover the additional revenue that an MNO would need to achieve in order to cover the costs of serving that area, based on the assumed discount rate and payback period.

There is limited widespread evidence of user willingness to pay for advanced wireless connectivity services over and above 4G in the UK, at this early stage of 5G roll-out. Therefore, there is not sufficient evidence to identify with any certainty whether there will be adequate demand or willingness to pay to meet the additional revenue requirements for a given quality-of-service level in each area (under the different scenarios).

However, one study (see the ‘Willingness to pay’ case study below) shows that some (but not all) customers may be willing to pay 5–10% more for access to 5G eMBB. We also note that some operators have recently announced new price increases. For example, VMO2 recently announced that from April 2022 customers will see higher prices on their bill: “[e]ach year, your Airtime Plan will be increased by the RPI rate of inflation announced in February plus 3.9%. If RPI is negative, we’ll only apply the 3.9%”.[181] That would lead to a price increase of over 11% this year based on February 2022 levels of retail price index (RPI), suggesting that VMO2 considers such price increases to be achievable within the competitive environment of the UK mobile market. Other operators have announced price

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[180] Ofcom (2022), ‘Ofcom’s future approach to mobile markets – a discussion paper’, 9 February 2022, paragraphs 1.21–1.24.

[181] https://www.o2.co.uk/prices

increases, at least in line with inflation, coming into force from April 2022. Given that these price increases have only recently been announced, it is not yet clear how consumers and operators will respond and whether any further price increases will be announced.

Willingness to pay for 5G

In a study conducted by Nokia, 3000 consumers (a thousand in the USA, a thousand in the UK and a thousand in South Korea) participated in a survey. The consumers were asked a series of questions to understand their perceptions of 5G, including understanding of the technology and willingness to pay.

The survey found that "[a]round two-thirds (63%) of survey respondents said they would pay up to 5% more for 5G eMBB, and just over half (52%) said they would even be willing to pay up to 10% more". This response was consistent across all three geographies surveyed.

However, deeper discussions in the consumer focus groups revealed that consumers would in fact look closely at pricing, and at different plans and bundles. The study as a whole showed that customers would find it worth paying extra for 5G, as 5G was different from and more advanced than previous technologies.

It was also revealed that consumers having a better understanding of the role and potential benefits of 5G could still play a key role in revealing the true value of 5G. The findings showed that only 23% of people who are unfamiliar with 5G find it appealing, but that this figure rises to 80% among those familiar with the new network.[182]

For illustrative purposes, we consider which areas could be deemed commercially viable under Scenario 1 given the ability to sustain a 5% national price increase. We also consider the outcomes under a 10% increase, should this be deemed feasible. We assess this price increase against estimates of existing mobile ARPU levels (based on estimate of UK mobile ARPU (excluding IoT), in 2022 of GBP13.99).[183] A 5% price increase amounts to an additional GBP0.70 and a 10% increase amounts to an additional GBP1.40.

The results provided below are illustrative supposing that a 5% or 10% price increase would be achievable. However, more detailed evidence on the willingness

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[182] Source: Nokia (2020), 'The value of 5G services: Consumer perceptions and the opportunity for CSPs', June 2020. Available at: https://www.5gcc.ca/wp-content/uploads/2020/06/Nokia-The-Value-of-5G-Services-June-2020.pdf

[183] Analysys Mason Research team database.

to pay would be needed for a more robust assessment of what price increases could be achievable. This might, for example, require a large-scale conjoint study, which would allow people and businesses to assess the value of particular use cases or features that could be enabled.

Under Scenario 1 (50Mbit/s per active user), we see that if a 5% increase in prices at the national level could be achieved, the MNO would find it commercially viable to roll out across the urban, suburban and rural geotypes (see Figure 7.1).

Figure 7.1: Modelling results by geotype (Scenario 1) [Source: Oxera, 2022]

Geotype	Additional revenue requirement per user per month in this area, required to cover additional cost of investment in this area	Roll-out commercially viable with a 5% price increase (GBP0.70)	Roll-out commercially viable with a 10% price increase (GBP1.40)
Urban	GBP0.11	Yes	Yes
Suburban	<GBP0.01	Yes	Yes
Rural	GBP0.69	Yes	Yes

However, it is more likely that the roll-out decision will be made at a more granular level, for example at a regional level (or even more granular).[184] While the model allows us to look at very granular levels, in the analysis below we consider a further disaggregation of the rural category into rural areas by region. We find that 5 out of 11 rural regions may not be commercially viable under a 5% national price increase, and only the Scotland rural region would not be commercially viable with a 10% increase in prices (see Figure 7.2).

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[184] It is instructive to consider the commercial viability of investment at more granular levels, as this is more reflective of the commercial decisions the MNO will face when considering roll-out to a specific area. Considering the results from the model at aggregate levels could provide misleading interpretations. For example, the additional revenue requirement in Scenario 1 when considering the national level as a whole is GBP0.28. Assessed against a 5% increase, this would suggest that national roll-out could be achievable. However, as we have illustrated, this may not be the case in light of how investors will likely make their decisions.

Figure 7.2: Results by region at a rural level (Scenario 1) [Source: Oxera, 2022]

Region	Additional revenue requirement per user per month in this area, require to cover additional cost of investment in this area (GBP)	Roll-out commercially viable with a 5% price increase (GBP0.70)	Roll-out commercially viable with a 10% price increase (GBP1.40)
North East rural	0.92	No	Yes
North West rural	0.60	Yes	Yes
Yorkshire rural	0.71	No (marginal)	Yes
East Midlands rural	0.34	Yes	Yes
West Midlands rural	0.27	Yes	Yes
East rural	0.24	Yes	Yes
South East rural	0.09	Yes	Yes
South West rural	0.40	Yes	Yes
Wales rural	1.17	No	Yes
Scotland rural	2.29	No	No
Northern Ireland rural	0.88	No	Yes

In those areas where the commercial case for investment cannot be made, there could be a case for intervention to help extend coverage to those areas, where the potential economic and social value of the investment exceeds the private cost of investment in these areas. A detailed case-by-case assessment of the wider benefits from access to advanced wireless connectivity in these areas would be necessary to support these conclusions, taking into account benefits from access to new services over the advanced connectivity and other benefits such as greater digital inclusion.

Where intervention in these areas can be justified, to give a sense of scale of the amount of government funding that might be needed to extend coverage to these commercially unviable areas in Scenario 1, we note that the additional annual revenue required over the payback period needed to serve these non-commercially viable areas (relative to the baseline) by the hypothetical modelled MNO with 25% market share, is **GBP39.6 million** in nominal terms. This represents an upper bound for any funding requirement for these areas since part of this can be expected to be achieved from end users (through the national 5% price increase). Taking this into account, any intervention funding would need to cover (at a minimum) the estimated residual revenue requirement, following the netting off of the 5% price increase, which in these commercially unviable areas in Scenario 1 would amount to **GBP19.8 million** per annum.[185]

Given these results are presented for just the hypothetical modelled MNO with 25% market share, to get an indication for the cost of serving all customers in the area with 50Mbit/s, we must multiply by four (noting in practice that costs of serving customers with 50Mbit/s will vary between MNOs depending on site numbers and locations, spectrum deployed and the MNO's customer base). This implies that the scale of funding that may need to be provided by government (or cost savings that would need to be found) to support the achievement of Scenario 1 targets in these areas will sit between **GBP79.2 million** and **GBP158 million** per annum in nominal terms. However, the actual level of subsidy needed to ensure all customers benefit from these services may be lower than four times these figures since it could be the case that fewer than four MNOs, or potentially even a single MNO, may be able to offer services to all businesses in an area and, thanks to the scale economies achieved, may require a smaller subsidy.

With a willingness to pay equivalent to a 10% increase in ARPU, only Scotland rural would not be commercially viable. There would be a case for intervention to help extend coverage to this region, where the expected economic and social value of the investment exceeds the private cost of investment in this area.

In that case, using a similar approach to the one described above, we estimate that the funding from government required for one MNO to extend coverage to Scotland rural under Scenario 1 would be between **GBP15.3 million** and **GBP22 million** per annum in nominal terms, equivalent to **GBP61.2 million and GBP88 million** per annum in nominal terms for four MNOs with a 25% market share each.

7.2 Scenario 2 – Enterprise traffic only

Scenario 2 focuses on the additional investment above the baseline to meet enterprise demand for advanced wireless connectivity services.

In the context of the extension of the public mobile network to serve business applications, MNOs may be able to develop new commercial models in which they can charge businesses directly for tailored services that meet their needs. However, given the significant cost of investment to meet business demand, and the smaller number of businesses (compared to active eMBB users), the revenue requirement per business to fund this investment could be significant. The key question is whether businesses would be willing to pay such an amount to receive improved

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[185] To calculate this estimate, we take the total annual revenue requirement for the area and deduct an amount equivalent to the 5% price increase (GBP0.70) multiplied by the number of end users in the area that are assumed to be served by the hypothetical modelled MNO operator with 25% market share.

connectivity and therefore meet the requirements for the business case to be commercially viable.

We have considered the extent to which a given quality-of-service improvement could bring economic benefits that come from the take-up by businesses of the advanced services (advanced services refer to the higher throughput services that businesses might use over 5G rather than a business user of 5G MBB services).

The value of the incremental expected private economic benefits to the business from taking up advanced wireless connectivity services sets an upper bound for what businesses should (in theory) be willing to pay to get access to these services (provided they internalise all of the private benefits in their willingness-to-pay assessment).

In those areas where the private benefit to businesses (and therefore the maximum willingness to pay) reflects an amount that at least meets the revenue requirement, the investment should (in theory) be commercially viable and proceed without the need for government intervention.

In areas where the private benefits to business are not sufficient (or not fully internalised in the willingness-to-pay decision) such that the willingness to pay falls below the revenue requirement, the investment will not be commercially viable. Whether there is a broader economic case for investment in that area will depend on the wider economic benefits that could be achieved as a result of roll-out in that area. While the specific impacts in each area would need to be assessed on a case-by-case basis to ensure a robust assessment process, in order to provide indicative results, our modelling has assessed the potential scale of the wider economic benefits for the area with reference to the overall GVA uplift that would be enabled by the availability and take-up of such services.[186] Consistent with the modelling approach described in Section 5, the analysis is focused on those businesses (and therefore the associated benefits) that would be served by the hypothetical MNO with 25% market share.

In cases where the wider economic benefits in a specific area served by the hypothetical MNO with 25% market share, (proxied by the GVA uplift) exceed the incremental revenue requirements to make the investment commercially viable, but the maximum willingness to pay is insufficient to meet the incremental revenue requirements, this would signal the existence of a market failure indicating the potential need for government intervention to subsidise roll-out in those areas.

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[186] This builds on the results of previous work for DCMS conducted by Analysys Mason and Cambridge Econometrics, Analysys Mason and Cambridge Econometrics (2021), 'Realising the Benefits of 5G', August 2021.

To assist with in the identification of these areas, we have sought to estimate the upper bound for the willingness to pay as the share of GVA uplift in an area that can be attributed to an increase in business profits. Specifically, GVA is split into compensation of employees (CoE), taxes less subsidies, gross operating surplus (GOS) and mixed income (which includes self-employment income and rental income). Therefore, GOS data can be used to estimate how much profit is generated by companies after considering labour costs and taxes less subsidies.

Based on ONS data, on average across industries throughout the UK, the share of GVA that is GOS is approximately 25%.[187] On the basis that in modelling business take-up in Scenario 2 our model assumes that larger businesses will make up a larger share of those using advanced wireless connectivity services, this implies that the GVA uplift likely to be generated will have a relatively low proportion of self-employment income, and hence, will be explained primarily by increases in GOS and CoE. Based on the fact that around 50% of GVA is reflective of COE, an upper bound estimate of the share of incremental GVA that can be explained by GOS would be 50%.[188]

For the purposes of our indicative analysis below, we assume a mid-point between these two bounds (25% and 50%) of the share of incremental GVA that represents GOS (profits) of 37.5%. We apply this share to our GVA uplift estimates as an indicative estimate of the profit uplift that may be obtained for businesses taking up advanced wireless connectivity services.[189] This is then used as a proxy for the

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[187] Based on ONS data, calculating the share of GOS of corporations (CP, SA) in the total GVA (average) at basic prices (current prices (CP), seasonally adjusted (SA) in 2019. We use 2019 data since this is the most recent year where the industry-level data is available.
See: ONS (2022), ‘Gross Value Added (Average) at basic prices: CP SA £m’, 11 February 2022; available at: https://www.ons.gov.uk/economy/grossvalueaddedgva/timeseries/abml/pn2 [accessed 28 March 2022]; ONS (2021), ‘Income based: Gross operating surplus of corporations : Total: CP SA £m’, 22 December 2021; available at: https://www.ons.gov.uk/economy/grossdomesticproductgdp/timeseries/cgbz/qna [accessed 28 March 2022].

[188] Based on ONS data, the total compensation of employees across the ten industry groups that make up the total GVA accounts for around 54% of the total GVA in 2019. See: ONS (2022), ‘Gross Value Added (Average) at basic prices: CP SA £m’, 11 February 2022; available at: https://www.ons.gov.uk/economy/grossvalueaddedgva/timeseries/abml/pn2 [accessed 28 March 2022]; ONS (2021), ‘The Industrial analysis’, 29 October 2021, Figure 2.3; available at: https://www.ons.gov.uk/economy/grossdomesticproductgdp/compendium/unitedkingdomnationalaccountsthebluebook/2021/theindustrialanalyses [accessed 28 March 2022].

[189] Note that this approach assumes that the same proportion of GOS to GVA will be accrued with regards to the incremental GVA uplift as is currently present in the existing level of GVA. We consider this to be a reasonable assumption.

maximum amount a business taking up advanced wireless connectivity services would be willing to pay for such access.

On this basis, we consider which areas may be commercially viable for the hypothetical modelled MNO with 25% market share under Scenario 2 and whether there are any areas that will be deemed not to be commercially viable, but for which there would be a wider economic case for investment.

The results from the model (see the key outputs reproduced in Figure 7.3 below) show that under Scenario 2 considered at the aggregate urban, suburban or rural level, the estimated GOS uplift exceeds the revenue requirement for urban and suburban areas, but not for the rural area as a whole. However, investment would be desirable from a wider economic benefits perspective in the rural area as a whole given that the potential GVA uplift exceeds the revenue requirement.

Figure 7.3: Scenario 2 (enterprise traffic) [Source: Oxera, 2022]

	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative GOS uplift expected over payback period (GBP million in 2020 terms)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Commercially viable? (GOS vs. revenue required)	Desirable from a wider economic benefits assessment? (GVA vs. revenue required)
Urban	224	483	1 288	Yes	Yes
Suburban	43	110	292	Yes	Yes
Rural	994	374	998	No	Yes

When assessed at a more granular level, under the assumption of GOS accounting for 37.5% of the incremental GVA, our model shows that of the 34 regional geotype areas, all urban and all suburban regional areas (except for North East suburban) are commercially viable but none of the rural, regional areas would be commercially viable under Scenario 2. However, there are a number of these areas where there would be a wider economic case for the investment (i.e. where the expected GVA uplift exceeds the revenue requirement). Specifically, in those areas where we find that the incremental GOS uplift is less than the revenue requirement, but the expected GVA uplift exceeds the revenue requirement, we find evidence of a likely market failure. This refers to a failure of commercial roll-out to reach areas where the wider economic value of the investment exceeds the private cost of roll-out, yet this is not fully internalised in the private investment decision, nor captured in end-user willingness to pay.

In particular, those regions that meet the conditions for a finding of market failure under this scenario include: North East suburban, East Midlands rural, West Midlands rural, East rural, South East rural and South West rural, as shown below. Therefore, if the Scenario 2 target was a key objective for the government, these rural regions are where intervention in the form of subsidies may be justified.

Figure 7.4: Results by region at a rural level (Scenario 2) [Source: Oxera, 2022]

	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative GOS uplift expected over payback period (GBP million in 2020 terms)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Commercially viable? (GOS vs. revenue required)	Desirable from a wider economic benefits assessment? (GVA vs. revenue required)
North East rural	38	9	23	No	No
North West rural	86	27	73	No	No
Yorkshire rural	94	28	74	No	No
East Midlands rural	74	53	141	No	Yes
West Midlands rural	61	28	75	No	Yes
East rural	76	45	120	No	Yes
South East rural	90	66	176	No	Yes
South West rural	101	44	117	No	Yes
Wales rural	107	23	62	No	No
Scotland rural	199	37	97	No	No
Northern Ireland rural	68	14	38	No	No

The total, cumulative revenue requirement over the payback period for serving these 'market failure' areas, through upgrades over the baseline to achieve the Scenario 2 target by the hypothetical modelled MNO with 25% market share is **GBP403 million** in 2020 terms. This represents the maximum subsidy that may need to be provided to our hypothetical MNO offering services to 25% of business in these areas. However, taking into account that businesses may be willing to pay up to the value of the expected GOS uplift and therefore cover some of this cost, any intervention funding would need to cover the estimated residual revenue requirement. In these areas that amounts to **GBP167 million** in 2020 terms, which represents the lower bound subsidy that would need to be provided to our hypothetical MNO.

Given these results are presented for just the hypothetical modelled MNO with 25% market share, to get an indication for the potential funding gap of serving all businesses in the area with four MNOs, these sums would need to multiplied by four (between **GBP668 million** and **GBP1612 million** in 2020 terms). However, the actual level of subsidy needed to ensure all business benefit from these services may be lower than four times these figures since it could be the case that fewer than four MNOs, or potentially even a single MNO, may be able to offer services to all businesses in an area and, thanks to the scale economies achieved, may require a smaller subsidy. Hence, the precise amount of government subsidies required will ultimately depend on the design of the subsidy scheme.

Furthermore, we note that in order for investment to occur in those areas that have been identified as commercially viable, the investment will only take place if the willingness to pay for businesses enables them to fully internalise the value of the expected private benefits (proxied by GOS). If, in practice, willingness to pay is below the GOS uplift, and this means some areas which were identified as commercially viable in the table above are no longer viable, but the evidence suggest the investment would be desirable from a wider economic basis, then such areas would also need to be added to the list of potential market failure areas, adding to the subsidy requirement.

As a further sensitivity to the assessment above, we can see that for Scenario 2, the results are fairly stable across the different assumptions for the GOS share of GVA. However, we do see a small number of areas become commercially unviable (and move into the market failure category) where the more conservative GOS assumption is used.

Figure 7.5: Aggregated results across all regional geotype areas (Scenario 2) [Source: Oxera, 2022]

GOS share of GVA	Commercially viable areas	Areas desirable from a wider economic benefits assessment	Market failure areas
50% of total GVA	23	28	5
37.5% of total GVA	22	28	6
25% of total GVA	20	28	8

7.3 Scenario 3 – Enterprise and consumer traffic

Scenario 3 combines the target requirements of Scenario 1 and 2 (i.e. 50Mbit/s per active user plus enterprise traffic). As explained in Section 5.2.3, the revenue requirement will likely come from a combination of users and enterprises in this scenario. Exactly how the costs will be apportioned will be a decision for the MNO. We can however, consider that at most, if all the cost was apportioned to one user type, considered at the national level, consumers would need to pay a maximum additional ARPU of GBP0.91 per month, or businesses would have to pay GBP12 839 per month, which, over the payback period, would correspond to 77% of the cumulative GVA uplift over the same period. However, considering the commercial viability of Scenario 3 against only the potential willingness to pay of business or users alone is unlikely to provide meaningful results.

One way of assessing this would be to consider, for those areas which are deemed commercially viable in Scenario 1, and therefore where investment to cover 50Mbit/s is expected, whether there would also be a case for serving enterprise traffic in that area. This requires an assessment of the incremental cost of serving Scenario 3 over Scenario 1, and the associated revenue requirement. We can do this using the findings from our model.[190]

As explained above, under Scenario 1 with at most a 5% increase in APRU, we found that all urban and suburban areas were deemed to be commercially viable, as well as all rural areas other than: North East rural, Yorkshire rural, Wales rural, Scotland rural and Northern Ireland rural.[191]

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[190] If we override the cost profile of the baseline with the cost profile of Scenario 1, then it is possible to calculate the incremental cost profile, and thus incremental revenue associated with the addition of enterprise traffic to Scenario 1.

[191] We also showed that none of the areas that are commercially unviable under Scenario 1 are commercially viable under Scenario 2, so in the absence of any intervention those areas will not see commercial roll-out beyond the baseline.

Focusing on these commercially viable areas under Scenario 1, as well as on our central estimate of GOS accounting for 37.5% of the GVA uplift, we find that in 11 out of 29 regions the incremental cost, and the associated incremental revenue requirement to **also** provide enterprise traffic in this area,[192] should be met by the incremental GOS uplift that businesses will experience. This is shown in Figure 7.6.

This means that the investment is unlikely to be commercially viable in 18 regional geotype areas, that were commercially viable under Scenario 1.[193] [194]

The model results show that 17 of the 18 non-commercially viable areas could experience wider economic value that exceeds the revenue requirement, and thus they represent areas where there could be a market failure justifying government intervention.[195]

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[192] The incremental cost and incremental revenue requirement to go from Scenario 1 to Scenario 3.

[193] North East urban, North East suburban, North West urban, North West suburban, North West rural, Yorkshire urban, Yorkshire suburban, East Midlands urban, East Midlands rural, West Midlands urban, West Midlands rural, East urban, East suburban, East rural, South East rural, South West urban, South West rural, Scotland suburban.

[194] Note that this also includes 11 areas that were commercially viable under Scenario 2, but not under this scenario (North East urban, North West urban, North West suburban, Yorkshire urban, Yorkshire suburban, East Midlands urban, West Midlands urban, East urban, East suburban, South West urban, Scotland suburban are no longer commercially viable). As explained in Section 5, in some areas Scenario 3 costs more than the combined cost of Scenarios 1 and 2. This is because some sites will already have all available spectrum bands deployed and in order to meet the combined demand, new sites need to be built. Building new sites is more expensive than the initial capacity increase accrued through adding spectrum bands.

[195] North West rural is the only area where it is not commercially viable, nor desirable from a wider economic benefits point of view, to meet Scenario 3 targets.

Figure 7.6: Results by region by geotype for the incremental investment to meet enterprise demand in addition to consumer demand in Scenario 1 [Source: Oxera, 2022]

	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative GOS uplift expected over payback period (GBP million in 2020 terms)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Commercially viable? (GOS vs. revenue required)	Desirable from a wider economic benefits assessment? (GVA vs. revenue required)
North East urban	14.5	13.5	36.1	No	Yes
North East suburban	6.3	3.7	10.0	No	Yes
North West urban	60.0	52.0	138.6	No	Yes
North West suburban	20.8	14.7	39.3	No	Yes
North West rural	106.7	27.4	73.1	No	No
Yorkshire and the Humber urban	34.9	24.9	66.4	No	Yes
Yorkshire and the Humber suburban	14.8	11.2	29.8	No	Yes
East Midlands urban	26.9	25.4	67.7	No	Yes
East Midlands suburban	7.8	9.8	26.1	Yes	Yes
East Midlands rural	87.5	53.2	142.0	No	Yes
West Midlands urban	39.0	35.7	95.1	No	Yes

	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative GOS uplift expected over payback period (GBP million in 2020 terms)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Commercially viable? (GOS vs. revenue required)	Desirable from a wider economic benefits assessment? (GVA vs. revenue required)
West Midlands suburban	8.2	9.8	26.2	Yes	Yes
West Midlands rural	72.7	28.1	75.0	No	Yes
East urban	27.4	27.1	72.2	No	Yes
East suburban	12.9	10.4	27.7	No	Yes
East rural	94.5	44.8	119.6	No	Yes
London urban	159.9	233.6	622.9	Yes	Yes
South East urban	55.5	65.0	173.4	Yes	Yes
South East suburban	23.7	26.0	69.3	Yes	Yes
South East rural	158.5	66.1	176.2	No	Yes
South West urban	25.8	24.9	66.4	No	Yes
South West suburban	6.6	8.2	21.8	Yes	Yes
South West rural	87.5	44.1	117.5	No	Yes
Wales urban	3.8	6.4	17.1	Yes	Yes
Wales suburban	4.6	5.7	15.2	Yes	Yes
Scotland urban	21.5	23.9	63.6	Yes	Yes
Scotland suburban	10.2	9.5	25.2	No	Yes

	Cumulative revenue required over payback period (GBP million in 2020 terms)	Cumulative GOS uplift expected over payback period (GBP million in 2020 terms)	Cumulative GVA uplift expected over payback period (GBP million in 2020 terms)	Commercially viable? (GOS vs. revenue required)	Desirable from a wider economic benefits assessment? (GVA vs. revenue required)
Northern Ireland urban	6.5	6.7	18.0	Yes	Yes
Northern Ireland suburban	0.0	0.6	1.6	Yes	Yes

For those areas we have identified as potentially indicating a market failure, the total, cumulative revenue requirement over the payback period for upgrading the network from Scenario 1 to Scenario 3, by the hypothetical modelled MNO with 25% market share, is **GBP795 million** in 2020 terms. This represents the maximum subsidy that may need to be provided to our hypothetical MNO offering services to 25% of business in these areas. However, taking into account that businesses may be willing to pay up to the value of the expected GOS uplift and therefore cover some of this cost, any intervention funding would need to cover (at a minimum) the estimated residual revenue requirement. In these areas that amounts to **GBP305 million** in 2020 terms**,** which represents the lower bound subsidy that would need to be provided to our hypothetical MNO.

Given these results are presented for just the hypothetical modelled MNO with 25% market share, to get an indication for the potential funding gap of serving all businesses in the area with four MNOs, these sums would need to multiplied by four (between **GBP1221 million** and **GBP3178 million** in 2020 terms). However, the actual level of subsidy needed to ensure all business benefit from these services may be lower than four times these figures since it could be the case that fewer than four MNOs, or potentially even a single MNO, may be able to offer services to all businesses in an area and, thanks to the scale economies achieved, may require a smaller subsidy. Hence, the precise amount of government subsidies required will ultimately depend on the design of the subsidy scheme.

However, we note that these results are particularly sensitive to the assumption on GOS share of GVA that is used. As for Scenario 2, we consider two sensitivities for the GOS share of GVA (25% and 50%) in addition to the central estimate of 37.5%. Figure 7.7 presents the number of areas which are commercially viable under Scenario 1, that are commercially viable with the addition of enterprise traffic, those areas which are desirable from a wider economic benefits assessment and those areas where there may be a market failure.

We can see that the results are very sensitive across the different assumptions for the GOS share of GVA. For example, when using the conservative GOS assumption (25% of total GVA), only two areas are found to be commercially viable compared to 20 areas when using the higher GOS assumption (50%).

This is an important insight as it highlights how sensitive the business case can be with respect to the expected revenue.

Figure 7.7: Summary results across all regional geotype areas (Scenario 3 with Scenario 1 as the baseline) [Source: Oxera, 2022]

GOS share of GVA	Commercially viable areas	Areas desirable from a wider economic benefits assessment	Market failure areas
50% of total GVA	20	28	8
37.5% of total GVA	11	28	17
25% of total GVA	2	28	26

7.4 Identifying whether there is a need for more understanding of the benefits of 5G on the demand side

The preliminary view from the model findings suggests that the ARPU uplift requirements for end users in Scenario 1 (50Mbit/s per active user) **may** be sufficiently small that users would be willing to pay and the revenue requirement could be met in the large majority of areas. However, this cannot be concluded with certainty without clearer data on the willingness to pay for advanced wireless connectivity services in the UK. Some uncertainty may remain among operators as to whether they can be sure users will meet the uplift requirement. This is particularly the case if users lack understanding of the additional benefits that could be enabled by upgrades to the network.

Similarly, our provisional findings on the enterprise scenarios, namely Scenario 2 (enterprise traffic) and Scenario 3 (50Mbit/s per active user plus enterprise traffic) show that the potential GVA benefits from advanced use cases could be sufficiently large that businesses should be willing to cover the required revenue requirement, at least in urban and suburban areas, and in some rural regions. However, we cannot be sure that businesses will fully take into account the private benefits in their willingness to pay.

This uncertainty on both the demand and supply side can create a ‘chicken and egg’ issue in the short term, as described in more detail in the case study that follows below.

The chicken-and-egg issue

A recent study by Cambridge Econometrics and Analysys Mason for DCMS assessed how the benefits of 5G can be realised. The study found that the business case for investment in 5G may be undermined by a chicken-and-egg problem.[196] Specifically, on the supply side, operators and vendors need a clear business case for investing in 5G public mobile networks. They therefore require clear demand from consumers and enterprises, and an understanding of their willingness to pay.[197] From a demand-side perspective, without clear, practical evidence of 5G use cases in practice, potential users of 5G may have a lack of understanding of its potential use cases and benefits and, therefore, willingness to pay.[198] For enterprises, this could be particularly pronounced, given the relatively nascent stage of practical use-case developments. Enterprises may also require bespoke solutions to meet their requirements. This creates a chicken-and-egg scenario, with both the supply side and the demand side needing each other to demonstrate the business case for 5G.

Over time, as 5G deployments progress and more practical examples of use cases develop, we would expect a better understanding of the potential benefits to materialise. As Ofcom notes in its recent Mobile Strategy Discussion paper: “Although there is uncertainty over the value of new uses, this is likely to reduce over time as those uses and customer demand both become clearer, and provide a stronger basis for making commercial investment decisions. MNOs are therefore able to make initial investments in rolling out 5G today and then make commercial decisions on further investments in light of market developments”.[199]

Increasing efforts to inform potential end users about the benefits that can be achieved and the value that can come from use cases supported by advanced wireless services can therefore lead to significant benefits in terms of faster roll-out. Benefits can be realised earlier than in instances where end-user uncertainty remains.

Particularly in the case of enterprise use cases, the promotion of findings from the 5G Testbeds and Trials programme can play a key role in creating awareness and understanding of value. As part of the stakeholder interviews, a stakeholder noted the positive role of the Testbeds and Trials programme in allowing 5G features to

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[196] Analysys Mason and Cambridge Econometrics (2021), ‘Realising the Benefits of 5G’, August 2021, p. [49].

[197] Ibid.

[198] Ibid., p. [49] , pp. [58–59], pp. [59–61].

[199] Ofcom (2022), ‘Ofcom’s future approach to mobile markets – A discussion paper’, 9 February 2022, paragraph 6.18; available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0027/231876/mobile-strategy-discussion.pdf

be seen in real life, which could encourage verticals to increase take-up.[200] Another stakeholder also noted that although the chicken-and-egg investment issue was still a challenge, the Testbeds and Trials programme had been very positive in demonstrating the value of 5G. It also mentioned that there would be risks in removing this support, as it felt the UK was on the cusp of getting use cases to deliver in those sectors.[201]

Any steps that can be taken to show the continued development of valuable use cases and inform potential users of the value of the new technologies should be pursued. Doing so would help to reduce the asymmetry of information between potential buyers and investors and increase the willingness to pay of potential buyers of these services.

7.5 Identifying whether there should be intervention on the supply side

In cases where there is a clear market failure, intervention in the form of public funding (including, for example, as subsidies to support the costs of investment on the supply side) may be justified.

As noted above, our model results suggest there could be instances of market failure[202] in the following cases:

- in Scenario 1, where only a 5% increase in prices to end consumers can be achieved, there could be a market failure in meeting the target in North East rural, Yorkshire rural, Wales rural, Scotland rural and Northern Ireland rural (subject to there being sufficient evidence to show that the wider benefit to achieving 50Mbit/s per user in these areas exceeds the costs of provision)
- in Scenario 1, where only a 10% increase in prices to end consumers can be achieved, there could be a market failure in meeting the target in In Scotland rural subject to there being sufficient evidence to show that the wider benefit to achieving 50Mbit/s per user in this area exceeds the costs of provision)
- In Scenario 2, those areas that meet the conditions for a finding of market failure could include: North East suburban East Midlands rural, West Midlands rural, East rural, South East rural South West rural
- In Scenario 3 (assessed as regards to whether the additional investment to serve enterprise demand over and above 50Mbit/s per user in those areas

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[200] Based on a stakeholder interview conducted for this study.

[201] Based on a stakeholder interview conducted for this study.

[202] In this context a market failure refers to a failure of commercial roll-out to reach areas where the wider economic value of the investment exceeds the private cost of roll-out. This wider benefit may not be fully internalised in the private investment decision, nor captured in end-user willingness to pay. The level of network infrastructure investment that would maximise wider economic value is therefore not met.

deemed to be commercially viable in Scenario 1) we find that of 18 non-commercially viable regional geotype areas,[203] the model results show that 17 of them could experience wider economic value that exceeds the revenue requirement, and thus they represent areas where there could be a market failure.[204]

The model results presented above also identified areas under the jump from Scenario 1 to Scenario 3 where the GOS uplift exceeds the incremental revenue requirement, such that the investment should be commercially viable if businesses internalise that private value in their willingness to pay. If, in practice, willingness to pay is below this level, but the evidence suggest the investment would be desirable from a wider economic basis, if we do not observe MNOs rolling out in such areas, this could also be a sign of a market failure in those areas.

These results are all indicative and it will be important for DCMS to continuously monitor progress on both the supply side (in terms of where the networks are being deployed and what is driving this investment) and the demand side (in terms of the practical use cases being taken up, the technical solutions being used and willingness to pay). This will allow DCMS to better understand and build evidence on the drivers and benefits of network roll-out. This in turn could help to identify areas that may be experiencing lower network coverage and/or quality due to market failures. The tools provided in the model will allow DCMS to undertake such an assessment.

We note, that it is important at this early stage in the roll-out of advanced wireless networks to allow time for commercial models to emerge and to build the evidence base to appropriately identify areas where market failures are present. This would be consistent with the UK government’s policy approach to the roll-out of previous mobile and fixed broadband technologies. In recent years, when the UK government has intervened in telecoms markets, providing public funding for investments in new telecoms infrastructure, this has been on the basis of clear evidence on the presence or expectation of identified market failures. For example, the UK government has subsidised network roll-out to increase coverage in rural areas in the case of mobile networks (e.g. the SRN; see the first case study below) and coverage for fixed broadband networks (e.g. the Superfast Broadband Programme; see the second case study below).

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[203] North East urban, North East suburban, North West urban, North West suburban, North West rural, Yorkshire Urban, Yorkshire suburban, East Midlands urban, East Midlands rural, West Midlands, urban, West Midlands rural, East urban, East suburban, East rural, South East rural, South West urban, South West rural, Scotland suburban.

[204] North West rural is the only area where it is not commercially viable, nor desirable from a wider economic benefits point of view, to meet Scenario 3 targets.

The SRN – timing and justification

The SRN agreement between the UK government and the four UK MNOs seeks to extend and improve 4G mobile coverage in partial not-spots (where there is not coverage from all four MNOs) and total not-spots (where there is no mobile coverage at all). As part of the SRN, the UK government will provide GBP500 million in funding, which will pay for mobile infrastructure to be built and used by the four MNOs to provide coverage in the total not-spot areas.[205] The agreement will help the UK achieve 84% 4G geographical coverage from all four MNOs and 95% geographical coverage from at least one MNO.[206]

As explained below, the SRN was introduced at a relatively late stage of 4G roll-out in the UK, and was clearly targeted at addressing a specific market failure, namely poor network quality and coverage in rural areas.

Timing

The SRN agreement formally began in March 2020 and the grant funding period started in March 2021.[207] This intervention came at a relatively late stage of the MNOs' 4G roll-out and there were reasonably high levels of coverage across the UK.

For example:

- EE commercially launched its 4G network in 2012, followed by Vodafone and O2 in 2013, and Three in 2014[208]
- at the time the SRN formally started, around 91% of the UK was covered by at least one MNO and 67% of the UK was covered by all four MNOs.[209]

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[205] DCMS (2021), 'Shared Rural Network (SRN) – transparency commitment publication', paragraph 2.

[206] Shared Rural Network, 'Programme Summary'; available at: https://web-cdn.srn.org.uk/blue/uploads/2021/06/Programme-Summary.pdf [accessed 10 February 2022].

[207] Shared Rural Network, 'About the Shared Rural Network – Programme timeline'; available at: https://srn.org.uk/about/ [accessed 10 February 2022].

[208] Ofcom (2014), 'Media releases: Ofcom publishes 4G and 3G mobile broadband speeds research', 13 November 2014, footnote 6; available at: https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2014/3g-4g-bb-speeds [accessed 10 February 2022].

[209] Ofcom (2021), 'Connected Nations 2021: Interactive Report: Mobile coverage (geographic, 4G)'; available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2021/interactive-report [accessed 10 February 2022].

Justification

The UK government considered there was a strong case for intervention in the total not-spots to “remedy market failures and the socio-economic consequences of poor coverage to businesses and consumers”.[210]

First, the government noted that 35 years of commercial investment had left some rural areas unconnected due to their challenging economics of deployment, including high infrastructure costs (due to the geographical challenges) and lower benefits (due to low population density).[211] It also highlighted that spectrum auctions had not found an effective way of delivering widespread coverage.[212] Overall the evidence suggested that, absent intervention, there was no expectation that the lack of investment would be remedied in the future.[213]

Second, there was evidence to suggest that the social benefits of delivering coverage to these areas could be significant. The government highlighted that the programme could capture positive externalities associated with mobile connectivity, including economic impacts and wider social benefits.[214] In addition, Ofcom had provided quantitative and qualitative evidence on the incremental benefits that could be achieved through extending mobile coverage beyond the level deployed commercially.[215]

The government undertook a rigorous economic assessment of the SRN against alternative options. The assessment found that the SRN would deliver greater coverage outcomes for a lower level of spend.[216]

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[210] DCMS (2021), ‘Shared Rural Network (SRN) – transparency commitment publication’, paragraph 6.

[211] Ibid.

[212] DCMS (2021), ‘Shared Rural Network (SRN) – transparency commitment publication’, paragraph 6.

[213] Ibid.

[214] DCMS (2021), ‘Shared Rural Network (SRN) – transparency commitment publication’, paragraph 27.

[215] Ofcom (2018), ‘Consultation: Award of the 700 MHz and 3.6–3.8 GHz spectrum bands’, 18 December 2018, section 4.

[216] DCMS (2021), ‘Shared Rural Network (SRN) – transparency commitment publication’, paragraph 16.

The Superfast Broadband Programme – timing and justification

The UK government has also provided funding to subsidise the roll-out of superfast broadband (i.e. broadband offering download speeds of at least 24Mbit/s) in areas that would not otherwise have received commercial investment. The Superfast Broadband Programme was announced in 2010 in response to concerns that the commercial deployment of superfast broadband infrastructure would fail to reach many parts of the UK.

Initially, the government established the programme with GBP530 million in public resources to fund further deployments, with the aim of extending coverage to 90% of UK premises.[217] The programme was extended in 2015 (Phase 2) to reach 95% of UK premises by the end of 2017, with a further GBP250 million in funding.[218] The programme was extended a second time (Phase 3). In this phase, and in line with the government's objective to increase FTTP coverage in the UK, there was a greater focus on providing funding for gigabit-connectivity contracts.[219]

While this came at an earlier stage and was more pre-emptive than the SRN intervention, the market had still been given time to begin roll-out. There was evidence that the market would not deliver to certain parts of the UK, thus failing to capture economic benefits.

Timing

As mentioned above, the Superfast Broadband Programme was first announced in 2010. The programme was expanded to Phase 2 in 2015, and to Phase 3 in 2016. At the time of the programme's announcement, next-generation access (NGA) products had already been commercially available in the UK market and coverage may have reached a reasonably high level:

- in 2007, Virgin Media announced plans to offer a new broadband service capable of delivering 50Mbit/s download speeds, and in 2008, BT announced plans to invest in an NGA network which would deliver download speeds of 40Mbit/s[220]
- in 2010, around 50% of households in the UK had access to a 50Mbit/s connection.[221]

At the time of the Phase 2 extension, around 85% of premises were covered by superfast broadband (which offered speeds of 24Mbit/s).[222] At the time of the Phase 3 extension, around 89% of premises were covered by superfast broadband (which offered speeds of 30Mbit/s).[223] However, only 0.8% of the UK had gigabit coverage at the time.[224]

Justification

In 2009, Ofcom published details on its regulatory strategy for promoting investment and competition to support the delivery of superfast broadband in the UK. Ofcom's view was that there were signs the private sector was investing in superfast broadband, whereas the majority of stakeholders were of the opinion that private-sector investments alone would not deliver to the whole of the UK.[225]

The programme was launched in response to concerns that commercial superfast broadband deployment would fail to reach many parts of the UK, due to the challenging economics (of high costs relative to expected revenue) in certain geographies.[226] The government believed there was a risk of a digital divide, i.e. unequal access to broadband service quality based purely on geography, absent intervention.[227]

The government took steps to ensure the intervention would be targeted at areas that would be unlikely to receive superfast broadband commercially. For example, it used an Open Market Review to establish providers' commercial roll-out plans. It identified areas that would not otherwise receive coverage and would, therefore, be eligible for subsidies.[228]

The government believed there was strong evidence of the benefits that the delivery of superfast broadband could have in these areas. The benefits included productivity growth, employment, public-sector efficiency, reduction of the digital divide,

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[217] DCMS (2021), 'Superfast Broadband Programme – State aid Evaluation Report 2020', January 2021, p. 16.

[218] Ibid.

[219] Ibid.

[220] Caio, F. (2008), 'The Next Phase of Broadband UK: Action now for long term competitiveness'; 'Review of Barriers to Investment in Next Generation Access; Final Report', September 2008, pp. 36–37.

[221] Department for Business, Innovation & Skills and DCMS (2010), 'Britain's Superfast Broadband Future', December 2010, paragraph 9.

[222] Ofcom (2015), 'Connected Nations 2015: Concise summary', 1 December 2015, p. 9.

[223] Ofcom (2016), 'Connected Nations 2016: Full Document', 16 December 2016, Figure 3.

[224] Ibid., Figure 6.

[225] Ofcom (2009), 'Delivering super-fast broadband in the UK: Promoting investment and competition', 3 March 2009, paragraphs 1.9, 1.11.

[226] DCMS (2018), 'Evaluation of the Economic Impact and Public Value of the Superfast Broadband Programme: Final report', August 2018, p. 18.

[227] Department for Business, Innovation & Skills and DCMS (2010), 'Britain's Superfast Broadband Future', December 2010, paragraph 15.

[228] DCMS (2018), 'Evaluation of the Economic Impact and Public Value of the Superfast Broadband Programme: Final report', August 2018, pp. 18–19.

development of public value, environmental benefits and stimulation of the broadband market.[229]

7.6 Alternative forms of intervention

Intervention to correct market failures may benefit from further evidence over time in order to ensure that funds are properly targeted. This does not mean, however, that there is no scope for further policy changes or interventions to be considered at this stage.

In the nascent stages of any network investment, a policy intervention priority should be to provide the best investment environment to ensure that private investment has the optimal possible impact. Barriers to investment should be removed – where justified on the basis of a cost–benefit analysis – to give private investment the best chance of success.

As discussed briefly in Section 6, a number of key barriers were raised by stakeholders that could be holding back investments from the private sector and would merit further consideration to assess the extent to which these barriers can be addressed and the impact this may have on the overall investment case.

In Section 8 below, we discuss the key barriers raised by industry in more detail. We critically assess the validity of the claims made, consider the mechanism through which the barrier may be affecting investments, and assess ways in which the barriers could be reduced or eliminated.

- Specifically, we consider the following issues: The regulatory and policy environment, particularly with regard to:
  - policies adding to operator costs, such as the impact of the high-risk vendor ban and the recurring ALF cost
  - market structure and the potential for consolidation and/or network sharing to unlock the scale of investment required
  - lack of clarity on the net-neutrality rules and the ability to commercialise investment, particularly for network slices on 5G-SA deployments.
- Barriers faced by alternative operators, particularly with regard to:
  - inability to obtain MNCs
  - the challenges related to setting up roaming agreements with MNOs

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[229] Ibid., Table 2.1.

  - the process of obtaining access to shared access and local access spectrum, and using this spectrum.

- Practical deployment barriers.

8 Assessment of key barriers and associated policy intervention options

In this section, we consider the following barriers in more detail:

- Regulatory and policy interventions that add to the cost of investment, with a particular focus on the claims that the requirement for MNOs to pay significant amounts in spectrum ALFs means they have less cash available for investments that would advance their infrastructure roll-out (see Section 8.1).

- Issues related to market structure and whether further network sharing and/or consolidation in the industry could lead to greater investments in advanced wireless connectivity (see Section 8.2).

- Possible impact of net-neutrality rules (see Section 8.3).

- Barriers faced by alternative operators; these operators may compete with MNOs to provide private networks, and may also establish multi-operator neutral host networks in not-spot areas, which could result in greater coverage of advanced wireless connectivity services (see Section 8.4).

- Practical deployment barriers (see Section 8.5).

Below, we consider each of the main issues in turn, and assess the need for policy interventions to address barriers. In doing so, we consider the following key points:

- we first discuss the nature of the barrier in question and the mechanism through which it may be holding back investment
- where possible, we provide an indication of the scale of the issue with regard to the cost savings and/or the additional revenue that could be made available for investment should the issue be addressed, and/or the types of innovations that may be stifled if the barrier persists
- where there is a clear case for a policy intervention, we consider a number of options that could be pursued and discuss the relative merits of each approach.

8.1 Regulatory and policy interventions adding to the costs of investment: annual licence fees (ALFs)

One of the key issues raised by stakeholders (MNOs) is that certain regulatory and policy interventions have increased the costs faced by the operators.

Specifically, the main issues stakeholders raised throughout the interviews relates to:

- The targets for vendor diversification and requirement to remove high-risk vendor equipment has imposed significant costs on their business, incurring significant time and resources. Whilst it cannot be disputed that operators will be facing additional costs when adjusting their network to remove high-risk vendor equipment, this is a direct implication of the Telecommunications (Security) Act 2021 and followed a cross-government review of UK telecoms supply chains led by the Department for Digital, Culture, Media and Sport from November 2018 and reporting in July 2019.[230]

- ALFs, as a recurring cost incurred by operators that hold spectrum,[231] take free cashflow out of the market, which has a direct impact on the level of investment given that such funds could be used to fund 5G deployments.[232]

The Act brings about a new regulatory framework for telecoms security. It aims to ensure that public telecoms providers operate secure and resilient networks and services and manage their supply chains appropriately, and brings in national security powers in relation to high-risk vendors. In bringing into force the Act, the UK government judged that the benefits[233] brought about by security and interoperability

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[230] DCMS, 'UK Telecoms Supply Chain Review Report, July 2019'; available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/819469/CCS001_CCS0719559014-001_Telecoms_Security_and_Resilience_Accessible.pdf

[231] Spectrum licences are awarded through auctions. These processes determine the lump-sum price paid by the winning bidder for access to the specific block(s) of spectrum that the bidder acquires from the spectrum award. As defined in Ofcom's approach to recent auctions, each spectrum licence has either a defined or an indefinite duration. If the licence has an indefinite duration, there is an initial term period (e.g. 20 years) for which the lump-sum price applies. After the expiration of the initial term period, ALFs come into force. The level of the ALFs is generally set by Ofcom at 'market value' at the time at which the ALFs are being applied. The ALF levels are then periodically reviewed at Ofcom's discretion. The aim of ALFs is to secure the optimal use of spectrum by providing long-term signals of the opportunity cost of spectrum. If the price charged for this limited resource does not reflect its opportunity cost, there could be less incentive to use it efficiently. Ofcom's principle is that if spectrum appears cheaper than its true opportunity cost, businesses will rationally use more spectrum, and invest less in equipment than the efficient balance. The result of this would be that fewer users overall will be able to access spectrum, thus limiting social benefits. According to Ofcom, ALFs should hence apply to spectrum for which there might be excess demand from existing and/or alternative feasible uses. Ofcom (2010), 'SRSP: The revised Framework for Spectrum Pricing: Our policy and practice of setting AIP Spectrum fees', 17 December 2010, p. 3.

[232] Stakeholder interview for this study.

[233] Benefits include reducing threats to national security, reducing dependence on high-risk vendors in the UK 5G and FTTP networks, reducing the risk of needing to remove high-risk vendor equipment from the network entirely in future, and unlocking 5G use cases that would not have otherwise been unlocked as they are reliant on highly secure and resilient networks.

enabled by these powers exceed the potential costs.[234] Therefore the scope for making significant changes to the decision to impose a ban on high-risk vendor equipment is limited and, as such, it will not be considered further in this report.

While the high-risk vendor ban has recently been subject to detailed consideration by the government, the scope for changes to the need for and level of ALFs is subject to continued review by Ofcom as part of its spectrum management functions. We consider the specific issue of the impact of ALFs on investment below.

8.1.1 Mechanism through which the barrier affects investment

Operators have claimed that high ALFs can directly affect network investment, by taking free cashflow out of the system and thereby crowding out investments.[235] The implicit claim is that lower ALFs would free up cashflow to support greater investment, leading to enhanced network coverage and capacity in the UK.

This issue has been framed as an issue of ALFs affecting cashflow and the funds available for investment, rather than as an ongoing operating expenditure that impacts on the expected profitability of any further investment. Thus, for reasons we explain below, any policy that simply provides more cash to operators as a result of lower ALFs is unlikely to affect the economics of the investment case in the same way as additional revenues from consumers would. While raising consumer revenues increases the expected return on new investments (and thus might make a difference to the commercial viability of deployment in a given area) extra cash from a reduction in ALF payments will not affect how profitable additional deployment could be and thus will not (directly) affect the investment decision.

Regarding whether a reduction in ALFs could result in further network roll-out by increasing the funds available for such investments, standard corporate finance and economic theory states that if the expected IRR on an investment exceeds the (project-specific) cost of capital, then it should be possible to fund that project, irrespective of the cashflow position or capex envelope under which a firm may be currently operating. This is because even a cash-constrained firm should be able to access the capital markets to raise funds via debt or equity in order to finance a profitable project, Thus, in theory, operators should not be exclusively reliant on existing free cashflows to support commercially viable investments.

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[234] For example, as noted in the Telecommunication Security Bill 2020: National Security powers in relation to high risk vendors, Impact Assessment, May 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938036/The_Telecommunications_Security_Bill_2020___National_security_powers_in_relation_to_high_risk_vendors_-_FINAL_upload.pdf

[235] Specifically, one stakeholder noted that it operates within a tight capex envelope, and that anything that impacts free cashflow has a direct impact on investment; it further noted that ALFs take free cashflow out of the sector and that this cashflow could be used to fund 5G deployments.

An operator that decides not to pursue profitable investment opportunities due to an inability to fund the project from existing cashflows can only be acting in an economically rational way if:

- It currently does not have sufficient internal cashflows to fund the investment, and
- There is a mismatch between the firm's assessment of the project-specific cost of capital and the rate at which it can secure funds externally, such that the IRR of the project is lower than the capital market's view of the project-specific cost of capital. This mismatch can occur when the capital markets judge the project to be more risky than the firm itself.

Despite these theoretical findings, a number of research papers have considered the empirical link between cashflow and the level of investment. According to empirical analyses, investment and cashflow have been shown to be related, although both the strength of the relationship and its cause are the subject of much debate.

A sample of related literature spanning over two decades[236] indicates a progressive decline in investment–cashflow sensitivities. In the late 1980s, this sensitivity was around 0.5 (meaning that a GBP1000 increase in free cashflow resulted in a GBP500 increase in investment). By the 2010s, it was close to zero.

Much of the recent literature confirms the theoretical claim that a change in cashflow has, at most, a small impact on investment. For example: Hennessy, Levy and Whited (2007),[237] Almeida, Campello and Galvao (2010)[238] and Erickson and

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[236] Source: Fazzari, S., Hubbard, R. G. and Petersen, B., 'Financing Constraints and Corporate Investment', Brookings Papers on Economic Activity, 1 (1988), pp. 141–195. Kaplan, S. and Zingales, L., 'Do Investment-Cash Flow Sensitivities Provide Useful Measures of Financing Constraints?', Quarterly Journal of Economics, 112 (1997), pp. 169–215. Cleary, S., 'The Relationship between Firm Investment and Financial Status', Journal of Finance, 54 (1999), pp. 673–692. Baker, M., Stein, J. and Wurgler, J., 'When Does the Market Matter? Stock Prices and the Investment of Equity-Dependent Firms', Quarterly Journal of Economics, 118 (2003), pp. 969–1005. Rauh, J., 'Investment and Financing Constraints: Evidence from the Funding of Corporate Pension Plans', Journal of Finance, 61 (2006), pp. 33–71. Hennessy, C., Levy, A. and Whited, T., 'Testing Q Theory with Financing Frictions', Journal of Financial Economics, 83 (2007), p. 691–717. Almeida, H., Campello, M. and Galvao, A., 'Measurement Error in Investment Equations', Review of Financial Studies, 23 (2010), pp. 3279–3328. Erickson, T. and Whited, T., 'Treating Measurement Error in Tobin's q', Review of Financial Studies, 25 (2012), pp. 1286–1329. Chen, H. and Chen, S., 'Investment-Cash Flow Sensitivity Cannot Be a Good Measure of Financial Constraints: Evidence from the Time Series', Journal of Financial Economics, 103 (2012), pp. 393–410. Lewellen, J. and Lewellen, K., 'Investment and Cash Flow: New Evidence', Journal of Financial and Quantitative Analysis, 51 (2016), pp. 1135–1164.

[237] Hennessy, Levy and Whited, 'Testing Q Theory with Financing Frictions'.

[238] Almeida, Campello and Galvao, 'Measurement Error in Investment Equations'.

Whited (2012)[239] estimate investment–cashflow sensitivities of just **0.01–0.09**, whereas Chen and Chen (2012)[240] find that investment–cashflow sensitivities have "completely disappeared in recent years" although they are unable to conclude on exactly what is driving this.[241]

However, a more recent paper by Lewellen and Lewellen (2016),[242] based on more recent data and a new estimation methodology,[243] estimated that **USD1** of additional cashflow is associated with a lower bound of **USD0.32** of additional investment for firms that are not financially constrained (i.e. that have sufficient internal funds to cover profitable investment opportunities), and an upper bound of **USD0.63** of additional investment for financially constrained firms. In the context of the overall literature on this subject, the results presented by Lewellen and Lewellen offer a more positive assessment of the likelihood of increased investment following increased cashflow. However, the strength of the relationship between cashflow and investment (and its cause) are the subject of much debate and a clear causal relationship has not been identified.

For this reason, it is not clear that simply removing ALFs would necessarily result in significant increases in investments by MNOs without any further policy or regulatory obligations to do so.

However, to the extent that operators consider that there is a causal link, or if policy interventions could be devised such that ALF payments by the operators could be hypothecated and reinvested into the networks (for example, in areas where a clear market failure emerges), it is important to understand the size of ALF payments relative to the overall scale of the investment and the revenue requirements to make such investments commercially viable.

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[239] Erickson and Whited, 'Treating Measurement Error in Tobin's q'.

[240] Chen and Chen, 'Investment-Cash Flow Sensitivity Cannot Be a Good Measure of Financial Constraints: Evidence from the Time Series'.

[241] The authors conclude that this result cannot be explained by the decreasing importance of cashflow as a source of financing, nor by increasing level of cash reserves. They also note that the decline and disappearance are unlikely to be explained by changes in firm composition, improvement in corporate governance or changes in market power, and note that further work is needed to understand the reason for the decline in recent years.

[242] Lewellen and Lewellen, 'Investment and Cash Flow: New Evidence'.

[243] In particular, the paper extends previous methodology by introducing (a) new measures of cashflow, (b) new instrumental variables, (c) a new sorting of constrained and unconstrained firms, (d) by analysing the relationship of investments to both current and lagged cashflows and (e) by considering all potential forms of cashflow expenditure.

8.1.2 Scale of the issue in the UK

At present, ALFs are being applied in the following spectrum bands:

- 900MHz and 1800MHz licences (2G, 3G, 4G), starting from 31 January 2019[244]
- 40MHz of 3.4GHz spectrum and 80MHz of 3.8GHz (spectrum that is currently licensed to Three (formerly UK Broadband)), starting from 31 July 2019[245]
- 2100MHz licences, starting from 1 January 2022.[246]

Figure 8.1 shows the price per MHz for ALFs in each spectrum band, both in the specific base year price and in 2022 prices.

Figure 8.1: Annual licence fees [Source: Oxera, 2022]

Spectrum band	Base-year price per MHz (GBP million)	2022 price per MHz (GBP million)
900MHz[247]	1.09 (April 2018)	1.21
1800MHz[248]	0.81 (April 2018)	0.89
2100MHz[249]	0.56 (April 2021)	0.61
3.4–3.8GHz[250]	0.44 (April 2018)	0.48

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[244] Ofcom (2018), 'Annual Licence Fees for 900 MHz and 1800 MHz frequency bands', 17 December 2018; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0020/130547/Statement-Annual-licence-fees-900-MHz-and-1800-MHz.pdf (last accessed on 1 March 2022).

[245] Ofcom (2019), 'Annual Licence Fees for UK Broadband's 3.4 GHz and 3.6 GHz spectrum', 7 June 2019; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0013/151231/statement-annual-licence-fees-uk-3.4-ghz-and-3.6-ghz-spectrum.pdf (last accessed on 1 March 2022).

[246] Ofcom (2021), 'Annual licence fees for 2100 MHz spectrum', 13 December 2021; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0027/229428/1900_2100-mhz-statement.pdf (last accessed on 01/03/2022).

[247] Ofcom (2018), 'Annual Licence Fees for 900 MHz and 1800 MHz frequency bands', 17 December 2018; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0020/130547/Statement-Annual-licence-fees-900-MHz-and-1800-MHz.pdf (last accessed on 1 March 2022)

[248] Ofcom (2021), 'Annual licence fees for 2100 MHz spectrum', 13 December 2021; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0027/229428/1900_2100-mhz-statement.pdf (last accessed on 1 March 2022)

[249] Ofcom (2019), 'Annual Licence Fees for UK Broadband's 3.4 GHz and 3.6 GHz spectrum', 7 June 2019; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0013/151231/statement-annual-licence-fees-uk-3.4-ghz-and-3.6-ghz-spectrum.pdf (last accessed on 1 March 2022).

[250] Ofcom (2019), 'Annual Licence Fees for UK Broadband's 3.4 GHz and 3.6 GHz spectrum', 7 June 2019; available at

Each MNO's spectrum holdings are shown in Figure 8.2 below.

Figure 8.2: MNO spectrum holdings [Source: Oxera, 2022]

Spectrum	Vodafone	VMO2	BTEE	Three
900MHz	34.8	34.8	-	-
1800MHz	11.6	11.6	90.0	30.0
2100MHz	29.6	20.0	40.0	29.5
3400–3800MHz	-	-	-	120.0[251]

The estimated total ALFs to be paid by each MNO between 2022 and 2030 are shown in Figure 8.3 overleaf.

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https://www.ofcom.org.uk/__data/assets/pdf_file/0013/151231/statement-annual-licence-fees-uk-3.4-ghz-and-3.6-ghz-spectrum.pdf (last accessed on 1 March 2022).

[251] The 120MHz comprises 40MHz of 3.4GHz spectrum and 80MHz of 3.6GHz spectrum that is licensed to Three, as it has acquired UK Broadband's business.

Figure 8.3: ALFs due to be paid by UK MNOs (GBP million) [Source: Oxera, 2022]

	ALFs								
Operators	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Vodafone	70.39	72.22	73.73	75.21	76.71	78.25	79.81	81.41	83.04
VMO2	64.54	66.22	67.61	68.96	70.34	71.75	73.18	74.65	76.14
BTEE	104.44	107.15	109.40	111.59	113.82	116.10	118.42	120.79	123.20
Three	102.35	105.02	107.22	109.37	111.55	113.78	116.06	118.38	120.75
Total	**341.72**	**350.61**	**357.97**	**365.13**	**372.43**	**379.88**	**387.48**	**395.23**	**403.13**

Each of the main MNOs is currently paying between GBP64.54 million and GBP104.44 million per annum in annual licence fees. This equates to a simple average of GBP85.43 million in 2022, increasing to an average of GBP100.78 million in 2030 (see Figure 8.3).

The ALF amounts can be compared to the total nominal annualised costs of roll-out as estimated by our hypothetical mobile operator model, under the baseline and each of the three scenarios modelled. We compare this against the annualised average ALF per operator across the whole period, which we estimate as GBP93.15 million.[252] The results of this comparison are shown in Figure 8.4 below.

Figure 8.4: ALFs compared to total annualised cost of network deployment (at national level) for the hypothetical modelled MNO [Source: Oxera, 2022]

Scenario	Annualised total costs (2022–30) (GBP million in nominal terms)	Annualised average ALF (2022–30) (GBP million)	ALFs as % of total annualised costs
Baseline	311.89	93.15	30%
50Mbit/s per active user (Scenario 1)	362.81	93.15	26%
Enterprise traffic (Scenario 2)	373.41	93.15	25%
50Mbit/s per active user plus enterprise traffic (Scenario 3)	436.02	93.15	21%

The results above illustrate that if ALFs were put toward the investment in their entirety, that would be sufficient to cover over 20% of the investment costs per annum, even in Scenario 3 (the most expensive scenario).

However, the model already assumes that operators will find it commercially rational to invest in the base case and thus the costs of that roll-out are already accounted for. It is more informative to look at the extent to which the cashflow currently being spent on ALFs could cover the additional cost associated with moving from the baseline to each of the three scenarios.

This exercise is first carried out at national level and the results are presented in Figure 8.5 below.

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[252] This is calculated as the total, cumulative ALF payments across all operators between 2022 and 2030 (GBP3353.56 million) divided across the nine years and then divided by four, given that our model focuses on a single hypothetical MNO.

Figure 8.5: ALFs compared to total annualised additional costs of deployment (at national level) for the hypothetical modelled MNO [Source: Oxera, 2022]

Scenario	Annualised additional costs (2022–30) Total (capex + opex) (GBP million in nominal terms)	Annualised average ALF (2022–30) (GBP million)	ALFs as % of additional annualised costs	Gap closed
50Mbit/s per active user (Scenario 1)	50.93	93.14	183%	Yes
Enterprise traffic (Scenario 2)	61.52	93.14	152%	Yes
50Mbit/s per active user plus enterprise traffic (Scenario 3)	124.13	93.14	75%	No

As shown in Figure 8.5 above, the average annual ALF that each MNO paid in 2022 would be sufficient to cover the additional costs required per network (based on the assumptions we have made on network roll-out) to satisfy the additional costs of investment in Scenario 1 or Scenario 2 for the hypothetical modelled operator with 25% market share. However, ALFs would not entirely cover the additional costs of investment of the network modelled in Scenario 3. Even the highest ALF payment by a single operator, EE, at GBP113.9 million per annum annualised over 2022 to 2030, is below the required investment.

It should be noted that the annualised nominal additional costs shown above cover network deployment in the period from 2020 to 2030. There would be additional costs to operators beyond 2030 (e.g. to continue to operate the additional infrastructure the model predicts will be deployed up to 2030, and to cover network equipment refresh), which are not included in the table above. Thus the conclusion on the gap being closed applies only to the additional costs forecast in the period up to 2030.

A similar exercise can be conducted at a more granular level under each scenario. Such an exercise could for example assess whether the highest net economic and social benefit would come from all funds from ALFs being targeted directly at investments in exclusively urban, exclusively suburban or exclusively rural areas.

The rural areas would require the highest level of investment to reach the targets. Such an exercise indicates that the average ALFs would be more than capable of covering the additional annualised costs associated with upgrading from the baseline to the target quality of service in each scenario in all cases.

However, as illustrated by the literature review in Section 8.1.1, the weak and uncertain link between cashflows and investments implies that simply removing or reducing ALF payments without any requirement to invest in the cellular network may not be a fully successful policy. By way of illustration, assuming an investment–cashflow sensitivity of 0.32 would imply that none of the three target scenarios would be fully achieved at a national level. Nevertheless, even at this level, an additional GBP29.8 million (0.32 * average annualised nominal ALFs in 2022–30) of funds per MNO could be made available for investment.

As we discuss below, it is important that any scheme to use ALF receipts to support funding should be targeted at specific areas where the investment case is most challenging, and more specifically where there are market failures. Therefore, the scale of ALFs could be compared against the costs of serving those areas as being potentially subject to market failures in each of the scenarios considered in Section 7. Specifically:

- In Scenario 1, where only a 5% price increase could be achieved, a potential investment gap could be between approximately GBP20 million–GBP40 million in nominal terms per annum for the modelled MNO with 25% market share.
- In Scenario 2, the cost of covering the market failure areas could be between approximately GBP14 million–GBP34 million in 2020 terms per annum for the modelled MNO with 25% market share.[253]
- When considering the incremental cost of upgrading the network from Scenario 1 to Scenario 3, the cost of covering the market failure areas could be between approximately GBP25 million–GBP66 million in 2020 terms per annum for the modelled MNO with 25% market share.[254]

8.1.3 Conclusions/recommendations

The above analysis indicates that if a policy intervention could be designed to reinvest ALFs into advanced wireless connectivity services, this could have a significant impact on helping to close the gap between the baseline model and the different target scenarios assessed in Section 5 and Section 7.

However, given that the link between cashflow and investment is not clear, the manner in which the ALFs are redistributed could have a significant impact on the

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[253] With commercial viability assessed against the central scenario of GOS representing a 37.5% share of GVA.

[254] With commercial viability assessed against the central scenario of GOS representing a 37.5% share of GVA.

level of investment that may result. There are a number of different approaches that could be used to link ALFs to the investment case, each with a number of important issues that ought to be considered carefully.

Simply reducing the level of ALFs, without requiring any commitments that the released funds be used to support the investment in advanced wireless connectivity, does not guarantee that operators will spend all (or any significant amount) of the fees on investments. Primarily, this is because a reduction in ALFs is unlikely to have a direct impact on the economics of the incremental investment (i.e. the investment to get from the baseline to the target) such that any investment that was not deemed commercially viable beforehand (i.e. because the expected IRR did not exceed the cost of capital) is unlikely to become commercially attractive due to a reduction in the level of ALFs.[255]

Furthermore, it is important to consider that a removal or reduction in the level of ALFs could also undermine the logic behind their imposition and thus be contrary to Ofcom's spectrum management practices. Ofcom has stated that it will review the arguments against ALFs as part of its ongoing strategic review of mobile markets, but in considering any proposal to lower the cost of ALFs below market value, or remove them entirely, it will need to consider the impact:

- of providing an implicit subsidy to operators holding this spectrum, as licence holders will not face the opportunity cost of such spectrum
- on incentives to hoard spectrum
- of using more spectrum than would be efficient (at market value) and thus reducing availability of an already scarce resource.

Hence, assuming Ofcom continues to find a role for ALFs to secure the optimal use of spectrum, an alternative option would be to use a hypothecation approach, whereby the revenue from ALFs is then re-distributed back into the system in the form of a subsidy. That subsidy process would need to be justified, as with any other subsidy regime, having regard to the identification of areas exhibiting a market failure, as discussed in Section 7.

Where a subsidy scheme funded through ALF funds is considered appropriate, the details of how those funds will be distributed back into the market would need to be carefully considered to avoid competitive distortions. For example, there should be no direct link between the specific amount paid by an MNO in ALFs and the amount of the subsidy it receives. A direct link would provide a competitive advantage to those operators who currently hold more spectrum in the bands for which ALFs are charged.

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[255] We implicitly assume that the investment needed to achieve the baseline model roll-out is commercially rational with the current level of ALFs.

This will not be based on a clear demonstration of their business case and why they are best placed to receive the subsidy to correct the market failure identified.

One potential transparent approach would be to run a subsidy scheme where there is an amount of money available (funded by ALFs) that operators can bid for to support their investment. In this case, the subsidy programme would need to define very clearly what the subsidy is for (e.g. what the intervention area is, and what the target quality of service is that must be achieved by the subsidised investment). Under this model, the subsidy price would be set by the operators through their bids to meet that specific target in the intervention area. This has the advantage of investment not being choked off because the price of the subsidy is set too low.

A further alternative may be to offer ALF rebates, contingent on meeting certain investment requirements and quality-of-service targets in the intervention area. The overall rebate to any one operator may have to be set at the lowest of the ALFs paid by the operators, to avoid a situation where the size of the rebate offered to an operator is greater than the amount it pays in ALFs. Under this approach, the price of the subsidy would have to be set by government and be transparently calculated and applied. However, under this approach, given that the ALF rebate would come after the investment is complete, MNOs may be less inclined to undertake the investment given that they will have to raise the funds for the investment ex-ante and may perceive a risk to not receiving the rebate ex-post.

Any approach to be taken forward would require detailed proposals to be developed through industry consultation.

8.2 Market structure: consolidation and network sharing

MNOs are faced with requirements to continue to invest in new technologies and upgrade and expand their networks in order to remain competitive and attract customers or meet government targets. MNOs are experiencing increased capex and opex requirements in an environment where retail revenue per user has declined before stabilising at a lower level in recent years.[256] In this context, operators may seek to pursue consolidation or network sharing as a means of reducing the costs of investment.

Following the posting of its full-year results in March 2022, Three’s CEO has publicly stated that its returns remain unsustainably below its level of investment, and that “the mobile market structure was limiting returns and stifling network

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[256] As indicated in Section 5, where it is noted that UK mobile ARPUs have been declining and stabilising in recent years.

investment”.[257] These comments are reflective of those made in the stakeholder interview process, in which an operator argued there was a link between the market structure of the mobile network, the level of investment and the resulting quality of the networks.[258] It believed that the current market structure in the UK was the primary factor hampering investment in mobile infrastructure, in particular due to investment being spread among “too many” operators in the market.[259] Separately, Vodafone has noted publicly that “consolidation, while retaining infrastructure competition, will be needed to unlock the scale [of investment] required to support Europe’s 5G acceleration and provide more value for consumers”.[260]

In its recent discussion paper, Ofcom considered drivers of investment and found that at an industry level, financial performance of the industry is supportive of investment on an economic basis given, “the average industry return on capital employed (ROCE) has been above the cost of capital”.[261] However, it accepted that: “there is variation between operators’ ROCE, and our analysis suggests that not all MNOs have covered their cost of capital on a continuous basis”, with Three being one of these operators.[262]

Furthermore, Ofcom also acknowledges the importance of economies of scale in mobile markets, which is the result of high fixed costs and subsequent benefits from wide-area deployment.[263] “Economies of scale in the mobile sector mean that MNOs need to serve a sufficiently large market share to achieve a minimum viable scale (MVS) – the minimum level of scale required for each MNO to be viable at the prevailing price level”. It also recognises that future market developments, such as the entry of new players across an increasingly fragmented value chain, could affect the importance of scale for MNOs, though it noted at present that it is difficult to determine whether these factors will make scale more or less important.[264] Changes in the importance of scale is relevant since, for example, MNOs with lower market share are less able to serve a sufficiently large market share to achieve

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[257] The Times, ‘The UK has too many mobile phone operators’, 18 March 2002; available at https://www.thetimes.co.uk/article/uk-has-too-many-mobile-phone-operators-gq97rh5fq

[258] Based on a stakeholder interview for this study.

[259] Based on a stakeholder interview for this study.

[260] Financial Times, ‘Europe’s digital targets are bold, but delivery falls short’, 13 December 2021; available at: https://www.ft.com/content/1787a81d-69de-468b-81cd-3849bb5ac9a9

[261] Ofcom (2022), ‘Ofcom’s future approach to mobile markets: A discussion paper’, 9 February 2022, paragraph 1.22.

[262] Ibid.

[263] Ofcom (2022), ‘Ofcom’s future approach to mobile markets: A discussion paper’, 9 February 2022, box 6.4.

[264] Ibid., paragraph 6.29 and box 6.4.

MVS which could in turn affect the profitability and competitive constraint a given operator can exert.[265]

In this subsection, we consider whether consolidation or network-sharing agreements (NSAs), as a way of helping operators share the costs of investment, could have a meaningful impact on the level of investment in advanced wireless connectivity services in the UK.

We first discuss the mechanisms through which consolidation could affect the level of investment, before considering the potential for NSAs to deliver some of the cost-saving benefits brought about by consolidation, while still preserving some degree of competition in downstream retail markets (depending on the type of sharing). We then go on to provide an indication of the potential scale of the impact on investment in advanced wireless connectivity in the UK of either consolidation or further NSAs.

8.2.1 Mechanism through which consolidation could affect investment

Ultimately, the question of whether the number of MNOs in the market impedes the level and quality of investment in the market is an empirical one, based on the observed impacts from actual mergers or predicted impact from a future merger. However, the direction of causality is not always clear cut. On the one hand, in markets with a larger number of operators, price competition can be more intense and it would be harder for individual MNOs to reach an efficient scale of operations. This can put pressure on profits and, in theory, impede investment if MNOs are facing difficulties in financing future investments. On the other hand, competitive tension between multiple infrastructure operators can be a powerful spur for investment, as MNOs aim to achieve first-mover advantages and win customers from each other.

If the first effect is stronger than the second, consolidation could, in theory, support investment in future wireless networks, if this means firms are able to achieve cost-saving efficiencies and increase profitability, without this undermining the competitive dynamics that would lead them to invest in order to gain an advantage in the market.

The effects of mobile consolidation on prices, investment and network quality has been a rich area of debate in economic literature, particularly following the wave of mobile consolidation in Europe from 2010 onwards. A range of studies has considered the impact of consolidation on these outcomes. These studies have generally relied on examining the impact from an ex-post perspective (i.e.

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[265] Ofcom (2022), ‘Ofcom’s future approach to mobile markets: A discussion paper’, 9 February 2022, box 6.4.

estimating the effects of historical consolidation and changes in concentration). Two main approaches are adopted:

- estimating the average effects of consolidation and increased concentration across Europe through a panel-data approach (cross-country and over time)
- estimating the effects of individual mergers in Europe on a case-by-case basis.

A key factor to be considered when assessing the effects of a merger between two MNOs is the potential for increased prices. Several studies have found that four-to-three mergers lead to higher mobile prices. For example:

- The findings of Genakos et al. (2018)[266] were based on a panel of mobile operators' prices and accounting information across 33 OECD countries between 2002 and 2014, and found that more concentrated markets lead to higher end-user prices. Specifically, they find that a four-to-three merger in a symmetric industry (raising the HHI[267] by 8 percentage points from 0.25 to 0.33), would increase prices by 16.3% based on an average effect based on the sample of all countries post-2005.

- Aguzzoni et al. (2015) use a difference-in-difference (DiD) framework to analyse the effects of mobile mergers in the Netherlands. The study assesses the four-to-three merger of T-Mobile and Orange that was unconditionally approved in 2007, which was preceded by a five-to-four merger between KPN and Telfort in 2005. The study finds price increases due to the merger between T-Mobile and Orange of 10% to 15% relative to the control countries.[268]

- Using a similar methodology, the Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR) (2016) finds a strong price-increase effect linked to the Hutchison and Orange four-to-three merger in Austria in 2013. The study estimates significant price increases in the range of 50–90% for smartphone users (i.e. those consuming a basket of services that include data voice and SMS) and 22–31% for traditional users (not using data) compared to

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[266] Genakos, C., Valletti, T. M. and Verboven, F. (2018), 'Evaluating market consolidation in mobile communications', Economic Policy, 33: 93, January 2018, pp. 45–100.

[267] Herfindahl–Hirschman index.

[268] Aguzzoni, L., Buehler, B., Di Martile, L., Ecker, G., Kemp, R., Schwarz, A. and Stil, R. (2015) for the European Commission: 'Ex-post analysis of two mobile telecom mergers: T-Mobile/tele.ring in Austria and TMobile/Orange in the Netherlands', December 2015; available at https://op.europa.eu/en/publication-detail/-/publication/0ba81733-f193-11e5-8529-01aa75ed71a1

the control group within the two years after the merger, i.e. in the period before the merger commitments (MVNO access).[269]

- Ofcom (2016) focuses on the effect of disruptive MNOs (so-called ‘mavericks’) on prices and presents findings that imply that a four-to-three merger in which a disruptive MNO disappears would result in a price increase of 22% to 27%.[270]

- BEREC (2018) conducts ex-post assessments of three three-to-four mergers in Europe (Hutchinson and Orange in Austria in 2012/2013; Hutchinson and Telefónica in Ireland in 2014; Telefónica and KPN in Germany in 2014).[271] This study also finds evidence that, even with merger remedies in place, the permitted mergers led to price increases (relative to a situation without the mergers) in the short to medium term of between 13% and 52%, depending on the case and the assumed usage profile of the end user.[272]

There are also a number of studies that find some instances of price decreases due to four-to-three mergers, but we note that BEREC highlights that these studies have been funded by operators involved in these mergers and should therefore be interpreted with caution.[273]

Price is not the only relevant factor when assessing consumer outcomes. It is also important to consider how consolidation could potentially affect investment levels and network quality, as these dimensions are important for competition and, ultimately, consumer welfare. The evidence on these effects is generally contradictory, potentially because the link between consolidation and investment and network quality is more complex.

In terms of the effect of consolidation on investment, there is some evidence which suggests that increased concentration in markets leads to higher investment. Notably, Genakos et al. (2018) find that more concentrated markets lead to higher investment per operator, however, this does not necessarily translate into an

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[269] RTR (2015), ‘Ex-post analysis of the merger between H3G Austria and Orange Austria’, March 2015; available at https://www.rtr.at/TKP/aktuelles/publikationen/publikationen/Analysis_merger_H3G_Orange.en.html

[270] Ofcom (2016), ‘A cross-country econometric analysis of the effect of disruptive firms on mobile pricing’ Research Document, 15 March 2016; available at https://www.ofcom.org.uk/__data/assets/pdf_file/0019/74107/research_document.pdf

[271] BEREC (2018), ‘BEREC Report on Post-Merger Market Developments – Price Effects of Mobile Mergers in Austria, Ireland and Germany’

[272] BEREC (2018), ‘BEREC Report on Post-Merger Market Developments – Price Effects of Mobile Mergers in Austria, Ireland and Germany’, 15 June, pp. 3, 16–35.

[273] For an overview of key results from the literature, see: BEREC (2018), ‘BEREC Report on Post-Merger Market Developments – Price Effects of Mobile Mergers in Austria, Ireland and Germany’, 15 June 2018, pp. 7–8 and Table 1.

increase in the total investment in the market. Note that this study focuses exclusively on examining the monetary value of investments and does not examine whether the additional investment per operator resulted in measurable increases in the quality of service of the networks.

Other studies have sought to estimate the impact of consolidation on network quality, with mixed results. For example, a study by mobile industry association GSMA (2017) finds that the Hutchinson and Orange merger in Austria in 2012/2013 enabled Hutchinson to accelerate its 4G population coverage and increase its network quality (measured by download and upload speeds).[274] However, Ofcom recently conducted its own analysis that examined the impact of market structure on investment and quality.[275] Ofcom's analysis estimates the average effects across 30 European countries over an 18-year period and finds that country-level investment is lower in more concentrated markets. It finds that having one less MNO in the market has the long-run effect of reducing country-level investment by an average of 13.2–18.5%, and a 600-points increase in HHI[276] has the long-run effect of reducing country-level investment by an average of 8.4–19.2%.[277] Ofcom also finds that that **network quality** (measured by download speeds) is lower in more concentrated markets. The study finds that one less MNO in the market leads to a reduction in download speeds of 5.1% to 7.4% and a 600-point increase in HHI leads to a reduction in download speeds of 3.0% to 7.8%.[278] Ofcom also conducts ex-post assessments of the same three mergers considered in BEREC (2018) and finds evidence that the mergers led to either no impacts or negative impacts on country-level investment and/or on country-level quality (measured by download speeds).[279]

In general, based on the above literature, the evidence on the impact of consolidation on prices is therefore stronger than its effects on investment.

Importantly, while these types of ex-post assessments can be informative of the potential effects of consolidation on market outcomes more generally, they cannot

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[274] GSMA (2017), 'Assessing the impact of mobile consolidation on innovation and quality: An evaluation of the Hutchinson/Orange merger in Austria', September 2017, pp. 21–27.

[275] Ofcom (2020), 'Market structure, investment and quality in the mobile industry', 22 December 2021.

[276] This represents the average increase in HHI resulting from the mergers in our sample. To put this number in context, a four-to-three merger between the second-largest and the smallest MNO with a share of 30% and 10% respectively in a market with two other MNOs with a share of 40% and 20% respectively, would result in an HHI increment of 600.

[277] Ofcom (2020), 'Market structure, investment and quality in the mobile industry', 22 December 2021, paragraph 6.2 and Table 6.1.

[278] Ibid., paragraph 6.11 and Table 6.2.

[279] Ibid., paragraph 8.19 and Table 8.1.

provide direct evidence on the potential effects of a proposed merger on a forward-looking basis. A case-by-case basis for assessing proposed mergers is therefore required and the investigation needs to take into account case-specific factors. This is recognised in Ofcom's study,[280] and more recently in the discussion paper on its approach to mobile markets:

"Our stance on a potential merger would therefore be informed by the **specific circumstances** of that particular merger, **taking into account how markets are evolving**.[281] […] This supports our view that potential mergers in telecoms markets need to be assessed on a **case-by-case basis, rather than on a presumptive view** of the appropriate number of competitors".[282] [emphasis added]

As noted by Ofcom, a case-by-case approach is important as it enables market evolution to be taken into account. Given that 5G is at an early stage of deployment, a key consideration of assessment in this context would be to consider the potential impact on competition and investment in relation to 5G.

8.2.2 Mechanism through which mobile NSAs could affect investment

Mobile network sharing refers to the situation in which two (or more) MNOs enter into an NSA which enables them to share elements on their mobile network infrastructure.

A brief overview of the different options available and the dimensions of network sharing is provided below. However, it should be noted that the general statements on network sharing provided below are based on general views and case law on network sharing to date. Since 5G deployments are at a relatively nascent stage, they are not automatically assumed to apply to 5G networks.

Overview of different types of NSA

In general, there are two main groups of mobile NSAs, which are specified in relation to the types of network infrastructure elements that are shared.

First, **passive sharing** describes the scenario in which MNOs share the passive elements of their networks. Passive elements cannot process or convert telecoms signals and are not part of the system used to convey signals. These elements are typically unpowered components, such as the physical site on which network infrastructure is deployed and mobile masts which host network equipment. This type of sharing typically takes one of two forms:

- Site or mast sharing: operators share the same physical location for the construction of base stations, for example two MNOs may share the same

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[280] Ibid., p. 43.

[281] Ibid., paragraph 7.20.

[282] Ibid., paragraph 7.22.

rooftop site; operators share the same physical mast or supporting construction (which, by definition, also includes sharing the physical site).

- Shared backhaul: operators share sites and backhaul.

Second, **active sharing** describes the scenario in which MNOs share the active elements of their networks. Active elements generate, process, amplify and control signals and typically include electronic equipment such as transmitters and receivers. Active sharing agreements will typically require the passive elements of the network to also be shared. Active sharing typically take two main forms:[283]

- Multi-operator radio access network (MORAN) sharing: operators share their radio access network equipment but do not share their spectrum, and each operator uses its own core network.
- Multi-operator core network (MOCN) sharing: operators share both their radio access network equipment and their spectrum, and each operator uses its own core network.

The types of passive and active sharing are illustrated below:

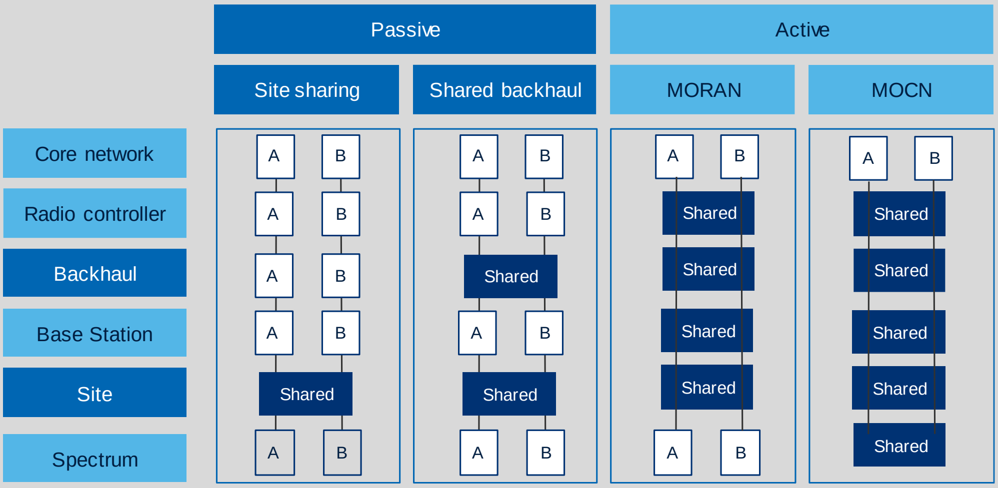

Figure based on GSMA representation: Figure 2 of: https://www.gsma.com/futurenetworks/wiki/infrastructure-sharing-an-overview/

NSAs can also vary across other dimensions. For example, the sharing agreement can be specific to a mobile technology (e.g. 3G, 4G or 5G) and can be defined geographically (e.g. the infrastructure may be shared in all areas of the country with the exception of large cities). Given the complex nature of sharing agreements, the effects, both in terms of efficiencies and the impact on competition, will be highly specific to the formulation of each sharing agreement.

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[283] National or local roaming, where one operator uses another MNO’s network infrastructure to provide end users with a mobile service, is also a form of active sharing.

NSAs are commonplace across Europe,[284] and there are currently two main network-sharing arrangements between MNOs in the UK:[285]

- Mobile Broadband Network Limited (MBNL) is a 50/50 joint venture which provides a shared site portfolio (i.e. passive network) which supports both shared (3G) and non-shared (2G/3G/4G/5G) technologies used by Three and EE.[286] However, these MNOs have rolled out 5G (and 4G) unilaterally. Three's new site builds are independent of EE.

- Cornerstone Telecommunications Infrastructure Limited (CTIL) was set up as a 50/50 joint venture between VMO2 and Vodafone that owns and operates the MNOs' network sites; VMO2 and Vodafone separately have a contractual arrangement to mutually share their (2G/3G/4G/5G) technologies in much of the country outside of the larger cities.[287]

In addition, the four UK MNOs reached an agreement to work with the UK government to deliver the SRN to improve network coverage in rural areas of the UK. The SRN includes shared network infrastructure in total not-spots, which will be funded by the government; in these areas, the four MNOs will have shared use of the infrastructure to provide coverage.

It is generally accepted that NSAs can potentially generate positive effects for consumers, but they also carry the risk of competition concerns.[288] Ofcom recognises the potential for benefits and competition concerns to arise from NSAs:[289]

"MNOs also have **options to reduce costs** which could alleviate these potential impacts. For example, while it is important that **any sharing arrangements preserve competition between networks**, there are a number of potential **sharing models which could be adopted,** including **infrastructure sharing** or working with a third party such as a neutral host, who would build and operate part of the network for one or more operators" [emphasis added]

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[284] See: CMS (2021), 'Interactive map of network shares'; available at: https://cms.law/en/gbr/publication/cms-network-sharing-4-point-5/interactive-map-of-network-shares [accessed 04/03/2021].

[285] Ofcom (2022), 'Ofcom's future approach to mobile markets: A discussion paper'; available at 9 February 2022, pp. 17–18.

[286] BTEE and Three have deployed their own separate 3G networks in high-traffic areas.

[287] We note that in March 2021, Vodafone transferred its site portfolio and listed Vantage Towers in Frankfurt.

[288] For example, see: BEREC (2019), 'BEREC Common Position on Mobile Infrastructure Sharing', 19 June 2019.

[289] Ofcom (2022), 'Mobile networks and spectrum: Meeting future demand for mobile data', 9 February 2022, paragraph 5.68.

In practice, while MNOs might choose to enter into network sharing in some areas where cost savings are mutually beneficial, there will be commercial reasons why network sharing is not desirable. For example, operators may want to preserve deployment flexibility to enable them to differentiate their networks/services compared to competitors. This may be the reason why the sharing agreement between VMO2 and Vodafone described above is in areas outside of larger cities only. Within city locations, there is value both from being the 'first-mover' in a given location, and from differentiating network quality from competitors.

An overview of the potential benefits and concerns associated with network sharing is provided below.

Overview of potential benefits and concerns associated with NSAs

Network sharing can deliver a number of benefits relative to independently deployed networks, as described below:

- **Network cost savings**: savings can be generated when sharing passive and active network infrastructure. The total number of sites that need to be deployed, maintained and operated to achieve a given level of coverage for both operators is reduced, relative to independently deploying two separate networks.[290] While the scale of cost savings will be highly specific to the NSA, NSAs that include active sharing are likely to deliver higher cost savings than NSAs that include only passive sharing. Importantly, to benefit consumers, these cost savings must be passed on in terms of lower prices, improved quality or greater coverage.
- **Faster network roll-out**: by collectively deploying a shared network, the sharing parties can pool and co-ordinate their resources, enabling a more rapid roll-out than if they had independently deployed separate networks. This can benefit consumers by enabling them to access services earlier than they would have been able to in the context of independent network deployment.

In theory, network sharing may also help to overcome some of the practical deployment barriers MNOs may face. If MNOs are jointly rolling out new sites, this could mitigate potential deployment barriers as both MNOs would gain access to a sufficient number of sites in urban areas, as well as to sufficient power and backhaul. From a planning perspective, it may be easier for MNOs that are sharing a network to negotiate permission from the local authority. In such a situation, a lower number of sites may be required to provide the same level of coverage in a given area across multiple providers on shared infrastructure, compared to independent deployments by each MNO. However,

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[290] Some studies have estimated the potential scale of cost savings that network sharing may deliver for 5G network deployment. For example, McKinsey & Co. (2018) estimates that network sharing could reduce 5G costs by more than 40%, while GSMA (2019) estimates network sharing could reduce the total cost of ownership by up to 40%. See McKinsey & Co. (2018), 'Network sharing and 5G: A turning point for lone riders', February 2018; GSMA (2019), '5G-era Mobile Network Cost Evolution', 28 August 2019.

there may be instances where the requirement to host multiple sets of equipment on a single site (as would be the case under a passive sharing agreement) means that any restrictions on increasing the size of sites without prior permission may be an issue. As we discuss later in this document a number of positive steps have been taken to address key issues on planning and development barriers.

However, since mobile NSAs constitute an agreement between competing MNOs, there is the potential for the agreement to weaken competition in the market. MNOs that share in specific areas will also experience commercial impacts (e.g. less flexibility to differentiate services).

In general, there are three main concerns with respect to anti-competitive effects:

- **Incentives to invest**: the incentive for an MNO to invest and innovate is driven by the benefits it can obtain (e.g. in terms of higher profitability or market share). If network sharing is in place, the gains from investing in and upgrading the network may be shared with the other party, which may dilute an MNO’s incentives to invest in the network.
- **Ability to compete**: the sharing of network elements means that MNOs may, in some cases, have a reduced ability to compete with each another, due to the limitations on the ability to differentiate their services (e.g. in terms of coverage and/or quality). For this reason, passive sharing is generally viewed as having a lower impact on competition than active sharing, since it relates only to the physical location of the shared network, but not other elements which are important for the service provided, such as the radio access network equipment.
- **Information sharing**: the operation of a shared network requires that the parties share information with one another. This may make the market more conducive to tacit co-ordination and could violate competition law if the level of information sharing is higher than necessary. The need to co-ordinate may also lead to slower network roll-out, if the joint decision-making process becomes more complex.

While the potential for anti-competitive effects is a vital consideration, it is important that NSAs are assessed on a case-by-case basis to determine the presence of these effects in relation to the specific NSA under question. This should take into account factors such as the degree of market concentration, type of sharing (i.e. active or passive) and other features of the NSA, such as the geographical scope. Any anti-competitive effects should be considered against the potential benefits and efficiencies delivered, to determine whether the net-effect is positive or negative for competition and ultimately consumers.

The type (or depth) of sharing in particular is likely to be a key determinant of the potential benefits and anti-competitive effects. In general, the ‘deeper’ the level of network sharing (i.e. the more network elements that are shared between operators), the greater the potential scope for efficiencies and cost savings. If the access network equipment as well as the physical site and mast are shared, this will likely generate greater cost savings than sharing the physical site and mast only. However, deeper levels of sharing may also be more likely to have anti-competitive effects, and may be impractical or undesirable for technical as well as commercial reasons.[291] For example, the ability of a sharing party to differentiate its network is likely to be higher in a passive sharing scenario than in an active sharing scenario.

There are reasons why the effects of network sharing may differ in the context of 5G networks. For example, 5G-SA deployment using NVF (as described earlier in the report) may allow the characteristics of the network to be adaptable in a way that abstracts from the underlying hardware. This will enable operators to adapt their networks without necessarily having to make changes to the physical infrastructure and thus still allow for service differentiation even where passive and even some active elements are shared. These technological developments could potentially mean MNOs are able retain greater independent control of the quality of the network in a shared scenario (compared to 4G), which may act to mitigate some of the competition concerns.

Similar to mobile consolidation, the choice of whether to pursue NSAs is primarily a commercial decision by the MNOs. There are, however, mechanisms which may enable Ofcom to mandate network sharing. The European Electronic Communications Code (EECC) contains provisions which empower national regulatory authorities (NRAs) to mandate network sharing to achieve their regulatory objectives.[292] NRAs can attach conditions to spectrum licences to ensure the effective and efficient use of spectrum or to promote coverage (including the sharing of active infrastructure).[293] NRAs can also impose access-related conditions in certain cases where market-driven deployment of infrastructure is subject to insurmountable economic or physical obstacles such that the mobile service is deficient or absent.[294] The EECC has been transposed into UK law[295] and such

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[291] For example, due to type of equipment already installed by the operator, different vendor solutions, the practicalities of consolidating equipment or sites in specific locations and other factors.

[292] Directive (EU) 2018/1972 of The European Parliament and of The Council of 11 December 2018 establishing the European Electronic Communications Code, Article 44, Article 47, Article 52 and Article 61.4.

[293] Ibid., Article 47.

[294] Directive (EU) 2018/1972 of The European Parliament and of The Council of 11 December 2018 establishing the European Electronic Communications Code, Article 61.4.

[295] The UK implemented the requirements of the EU EECC through the Electronic Communications and Wireless Telegraphy (Amendment) (European Electronic Communications Code and EU Exit) Regulations 2020. These Regulations amended existing UK legislation (namely the Communications Act 2003 and Wireless Telegraphy Act 2006). These amendments entered into force on 21 December 2020.

conditions have been inserted as Section 74A of the Communications Act 2003. This change allows Ofcom to apply a condition on an electronic communications network to provide access in relation to network elements which are not active, under a number of scenarios, including where:

- “access by end-users to electronic communications services which depend on the use of wireless telegraphy is unavailable or severely restricted” and
- “the unavailability or restriction results from the physical characteristics of the relevant area or from other characteristics of the relevant area that tend to make the bringing into operation of infrastructure uneconomic”.

Since Ofcom has auctioned most of the spectrum bands in the UK that are suitable for 5G, the ability to attach any network-sharing conditions to the licences is constrained. There may be some cases in which network sharing can be mandated by Ofcom, however, these are likely to be limited in nature given the specificity of the conditions for intervention.[296] Therefore network sharing in the UK is likely to be driven by commercial decisions taken privately by MNOs. Involvement from the public sector is expected to be limited to reviewing NSAs where appropriate.

8.2.3 Scale of the issue in the UK

In this subsection, indicative results are provided of the potential scale of the impact that consolidation and mobile network sharing could have on investment in advanced wireless connectivity in the UK.

Consolidation

Section 8.2.1 above described how a number of studies of four-to-three mobile mergers throughout Europe have found evidence of price increases. To the extent that such price increases could be achieved, this may be sufficient to cover the APRU uplift requirements discussed in Section 7. For example, the review of the literature above showed that price rises following specific mergers may have increased between 10% and 52%. Genakos et al. (2018) finds an average impact of 16.3% based on an average effect across panel data of 33 OECD countries between 2002 and 2014.

As a simple illustration of scale, a 16% increase in APRU (based on an ARPU of GBP13.99[297]) amounts to an extra GBP2.23. Comparing this to the APRU uplifts

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[296] Directive (EU) 2018/1972 of The European Parliament and of The Council of 11 December 2018 establishing the European Electronic Communications Code, Article 44 and Article 61.4.

[297] Total ARPU (excl. IoT), residential, UK, GBP in 2022. Analysys Mason Research team database.

needed, this would be sufficient to cover the additional revenue requirement under Scenario 1 in urban and suburban areas and nearly all regional rural areas, with the exception of the Scotland rural area. In this area, the ARPU uplift required is GBP2.27 and thus is very nearly met.

In presenting these results, it is not implied that consolidation in the UK market would result in such ARPU uplifts being observed nor that this will definitely lead to greater investment. However, the results are indicative of whether the scale of the required ARPU uplift is broadly in line with the additional price rises that could be achieved in a more concentrated market. There is no certainty that this increase in prices would necessarily be used to fund investment.

Network sharing

In some cases and in some environments, network sharing can generate efficiencies in the form of network cost savings. These cost savings could have a positive impact on the level and quality of coverage that could be achieved relative to MNOs deploying their network independently.[298] In order to provide insights into the extent to which network sharing could help close the gap between the baseline scenario and the three modelled scenarios described in this report, we have considered the impact of four network-sharing scenarios on the network costs.

This analysis only captures the effect of sharing on any **new sites**, or additional spectrum deployment on SRN sites, that would be added to the baseline deployment we have modelled between 2022 and 2030 to meet an additional target quality-of-service level that might be set by UK government policy.[299]

We note that this analysis may not reflect the actual ability of MNOs in the UK to share their network in practice. MNOs are already rolling out 5G, and will have planned the deployment of further sites in conjunction with their chosen vendors, in a unilateral manner (i.e. without sharing).[300] Existing vendor agreements (which we note have already been changed as a result of the government's direction on high-risk vendors) may constrain the MNOs' ability to share on new sites, where they have been deployed or are planned to be deployed unilaterally. Moreover, there are also technical and commercial challenges associated with reaching an NSA. Therefore we note that the stylised analysis provided below is intended to give

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[298] For example, network sharing may reduce the costs of deploying to a given area such that investing in deploying infrastructure in that area is now commercially viable.

[299] The analysis models the additional costs associated with meeting all business traffic and providing a service with 50Mbit/s to active users.

[300] For example, this may be due to the difficulty of sharing infrastructure in these areas given the additional strain that hosting two sets of active equipment could have on the passive infrastructure.

illustrative results. It is not an estimate of the network-sharing cost savings that could be achieved in practice in the UK.

Below we provide an overview of the modelling approach to estimate the cost savings that network sharing between two MNOs, with 25% market share each (in line with our hypothetical modelled MNO) could deliver and the key illustrative results.

We estimate the scale of network cost savings (per MNO) that could be generated by an NSA between two MNOs under our modelled Scenario 3 as follows:[301]

- Estimate the total cost (per MNO) associated with meeting the target quality of service under Scenario 3 (50Mbit/s per active user plus enterprise traffic) over and above the baseline, with no network sharing in place.
- Estimate the total costs (per MNO) associated with meeting the target quality of service under Scenario 3, under four different network-sharing scenarios.
- Compare the results above to give the scale of network cost savings (per MNO) associated with each network-sharing scenario relative to the No-sharing scenario.

Four different network-sharing scenarios are considered. These vary depending on: (a) the type of network sharing in place (i.e. passive or active sharing); and (b) the geographical basis of the network sharing. We account for the effect of different types of network sharing on network costs in the following way:[302]

- **Passive sharing**: the passive costs associated with each new mini macro site, or additional deployments on SRN sites, are reduced by 50%.
- **Active sharing**: the active costs (except for carrier charges) associated with each new mini macro site, or additional deployments on SRN sites, are reduced by 50%.

Reducing the passive and active costs by an assumed 50% is intended to reflect that the modelled sharing agreement is between two (hypothetical) MNOs, i.e. the MNO’s passive and active costs are halved.

Across the four sharing scenarios, we vary the geographical basis of network sharing. Figure 8.6 provides an overview of the geographical basis for active and passive sharing on new sites under each scenario.

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[301] In the analysis, the network costs are measured in terms of the total (i.e. including capex and opex) annualised nominal costs from 2022 to 2030.

[302] These sources of cost saving from passive sharing and active sharing is held constant across the scenarios – on each new site, the proportion of cost savings from passive and, where relevant, active sharing is the same in each scenario.

Figure 8.6: Geographical basis for network sharing on new sites [Source: Analysys Mason, 2022]

Scenario name	Passive sharing	Active sharing
No sharing	None	None
Sharing scenario Variant A	Nationwide	None
Sharing scenario Variant B	50% of the most rural sites	50% of the most rural sites
Sharing scenario Variant C	Nationwide	50% of the most rural sites
Sharing scenario Variant D	Nationwide	Nationwide

Figure 8.7 below provides an overview of the scale of the cost savings that each of the two sharing MNOs could achieve relative to the no-sharing scenario at a national level, and by geotype. The network cost savings that can be achieved as a result of network sharing relative to the costs from the no-sharing scenario are presented (in absolute and percentage terms) under each sharing scenario.

Figure 8.7: Network cost savings (per MNO) by sharing scenario [Source: Analysys Mason, 2022]

Scenario	Urban (GBP million)	Suburban (GBP million)	Rural (GBP million)	National (GBP million)
Modelling Scenario 3 (described in Section 5) (No sharing): total costs	**69.5**	**50.3**	**316.2**	**436.0**
Sharing scenario Variant A: cost savings	4.6	1.3	10.3	16.1
	7%	3%	3%	4%
Sharing scenario Variant B: cost savings	-	-	3.5	3.5
	-%	-%	1%	1%
Sharing scenario Variant C: cost savings	4.6	1.3	12.7	18.5
	7%	3%	4%	4%
Sharing scenario Variant D: cost savings	16.6	2.6	18.7	37.9
	24%	5%	6%	9%

Note: costs and cost savings measured in terms by total (capex + opex) annualised nominal costs (2022–30).

As expected, the results show that the more extensive the network sharing, both with respect to the geographical basis and network elements shared, the greater the network cost savings. The network cost savings are driven by mainly by the capex savings that can be achieved.[303]

In the context of passive sharing only on all new sites (Sharing scenario Variant A), the cost savings per MNO are relatively modest (4% at a national level). The scale of cost savings increases when active sharing is introduced. Under Sharing scenario Variant D, which has the most extensive network sharing in place (active and passive sharing on all new sites), the cost savings amount to a reduction of 9% at the national level).

While the results are illustrative in nature, they demonstrate an important mechanism through which network sharing can directly affect the economics of network deployment: they generate network cost savings which can support the investment case for deployment in a given area. Where network cost savings are achieved through network sharing, this would reduce the additional revenue requirement and corresponding ARPU uplift requirements. Network sharing can therefore improve the economics of network roll-out and could potentially tip the investment case in a given area from being commercially unviable to commercially viable.

8.2.4 Conclusions/recommendations

Overall, the impact of mobile consolidation on investment is unclear. While some studies point to increases in operator-level investments and improvements in network quality, there is also evidence to suggest that consolidation has either no effect or even a negative effect on industry-level investment and network quality. The evidence on the impact on consolidation on prices, however, is more clear cut. Nearly all studies find an increase in prices following market consolidation. Importantly, the conclusions from any analysis of past increases in concentration and consolidation cannot be directly applied to prospective mergers, which need to be assessed on a case-by-case basis as has been clearly acknowledged by Ofcom.

Indeed, the choice of whether to pursue consolidation is ultimately a commercial decision made by the MNOs. The role of the public sector, in terms of the national competition authority and the sectoral regulator, is to assess the effects of a merger

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[303] At a national level, between 69% and 83% of the cost savings are attributable to capex savings. However, the proportion of savings attributable to capex varies by geotype; across individual geotypes, the cost savings attributable to capex make up at least 35% of the total savings for each geotype under each of the four scenarios.

and decide whether to block or clear it[304] (potentially with remedies[305]). There is thus limited scope for active policy interventions to encourage consolidation.

Network sharing is an alternative way in which operators could potentially generate some of the same cost-efficiency savings available through consolidation, for example, in terms of network cost savings, while mitigating the potential competition concerns that can arise with consolidation.

Ultimately, however, the choice of whether to pursue consolidation or enter into an NSA is also a commercial decision by the MNOs. It cannot be mandated as a matter of public policy (except under certain conditions such as in the case of SRN). As in the case of consolidation, the role of the public sector would be primarily focused on assessing the effects of an NSA and, provided it meets the thresholds for merger notification, deciding whether to block or approve it (potentially with remedies), based on assessment of its potential anti-competitive effects and pro-competitive efficiencies. Alternatively, extensions to existing NSAs in the UK to cover roll-out of 5G and other advanced wireless networks may not require notification to competition authorities but could be subject to ex-post reviews under competition law.

Even though such deals will ultimately be assessed on a case-by-case basis, there is scope for competition and regulatory authorities to provide greater clarity and guidance to operators on the key factors that will be considered in such assessments. This can be particularly valuable at this early stage in 5G network roll-out where operators are making decisions on how, where and with whom to partner (if necessary).

In the draft Revised Horizontal Guidelines (which are currently being consulted on), the European Commission has provided broad principles on the relevant factors it would consider when assessing the effect on competition and the minimum

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[304] The merging parties would need to report any potential consolidation in the market to the relevant competition authority, i.e. the Competition and Markets Authority (CMA). The CMA would then undertake an assessment of the proposed merger to determine the potential effects on competition and consumer welfare. It will assess whether the merger could lead to a substantial lessening of competition, with respect to specified theories of harm and consider whether there will be any efficiencies created by the merger which could benefit consumers and will work closely with Ofcom to understand the specific market context.

[305] There have been several cases where four-to-three mergers have been approved, with remedies, in Europe. These remedies are generally aimed at mitigating the loss of competitive pressure, by facilitating entry. For example, in all three of the cases examined by BEREC in the aforementioned study, commitments were secured which sought to provide mandated access to MVNOs and/or facilitate entry by new-entrant MNOs through the divestiture of spectrum. However, as noted above, any remedies imposed will be based on the facts of the case at hand.

conditions that would need to be satisfied for the agreement to be considered, prima facie, as being unlikely to have restrictive effects on competition.[306]

In the specific case of network sharing, BEREC has issued a common position on mobile infrastructure sharing and describes criteria that can be taken into account by national regulators when evaluating the impact of infrastructure-sharing agreements.[307] In the UK, there could be a role for Ofcom, for example, to prepare similar guidance and updating it to account for the technological advances and capabilities of advanced 5G wireless networks. These networks, as discussed above, could provide greater scope for downstream competition compared with previous mobile technologies.

8.3 Net neutrality

In interviews conducted for this study, MNOs raised the following concerns regarding current net-neutrality rules:

- the rules are unclear on how innovative 5G services (e.g. services with speed and other quality-of-service guarantees) can be delivered
- it is not clear whether these services can be commercialised with differential pricing based on different quality of service.

In some cases, MNOs are concerned that net-neutrality rules could limit their ability to differentiate the services they offer. This is particularly relevant for the commercialisation of network slices,[308] a key feature of standalone 5G (5G-SA).

During the stakeholder interviews, a stakeholder noted that the current net-neutrality rules have the potential to impede operators’ ability to monetise their investment in 5G infrastructure.[309] The issue is related to customisation in 5G services delivered to end users and the ability to set prices based on quality-of-service parameters rather than data usage, for example. This quality-of-service customisation might be done via 5G-SA network slicing (which would be viable once operators migrate to using 5G-SA in combination with 3.5GHz deployment). In its

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[306] European Commission (2022), ‘Annex to the Communication from the Commission: Approval of the content of a draft for a Communication from the Commission; Guidelines on the applicability of Article 101 of the Treat on the Functioning of the European Union to horizontal co-operation agreements’, 1 March 2020, pp. 61–68.

[307] BEREC (2019), ‘BEREC Common Position on Mobile Infrastructure Sharing’, BoR (19) 110.

[308] Network slicing refers to the segmentation of the 5G network into virtual, bespoke networks that can provide distinct properties and characteristics to specific customers and use cases without the need to build separate, physical networks.

[309] Based on a stakeholder interview for this study.

response to Ofcom's call for evidence on net neutrality,[310] the stakeholder highlights two issues related to the interpretation of net neutrality in this context:

- First, the stakeholder argues there is uncertainty over whether network slicing can be classed as a specialised service. Specialised services "are optimised for specific content, applications or services under certain conditions" and operators may "offer or facilitate such services only if the network capacity is sufficient to provide them in addition to any internet access services (IAS) provided".[311] The stakeholder commented it is unclear whether network slicing could be used to provide customised services to end users, as this could potentially have a detrimental impact on IAS.[312] If this is an issue, it could potentially prevent, for example, an optimised slice for manufacturing use cases being sold to enterprises.

- Second, from a commercial perspective, it argues that the demand for network slices will come from enterprises and content providers, rather than consumers, and that these upstream businesses will benefit the most from access to sliced offerings. Therefore it argues that operators must be able to charge businesses for access to the network slices. This could run contrary to net-neutrality rules, which prevent IAS (including mobile) from entering into commercial relationships[313] and quality-of-service differentiation is only permitted on broad categories of traffic.[314]

Another stakeholder mentioned the uncertainty around composing network slices with price differentiation, as regards to net-neutrality rules, and also noted the

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[310] Three (2021), 'Three's response to Ofcom's call for evidence on Net Neutrality: Non-Confidential', 21 November 2021.

[311] Article 3(5) of Regulation (EU) 2015/2120 of the European Parliament and of the Council of 25 November 2015 laying down measures concerning open internet access and retail charges for regulated intra-EU communications and amending Directive 2002/22/EC and Regulation (EU) No 531/2012. Referred to hereafter as the Regulation.

[312] Three (2021), 'Three's response to Ofcom's call for evidence on Net Neutrality: Non-Confidential', 21 November 2021, p. 12.

[313] Article 3(2) of the Regulation states: "Agreements between providers of internet access services and end-users on commercial and technical conditions and the characteristics of internet access services such as price, data volumes or speed, and any commercial practices conducted by providers of internet access services, shall not limit the exercise of the rights of end-users laid down in paragraph 1."

[314] Article 3(3) of the Regulation notes that in order for traffic management to be deemed reasonable, "such measures shall be transparent, non-discriminatory and proportionate, and shall not be based on commercial considerations but on objectively different technical quality of service requirements of specific categories of traffic. Such measures shall not monitor the specific content and shall not be maintained for longer than necessary."

importance of being able to treat slices as a specialised service.[315] It argued that the importance of ensuring net neutrality should not hinder innovation.[316] A further stakeholder also cited that there was insufficient clarity over net-neutrality rules to unlock the power of mobile private networks.[317]

Some stakeholders have also made statements publicly. For example, Ericsson has noted:

“A strict interpretation of net neutrality, whereby ISPs should treat all data on the internet equally, without differentiating traffic on the basis of speed, cost, latency, etc., regardless of user preference, content, location, platform, application, type of equipment, or mode of communication would hinder ISPs’ ability to manage networks efficiently. If not done carefully net neutrality regulation risks hindering innovation in networks, like network slicing – a key 5G fundament; and threatening the viability of IoT. Modern infrastructure for a smart society will require the flexibility to create network services that appropriately handle unique requirements”.[318]

We note the issues focused on here are distinct from more general calls from investors (in both fixed and mobile networks) that big-tech companies should contribute to the costs of rolling out networks more generally. This is a significantly broader subject with considerations that extend beyond the wireless market issues focused on in this report.

The discussion in the remainder of this section is specifically related to the ability to offer differential quality of service over network slices, and the freedom to explore different options for commercialising such services.

The discussion is also set in the context of the relevant legislation. EU rules aimed at protecting the principle of the open internet (the ‘Open Internet Regulation’) were agreed in 2015 and came into force at the end of April 2016.[319] The UK left the EU on 31 January 2020, with a transition period until 31 December 2020 (the ‘transition period’). Following the end of this period, the EU rules on net neutrality became part of domestic UK law. A number of small changes were subsequently made to the rules, so as to deal with minor issues arising from the UK’s withdrawal from the

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[315] Based on a stakeholder interview conducted for this study.

[316] Ibid.

[317] Based on a stakeholder interview for this study.

[318] https://www.ericsson.com/en/public-policy-and-government-affairs/net-neutrality

[319] Regulation (EU) 2015/2120 of the European Parliament and of the Council of 25 November 2015 laying down measures concerning open internet access and retail charges for regulated intra-EU communications and amending Directive 2002/22/EC and Regulation (EU) No 531/2012.

EU.[320] Below, we provide specific language from the EU legislation (as transposed into UK law), but note that the scope for legislative change is discussed with specific reference for doing so at the UK level.

8.3.1 Mechanism through which the barrier affects investment

MNOs indicated in interviews for this study that network slicing would be used within the footprint of 5G-SA coverage. Consistent with what we identified in stakeholder interviews, we understand that the UK MNOs are likely to focus on 5G-SA in those areas within the 3.5GHz coverage footprint. Figure 5.8 shows how far the 3.5GHz footprint will extend in each of the scenarios we have modelled, based on demand, and indicates regions where a purely population driven roll-out may not provide sufficient capacity to meet business demands. However, this coverage will depend on there being sufficient ability to commercialise deployment to meet the revenue requirement to justify the investment cost.

If differentiated quality of service cannot be commercialised so that differentiated charges are made to enterprises, the burden of the revenue requirement to support investment could fall more predominantly on end-user consumer tariffs. If users are not willing to pay these higher tariffs, the investment case may be undermined, particularly in rural areas. This would be an extreme scenario, as some enterprise revenue may still be possible without differentiated charges, but the revenue-raising capability may be limited without the ability to engage further price discrimination through differentiated quality-of-service slices for B2B services.

5G-SA and network slicing could enable:

- provision of new use cases and customised services to specific industry verticals provided over network slices in a public mobile network
- private networks provided over public networks using network slicing or via a hybrid public/private deployment model – these would be distinct from other private networks such as the dedicated, on-premises networks described in Section 3.2.

The innovations and benefits associated with these alternative use cases that could be enabled over network slicing on the public network may be lost where network slicing is not offered on a widespread basis. The lack of certainty surrounding the

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[320] Pursuant to section 8(1) of the EU Withdrawal Act 2018. For example, Ofcom is no longer required to take utmost account of the BEREC Guidelines or to submit an annual compliance report to the European Commission (although it is still required to publish a report). References to EU laws and national regulatory authorities (NRAs) were also deleted or replaced with references to national laws and Ofcom, respectively.

business case is due to insufficient clarity on net-neutrality rules and the restrictions that these rules may impose.[321]

8.3.2 Scale of the issue in the UK

Modelling Scenarios 2 and 3 include advanced enterprise traffic and assume that advanced data traffic will be provided by orchestrating network slices in 5G-SA networks. In the absence of network slicing, the hypothetical MNOs' ability to serve enterprise traffic (which has an associated cumulative GVA uplift of GBP2.6 billion between 2022 and 2030 in 2020 terms[322]) may be significantly impacted. Any uncertainty on network slicing could slow down the timing of realising these benefits or may lead to them not being realised at all.

However, as discussed in Section 3.2, specific enterprise demands and use cases could still be served by dedicated, on-premises private networks, and these are unlikely to be affected by net-neutrality rules, if they can be provided without detriment to the public internet access service. This is likely to be the case for alternative operators providing private networks based on shared access or local access licences. Therefore, in the event that MNOs are unable to offer tailored services to enterprises through differentiated network slices, not all of the potential benefits associated with tailored connectivity solutions will be lost, as these could still be offered via dedicated private networks. However, this may come at a higher cost since it is likely that these private networks will have a higher capital cost requirement than hybrid networks or network slicing, due to the need to install separate on-premises infrastructure (but potentially lower operational costs than those of hybrid networks), as discussed in Section 3.2, and alternative operators may face some barriers to providing such solutions (as explored further below).

8.3.3 Possible options to address the issue

Providing further clarity on the interpretation of net-neutrality rules could provide more certainty on slice composition and pricing. We note that Ofcom has already actively reviewed net-neutrality rules – its call for evidence closed at the start of November 2021 and its initial findings are expected to be published in spring 2022.

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[321] For example, in cases where the absence of being able to differentiate pricing to reflect different quality of service means the revenue requirement needed to justify the shift to 5G-SA and offer network slicing is not met. Alternatively, in cases where network slicing is not launched because it is considered to be a permanent differentiation of service quality, with an impact on the quality of the general internet access service.

[322] This is the GVA uplift estimated from Scenario 2, which focused purely on enterprise traffic, and reflects the GVA uplift that may be experienced by the businesses that will be served by the hypothetical modelled MNO with 25% market share. Therefore, the overall GVA uplift across all business in the area that takes up advanced wireless connectivity services could be as high as GBP10.4 billion.

In setting out the purpose of its review, Ofcom references the significant technological developments since the net-neutrality rules were established, and notes it will look at developments including “consumer and industrial IoT, trends in usage of Virtual Private Networks and encryption, augmented/virtual reality, cloud computing, and 5G services”.[323]

As part of this review, Ofcom is engaging with mobile operators to better understand the practical applications of 5G network slicing and how these may evolve into the future. It intends to look at whether there is scope to provide more clarity and certainty on existing rules and guidance as to what constitutes a specialised service.

This is already a clear positive step to assessing the issue in more detail and considering ways to provide more certainty. In this regard, Ofcom’s review and its findings may be very instructive with regards to changes that could be made or further guidance offered.

Notwithstanding the outcome of Ofcom’s detailed review, we discuss some of the options that could be pursued to address the potential issues with net-neutrality and unlocking the full value of 5G-SA, below:

- provision of further clarity on the interpretation of specialised services
- amendments to legislation regarding traffic management rules.

Provision of further clarity on the interpretation of specialised services

On specialised services, Article 35(5) of the Regulation notes that:[324] [325]

“Providers of electronic communications to the public, including providers of internet access services, and providers of content, applications and services shall be free to offer services other than internet access services which are **optimised for specific content, applications or services, or a combination thereof, where the optimisation is necessary in order to meet requirements of the content, applications or services for a specific level of quality**.

Providers of electronic communications to the public, including providers of internet access services, may offer or facilitate such services **only if the network capacity is sufficient to provide them in addition to any internet access services**

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[323] Ofcom (2021), ‘Net neutrality review: Call for evidence’, 7 September 2021, p. 10.

[324] Article 35(5) Regulation (EU) 2015/2120 of the European Parliament and of the Council of 25 November 2015 laying down measures concerning open internet access and retail charges for regulated intra-EU communications and amending Directive 2002/22/EC and Regulation (EU) No 531/2012.

[325] Note, the UK left the EU on 31 January 2020, with a transition period until 31 December 2020. Following the end of this period, the EU rules on net neutrality became part of domestic UK law.

provided. Such services shall not be usable or offered as a replacement for internet access services, and **shall not be to the detriment of the availability or general quality of internet access services for end-users**.” [emphasis added]

For network slicing to be classified as a specialised service, it must be accepted by policy makers and MNOs that while in certain instances network slicing may reserve capacity for some providers or services, this would not have an impact on the general quality of IAS. Insufficient capacity in the network could create difficulties if reserving capacity for specific users results in lower quality of service for general use. However, if enterprise 5G demand becomes widespread, and capacity is orchestrated on network slicing, then the IAS may have lower capacity than it once had, absent of network capacity upgrades being made. As the general demands on the network increase, the average quality of connection might degrade (e.g. average Mbit/s per user). However, if network slicing means that particularly demanding applications can be served off the IAS through additional capacity provisioned in the network, then this could mean that IAS performance could be protected or even increased.

In the absence of legislative changes, the wording of Article 3(3) of the Regulations may still suggest it would be sensible to ensure the provision of specialised services is not adversely affecting the services being provided over the IAS.

In this regard, BEREC[326] has noted the following in line with Recital 17 of the Regulation: “In mobile networks – where the number of active users in a given cell, and consequently traffic volumes, are more difficult to anticipate than in fixed networks – the general quality of IAS for end-users should not be deemed to incur a detriment where the aggregate negative impact of specialised services is unavoidable, minimal and limited to a short duration”.[327]

This is potentially helpful, but there is a need for further guidance from Ofcom about how it would expect to interpret and assess these concepts in the UK context, noting that Ofcom’s net-neutrality guidance is currently limited to outlining its approach to assessing compliance with net-neutrality rules in the context of zero rating offers and traffic management measures for compliance with the Open Internet Regulation, based on its experience to date.[328]

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[326] As noted above, following the end of the transition period, Ofcom is no longer required to take utmost account of the BEREC Guidelines. However, Ofcom can continue to reference these where it considers this to be appropriate.

[327] BEREC, ‘BEREC Guidelines on the Implementation of Open Internet Regulations, 2020’, paragraph 123.

[328] Ofcom (2019) ‘Ofcom’s approach to assessing compliance with net neutrality rules – Frameworks for assessing zero rating offers and traffic management measures for compliance with the Open Internet Regulation’, 16 May 2019.

As set out in Ofcom's net-neutrality review call for evidence, it has already expressed an intention is to look at whether there is scope to provide more clarity and certainty as to what constitutes a specialised service, and it is seeking views specifically on whether it would be beneficial to provide further UK-specific guidance in this area. In light of the discussion above, such guidance would be very welcome.

Ofcom could, for example, consider providing clarification on how it will seek to measure IAS quality of mobile networks (and changes over time) and what assurances it would need from network operators for network slice orchestration to be offered without a detrimental impact on the IAS. Further clarification would be required on how often reviews of the impact on the IAS would take place, and how Ofcom would seek to phase out a specialised service if it was found to be in breach of the rules. We note that BEREC guidance states that "the ISP should be allowed a reasonable transitional phase for phasing out of the specialised service. In these circumstances, national administrative and procedural laws apply, including observing the principle of proportionality".[329] And this could be expanded upon under UK specific guidance.

Amendments to traffic management rules

Alternatively, amendments to or further guidance on traffic management rules could lead to changes that may enable network slicing.

Article 3(3) of the Regulations sets out the conditions for traffic management:

"Providers of internet access services shall treat all traffic equally, when providing internet access services, without discrimination, restriction or interference, and irrespective of the sender and receiver, the content accessed or distributed, the applications or services used or provided, or the terminal equipment used.

The first subparagraph shall not prevent providers of internet access services from implementing reasonable traffic management measures. In order to be deemed to be reasonable, such measures shall be transparent, non-discriminatory and proportionate, and **shall not be based on commercial considerations** but on objectively different technical quality of service requirements of specific categories of traffic. Such measures shall not monitor the specific content and **shall not be maintained for longer than necessary.**

Providers of internet access services shall not engage in traffic management measures going beyond those set out in the second subparagraph, and in particular

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https://www.ofcom.org.uk/research-and-data/internet-and-on-demand-research/net-neutrality

[329] BEREC, BEREC Guidelines on the Implementation of Open Internet Regulations, 2020, paragraph 112.

shall not block, slow down, alter, restrict, interfere with, degrade or discriminate between specific content, applications or services, or specific categories thereof, except as necessary, and **only for as long as necessary,** in order to:

(a) comply with Union legislative acts, or national legislation that complies with Union law, to which the provider of internet access services is subject, or with measures that comply with Union law giving effect to such Union legislative acts or national legislation, including with orders by courts or public authorities vested with relevant powers;

(b) preserve the integrity and security of the network, of services provided via that network, and of the terminal equipment of end users;

(c) prevent impending network congestion and mitigate the effects of exceptional or temporary network congestion, provided that equivalent categories of traffic are treated equally." [emphasis added]

If network slicing is to become a permanent fixture in the quality of service for delivery of IAS, the regulation would need to include a permanent differentiation of services (rather than the temporary changes under the existing regulation). There would also need to be clarity that network slicing would satisfy the conditions under which traffic management is allowed.

This may prove challenging without opening up to other forms of traffic management that the current regulation intends to avoid. The phrase "not based on commercial considerations" would also need to be removed in order to allow differential charging of network slices. Removing both traffic management controls and allowing traffic management based on "commercial considerations" could again open up the possibility of discriminatory traffic management. This would be out of line with the principles of the open internet, risking unintended consequences that undermine the protection of open internet principles.

However, there may be benefits for the system if operators are allowed to explore different options for the commercialisation of differentiated quality of service (including network slices). MNOs could look for innovative ways to monetise additional investments in their networks to provide tailored pricing solutions for customised services and offer differential pricing to businesses.

These commercial deals would need to be compliant with competition law rules that prevent discriminatory and/or exploitative terms and conditions. Rules that limit commercial freedom could run counter to policy makers' objectives to create an environment conducive to innovation and investment in high-capacity networks.

In the event that the commercial deals are offered and not accepted (e.g. if the user still wants to use to IAS and not pay more), there would be no additional source of revenue for the MNO if the end user is not willing to pay for the investment case to be made. However, providing guidance that could provide confidence in the ability of operators to offer such commercial solutions could help to unlock the possibility of the user accepting these tailored commercial deals.

One potential approach would be to consider ways in which network slices could be defined as a specific category of service that is distinct from a specialised service and an IAS. Traffic management with commercial considerations could be allowed for network slices, subject to the terms being fair, reasonable and non-discriminatory (FRAND), and Ofcom could commit to publish further guidance on how such FRAND terms should be interpreted in relation to network slices.

8.3.4 Conclusions/recommendations

As part of its call for inputs, Ofcom noted that whilst it can offer guidance on applying net-neutrality rules, the rules themselves are set out in legislation and hence any changes will require legislative change, and hence be a matter for government.

We note that the main piece of guidance from Ofcom currently is the document entitled ‘Ofcom’s approach to assessing compliance with net-neutrality rules – Frameworks for assessing zero rating offers and traffic management measures for compliance with the Open Internet Regulation’ (16 May 2019). This contains Ofcom’s approach to assessing compliance with certain aspects of the Open Internet Regulation, based on its experience to date.[330]

Such guidance could be very helpful if it is extended to more explicitly address how network slicing as a technology and the options for commercialisation of such a technology would be treated under any assessment of compliance with the net-neutrality rules, in line with the discussion above. To the extent that this can be done clearly, stating what will be permitted, this could allow operators to invest and launch such services with confidence.

However, any approach that would require a definition of network slices as a specific category of service, distinct from a specialised service and an IAS (for example to allow for traffic management with commercial considerations subject to the terms being FRAND), may be beyond the powers of Ofcom. Any changes would need to be considered together with whether DCMS and government propose to make explicit changes to legislation.

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[330] Ofcom (2019) ‘Ofcom’s approach to assessing compliance with net-neutrality rules – Frameworks for assessing zero rating offers and traffic management measures for compliance with the Open Internet Regulation’, 16 May 2019. https://www.ofcom.org.uk/research-and-data/internet-and-on-demand-research/net-neutrality

In the event that such a distinction of network slicing could be made, the Ofcom guidance could extend to outlining how such FRAND terms should be interpreted in relation to network slices.

8.4 Barriers faced by alternative operators

As described in Section 3.3, alternative operators may be able to provide alternative solutions that are not available over the MNO wide-area public networks, including:

- private networks to meet specific needs in defined localities
- neutral host solutions provided over shared or local access spectrum in areas where there may not be full coverage by all MNOs.

However, in order to provide this infill, the alternative operators will need:

- **Mobile network codes** – if intending to offer services directly to consumers or businesses, operators will need to be assigned a mobile network code (MNC).[331]

- **Roaming agreements** – to enable roaming between public MNO networks and the alternative operator network for multi-operator neutral host solutions relying on shared or local access spectrum or for allowing transition from private networks to public networks. For example, roaming agreements will be needed to enable continuity of connections for moving devices beyond the private network such as automated guided vehicles or applications used by field personnel, or for tracking shipments in and out of enterprise hubs.[332]

- **Access to spectrum** – currently available through shared access (including 1800MHz, 2300MHz, 3.8–4.2GHz[333,334]) or local access licences. The latter type of

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[331] MNCs are issued in combination with a mobile country code to uniquely identify a mobile network operator (carrier) using the GSM (including GSM-R), UMTS, LTE and 5G public land mobile networks.

[332] We note that Ericsson has highlighted that 'interworking' with public networks is an important capability requirement for 5G private networks. It cites the example of critical services like ambulances needing service continuity while moving from one network to another, for instance from a private network to a public network. See Ericsson White Paper, 'Critical capabilities for private 5G'; available at networks:https://www.ericsson.com/en/reports-and-papers/white-papers/private-5g-networks

[333] Shared access licences are available per 10MHz (up to 100MHz) in 3.8–4.2GHz, per 10MHz in 2.3GHz bands, and per 2×3.3MHz in the 1800MHz band. For the 26GHz band, 50, 100 or 200MHz channels can be applied for, but are for indoor use only.

[334] At the time of producing this report, Ofcom has announced a consultation related to adding the upper 6GHz band from 6425–7025MHz into the shared access licence regime, for low-power, indoor use: https://www.ofcom.org.uk/consultations-and-statements/category-2/spectrum-sharing-upper-6-ghz-band

licence provides access to spectrum already licensed to MNOs, provided this does not interfere with the MNO's network or constrain its future plans.[335]

As noted in Section 8.3.2, alternative operators have experienced barriers to obtaining access to spectrum, setting up roaming agreements and obtaining MNCs. This may prevent them from entering the market with a compelling service offering.

Below, we assess some of the key issues raised by stakeholders, noting that removing barriers to entry and providing a supportive investment environment for alternative operators could lead to a number of benefits compared to the business case where MNOs are the main driver of roll-out.

Alternative operators may be able to provide tailored solutions to enterprises to some extent, for example. This could have the following types of impact:

- Areas and businesses affected will obtain access to advanced wireless connectivity earlier than they otherwise would, thus bringing forward the realisation of benefits associated with these services.
- The more cases where solutions have been successfully implemented and seen to bring benefits, the more certainty will be provided on the business case for such services. As acceptance of the benefits that could be achieved increases, willingness to pay will also grow as users will internalise the benefits.[336]
- This could stimulate competition and innovation in the provision of private networks driving MNOs to develop hybrid-network or network slicing alternatives (as described in Section 3.2) more quickly, giving enterprise and industrial users more choice for meeting their (private) connectivity needs.

If multi-operator neutral host network models emerge that use access to local or shared access spectrum to provide specific cellular coverage indoors, in dense city locations, or for rural coverage where MNOs will not deploy directly, this can be net beneficial where this is supportive of roll-out of advanced wireless connectivity services outside of the MNO footprint. This could help reduce the gap between the baseline model and the policy targets, given that these alternative operators could support incremental coverage.

The types of impact described above may occur in instances where neutral hosts target areas where the MNOs will be slow to deploy, or if there are innovative business models that would enable the neutral host to provide the coverage on a more cost-effective basis, such that the coverage can be extended to areas deemed

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[335] This includes spectrum in the 800MHz, 900MHz, 1400MHz, 1800MHz, 1900MHz, 2100MHz, 2300MHz, 2600MHz and 3.4GHz bands.

[336] As discussed in Section 7, this is a key enabler of avoiding market failures in network roll-out requirements.

uneconomic my MNOs. For example, if alternative operators could enter and provide coverage in those areas deemed uneconomic for public mobile networks under the modelling exercise, significant additional value could be unlocked.[337] Whether this is possible would depend on the specific business plan of the alternative operator, and this has not been modelled as part of this project.

Given the scope for such benefits, any interventions that can be made to remove barriers and support the efficient entry of alternative operators should be considered, particularly where it can be done at relatively low cost.

8.4.1 MNCs

In order for cellular networks to function, they require the mobile network to be identified by an MNC. Details of how MNCs are allocated in the UK are set out in Ofcom's local access licence guidance document:[338]

- It is Ofcom's duty to administer the UK's National Telephone Numbering Plan, including allocating MNCs and telephone numbers.
- Allocations of numbers to communications providers for public network use is carried out via Ofcom's number management system (NMS).
- Licensees wishing to deploy a public network and in need of an MNC should apply for allocation via the NMS.
- Ofcom's policy is not to allocate an exclusive MNC or telephone numbers for use in private networks.
- For private networks needing to input an MNC, the International Telecommunications Union (ITU) has made available the mobile country code (MCC) 999 for internal use within a private network.
- Users are able to select any two- or three-digit code for their network.

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[337] For example, in Section 7.1.2 we demonstrated that under Scenario 3, a large number of regional, rural areas were deemed uneconomic (see Figure 7.9). However, the cumulative GVA uplift expected across the payback period for those areas should advanced wireless connectivity services be taken up, as determined in the model, amounts to a total of over GBP570 million in 2020 terms. We note that this value relates to the GVA uplift counting only those businesses that would be served by a single hypothetical MNO in the UK market under this scenario, so the overall value of serving business customers that are not served by any UK MNO could be a multiple of this. If alternative operators can unlock even a share of this value, then the benefits could be significant.

[338] Ofcom, Local Access Licence, Guidance document; available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0037/157888/local-access-licence-guidance.pdf

- No interaction with ITU or Ofcom is required to use an MNC under this MCC for **internal use** within a private network. However, as MNCs are not subject to assignment, they are not unique.

Alternative operators face difficulties in accessing unique MNCs for private networks. For example, in the stakeholder interviews a stakeholder explained that while it has one network code, it needed at least two as separate codes are needed for public and private use.[339]

Under the current approach, the private network codes obtained from the ITU do not give a unique assignment, and our understanding is that this code would not be suitable to enabling roaming with any other network. Without a unique MNC, 3GPP protocol-based roaming – logging on to the visited network with the access data of the home network – is therefore not possible. We note that similar issues have been discussed elsewhere. In Germany, the BNetzA manages network identifiers nationally. It had previously adopted the same concept as in the UK, not issuing unique codes for private networks and requiring operators to use the ITU MCC 999, but without a unique identifier, thus meaning that roaming was not possible. In February 2022, BNetzA announced a series of rules to assign specific network identifiers to operators of local, non-public mobile networks, making it possible to differentiate networks safely.[340]

Given that this is a significant barrier, we believe that Ofcom should investigate this issue in more detail and identify solutions for offering exclusive identifiers for use in private networks.

8.4.2 Roaming agreements

Alternative operators raised the prospect of needing to set up roaming agreements with MNOs. We understand that there would be two main instances where such roaming agreements would be required:

- An alternative operator has set up a private network and there is a need for uninterrupted connection of an end-user device to a service or application when leaving the area of the private network (i.e. 'roaming out' onto the public mobile network), where continuity of connections for moving devices beyond the private network is necessary.
- An alternative operator has established a neutral host solution by deploying small-cell radio infrastructure within not-spots, using its own spectrum under a shared access (or local access) licence. It then needs roaming agreements with

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[339] Based on a stakeholder interview for this study.

[340] https://www.telecompaper.com/news/german-regulator-updates-numbering-for-campus-networks-prepares-for-de-alert--1415268

UK MNOs so that users can roam onto a UK MNO network when outside of the coverage of the not-spot local network, or for MNO users to roam on the alternative operator's neutral host network, to gain coverage in the local area in which the small-cell infrastructure is deployed. This is in line with the operating model of companies such as Telet.[341]

Some of the issues raised will be due to technical difficulties, such as those related to the issue of MNCs or because the framework for 5G-SA roaming and its technical feasibility and testing is still being developed.[342] Until there is roaming on 5G-SA, roaming will need to take place on the 4G layer under 5G-NSA. This will influence the way in which alternative operators that require roaming will have to build their advanced wireless connectivity solutions. There are also ongoing efforts to identify alternative solutions to support the technical ability to enable roaming between private and public networks. For example, Ireland-based private core network provider Druid Software is working with Proximus and BICS in Belgium to test outbound roaming between public 5G-SA networks, as well as to enable enterprises to roam between private and public network infrastructures.[343] These technical issues form part of broader industry investigations and are not considered further in this report, as there is a broader industry effort to seek ways of resolving the issues.

If the technical issues can be resolved, and where alternative solutions such as eSIMs are not in place,[344] policy intervention considerations should focus on the extent to which there may be strategic or anti-competitive reasons why MNOs may refuse to offer commercial roaming on reasonable terms, such that alternative operators will be foreclosed from entering the market.

Evidence of existing commercial agreements between MNOs and alternative operators would suggest that there are cases in which MNOs would have the

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[341] As noted in Section 3.3.1, the operating model of the company was described as a multi-operator neutral host (MONH) model. The company installed small-cell radio infrastructure within not-spots under a shared access licence, and then entered into roaming agreements with UK MNOs so that users can roam between the not-spot local network and a UK MNO network.

[342] There is ongoing work to arrive at technically feasible and workable solutions. For example, the GSMA has established the 5G Mobile Roaming Revisited (5GMRR) Task Force with the mission to define a scalable, usable and secure solution for 5G mobile roaming.

[343] https://enterpriseiotinsights.com/20211007/channels/news/druid-software-recruited-by-proximus-and-bics-to-enable-private-public-5g-sa-roaming

[344] eSIM is a global specification by the GSMA that enables remote SIM provisioning of any mobile device. End users can add or remove operators without the need to physically swap a SIM from the device, meaning the device could work on different networks depending on location. GSMA defines eSIM as the SIM for the next generation of connected consumer devices. Networking solutions using eSIM technology can be widely applied to various IoT scenarios.

incentive to offer commercial roaming subject to negotiation. The case of MVNOs is a useful example, given the prevalence of MNO–MVNO agreements throughout the UK and across Europe. Such agreements allow MNOs to fill capacity in their networks and reach end users they may otherwise not have been able to reach. If an MNO were to enter a roaming agreement with a neutral host operator using shared access or local access spectrum, this would allow the MNO to provide advanced wireless services to its own customers in areas where it is not anticipating rolling out its own infrastructure. The MNO may be willing to enter into this kind of commercial agreement if it expands coverage to its users in a more cost-effective way than extending its own network to these hard-to-reach areas.

The incentives for an MNO to allow an alternative operator to roam onto its network may be less clear, especially where the MNO sees this as a threat to its market position. This might be the case if the MNO believes that by refusing roaming, the alternative operator would not be able to provide a compelling offering in a market, for example offering a private network solution with ability to also connect to the public network when outside of the private network area.

However, it is not clear that this would be the case. There is evidence of agreements in the past where there has even been competition between MNOs to provide national roaming agreements to new entrants that would ultimately compete with the host operator in the retail mobile market. For example, when Three first entered the UK market and only had access to 3G spectrum, it needed to agree a national 2G roaming deal with other MNOs in order to offer a compelling offer to its consumers. Following the auction, Three was announced as the new entrant in the UK mobile market after acquiring 3G spectrum and it successfully negotiated a national roaming contract with O2.[345] In 2004, Ofcom remained committed to ensuring that Three could continue roaming, but it concluded that there was quite high certainty that roaming agreements would continue in the absence of regulation, given its ongoing agreement with O2 and “the willingness of at least one other 2G operator committed to negotiate”, alongside Ofcom’s ability to resolve disputes in

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[345] Ofcom’s original proposal was that 2G operators bidding in the 3G auction (in 2000) have their licences amended. It required the operators to provide national roaming to the new entrant who would be awarded 3G spectrum in the auction. However, O2 and Vodafone voluntarily accepted these amendments, known as the National Roaming Condition (Condition 69A). In 2003, Ofcom extended Condition 69A, pending consultation on whether to remove or re-impose it through another form of regulation. Sutherland (2021), ‘The regulation of national roaming’, International Telecommunications Society Budapest, 18-21 September 2021; available at https://www.econstor.eu/obitstream/10419/52213/1/672585162.pdf

negotiations should they arise.[346] Subsequently, Three held a competitive tender for 2G roaming beyond the fourth quarter of 2006, which was won by Orange.[347]

Three's experience of successfully negotiating national 2G roaming agreements demonstrates that, where the conditions are right, there can be incentives for MNOs to enter into roaming agreements even where this would enable a new entrant to compete with it in the retail market.

However, the potential to set up commercial agreements will be influenced by the bargaining power of each party and the available capacity of the host operator's network. In the case of the historical 2G national roaming agreements, Three was a new national MNO and likely to have had good bargaining power when compared to other MNOs looking to fill their networks with more traffic. Three's position would have been helped by Ofcom's clear intention to assist it in signing such a deal through MNO licence amendments and/or as a dispute resolution body.

In the present case, alternative operators aiming to provide localised private networks and/or neutral host solutions may find themselves in a weaker bargaining position. There may be a role for Ofcom to exercise its regulatory powers in order to assist alternative operators in striking such deals. The conditions under which Ofcom can currently intervene to impose a roaming obligation appear to be quite restrictive and require a high evidentiary burden. Under Section 74A of the Communications Act (2003), as amended following the implementation of the EECC,[348] Ofcom could impose a condition on a host network, "to enter into wholesale roaming access agreements relating to the relevant area or any part of the relevant area"[349] where four conditions are met:

(i) the relevant area is defined as an area where "access by end-users to electronic communications services which depend on the use of wireless telegraphy is unavailable or severely restricted"[350]
(ii) the restriction is a result of "characteristics of the relevant area that tend to make the bringing into operation of infrastructure uneconomic"[351]

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[346] https://www.ofcom.org.uk/cymru/consultations-and-statements/category-3/roaming

[347] https://www.commsupdate.com/articles/2006/05/11/h3g-switches-to-orange-for-nationwide-roaming/

[348] The UK implemented the requirements of the EU Electronic Communications Code (EECC) through the Electronic Communications and Wireless Telegraphy (Amendment) (European Electronic Communications Code and EU Exit) Regulations 2020. These Regulations amended existing UK legislation (namely the Communications Act 2003 and Wireless Telegraphy Act 2006). These amendments entered into force on 21 December 2020.

[349] 74(2)(b) of the Communications Act 2003.

[350] 74(1)(a) of the Communications Act 2003.

[351] 74(1)(b) of the Communications Act 2003.

(iii) "the provider of the host network has not made network access available on fair and reasonable commercial terms and conditions to other persons providing electronic communications services"[352] and

(iv) the wireless telegraphy licence relating to the host network must have "made clear the possibility that a requirement to provide network access or to enter into wholesale roaming access agreements might subsequently be imposed".[353]

The latter two conditions currently represent the most important obstacles for the imposition of wholesale roaming access obligations:

- First, it is not yet clear that alternative operators have tried to reach commercial roaming agreements with MNOs and whether, if they have tried, the failure to reach an agreement is due to the host network making an offer that was not fair and reasonable.

- Second, even there was evidence of unreasonable commercial terms being offered, it is unclear whether MNOs' existing licences explicitly account for the possibility that a wholesale roaming access requirement would be imposed on them.

Set against these constraints, Ofcom does ultimately have powers under Section 73(2) of the Communications Act 2003 to impose access-related conditions for the purpose of securing: (a) efficiency; (b) sustainable competition; (c) the bringing into operation, where Ofcom considers it appropriate, of very-high-capacity networks; (d) efficient investment and innovation; and (e) the greatest possible benefit for the end users of public electronic communications services.

In the absence of access-related obligations, national roaming will remain subject to commercial agreements and the terms of the agreement will be open to negotiations. There may be merit in Ofcom investigating this issue further and providing guidance on whether it considers that amendments to MNO licences may be required. This would be particularly relevant if there is evidence of specific agreements not being reached due to unreasonable refusals by MNOs to enter into roaming agreements and/or the failure to offer fair and reasonable terms of access.

8.4.3 Local access spectrum

Under the local access licence scheme, a licence can be granted in a particular area if Ofcom and the relevant MNO agree that the MNO will not be using the spectrum at that location, or is not planning to do so within the time period requested (a default of three years), and that the transmitter would not cause interference to

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[352] 74(1)(c) of the Communications Act 2003.

[353] 74(1)(d) of the Communications Act 2003.

nearby deployments.[354] In this case the licence will be granted to the alternative operator for a one-off flat fee of GBP950.

In launching this option, Ofcom stated that:

"Allowing access to these bands potentially provides additional spectrum options for people wishing to use spectrum that supports mobile technology, whilst recognising the fact that there are licensees with existing rights of access to mobile spectrum on a UK-wide basis […] Given the nature and extent of existing use of licensed mobile spectrum we anticipate that spectrum is only likely to be available to share in remote areas to support, for example, private networks or wireless broadband services. There may also be other specific locations that are not served by the existing mobile network, for example underground mining operations, where mobile technology to support a private network could be utilised without impacting the incumbent network or future plans".[355]

This provides a welcome route to allowing alternative operators access to spectrum in specific local areas at low cost, stimulating innovation and extra coverage and services beyond those areas covered by MNOs.

As mentioned, however, licences are granted for a default duration of three years.[356] Despite there being evidence of take-up of a number of these bands,[357] there is considerable uncertainty associated with having a licence revoked after just the default period of three years. This suggests it would be difficult to build a strong business case in the context of a three-year licence that has no guaranteed prospect for renewal. These licences may allow for testing of new innovations, but cannot be guaranteed for longer-term use.

It is relevant to consider whether making policy changes that could lead to increased certainty for businesses wishing to make use of local access licences in the longer term could be justified. Such policy changes could provide opportunities for longer-term entry and innovation. We consider two policy change options below.

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[354] Given the amount of spectrum requested, proposed location and requested technical parameters put forward by the alternative operator. Paragraph 1.9 , https://www.ofcom.org.uk/__data/assets/pdf_file/0037/157888/local-access-licence-guidance.pdf

[355] Paragraphs 4.1–4.2 of Ofcom, 'Enabling wireless innovation through local licencing'

[356] However, as we discuss below, in some cases requests for longer-duration licences are possible, but will likely require a prior agreement with the incumbent operator to be in place before Ofcom proceeds with the application.

[357] For example, see: https://www.ofcom.org.uk/__data/assets/pdf_file/0021/222591/local-access-licences.pdf

Extending the default licence period

One option would be to consider extending the default licence period beyond three years. An extreme case would be to extend the licence for indefinite use. In the stakeholder interviews, a stakeholder noted that a ten-year licence may be more appropriate than the current three-year licence. Extending the licence might provide increased certainty to invest, however the incentives for an MNO to give up its rights to use that spectrum indefinitely will be low. There is an option value associated with retaining access to spectrum which the MNO has paid market value for in an auction.

Extending the default licence period may reduce the amount of spectrum available for local access licences, given that under this regime the MNO would not receive a payment for sub-licencing the spectrum. This could be resolved if there is an opportunity for commercial negotiations in which the MNO would be able to strike a deal with the alternative operator. This option is discussed further in the following subsection.

In the case of significantly longer default licence durations under the local access regime, existing licence holders may prefer to instead operate under the existing spectrum trading framework. Under this framework, it is possible for third parties to gain longer-term access to currently licensed mobile spectrum, but this would be based on a commercial agreement between the parties, and Ofcom would have limited involvement. The ability to enter into commercial agreements for leasing of spectrum to third parties would provide greater incentives for the MNO to provide access to some spectrum. As discussed below, this will likely result in alternative operators facing much higher prices for access, potentially limiting the number of transactions that will take place.

Allow for negotiation for longer agreements

Ofcom notes that in some cases, it may be desirable and possible to negotiate (through agreement with the existing licensee) a term of licence that is longer than the default of three years.[358] Commercial negotiations may also involve arrangements such as: “an MNO deciding to forgo deployment in that area or make changes to its network to accommodate the third party user. Alternatively, the third party may offer to extend the MNO’s coverage at that location […] These negotiations will be between the applicant and incumbent MNO and Ofcom will not impose such terms”.[359] As such, an existing licensee is not obliged to share its

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[358] See paragraph 1.10; https://www.ofcom.org.uk/__data/assets/pdf_file/0037/157888/local-access-licence-guidance.pdf

[359] See paragraph 3.11; https://www.ofcom.org.uk/__data/assets/pdf_file/0037/157888/local-access-licence-guidance.pdf

spectrum nor would necessarily agree to a commercial agreement beyond the default terms of the local access regime (presumably unless the value the alternative operator is willing to pay for access to spectrum is greater than the value the MNO attaches to it).

Larger, more established alternative operators may already be operating at scale in other jurisdictions, have a proven business case and/or have strong financial backing. These operators may be able to enter into successful commercial negotiations with MNOs in some cases. However, where the alternative operators are small and looking to obtain licences to enter the market at a very local level for a very specific purpose, they may not have sufficient access to funds to negotiate a commercial agreement with MNOs for use of spectrum based on different terms of access beyond the default provisions.

This in itself is not evidence of a market failure and does not, on its own, provide justification for more regulatory interventions.

Such interventions would require a finding of a market failure in the form of:

- very strong demand for spectrum from alternative operators to provide services with a positive social benefit that exceeds the costs to MNOs of holding on to spectrum, and
- MNOs amassing spectrum by unreasonably refusing requests from applicants for access or offering unfair terms, on a wide scale.

Regulatory interventions could include imposing access conditions on MNOs to require operators to share their unused spectrum on FRAND terms, subject to review from Ofcom of what would be deemed a reasonable request. The regulatory powers Ofcom could use to mandate MNOs to share access could either be anchored in article 73(2) of the Communications Act 2003, or may require separate legislation, such as the Communications (Access to Infrastructure) Regulations 2016, which is currently limited to physical infrastructure assets.[360]

When considering the need to impose more intrusive obligations in the context of the local access spectrum regime, it is important to note that alternative operators also have the option of accessing spectrum on a long-term basis, at low cost and with an indefinite licence through the shared access spectrum regime.

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[360] The Communications (Access to Infrastructure) Regulations 2016.

8.4.4 Shared access spectrum

As an alternative to local access licences, alternative operators could seek access to spectrum in a defined shared access band (including 1800MHz, 2300MHz, 3.8–4.2GHz) which is granted for an indefinite period.[361] [362]

Under the current shared access licencing system:

- users apply to Ofcom for licence(s) for the location(s), band(s) and bandwidth(s) that they need to provide a service
- Ofcom assesses requests with regards to interference to and from other licensees in the band
- Ofcom grants individual licences for the requested location(s), band(s) and bandwidth(s) on a first-come, first-served basis, where there is no undue interference with other users[363]
- licences are granted with some restrictions on deployment (such as height of sites and power limitations).

However, some issues with the current shared access regime were raised in stakeholder interviews conducted as part of this project. These issues may be restricting alternative operators' ability to obtain access quickly and with certainty, and to be able to use any licence granted to its full potential, given the technical limitations imposed. Specifically, we consider issues raised in relation to:

- the process for getting access to licences, including issues with the 'first-come, first-served' basis of award; the (lack of) predictability in the application process; the (lack of) transparency in the process; and the absence of an automated system for awarding spectrum
- technical limitations imposed on shared access licences.

The first-come, first-served approach

Under the shared access regime, licences are issued on a first-come, first-served basis. We understand that Ofcom is not the only regulator to offer licences targeted at supporting innovation for enterprise use cases on a first-come, first-served basis[364]

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[361] Shared access licences are available per 10MHz (up to 100MHz) in 3.8–4.2GHz, per 10MHz in 2.3GHz bands, and per 2×3.3MHz in the 1800MHz band. For the 26GHz band, 50, 100 or 200MHz channels can be applied for, but are for indoor use only.

[362] We note that Ofcom has also recently announced a consultation on adding the upper 6GHz band from 6425–7025MHz into the shared access licence regime, for low-power, indoor use: https://www.ofcom.org.uk/consultations-and-statements/category-2/spectrum-sharing-upper-6-ghz-band

[363] Paragraph 3.5 of Ofcom, 'Enabling wireless innovation through local licencing'.

[364] Digital Regulation Platform (2020), Spectrum licencing: local and private networks in Germany, 6 October. https://digitalregulation.org/spectrum-licensing-local-and-private-networks-in-germany/

and that awarding spectrum in this way is aligned with policy goals to promote access to spectrum for rapid deployment and adoption of new 5G applications.

While the first-come, first-served system may not necessarily be a problem in the initial stages of deployment, a stakeholder noted that such an approach could expose some potential users to the risk of not receiving spectrum where there are competing applications for use of this spectrum. This could create issues for the efficient allocation of spectrum and the risk that the spectrum is used for a sub-optimal purpose where competing demands emerge for spectrum at specific locations.[365]

An alternative approach would be to move to a 'command and control' or 'beauty contest' approach. Ofcom would consider a range of potential uses for the spectrum in a given area, based on a range of submissions, and would then choose which one(s) should be awarded the licence based on its assessment of which candidates will make the best use of the spectrum. However, this would go against the principle of allowing a wide range of different innovations to be tested. Alternatively, Ofcom could ask alternative operators to submit bids that express the value they have attributed to the spectrum to determine the most efficient allocation. However, this would add to the cost and complexity of the system and also result in delays or administrative barriers for smaller players. In both cases, this would also require waiting until there are a number of competing requests for access, the timing of which would be uncertain and may never emerge. Waiting until there is demand across different operators, would mean a delay to the emergence of services and, therefore, a delay in the potential benefits that could be achieved by facilitating innovation by allowing access to requests on a first-come, first-served basis. As noted by Ofcom, its "overarching principle is to ensure that lack of access to the radio spectrum is not an inhibitor of innovation and that new users who need to access to spectrum are able to do so under a simple and common approach".[366]

We believe that delays to allow for an assessment across competing uses would stifle innovation, and that the first-come, first-served approach has the benefit of spurring innovation without delay. Attentive providers will be incentivised to seek access before others do, thereby bringing forward innovation. This will continue to be a favourable approach provided there are options to ensure local licences cannot be exploited to limit local competition, for example by ensuring that there is no local spectrum hoarding by holders of shared access spectrum. With regard to preventing hoarding, a 'use it or lose it' approach is currently in place for shared access licences. Ofcom has also stated that transmissions must commence within six months of the licence being issued, else there is a risk of the licence being revoked.[367]

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[365] Where subsequent requests for spectrum in a given location cannot be accommodated due to a first application being granted in that location, depending on spectrum available and interference, but use of that spectrum could bring greater value.

[366] Paragraph 2.4 of Ofcom, 'Enabling wireless innovation through local licencing'.

[367] Paragraph 1.9 of Ofcom, 'Enabling wireless innovation through local licencing'.

At present, we believe that changes away from the first-come, first-served approach would be more likely to hinder innovation and delay the launch of new services, and are therefore unjustified.

The lack of predictability, transparency and automation in the application process

A local network provider believed there were several issues with the shared access licensing process, including that the spectrum system was not yet fit for purpose, particularly if shared and local access spectrum were to be rolled out at a much larger scale.[368] It also believed that, in order to be fit for purpose, the shared spectrum application and award process needs to be more predictable and repeatable; for example, it noted there is currently no defined timeframe for a licence to be granted.[369]

The UK Spectrum Policy Forum[370] identified similar process-related issues. In a workshop that reviewed the extent to which current shared spectrum access is creating the right conditions for new players to provide innovative 5G services, it was noted that:

- where the shared access licensing process takes too long, it can hinder commercial discussions between suppliers and customers[371]
- administrative improvements to the application were needed, e.g. allowing applicants to modify applications after being submitted, to enable more efficient application processes, lowering the barriers to applying[372]
- automation of Ofcom's processes for shared access licences would help provide applicants with a better and more timely view of spectrum usage in the areas being considered by the applicant, and help streamline the process enabling faster access.[373]

In order to scale up business plans and commercial deployment, we believe that alternative operators would benefit from more clarity on the process, in particular regarding how long the process is going to take from initial application to approval and clearer early indications of the feasibility of obtaining a spectrum licence.

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[368] Based on a stakeholder interview for this study.

[369] Ibid.

[370] The UK Spectrum Policy Forum is part of TechUK and is a group of stakeholders who act as an industry-led 'sounding board' to UK government and Ofcom on future policy and approaches on spectrum. It seeks to promote the role of spectrum in society and the maximisation of its economic and social value to the UK.

[371] Plum (2022), 'SPF Cluster 3: The future of spectrum sharing in the UK', 27 January 2022, p. 8.

[372] Ibid.

[373] Ibid.

As noted above, the current system is assessed on demand and on a case-by-case basis. Therefore any potential friction will become apparent at the second stage in which interference assessment is considered. We understand that the interference/co-existence assessment can take time and requires engagement between all parties that may be subject to interference, to assess how interference can be resolved and whether there is a workable solution.

We consider two broad options that could be applied to help improve the shared access approach:

- introduce more transparency into the regime, automating as many steps as possible to help speed up the process
- shift to a more dynamic approach to spectrum management in these bands, such that there is greater flexibility in the regime.

► *Greater transparency*

There are two key areas where greater transparency in the application and approvals process could help provide increased certainty to applicants on the likelihood of being granted access and the time taken for approval, thus allowing them to build a business case with certainty. This will be particularly helpful if the business case is dependent on deploying a solution in a number of locations and with similar technical parameters.

Ideally this would involve setting an upper limit on how long it should take to get licence approval. For example, it is clear that, if demand for shared access spectrum increases, a rapid turnaround in application times will be needed. It would be helpful if Ofcom considers improved online access for shared access spectrum so that applications could be instantly co-ordinated, or co-ordinated in a matter of days, such that provisional agreement can be granted. Furthermore, there should be a target on completion of the whole process (including full approval and issue of licensing documentation), such as a four-week turnaround from application to grant of licence.

Further, providing a clear record or prior assessment of the location(s), band(s) and bandwidth(s) that would be permitted in each local area for which licences could be awarded could also support a forward view of the likelihood of new applications from an alternative operator being approved.

Under the current licensing process, such steps may be difficult to achieve. A time limit on manual checks could put extra pressure on Ofcom resources if there is a surge in applications, for example. A comprehensive overview of pre-approved cases would likely be very complex, given it will be dependent on the specific requirements of the alternative operator and the deployments in an area. These may change over time as other licensed operators change deployments in that area, potentially altering any prior co-existence analysis.

There would be merit in Ofcom considering how much of the overall process could be automated to help ease some of these constraints, and as discussed below, this is something Ofcom has already considered. We note in this regard that the French NRA, ARCEP, has introduced automated processes for shared spectrum. It uses a web-based platform to manage online applications and other elements of the authorisation process.[374] Once the application has been submitted, the regulator can easily identify any frequencies with which the applied spectrum overlaps; the status of the application is also updated through the process, giving the user more transparency.[375]

To the extent that Ofcom is able to automate the authorisation process, this could give users more rapid access to spectrum which suits their needs. In general, this could help overcome some of the process-related issues that stakeholders have experienced when using the existing licensing process for shared spectrum, and could expedite the licensing process. A faster and more transparent process could also make it more available for widespread use, potentially enabling more users to seek access to shared access bands, in line with Ofcom's objective.

However, the key enabler of moving to such an approach would be the development of a database with accurate and up-to-date spectrum information and transparency about the way in which this information is sourced.[376] The main hurdle to establishing such a process would be the significant resources required to build such a database, as it will need to hold all up-to-date information about the location and frequency of all users and support automated co-existence analysis.

We observe that in its Plan of Work for 2022/23, Ofcom has noted that it will consider the potential role of automated assignment databases in future spectrum management.[377]

Once such a database is in place, there would be scope for shifting to more dynamic spectrum management of shared access spectrum, which could support more efficient use of shared spectrum as more demand and potentially competing demands emerge. We provide an overview of what this could involve and the potential costs and benefits below.

- ► *Dynamic spectrum access*

Dynamic spectrum access (DSA) is a process whereby radio equipment accesses spectrum at the location and time required on frequencies not used by other

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[374] ATDI (2021), 'Managing Dynamic Spectrum Analysis', 20 May 2021; available at https://atdi.com/managing-dynamic-spectrum-access/ [accessed 10 March 2022].

[375] Ibid.

[376] Plum (2022), 'SPF Cluster 3: The future of spectrum sharing in the UK', 27 January 2022, p. 11.

[377] https://www.ofcom.org.uk/__data/assets/pdf_file/0019/234334/Statement-Plan-of-Work-2022_23.pdf

licensed uses in that band. These frequencies are typically located through communication with a database that provides a determination of spectrum availability. Ofcom has defined DSA as “a technology for a variety of reconfigurable radio equipment allowing it to select the frequency on which it will operate at a given location and over a given period of time to optimise the use of available spectrum and avoid interference with other radios or other systems.”[378]

An example of DSA in use is in the USA, as part of the Citizen’s Broadband Radio Service (CBRS), which is a digital automated system designed to enable local users to gain access to spectrum that is already used by incumbent services specific to the market in the USA. Automated systems are designed to determine if usage is feasible in a given location and frequency to avoid interference to the incumbent service.[379] Automatic frequency co-ordination systems are also proposed in the USA for use in the 6GHz band, which the USA has opened for licence-exempt use.[380]

CBRS: an overview

In 2015, the Federal Communications Commission (FCC) adopted rules which enabled shared commercial use of 150MHz of spectrum in the 3.5GHz band (3350–3700GHz).

The FCC established the CBRS as a three-tiered authorisation framework to enable shared access to spectrum in this band. The three tiers comprise:

- **Incumbent access**: authorised federal users, fixed satellite service and legacy wireless broadband licences; these users receive protection from harmful interference from priority access and general authorised access (GAA) users.
- **Priority access**: users hold Priority Access Licences, or PALs (which are being auctioned on a regional basis); these users, who receive a 10MHz channel, must protect and accept interference from incumbent users, but receive protection from GAA users. Licence conditions include power limits to prevent interference to incumbent users, which are more restrictive than the power limits typically applied in licensed mobile spectrum.
- **GAA users**: this licensed-by-rule tier (i.e. unlicensed but users must adhere to FCC rules) provides access to the widest possible group of users; these users must not cause interference to incumbent access or priority access

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[378] Ofcom (2020), ‘Supporting the UK’s wireless future: Our spectrum management strategy for the 2020s: Consultation’, 4 December 2020, p. 106.

[379] Based on a stakeholder interview for this study.

[380] https://www.federalregister.gov/documents/2021/10/21/2021-22765/fcc-requests-6-ghz-automated-frequency-coordination-proposals?msclkid=b2174e8aa5e411ec9376d6421aaabf95

users and must accept interference from these users, and also do not have interference protection from other GAA users. Power limits also apply.

CBRS dynamically manages the use of this shared spectrum across the different tiers of users, to protect incumbent access users and manage GAA use alongside priority access. This is enabled by:

- **Spectrum Access System (SAS):** this is an automated frequency co-ordinator tool, which dynamically manages spectrum use via an Environment Sensing Capability sensor (see below).
- **Environment Sensing Capability:** this detects and communicates the presence of a signal from an incumbent user to an SAS to facilitate shared access.

As an example of the type of use that CBRS has enabled via the GAA layer, CBRS spectrum has reportedly been used by a baseball stadium to support internal communications used within the stadium, as well as for a neutral host provider which offers support to MNOs managing traffic demand for customers attending events.

Sources: Federal Communications Commission (2020), '3.5GHz Band Overview', 10 March 2020; available at: https://www.fcc.gov/35-ghz-band-overview (last accessed 7 March 2022); Dynamic Spectrum Alliance (2020), 'CBRS: A Spectrum Sharing Success', 29 September 2020; available at: http://dynamicspectrumalliance.org/cbrs-spectrum-sharing-success/ (last accessed 7 March 2022); RootMetrics (2020), 'CBRS spectrum: An overview of use cases and user tiers', 30 November 2020; available at: https://rootmetrics.com/en-US/content/new-ebook-an-overview-of-cbrs-spectrum-use-cases-and-user-tiers (last accessed 7 March 2022).

The benefits of automated spectrum management tools might include the following:

- Making it quick (in 'near real-time') to authorise and modify spectrum access. This can be faster than manual processes, which rely on human interaction and the potential need to manually reconfigure equipment.[381]
- Improving the flexibility of access: it can make it easier to change the frequency assigned to specific users and enable users to change their operating parameters over time, if permitted to do so.[382]
- Enabling shared access spectrum to be used efficiently, e.g. providing users with greater access to the spectrum
  - automated spectrum management could enable access to spectrum that might go unused under a conventional licensing regime

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[381] Ofcom (2020), 'Supporting the UK's wireless future: Our spectrum management strategy for the 2020s: Consultation', 4 December 2020, paragraphs 6.17 – 6.18.

[382] Ibid., paragraph 6.19.

  - for example, this could allow more opportunistic access (e.g. on a short-term basis) to shared spectrum and enable shared frequencies to be made available automatically when they are not being used by other users.[383]

- If the automated database records the location and frequency of all users, it could make it faster and easier to locate sources of interference, supporting an improved approach to managing coexistence, which could support improved spectrum sharing.[384]

There are, however, some drawbacks associated with automated spectrum management approaches, such as the additional time, costs and complexity of developing, maintaining and operating the necessary database(s). The CBRS implementation imposes transmitted power limits in PALs and GAA to avoid interference to the incumbent services. This reduces potential for the PALs to be used for wide-area mobile connectivity, unlike in the UK, where the 3.5GHz spectrum licensed to MNOs can be deployed on macro sites and with higher transmitted power. There may also be issues with availability of spectrum in some locations for GAA use, for example in locations where PALs are in use. There could also be additional costs to industry to develop radio equipment that is compatible with the automated database system.[385]

Ofcom has already implemented shared use of mobile spectrum via the local licensing approach, which creates a shared access environment but without the use of databases.

In terms of the potential for implementation of DSA approaches in selected bands in the UK market, we note that there are mixed views among stakeholders. The UK Spectrum Policy Forum has found that, while its stakeholders agreed there is a need for existing mechanisms to be automated, there was no clear position on how far this should go with respect to DSA. There were three broad points of view:[386]

- **Move to DSA**: some stakeholders believe the move to DSA should be made straight away since the systems needed already exist and waiting means innovation opportunities will be missed and it will be too late to ensure spectrum is used efficiently.

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[383] Ofcom (2020), 'Supporting the UK's wireless future: Our spectrum management strategy for the 2020s: Consultation', 4 December 2020, paragraph 7.36.

[384] Ibid., paragraph 7.38.

[385] In the USA, a range of vendors (including Nokia and Ericsson) have developed equipment certified to work with CBRS spectrum. See OnGo Alliance Certified Devices, https://ongoalliance.org/certification/ongo-certified-devices/ [accessed 10 March 2022].

[386] Plum (2022), 'SPF Cluster 3: The future of spectrum sharing in the UK', 27 January 2022, p. 11.

- **Develop a pragmatic roadmap**: some stakeholders were of the opinion that the transition to DSA should be a multi-step process requiring active discussion to ensure a widely standardised ecosystem, ensuring transparency over how information is sourced.

- **No need for DSA**: some stakeholders stated that the first-come, first-served system (which applies to shared access licences) would be sufficient for the foreseeable future.

We note that Ofcom has already considered the steps required to move to a more automated, dynamic approach in future should this be required in the UK market, as set out below.

Ofcom’s position on moving towards a dynamic approach

Ofcom has explained that the current shared access regime is an interim measure and that, in time, it would move to a fully automated database approach (if appropriate).[387]

With this future potential transition in mind, Ofcom states that it has already embedded the DSA concept in its shared access licensing approach: it can notify included licensees of the need to change frequencies in the 3.8–4.2GHz band. It also requires equipment to transmit within six months of the licence being issued and can revoke the licence if the equipment is not transmitting, which helps to ensure that spectrum is used by those who need it.[388] Ofcom also encouraged users to deploy equipment that has the capability to be used across the full 3.8–4.2GHz band, which enables it to be flexible and efficient in managing future access.[389]

Ofcom has stated that it will continue to develop automated spectrum management tools to support its objectives of providing flexibility in spectrum use to support innovation, with appropriate assurances for continued use; and to encourage sustained improvements in the efficiency of spectrum use.[390] In its workplan for 2021/22, Ofcom has stated it will explore a fully automated authorisation approach for access to shared spectrum, which could enable more efficient access to spectrum in the future.[391] It has renewed this commitment in its 2022/23 workplan.

Overall, Ofcom believes that while there are benefits associated with an automated spectrum management approach, it will also add complexity and cost. Therefore, it will make judgements as to when this approach should be used, and will focus on the bands where it is most relevant and brings the biggest benefits.[392] Ofcom has, however, cited the 3.8–4.2GHz band as being the most promising band for automated spectrum management.[393]

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[387] Ofcom (2019), ‘Enabling wireless innovation through local licensing: Shared access to spectrum supporting mobile technology’, 25 July 2019, paragraph 186.

[388] Ibid., paragraph 187.

[389] Ibid.

[390] Ofcom (2021), ‘Supporting the UK’s wireless future: Our spectrum management strategy for the 2020s: Statement’, 19 July 2021, pp. 25–26.

[391] Ofcom (2021), ‘Ofcom’s plan of work 2021/22: Making communications work for everyone’, 26 March 2021, p. 40.

[392] Ofcom (2020), ‘Supporting the UK’s wireless future: Our spectrum management strategy for the 2020s: Consultation’, 4 December, paragraph 6.21.

[393] Ofcom (2020), ‘Supporting the UK’s wireless future: Our spectrum management strategy for the 2020s: Consultation’, 4 December 2020, paragraph 6.20.

Overall, the long-term approach to shared spectrum licensing should be driven, at least in part, by the level of demand by users. In the short term, further clarity on the existing shared access licensing regime and making spectrum available in a timely manner would be beneficial. In particular, it might be appropriate for Ofcom to:

- Consider providing greater clarity to potential and existing spectrum users about the timeframes in which licence applications would be processed.
- Consider improved online access for shared access spectrum so that applications could be instantly co-ordinated, or co-ordinated in a matter of days, such that provisional agreement can be granted. Furthermore, there should be a target on completion of the whole process (including full approval and issue of licensing documentation), such as a four-week turnaround from application to grant of licence.
- Continue to work on automated spectrum management processes, in particular focusing on areas of the process (e.g. application form, co-existence analysis and licence issuance) which could be automated sooner in order to tackle some of the issues faced by stakeholders.
- Continue its monitoring and engagement with industry to understand the demand for shared access spectrum, so that it can flexibly respond to evolving demand.
- Continue to work closely with industry on DSA implementation, and provide a clear roadmap on timescales for implementation if this option is being pursued. We note if there are relatively low levels of demand for shared spectrum, the benefits of implementing a fully automated approach risk being outweighed by the costs of implementation.

Technical limitations

With regard to technical limitations associated with shared access licences, two main issues were raised:

- Power limitations imposed on shared access licences – the current rules impose some restrictions on power, setting out different restrictions depending on whether the area is considered to be urban or rural. In rural areas, medium-power licences are allowed, while in urban areas lower-power licences will be issued. One stakeholder noted that the definitions of urban and rural are unclear.[394] Another stakeholder mentioned that power restrictions in the 3.8–4.2GHz band for the lower-power licences restrict coverage possibilities, and may not be aligned with the equipment types currently available.

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[394] Based on a stakeholder interview for this study.

- Limitations on the height that equipment such as antenna can be deployed above ground, which may limit certain deployments.[395]

It was noted that, while the limitations may not prevent development of proof-of-concept implementations, they may hold back commercialisation of the solutions at scale. We note Ofcom is seeking to address this issue through its recent spectrum roadmap, and proposals for accelerating innovation and sharing with spectrum sandboxes.[396]

► *Power limitations*

Ofcom has been clear on how it defines urban and rural areas, noting that its approach is in line with that used by the ONS, Scottish government and NISRA.[397] Ofcom has also proposed to make an interactive map available on its website to help prospective licensees check whether their deployment location falls within the rural or urban category.[398] Together, these issues should help address any uncertainty about which areas are classed as urban or rural for the purposes of power limitations and we recommend that Ofcom does follow through with its plan as early as is practicable.

We also note that Ofcom has clearly defined the process by which operators can seek to use a higher-powered licence product outside of the rural areas, in order "to strike the right balance between securing optimal use of spectrum and encouraging new uses".[399] It has stated that "[if] applicants wish to deploy in areas outside the above, but believe their use is still consistent with our policy objectives, they can approach Ofcom for us to consider their individual case". It has also set out the criteria that would need to be satisfied, including evidence that the intended use would not be technically possible using a low powered licence product.[400] The existing regime thus allows for negotiation on power limitations in specific cases and provides scope for changes where this would be essential and feasible for a specific use case, given co-existence requirements.

► *Antenna height*

The restrictions on outdoor antenna height limit outdoor base station antenna systems to be no more than 10m above ground, with the exception of the medium-power licence

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[395] Ibid.

[396] https://www.ofcom.org.uk/__data/assets/pdf_file/0021/234633/spectrum-roadmap.pdf

[397] Ofcom, 'Enabling wireless innovation through local licencing', paragraph 3.60.

[398] Ibid., paragraph 3.63.

[399] Ibid., paragraph 3.62.

[400] Ibid.

in the 3.8–4.2GHz band, where this restriction does not apply.[401] Ofcom described such restrictions as necessary "to ensure that we can accommodate as many uses as possible. Increasing outdoor antenna height has the effect of increasing the interference range which may limit others' ability to deploy."[402]

Ofcom has noted that certain deployments in rural areas may be constrained by the antenna height restriction for medium-power outdoor base stations in the shared access bands. It has therefore made clear that it can "consider exceptions to the maximum antenna height on a case-by-case basis, taking into account the potential for other users to be denied access to spectrum by the increased potential for interference".[403] Furthermore, there is no antenna height restriction for medium-power outdoor base stations in the 3.8–4.2GHz shared band, and no restrictions on indoor antenna height for any of the shared access bands. The existing regime thus allows for negotiation on antenna height limitations in specific cases and provides scope for changes where this would be essential and feasible for a specific use case, given coexistence requirements.

8.4.5 Conclusions/recommendations

We believe that the following policy considerations should be made with regard to removing potential barriers to alternative operators:

- Ofcom should investigate the issue of unique MNCs for private networks in more detail and identify solutions for offering exclusive identifiers to be used in private networks.

- To provide further confidence to alternative operators when engaging in commercial negotiations with MNOs on roaming agreements, there may be merit in Ofcom providing guidance on whether it considers that amendments to MNO licences may be required to facilitate the negotiation of roaming agreements. This would be needed, in particular, if there is clear evidence of specific agreements not being reached due to unreasonable refusals by MNOs to enter into roaming agreements and/or the failure to offer fair and reasonable terms of access. Such guidance could also address Ofcom's potential role as an arbiter in any negotiations should an agreement not be reached.

- Ofcom should continue to consider the shift to automating the shared access application and licence granting process. Should there be significant demand for such spectrum in future, DSS may need to be considered to enable further automation of the shared access licensing regime and allow for different

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[401] Ofcom, 'Enabling wireless innovation through local licencing', paragraph 3.68(b).

[402] Ibid., paragraph 3.78.

[403] Ibid.

spectrum users to co-exist. Clear priorities should be defined across users to control interference between users.

8.5 Practical deployment barriers

Deploying wireless infrastructure requires operators to co-ordinate with a range of stakeholders and comply with a range of planning rules and regulations (governed by town and country planning legislation and local regulations) as well as seeking access to land (governed by the Electronic Communication Code (ECC)).

Where there are difficulties or uncertainties with existing rules, barriers to investment may arise from frictions caused by practical challenges to deploying infrastructure which add complexity and/or are overly burdensome or time consuming, particularly where legislation is not clear. Such barriers can impede network deployment, in terms of increasing transaction costs or reducing the speed of deployment. These practical deployment barriers have been widely considered and are well documented.[404] Throughout the stakeholder interview process conducted for the present study, multiple parties mentioned the importance of minimising practical barriers, in order to reduce transaction costs and enable network roll-out. The stakeholder comments focused on a small number of specific deployment barriers related to planning for site development and negotiating with landlords.

One important practical deployment barrier in the context of wireless infrastructure is the need to acquire planning permission, and the inconsistency with which planning applications are handled. For example, Analysys Mason previously found, in a 2018 study, that the “fragmented application of planning regulations for mobile equipment, and a lack of best practice guidance, introduced additional costs for both local authorities and network providers and is limiting the ability of network providers to plan an efficient deployment of 5G”.[405] In the course of the stakeholder interviews, two participants noted that gaining planning permission for mobile equipment continues to be a challenge.[406] One of these participants highlighted the inconsistency in the application of planning rules and acceptance rates for planning permission, which impedes its ability to upgrade existing sites and deploy infrastructure in new sites in some locations of the UK – it noted that a primary reason was the appearance of mobile infrastructure in the street.[407]

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[404] See for example: Analysys Mason and Cambridge Econometrics (2021), ‘Realising the Benefits of 5G’, August 2021; Analysys Mason (2018), ‘Lowering the barriers to 5G deployment’, July 2018.

[405] Analysys Mason (2018), ‘Lowering the barriers to 5G deployment’, July 2018, pp. 19–21.

[406] Based on a stakeholder interview for this study.

[407] Based on a stakeholder interview for this study.

Another practical deployment barrier faced by operators seeking to deploy mobile infrastructure is the need to agree rentals with the landowners of the site where the operators' infrastructure is situated. The rules governing this are contained within the ECC, which was last revised in 2017. Notably, the key revisions at the time included changes in the approach to valuing sites for deployment and clarifying the process for siting and removing infrastructure, as well as providing guidelines for managing the process.[408] In its 2018 study, Analysys Mason found that while these changes were welcomed by industry stakeholders, it temporarily created uncertainty around the process while landowners adapted to the implications of the new regulations.[409]

In the course of the stakeholder interviews, one stakeholder noted that it continues to face challenges with respect to negotiating with landlords. In particular, it argued that landowners have incentives to defer renegotiations and not reach new agreements with operators since, in the absence of new agreements, they would continue to receive the old higher rental rates, and have deployed delaying tactics to achieve these higher rates.[410] It was noted that it is easier for MNOs to stay within the existing agreements, in terms of the numbers and sizes of radios, since they would need to renegotiate the lease to change this and can end up facing lengthy site acquisition issues.[411] This presents a significant challenge when rolling out 3.5GHz infrastructure since site strengthening or other significant site work (including moving from pole-mounted base stations to lattice towers) may be needed to accommodate the mMIMO antennas deployed with 3.5GHz.

One stakeholder highlighted that many of the practical barriers identified in the 2018 Analysys Mason study – including access to small-cell sites, street furniture and power – are still present in the market.[412]

8.5.1 Mechanism through which the barrier affects investment

Operators looking to invest in network expansion and improvement through upgrades to existing sites or deployment of new sites face deployment barriers that can affect the investment decision in two ways:

- Deployment barriers can impact the timing of the investment through additional transactions costs. Operators may have to go through detailed planning approval processes, with no certainty on approvals, or they may face an inconsistent

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[408] Analysys Mason (2018), 'Lowering the barriers to 5G deployment', July 2018, pp. 22–23.

[409] Ibid., pp. 22–23.

[410] Based on a stakeholder interview for this study.

[411] Based on a stakeholder interview for this study.

[412] Based on a stakeholder interview for this study.

approach to planning approvals. This means the operator's ability to actively roll out network improvement or expansion is delayed and slowed down, even in those areas where there is a clear economic case for network upgrades.

- Deployment barriers can add to the cost of investment. Operators may face restrictions on the height of poles or the ability to widen and strengthen certain site infrastructure, which may mean additional sites would need to be built in order to meet the desired coverage or quality improvement (and increasing the number of sites may then also be met with challenging planning approval processes).

In the former case, while this does not change the economics of the investment decision (i.e. where the investment decision is based on investing in those areas where the IRR exceeds the cost of capital) it will have an impact on the ability and the time it takes for deployment to occur in those areas. Removal of these barriers, which can be thought of as transaction costs, would enable the benefits of network upgrades/expansion to be experienced earlier.

In the latter case, where the barriers do have a direct impact on the costs of the investment, this may mean that there are a number of areas that are considered not to be economic under the current system. These areas could be considered to be economic if, for example, certain planning restrictions were relaxed such that the costs of site upgrades could be lowered. The benefit would come from a greater number of areas receiving network upgrades, potentially reducing the gap between the baseline level of coverage and the different target scenarios modelled in this report.

For example, where changes are brought in to support further strengthening of new sites (increasing height or increasing width to enable upgrading of existing sites) without the need for prior approval, this should allow greater speed of deployment. It could also mean that fewer new sites will be required which could also save on costs and the timing of roll-out. Where new sites are required, changes that would result in quicker approval of sites, and also would enable sites without the aforementioned height limitations, could again mean that greater coverage can be provided more easily, particularly in rural areas.

The main benefit of addressing these practical deployment barriers would come from lowering transaction costs such that any investment that is deemed economic can go ahead without undue delay.

8.5.2 Intervention options

In its 2018 report, Analysys Mason set out a number of recommendations on what steps can be taken to lower barriers to deployment.[413] Intervention could take the form of:

- legislative changes (e.g. to planning rules)
- communication to support a more consistent approach to applications and approvals
- supporting deployment by improving the methods used to gain access to essential inputs such as street furniture, backhaul and power.

Legislative changes

Legislative changes were one of the key levers identified through which changes could be made. Specifically, changes could be made to two key areas of legislation:

- The ECC – the legal framework underpinning rights to install and keep electronic communications apparatus on public and private land, and to carry out other activities needed to provide digital communications networks.

- The permitted development rights – this legislation provides broad rights that allow network providers to deploy equipment without undergoing a full planning application. England and each of the devolved nations have their own planning legislation, in terms of what is classed as permitted development (or required prior approval) and what requires full planning applications.

The issues being raised by stakeholders in interviews conducted as part of this study are very closely related to issues that could be clarified or resolved through changes to these pieces of legislation. We note that DCMS has been actively engaged on proposals for further amendments to these two key areas of legislation and has made good progress.

In fact, DCMS made two significant announcements during the course of this project and after the majority of stakeholder interviews were conducted, proposing a host of significant changes to the abovementioned two key areas of legislation, which should address many of the issues that operators are facing when seeking to upgrade and expand their networks.

First, a number of the challenges related to planning applications have been addressed following a review by DCMS – alongside the Department for Levelling up, Housing & Communities – of potential changes to permitted development rights

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[413] See for example: Analysys Mason and Cambridge Econometrics (2021), 'Realising the Benefits of 5G', August 2021; Analysys Mason (2018), 'Lowering the barriers to 5G deployment', July 2018.

for electronic communications infrastructure.[414] On 7 March 2022, the UK government announced the changes it will take forward to permitted development rights to provide greater certainty of what developments can be made without prior approval (in England).[415] This seeks to address many of the issues that have been raised by stakeholders to date.

Second, in November 2021, DCMS set out its findings with regard to other barriers faced in coming to agreements, based on feedback from stakeholders. DCMS set out its view on further revisions to the ECC, in particular to achieving its ambitions with regards to gigabit broadband and 5G in the UK. It is seeking to tackle three key areas where a range of reforms to the ECC could have the biggest benefit:[416]

- **The attainment and use of code agreements**, including a range of measures to tackle the lack of engagement and collaboration in negotiations; a process to help address non-responsive and non-identifiable occupiers; and clarifications regarding who can agree code rights.
- **The right to upgrade and share apparatus**, including clarifications with regards to sharing infrastructure and amendments in relation to the process for upgrading; and sharing apparatus installed before the 2017 reforms to the ECC.
- **Expired agreements**, including enabling different routes to renewal; reforms to improve the timescales for ECC disputes; and introducing a procedure to permit interim arrangements for renewal negotiations.

DCMS also completed a review of the ‘Access to Infrastructure' regulations in November 2021. This should provide clarity on how infrastructure can be shared across electronic communications, gas, electricity (including public lighting, heating,

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[414] Department for Digital, Culture, Media & Sport, Department for Levelling up, Housing & Communities (2021), ‘Changes to permitted development rights for electronic communications infrastructure: technical consultation’, 20 April 2021; available at: https://www.gov.uk/government/consultations/changes-to-permitted-development-rights-for-electronic-communications-infrastructure-technical-consultation.

[415] https://www.gov.uk/government/consultations/changes-to-permitted-development-rights-for-electronic-communications-infrastructure-technical-consultation.

[416] Department for Digital, Culture, Media & Sport (2021), ‘Access to land: consultation on changes to the Electronic Communications Code - government response’, 24 November 2021; available at: https://www.gov.uk/government/consultations/consultation-on-changes-to-the-electronic-communications-code/outcome/access-to-land-consultation-on-changes-to-the-electronic-communications-code-government-response.

water and transport), reducing the time and cost it could take to roll out new telecoms networks.[417]

While the recent legislative changes are positive, it will take time before the impact on the telecoms market can be determined.

A clear and consistent communications strategy

The proposed changes to legislation could have a significant impact and may address a number of the key issues raised by stakeholders with regard to planning and negotiations. However, in order for these changes to be made quickly and taken into account and implemented in a consistent way, and to avoid a fragmented approach, support should be provided for operators, councils, landlords and intermediaries to better understand the revisions and implement the changes. In this regard **a collaborative approach with government, operators and landlords will be needed to ensure everyone is aware of the changes. Changes need to be implemented and reflected across the board in a timely manner so the benefits of the changes can be realised as soon as possible**. We understand that there is currently work ongoing that will help with this objective. Specifically, a new Code of Practice for Wireless Network Development in England will provide further guidance for representatives of the mobile industry, other government departments, regulators and local planning authorities focused on the siting and design of wireless infrastructure and the process for engaging with local authorities and communities.[418]

As planning is a devolved matter, the changes to permitted development rights are currently focused on changes in England only. Hence, **DCMS and the** Department for Levelling up, Housing & Communities **should consider collaborating with the devolved governments to develop a harmonised approach to planning regulations for mobile infrastructure**.

A clear communication strategy could also be beneficial. Such a strategy could raise awareness of the benefits of advanced wireless connectivity, specifically to local areas, which can provide targeted messaging for local authorities and the public of the benefits of these new services. Working alongside communications to

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[417] https://www.gov.uk/government/publications/review-of-the-access-to-infrastructure-regulations-call-for-evidence/review-of-the-access-to-infrastructure-regulations-call-for-evidence-government-response

[418] https://www.gov.uk/government/consultations/changes-to-permitted-development-rights-for-electronic-communications-infrastructure-technical-consultation/outcome/changes-to-permitted-development-rights-for-electronic-communications-infrastructure-government-response-to-the-technical-consultation

address the specific concerns of local authorities or individuals,[419] this communications strategy could help build further support for approvals beyond local authority ‘digital champions’ and get deeper buy-in from across teams within a local authority and from the local public. This work could be led by DCMS with support from industry organisations such as the Broadband Stakeholder Group[420] and the ‘Local Connectivity Group (set up by DCMS with assistance from TechUK) and the Digital Connectivity Portal.[421]

Deployment support

There are a number of challenges related to the deployment of wireless networks. They include getting access to publicly owned infrastructure assets to support the roll-out of advanced wireless connectivity. We note that further steps are being taken to try and find other ways of reducing barriers, through making interactions with local authorities easier and by means of lower transaction costs. For example, the ‘Digital Connectivity Infrastructure Accelerator’ (DCIA) programme has been launched. In this programme, eight winning projects will receive a share of GBP4 million to explore how digital software can help simplify processes involving local authorities. The details of the project are provided below.

The DCIA programme

In the DCIA programme, eight winning projects will receive a share of GBP4 million to explore how digital software can help simplify local authority processes when telecoms operators request access to publicly owned buildings and curb-side infrastructure.

Street furniture such as road signs and CCTV poles can be used to improve 4G coverage. They are also integral to the roll-out of 5G, which requires a larger number of smaller cell sites – where antennas and other telecoms equipment are placed to form a network – to ensure seamless coverage and to meet surging demand for connectivity.

However, telecoms firms often find it challenging and time consuming to acquire the information needed to verify that a structure is suitable for hosting network

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[419] Such as Ofcom’s ‘Guide to 5G Technology’ to support local authorities and address unfounded safety claims; see https://www.ofcom.org.uk/__data/assets/pdf_file/0015/202065/5g-guide.pdf

[420] The Broadband Stakeholder Group has already done some work in this area, looking at ways to promote the benefits of very-high-capacity networks at a local level; see Broadband Stakeholder Group, Local Benefits of Full Fibre and 5G’: http://www.broadbanduk.org/2019/09/13/bsg-report-local-benefits-for-full-fibre-and-5g-2/

[421] https://www.gov.uk/guidance/digital-connectivity-portal

equipment, which is slowing down the pace of deployment. Such information could include the structure's location, physical dimensions, proximity to the street or access to a power source.

In response, the government will invest in piloting the latest innovations in digital asset management platforms. This software will enable local councils to more easily share the data that mobile companies need to accelerate their roll-out plans and deliver the revolutionary benefits of 4G and 5G to people and businesses.

Source:https://www.gov.uk/government/news/new-plans-to-slash-red-tape-from-5g-roll-out-and-improve-mobile-phone-connectivity

8.5.3 Conclusions/recommendations

DCMS and industry players have made good progress towards addressing a large number of underlying historical barriers, through recently proposed legislative changes and other schemes undertaken by the well-established 'barrier busting taskforce'.

However, in order to ensure that these changes lead to improvements and a more consistent approach across local authorities necessary to unlock the investments required, clear communication and collaboration is needed.

9 Conclusions and recommendations for further work

A summary of our conclusions from the study, and recommendations for further work, are as follows.

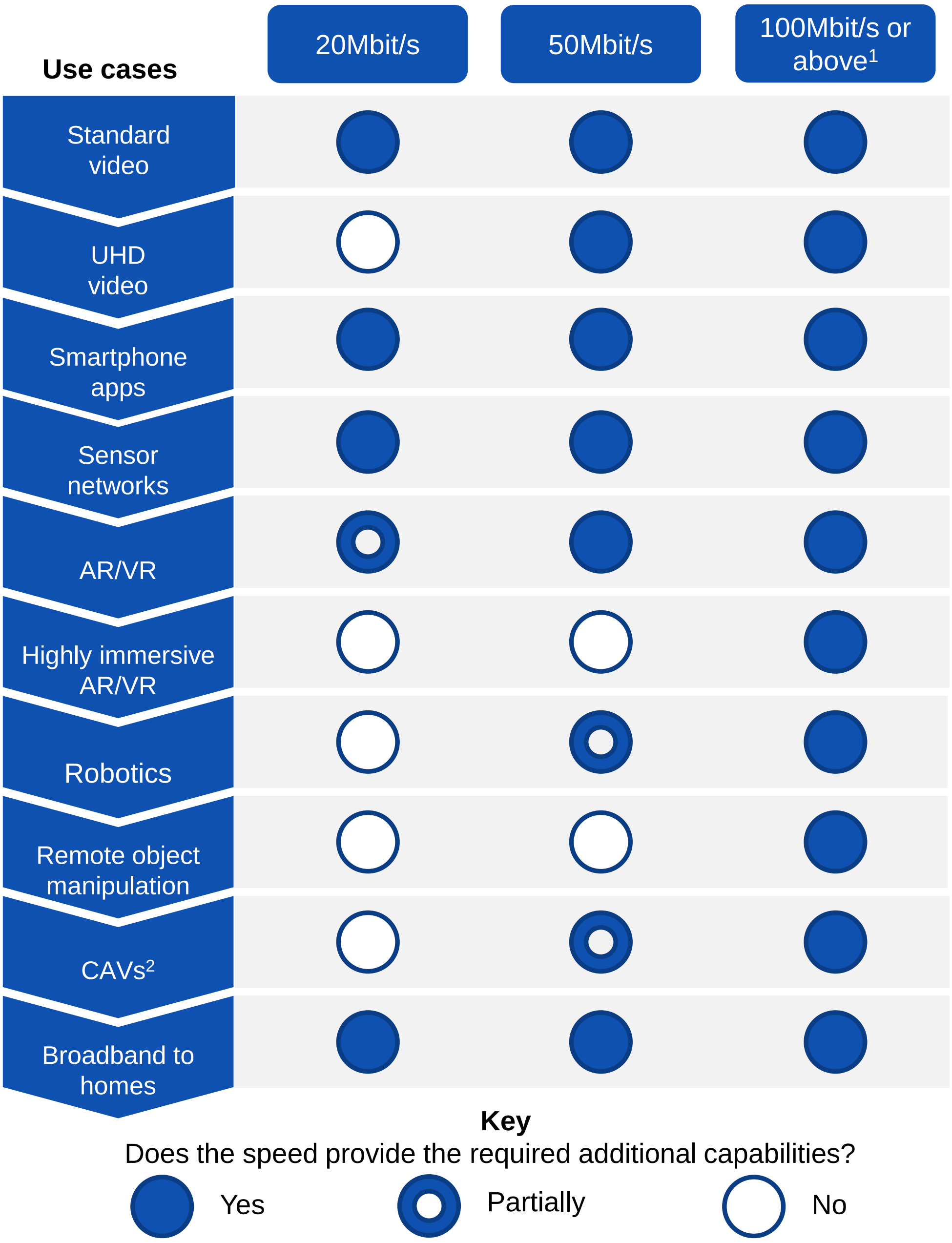
9.1 Conclusions

9.1.1 Level of connectivity needed to support future (current and new) use cases over the next decade

The level of wireless connectivity needed for wireless use cases up to 2030 varies from hundreds of kbit/s for low-data rate applications through to 1Gbit/s or more for the most advanced services (see Figure 9.1). Far higher data rates, very low latency and guaranteed quality-of-service (hundreds of Mbit/s up to 1Gbit/s and above) will be needed for some future applications such as robotics or connected and autonomous vehicles (CAVs).

Our overall findings on the applications enabled through different levels of wireless quality of connection are summarised in Figure 4.19. Our findings on the quality of connection needed for different use cases was then used to inform the quality-of-connection scenarios modelled in the study.

Figure 9.1: Applications enabled through different levels of wireless quality of connection [Source: Analysys Mason, 2022]



Use cases	20Mbit/s	50Mbit/s	100Mbit/s or above[1]
Standard video	●	●	●
UHD video	○	●	●
Smartphone apps	●	●	●
Sensor networks	●	●	●
AR/VR	◉	●	●
Highly immersive AR/VR	○	○	●
Robotics	○	◉	●
Remote object manipulation	○	○	●
CAVs[2]	○	◉	●
Broadband to homes	●	●	●

Key

Does the speed provide the required additional capabilities?

● Yes ◉ Partially ○ No

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[1] Applications requiring very high data rates also require other characteristics, such as low latency

[2] Connected autonomous vehicles

9.1.2 Choice of wireless solution

A summary of key conclusions is as follows.

Consumers, industry and the public sector make use of a range of wireless technologies today, designed for different applications, and this will continue to be so in the future.

UK consumers and businesses use numerous wireless technologies. Key options include nationwide cellular networks provided by national MNOs, alternative cellular networks (operated by non-national operators, which might be available in selected locations), satellite networks, low-power wireless solutions and various sector-specific wireless systems. Users leverage different solutions based on availability and need. Emerging 5G services are being delivered by national MNOs. 5G technologies might also be deployed in private networks, and in networks provided by non-national operators. There will also be new forms of satellite network (principally LEO services) and new generations of Wi-Fi. Solutions can be used together via the same device. For example, a 5G device can use Wi-Fi, and hybrid terrestrial 5G/LEO satellite services may emerge to provide connectivity in the UK over the remainder of this decade. It is not possible to predict the technology choices of all future users, nor the bundles of services individuals or businesses consume. Individual preference, devices being used and budget will all influence choices.

The applications that might use public 5G networks are wide ranging, though operators are currently deploying networks principally to provide more MBB capacity.

Demand for consumer-based MBB services has driven the initial 5G roll-outs in the UK, according to evidence gathered as part of this study. This MBB demand is driven by consumers replacing 4G devices with 4G/5G devices. Over the remainder of this decade, 5G demand might be driven increasingly by industrial and business applications, on top of growth in consumer MBB use. Industrial and businesses users might require the most advanced services that 5G technologies allow. The quantity of demand for these advanced 5G services is not yet clear, being a function of user choice, network quality, price and willingness to pay. A clearer picture of demand for the most advanced services may emerge once the current 5G-NSA network architectures that UK MNOs currently operate have evolved to full 5G-SA, after which the capability and pricing of the more advanced deployments will become clearer. Based on evidence captured for this study, it will be 2023 before the UK MNOs transition to SA architectures in their national networks.

The market for 4G/5G private networks looks likely to become increasingly vibrant but whether more industrial users will select private deployment or use public mobile networks is still unclear.

The private 4G/5G network market is evolving rapidly, primarily driven by the need for wireless connectivity for industry to support the advanced wireless applications discussed in this report, such as industrial automation, AR/VR and robotics. These private cellular networks might range from single site/single base station deployments through to larger, multi-site networks. The most complex private 4G/5G network demands might be from businesses that require private network capabilities across multiple UK locations, with mobility applications requiring wide-area connectivity. This sort of deployment would be costly and complex to deliver without using a public mobile network in some form to provide the wide-area capability – either through an MNO deploying the private networks and integrating those to its wide-area network via network slicing, or via an alternative operator or third party deploying the private networks and entering into a roaming agreement with an MNO.

Not all enterprise and business users will use cellular technology and some will use Wi-Fi.

Not all enterprise and business users will opt to use cellular technology, and some users will choose Wi-Fi as an alternative (especially where applications are not highly mobile). In addition, the choice of solution might be due to cost reasons, because some users have already invested in a Wi-Fi solution or because Wi-Fi is the solution offered to them by their network supplier. The role of Wi-Fi is well established in the UK market in homes and businesses and could also expand to providing new applications in industrial settings, as an alternative to private cellular networks. New forms of Wi-Fi are emerging, including Wi-Fi 6E and Wi-Fi 7 (in future).

New forms of cellular solution supply are emerging, including not-spot providers and third-party private network providers using cellular technology.

If choosing a cellular solution, enterprises and businesses will also face a choice of different suppliers of 4G/5G connectivity.[422] There is no limitation on where in the UK these private networks might be deployed, provided spectrum is available at the location(s) that the business requires, and that the business has access to a fixed-link backhaul, if connectivity to other networks (e.g. for internet connectivity) is needed.[423] A key uncertainty is the pricing of private network solutions, if the private

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[422] Suppliers of private networks could include MNOs, alternative operators, infrastructure providers, public cloud providers (PCPs) and equipment vendors.

[423] The first-come, first-served nature of Ofcom's shared access licensing means that late applicants could miss out. Shared access licensing refers to four spectrum

network is being provisioned via a bespoke configured slice from an MNO's network (i.e. via network slicing). There may also be barriers to the entry of alternative operators wishing to offer private 4G/5G solutions to enterprises and businesses. Alternative operators are reliant on access to shared spectrum and require roaming agreements with wide-area networks to ensure continuity of service beyond local private networks, for example.

9.1.3 How far the market will go to deliver 4G/5G infrastructure, and juncture between investment that is commercially viable, and not

A summary of the key conclusions from modelling of how far the market will go to deliver 4G/5G connectivity is as follows.

Assuming a population driven roll-out, mid-band 5G spectrum might be deployed to cover just under 94% of UK population in our model baseline.

Our modelling suggests that by 2030, a hypothetical UK MNO[424] might deploy sub-1GHz spectrum on most of its sites for coverage reasons, but would deploy 3500MHz (offering the highest capacity and quality of connection) mainly in urban and suburban locations to meet capacity requirements. By 2030, we estimate 100% of urban and suburban macro sites will include 3.5GHz and 56% of rural sites will include 3.5GHz, equating to 93.8% population coverage. This represents our model baseline, for which deployment is estimated to cost the modelled operator GBP2.8 billion (i.e. GBP312 million per annum) in nominal terms by 2030. With this baseline deployment, we estimate that a 50Mbit/s service will be available to 55% of the UK population by 2030, compared to 15% today. By 2030, 45% of active users[425] in the UK would receive an average speed of less than 50Mbit/s and 12% of active users would receive an average speed of less than 30Mbit/s, the majority of whom are located in rural areas. These sub-30Mbit/s levels of connectivity are similar to what 4G provides, suggesting users might not see any benefit from using 5G offers (raising questions over willingness to pay for a 5G service in locations where lower speeds are being offered). UK locations that remain uncovered by 2030 in our model correspond to the final 5–10%[426] of UK geography/landmass that will not be covered by mobile sites. This is on the basis that the factors preventing operators making 4G investments in these locations will endure with 5G.

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bands, which are 1781.7–1785MHz paired with 1876.7–1880MHz, 2390–2400MHz, 3800–4200MHz and 24.25–26.5GHz (indoor low-power licences only).

[424] This operator is not specific to or based on any individual UK MNO.

[425] Active users are those concurrently using the network within the busy hour.

[426] The model is calibrated to align with feedback from stakeholders on the landmass coverage for mobile networks individually and collectively, in line with the SRN.

The quality of network coverage from cellular networks by 2030 will not be sufficient in all locations to cater for all future use cases, such as video-controlled drones, AR/VR, connected vehicles or robotics.

Published information supports a view that public mobile networks in the UK today are mostly performing at around the 20–30Mbit/s level in many locations,[427] rising to 50Mbit/s or above in some locations. Our analysis of the level of connectivity needed to support future use cases suggests 50Mbit/s is insufficient to accommodate some envisaged future 5G applications. Users today who can experience speeds of 20–30Mbit/s should find this to be sufficient to enable UHD video streaming and typical MBB applications. Where the quality of connection per active user reaches over 50Mbit/s, this will additionally enable good-quality video-controlled drones and good-quality AR/VR experience. Our modelling suggests 55% of the UK population would be able to receive a service of 50Mbit/s or higher by 2030 in the model baseline. Coverage at these speeds will not be guaranteed, due to propagation variations in wireless signals and the effects of factors such as site placement and traffic load at different times of the day on the network quality that a user will receive. Thus demand for any use cases requiring a consistently high data speed over a wide area would not be met through commercial investment alone, absent of specific network upgrades being commissioned, tailored to specific sector need.

Delivering higher quality-of-coverage levels for consumers and enterprises would require a wider 3.5GHz footprint.

We modelled three scenarios of additional quality of connection (referring to the throughput that a user might receive, e.g. 30Mbit/s, 40Mbit/s), compared to the baseline model, to estimate the additional investment costs. Scenario 1 set a throughput threshold of 50Mbit/s per active user in all locations, Scenario 2 modelled an increase in enterprise traffic demand over public mobile networks and Scenario 3 modelled both 50Mbit/s to consumers plus increased enterprise demand. In each scenario, the required 3.5GHz footprint extends into more areas than the model baseline, and significant network densification must also occur in the scenarios involving meeting enterprise traffic.

There are significant additional costs for MNOs to deploy additional infrastructure for the more advanced 5G use cases.

Our modelling predicts that Scenario 1 (achieving 50Mbit/s throughput across the UK) requires a GBP3.3 billion investment per mobile network between now and 2030,

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[427] Reported performance for BTEE’s network was higher than this with reference to published information at the time of producing this report.

compared to GBP2.8 billion in our baseline model. This is equivalent to an additional GBP51 million per annum, per operator, in nominal terms compared with the baseline.

The modelling results can also indicate the additional revenue that an MNO would need to achieve in order to cover the costs of meeting a quality-of-service target over the baseline roll-out, based on the assumed discount rate and payback period. The annual additional revenue needed for commercial viability has been reported in Scenario 1 as an ARPU uplift across all end users served by an MNO, to give a sense of whether the additional revenue needed might be realistically achieved.

In Scenario 1, an additional annual revenue of GBP69 million in nominal terms is required over the payback period in order for the additional deployments to be commercially viable.[428] This equates to an additional GBP3.32 per UK user annually,[429] or an ARPU uplift of GBP0.28 per month (approximately 2% of total UK mobile ARPU). Adding further enterprise traffic to a public network (Scenario 2) results in a further GBP61 million of investment, per mobile network per annum, between now and 2030, over and above our modelled baseline. Combining the 50Mbit/s target for consumers with an assumption of increased enterprise traffic on public mobile networks (Scenario 3) results in a GBP124 million increase in investment needed per mobile network per annum between now and 2030 over the baseline. In order for this to be commercially viable, an additional annual revenue of GBP228 million in nominal terms is required per MNO over the payback period. Our viability assessment results below consider these points.

Our modelling indicates that additional investment to achieve a 50Mbit/s quality of connection should be commercially viable in all urban, suburban and most rural areas with a consumer price increase of 5%.

We have used illustrative analysis based on the assumption that a 5% nominal price increase for consumers sustained over the payback period (approximately GBP0.70) would be achievable.[430] Based on our modelling results, we have identified those areas where the additional investment to achieve a 50Mbit/s quality of connection across the UK should be commercially viable. We note that, in practice, there is no geographical pricing differentiation in the UK mobile market

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[428] Based on the additional revenue an operator would need to make the investment commercially viable, estimated over a 12-year period, assuming a discount rate of 8%. The 12-year period was chosen as being indicative of a typical active radio equipment lifecycle.

[429] Estimated by dividing GBP69 million by the estimated number of users on the mobile network of just over 21 million customers.

[430] Based on the results of a survey of 3000 consumers across USA, UK and South Korea on perceptions of 5G, including willingness to pay. Nokia (2020), ‘The value of 5G services: Consumer perceptions and the opportunity for CSPs’, June 2020; available at: https://www.5gcc.ca/wp-content/uploads/2020/06/Nokia-The-Value-of-5G-Services-June-2020.pdf

and hence any price changes would be at a national level. Breaking down the ARPU requirement at a sub-national level, we estimate the additional ARPU requirement per month would equate to GBP0.11 in urban locations, less than GBP0.01 in suburban locations, and GBP0.69 in rural locations. The investment should be commercially viable in urban and suburban areas, but considering rural areas by region, we find that a few areas[431] may not be commercially viable under a 5% national price increase since the ARPU per month uplift requirement exceeds GBP0.70.[432] Assuming a 10% increase in price (approximately GBP1.40), only the Scotland rural region would remain unviable.

Our modelling indicates that additional investment to meet enterprise demand should be commercially viable in almost all urban and suburban areas, but without intervention all rural areas are likely to be market failures.

Under Scenario 2, we base our viability assessment on the increase in GVA that would be achieved through adoption of advanced wireless technologies, and estimate the share of this additional GVA that corresponds to the gross operating surplus (profits) of the businesses.[433] If the value of the incremental business profits is greater than the incremental revenue requirement for our hypothetical MNO to invest in a given area, then businesses should (in theory) be willing to pay an amount that at least meets the revenue requirement, provided they internalise all of the expected increase in profits in their willingness-to-pay assessment.

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[431] The North East rural, Yorkshire and the Humber rural, Wales rural, Northern Ireland rural and Scotland rural areas.

[432] The total annualised nominal additional cost (2022–30) of serving these non-commercially viable areas (relative to the baseline) to achieve the Scenario 1 target of 50Mbit/s by the hypothetical modelled MNO with 25% market share, is GBP39.6 million. This is an upper bound for the funding gap for these areas. However, taking into account the fact that users will already be covering some of this cost (through the national 5% price increase), any intervention funding would need to cover, at a minimum, the estimated residual revenue requirement. In these areas, that amounts to GBP19.8 million per annum. Given these results are presented for just the hypothetical modelled MNO with 25% market share, to get an indication for the cost of serving all customers in the area with 50Mbit/s, we must multiply by four. This implies that the scale of funding that may need to be provided by government (or cost savings that would need to be found) to support the achievement of Scenario 1 targets in these areas will sit between GBP79.2 million and GBP158 million per annum.

[433] GVA comprises the sum of compensation of employees (CoE), taxes less subsidies, gross operating surplus (GOS) and mixed income (which includes self-employment income and rental income). Therefore, GOS data can be used to estimate how much profit is generated by companies after considering labour costs and taxes less subsidies. GVA impact estimates are taken from a previous study conducted by Analysys Mason and Cambridge Econometrics for DCMS in 2021, on realising the benefits of 5G. The share of GVA that is GOS is estimated using ONS data.

Using this approach, we find that the estimated increase in business profits exceeds the revenue requirement for businesses located in all urban and suburban locations apart from North East suburban. This implies that investment could be commercially viable and go ahead in these areas.

When considered at the rural level, we find that no rural regional areas would be commercially viable, suggesting there is no commercial case for investing in those areas. However, the wider economic benefits to the areas (measured with reference to the total GVA uplift) does exceed the revenue requirement in some areas[434] and therefore in these areas there is likely to be a market failure.[435] If the government were to prioritise the targets set under Scenario 2, there should be support for intervention in these areas.

Meeting the 50Mbit/s threshold for consumers becomes more challenging if MNOs are also densifying networks to accommodate advanced 5G applications for enterprises.

Our modelled Scenario 3 indicates that the business case for investing to serve enterprise demand in addition to the 50Mbit/s per user may be more challenging in some areas than under Scenario 1 alone.

We consider those areas which are commercially viable under Scenario 1 and then assess whether the revenue requirement associated with the incremental investment required to achieve Scenario 3 quality of service in those areas would be met by business incremental profits.

We find that the investment case is not commercially viable in 18 regional geotype areas.[436] Nearly all (17) of these non-commercially viable areas suggest there is a wider economic value to having both user and enterprise demand in that area, which indicates the likelihood of a market failure.[437] However, we find that these results are very responsive to assumptions on business willingness to pay,

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[434] East Midlands rural, West Midlands rural, East rural, South East rural and South West rural, in addition to North East suburban.

[435] This refers to a failure of commercial roll-out to reach areas where the wider economic value of the investment exceeds the private cost of roll-out, yet this is not fully internalised in the private investment decision, nor captured in end-users' willingness to pay.

[436] North East urban, North East suburban, North West urban, North West suburban, North West rural, Yorkshire urban, Yorkshire suburban, East Midlands urban, East Midlands rural, West Midlands urban, West Midlands rural, East urban, East suburban, East rural, South East rural, South West urban, South West rural, Scotland suburban.

[437] North West rural is the only area where it is not commercially viable, nor desirable from a wider economic benefits point of view, to meet Scenario 3 targets.

highlighting how sensitive the business case can be with respect to expected revenue.

9.1.4 Policies to stimulate the market

Intervention in the form of public subsidies may be appropriate where there is a market failure, but at this early stage of advanced wireless connectivity roll-out it will be important to allow time for commercial models to emerge before identifying areas where market failures are present.

We have identified some areas, under our various scenarios, where there may be evidence of market failure. If we do not observe network roll-out in areas where the wider economic benefits are greater than the costs of investment, this could be a sign of a market failure, and government intervention (e.g. in the form of subsidies) could be justified. However, it is important at this early stage in the roll-out of advanced wireless networks to allow time for commercial models to emerge and to build the evidence base to appropriately identify areas where market failures are present. It will be necessary to continuously monitor progress on both the supply side (in terms of where the networks are being deployed and what is driving this investment) and the demand side (in terms of the practical use cases being taken up, the technical solutions being used, the benefits enabled and willingness to pay). This will allow DCMS to better understand and build evidence on the drivers and benefits of network roll-out. This in turn could help to identify areas that may be experiencing lower network coverage and/or quality due to market failures, using the tools identified in our model.

Where end users and businesses understand the benefits that can come from advanced wireless services and therefore take this into account in their willingness to pay, the likelihood of finding market failures is reduced.

If market failure occurs because willingness to pay does not fully internalise the expected benefits and where there is information asymmetry or uncertainty regarding the value of a given level of quality of service or use case, then further promotion of the potential value of these services will be required. Over time, as 5G deployments progress and more practical examples of use cases develop, we would expect a better understanding of the potential benefits to materialise. However, any steps that can be taken to show the continued development of valuable use cases and inform potential users of the value of the new technologies should be pursued. Making results from the 5G Testbeds and Trials programme more widely available to the market will widen the evidence base on the capabilities and benefits of 5G whilst new applications are still emerging. Tracking growth in business adoption of advanced 5G services once demand emerges could also help to reduce some of the uncertainties that could hold back investment in 5G.

Policies can increase costs for MNOs, e.g. annual licence fees and cost of re-procuring 5G network equipment.

Operators have claimed that the costs they face on annual licence fees for spectrum holdings affect cashflow. Some operators that fund investments primarily out of free cashflow and operate within a capex envelope claim that annual licence fee costs have a direct effect on investment. Operators also reiterated feedback on the cost of implementing other policies such as in relation to removal of high-risk vendors from the 5G estate.

We find limited evidence for a direct link between ALFs and the level of investment. As such, a simple discount on, or removal of ALFs without further obligations to reinvest the funds in network roll-out, is likely to have a limited impact on the level of investment. However, we acknowledge that the scale of ALFs relative to the investment requirement from the baseline to our various scenarios is significant.

Reinvesting ALFs into network expansion could help to close the gap between the baseline roll-out and the target scenarios in some areas.

Annual average ALFs per operator of GBP93.14 million exceed the annualised addition costs of meeting Scenario 1 (over the baseline) of GBP50.91 million. Annual ALFs could cover 75% of the additional annual costs of meeting even the most expensive Scenario 3 nationally (GBP123.01 million). Notably, if the ALFs were put purely to funding rural coverage, this would be more than sufficient to cover the additional cost requirement in all rural areas, even under Scenario 3.

Policies aimed at ensuring that these funds are redeployed towards investment in advanced wireless connectivity services could thus have a material impact on closing the gap between the baseline costs and the infrastructure costs for the modelled scenarios in our analysis.

One approach would be to run a subsidy scheme funded by ALFs that operators can bid for to support their investment in those areas where a market failure has been defined. In this case, the subsidy programme would need to define very clearly what the subsidy is for (e.g. what the intervention area is, and what the target quality of service is that must be achieved by the subsidised investment). The subsidy price would be set by the operators through their bids to meet a specific target in the intervention area.

An alternative may be to offer ALF rebates, contingent on meeting certain investment requirements and quality-of-service targets in the intervention area. The overall rebate to any one operator may have to be set at the lowest of the ALFs paid by all operators, to avoid a situation where the size of the rebate offered to an operator is greater than the amount it pays in ALFs. The price of the subsidy would have to be set by government and be transparently calculated and applied. Given that the link between cashflow and investment is not clear, the manner in which the ALFs are redistributed could have a significant impact on the level of investment that may result. A simple discount or the removal of ALFs, without further obligations to reinvest the funds, may have a limited impact on the level of investment.

Any funding or subsidy programme from ALFs would need to define very clearly what the subsidy is for (e.g. what the intervention area is, and what the target quality of service is that must be achieved by the subsidised investment). The subsidy price would be set by the operators through their bids to meet a specific target in the intervention area.

An alternative may be to offer ALF rebates, contingent on meeting certain investment requirements and quality-of-service targets in the intervention area. The overall rebate to any one operator may have to be set at the lowest of the ALFs paid by all operators, to avoid a situation where the size of the rebate offered to an operator is greater than the amount it pays in ALFs. The price of the subsidy would have to be set by government and be transparently calculated and applied.

Increased network sharing could generate cost-efficiency savings, changing the viability of investment in some rural areas.

During the stakeholder interviews, some stakeholders stated that market consolidation may be needed in the mobile sector to unlock the scale of investment required to meet targets. We note that the literature on the effects of consolidation finds stronger evidence for increased prices than a positive effect on investment. Network sharing could be an alternative way in which operators could potentially generate some of the same network cost-efficiency savings that could be unlocked through consolidation, whilst mitigating the potential competition concerns that can arise with consolidation. Furthermore, network-sharing agreements can directly affect the economics of network deployment since they generate network cost savings which can support the investment case for deployment in a given area.

Even though consolidation and network sharing will ultimately be assessed on a case-by-case basis, there is scope for competition and regulatory authorities to give greater clarity and guidance to operators on the key factors that will be considered in such an assessment. This would build on existing guidance[438] and update it to explain how the technological advances and capabilities of advanced 5G wireless networks could affect the trade-offs between cost efficiencies and the impact on competition. There is greater scope for service differentiation downstream, and the

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[438] For example, BEREC has issued a common position on mobile infrastructure sharing describing criteria that can be taken into account by national regulators when evaluating the impact of infrastructure sharing agreements. BEREC (2019), ‘BEREC Common Position on Mobile Infrastructure Sharing’, document number BoR (19) 110.

scale of network savings, and the value these savings can unlock, is potentially much larger than for previous technologies.

Further clarity on implications of net-neutrality rules for orchestrating network slices could avoid uncertainty in the business case for 5G-SA.

Network slicing is a key feature of 5G-SA and could enable highly flexible, secure and reliable wireless connectivity suited to delivering bespoke applications for enterprise users that can take advantage of the full range of 5G capabilities. The innovations and benefits associated with these alternative use cases that could be enabled over network slicing could be lost if network slicing is not offered on a widespread basis (due to an uncertain business case because of restrictions imposed by net-neutrality rules).

Modelling Scenarios 2 and 3 include advanced enterprise traffic and assume that advanced data traffic will be provided by orchestrating network slices in 5G-SA networks. In the absence of network slicing, MNOs' ability to serve enterprise traffic (which has an associated cumulative GVA uplift of GBP2.6 billion between 2022 and 2030 in 2020 terms) may be significantly impacted. Any uncertainty on network slicing could slow down the timing of realising these benefits or may lead to them not being enabled at all.

Specific enterprise demands and use cases could still be served by dedicated, on-premises private networks. In the event that MNOs are unable to offer tailored services to enterprises through differentiated network slices, not all of the potential benefits associated with tailored connectivity solutions will be lost, as alternative operators could still offer these via dedicated private networks.

Addressing barriers to alternative operators could enable new entrants to provide competing or complementary services to support the achievement of target quality of service and coverage.

Alternative operators may be able to provide alternative solutions that are not provided over the MNO wide-area public networks. For example:

- private networks to meet specific needs in defined localities, or
- neutral host solutions provided over shared or local access spectrum in areas where there may not be full coverage by all MNOs.

However, in order to provide this infill, the alternative operators will need access to spectrum, roaming agreements and access to mobile network codes (MNCs).

Steps that could be taken to ensure lower barriers to entry for these alternative provides include the following:

- Ofcom should identify solutions that offer exclusive network identifiers in private networks, rather than requiring operators to use the ITU code, which is not suitable to enable roaming with other networks.

- In the absence of access-related obligations, national roaming will remain subject to commercial agreements and the terms of the agreement will be open to negotiations. Given roaming may be needed for providers of private networks to ensure uninterrupted coverage beyond the private network or for neutral hosts with their own spectrum to allow MNO customers to roam onto their network in not-spot areas, there may be merit in Ofcom investigating this issue further and providing guidance on whether it considers that amendments to MNO licences may be required (in order to be able to mandate access-requirements such as roaming). This is particularly relevant if there is evidence of specific agreements not being reached due to unreasonable refusals by MNOs to enter into roaming agreements and/or there is a failure to offer fair and reasonable terms of access.

9.2 Recommendations

The following four subsections summarise the key recommendations for this study.

9.2.1 There are evidence gaps in how the 5G market will evolve, which could be the subject of future study

As demand for 5G use cases become more proven and case studies of actual supply-side deployments start to emerge, the assumptions and model inputs described in this report can be refined. Further evidence of 5G willingness to pay would be desirable to evidence various assumptions in this study.

Other activities that can be undertaken by DCMS to monitor ongoing developments are as follows:

- engage in interactions with other government departments and enterprises across sectors involved in 5G test beds and trials to understand how demands changes over time
- engage in further study into 5G willingness to pay and how this might vary between use cases/ sectors/locations in the UK
- aggregate results from existing and future 5G testbeds and make these available to the market to widen the evidence base on 5G capabilities
- establish platforms for interactions between network providers (MNOs/others) and enterprise users.

9.2.2 The shared access licensing scheme could be kept under review to ensure the application and licensing process is meeting market demand

Steps could be taken to improve the speed with which the shared access licensing regime operates, to remove factors that could be slowing down the roll-out of local solutions provided by alternative operators. Automating the application and approval process would help remove a number of the constraints that are currently adding extra time and frictions into the process.

9.2.3 Specific industry guidance on implementing network slicing within current regulations could be developed by Ofcom

Guidance could be issued by Ofcom to provide more clarity and certainty as to what constitutes a specialised service, whether network slicing can be assessed as such, and how any detriment to the general internet access service (IAS) as a result of network slicing would be assessed.

Alternatively, a network slice could be defined as a specific category of service, distinct from a specialised service and an IAS, for which traffic management with commercial considerations would be allowed, subject to the terms being fair, reasonable and non-discriminatory (FRAND). We note that ideally there should be a commitment from Ofcom to publish further guidance on how such FRAND terms should be interpreted in relation to network slices.

9.2.4 Recent changes to legislation to address practical deployment barriers should be monitored closely to assess their impact

Deploying wireless infrastructure requires operators to co-ordinate with a range of stakeholders and comply with a range of planning rules and regulations. Significant progress has been made to make legislative changes to remove a large number of the practical deployment barriers raised by stakeholders, particularly with recent updates to legislation on the permitted development rights (March 2022) and changes to the ECC (November 2021). The impact of these changes will lead to greater certainty for the telecoms market in relation to access to sites for mobile equipment and the planning process. In order for these changes to be made quickly and taken into account and implemented in a consistent way, support should be provided for operators, councils, landlords and intermediaries to better understand the revisions and implement the changes. In this regard, a collaborative approach with government, operators and landlords will be needed to ensure that everyone is aware of the changes, and that changes are implemented and reflected across the board in a timely manner.

A clear communication strategy to raise awareness of the benefits of advanced wireless connectivity, specifically to local areas, which can provide targeted messaging for local authorities and the public of the benefits of these new services could also be beneficial. Working alongside existing communications to address specific concerns of local authorities or individuals, this communications strategy could help get further support for approvals beyond local authority 'digital champions' and achieve deeper buy-in from across teams within a local authority, and from the local public.

Annex A Connectivity requirement literature review

A.1 Introduction

This annex describes the evidence captured through a literature review to better understand the level of wireless connectivity needed to support future use cases and applications across different user groups over the next decade.

The evidence points to an extremely diverse set of future connectivity requirements spanning different sectors and environments. Many of the requirements described would not currently be supported by 5G networks in the UK from a capacity standpoint alone, and there are also several other requirements to be met, such as latency and network availability.

The review is split up by use cases, and for each use case we discuss the general requirements, and any sector-specific variations, found in literature. For sectors where there was either no information, or very little information uncovered during the review, we use the generic use case requirements as an estimate of what the future connectivity needed might be.

A.2 AR/VR

A.2.1 Generic requirements

There are a wide range of reported connectivity requirements for AR/VR use cases that vary depending on video quality and DoFs,[439] as detailed below. In the wide area environment, an AR/VR use case (e.g. remote experts, maintenance and repairs) would not typically require the very high capacity connection that would be needed to deliver the experience that applications such as Metaverse would need. This is because wide-area AR/VR use cases such as remote expert would be less immersive than the Metaverse is indicated to be, hence some level of delay might be tolerated without detrimental impact on the user/use case delivery.

In a 2017 white paper, Huawei identified four distinct stages of cloud VR (see Figure A.1), and at the time suggested the market would reach the advanced VR stage by 2020.[440] However, a paper published in 2020 stated that current devices

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[439] Typically there are either three or six DoFs. Three DoFs result from rotation about each of three perpendicular axes; six DoFs result from motion along each of the three axes in addition to the rotation about each axis.

[440] https://www.huawei.com/~/media/CORPORATE/PDF/ilab/cloud_vr_oriented_bearer_network_white_paper_en_v2

were in the pre-VR and entry-level VR stages,[441] which suggests that the market is advancing less quickly than anticipated.

Figure A.1: Network requirements at different cloud VR stages [Source: Huawei, 2017]

Type of VR	VR resolution	Typical bitrate (Mbit/s)	Typical round-trip time (ms)	Typical packet loss ratio (PLR)
Pre-VR – weak interaction	2D, 30 frames per second (fps), 4K	Full-view: 16	30	2.4×10^{-4}
Pre-VR – strong interaction	2D, 90fps, 4K	Field of view (FOV): 18	10	1×10^{-6}
Entry-level VR – weak interaction	2D/3D, 30fps, 8K	Full-view: 2D: 50 Full-view: 3D: 80 FOV 2D: 26 FOV 3D: 42	2D: 30 3D: 20	2.4×10^{-5}
Entry-level VR – strong interaction	2D/3D, 90fps, 8K	FOV 2D: 40 FOV 3D: 60	10	1×10^{-6}
Advanced VR – weak interaction	3D, 60fps, 12K	Full-view: 420 FOV: 220	20	1×10^{-6}
Advanced VR – strong interaction	3D, 120fps, 12K	FOV: 390	5	1×10^{-6}
Ultimate VR – weak interaction	3D, 120fps, 24K	Full-view: 2940 FOV: 1560	10	1×10^{-6}
Ultimate VR – strong interaction (i.e. fully immersive)	3D, 200fps, 24K	FOV: 680	5	1×10^{-6}

In 2018, Qualcomm published a document on VR and AR which illustrated the range of connectivity requirements depending on the use case, with “current-gen” 360° 4K VR video, the minimum required for immersive experiences, requiring

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[441] https://www.researchgate.net/publication/338688467_Cellular-Connected_Wireless_Virtual_Reality_Requirements_Challenges_and_Solutions

10–50Mbit/s and highlighting that “motion-to-photon (MTP) latency below 15ms generally avoids discomfort”.[442]

Bandwidth requirements for less advanced and more advanced use cases are provided in Figure A.2. The table also gives an example of user-generated 4K 360° video uploading at 25Mbit/s.[443]

Figure A.2: Bandwidth requirements for AR and VR use cases [Source: Qualcomm, 2018]

Use case	Bandwidth (Mbit/s)
Image and workflow downloading	1
Video conferencing	2
3D model and data visualisation	2–20
Two-way telepresence	5–25
Current-gen 360° video (4K)	10–50
Next-gen 360° video (8K, at least 90fps, high definition resolution, stereoscopic)	50–200
6 DoF or free-viewpoint	200–5000

A 2018 white paper by Keysight technologies depicts the throughput and delay of various applications enabled by future 5G standards (note that at the time Release 16 had not yet been released). AR and VR are depicted as requiring 100–1000Mbit/s throughput and 1ms delay.[444]

ITU recommendation F.743.6 (Service requirements for next-generation content delivery networks), which was published in 2018, lists “current” VR as early stage, with 4K resolution requiring 25Mbit/s bandwidth and 40ms latency. VR bandwidth and latency requirements for other stages are shown in Figure A.3.[445]

Figure A.3: VR bandwidth and latency requirements [Source: ITU, 2018]

Type of VR	VR resolution	Bandwidth (Mbit/s)	Latency (ms)
Early-stage VR	2D, 30fps, 4K	25	40
Entry-level VR	2D, 30fps, 8K	100	30
Advanced VR	2D, 60fps, 12K	400	20

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[442] https://www.qualcomm.com/media/documents/files/vr-and-ar-pushing-connectivity-limits.pdf

[443] Ibid.

[444] https://www.keysight.com/gb/en/assets/7018-06129/white-papers/5992-2921.pdf?success=true

[445] Available at https://www.itu.int/rec/T-REC-F.743.6-201808-I

Type of VR	VR resolution	Bandwidth (Mbit/s)	Latency (ms)
Extreme VR	3D, 1200fps, 24K	1000–2350	10

In a 2019 white paper, GSMA Future Networks identified "current" 360 degree 4K VR video as requiring 20–40Mbit/s and less than 50ms round-trip-time latency; it also described computer-generated (CG) VR as "delivering 2K services in its infancy", which required 30–50Mbit/s and less than 20ms of latency. However, the paper specified that the MTP latency in VR is commonly targeted at 20ms, but for some AR use cases it could be as low as 5ms. Thus, although stationary AR/VR may be possible at higher latencies, if there is any motion involved, latencies should be below 20ms. The requirements for more advanced VR options, which are possible with improved data rates, are presented in Figure A.4.[446]

Figure A.4: Data rate and latency requirements for VR video and CG VR [Source: GSMA Future Networks, 2019]

Type of VR	Resolution and transmission	Data rate (Mbit/s)	Latency (ms)
Video	4K (3840×2160) – sphere	20–40	≤50
Video	8K (7680×4320) – sphere	90–130	≤20
Video	8K (7680×4320) – field of view (FOV)	30–50	≤20
Video	12K 3D (11 520×6480) – sphere	500–700	≤10
Video	12K 3D (11 520×6480) – FOV	200–300	≤10
CG	2K (2560×1440)	30–50	≤20
CG	4K (3840×1920)	50–200	≤16
CG	8K (7680×3840)	200–800	≤10

The latest version of 3GPP specification 26.925 for Release 16 (Typical traffic characteristics of media services on 3GPP networks), lists typical streaming/broadcast 360 VR bitrates, as shown in Figure A.5.[447] The values remain

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[446] https://www.gsma.com/futurenetworks/wiki/cloud-ar-vr-whitepaper/

[447] Version 16.0.0 uploaded 2020-03-24 available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3533

the same in the latest Release 17 version. The professional content uplink bitrates are in draft form, however for user-generated content, basic 360 VR has a typical bitrate of 10–85Mbit/s uplink and, for HD 360 VR, a 20–150Mbit/s uplink (the ranges are large as this category may include semi-professional content).[448]

Figure A.5: Typical streaming/broadcast 360 VR bitrates [Source: 3GPP, 2020]

Type of VR	Bitrate (Mbit/s)
Basic 360 VR	2.5–25
HD 360 VR	10–80
Retinal VR	15–150

According to 3GPP specification 22.847 (Study on supporting tactile and multi-modality communication services), MTP delay (defined here as "the time difference between the user's motion and corresponding change of the video image on display") should be less than 20ms, so the communication latency should be lower than this. Potential key performance requirements for immersive multi-modality VR applications for 3GPP Release 18 are presented in Figure A.6.[449]

Figure A.6: Potential key performance requirements for immersive multi-modality VR applications [Source: 3GPP, 2021]

Use case	Data rate (Mbit/s)	Maximum allowed end-to-end latency (ms)	Reliability
Haptic feedback	Uplink (UL) and downlink (DL): 0.016 – 2 (without compression), 0.0008 – 0.2 (with compression)	5	99.9% (without compression), 99.999% (with compression)
Sensing information	UL: <1	5	99.99%
Video	DL: 1–100	10	99.9%
Audio	DL: 0.005–0.5	10	99.9%

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[448] Version 17.0.0 uploaded 2021-09-24 available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3533

[449] Version 18.0.0 uploaded 2021-09-24 available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3848

In its 2022 discussion paper on mobile networks and spectrum, Ofcom states that throughput for augmented reality "depends heavily on quality" and that latency should "ideally [be] below 10ms for interactive AR". Similarly for VR the paper states that "throughput requirements can range from 25Mbit/s to multiple Gbit/s depending on quality. Latency ideally below 10ms for interactive VR".[450]

Based on the literature review, it appears that the typical current requirements for AR/VR use cases are as shown in Figure A.7.

Figure A.7: Typical connectivity requirements for generic AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements [451]	Additional comments
Generic AR/VR	10–50 (UL and DL)	Generally <20	High reliability	Capacity likely to increase significantly over time, some mission-critical applications may have lower latencies

However, within the next decade much higher data rates can be expected. 3GPP Release 18 expects 5G to support at least 100Mbit/s for the video element of AR/VR,[452] and with increasing demand for higher definition and more degrees of freedom, data rates may reach gigabit levels and require ultra-low latency in the near future. According to the 3GPP timetable, work on 3GPP Release 18 will not commence until after Release 17 has been largely stabilised, which is not until 2022. We would not expect Release 18 specifications to be finalised until 2024–2025 (and thus solutions meeting those specifications would emerge only towards the end of this decade).

A.2.2 Sector-specific AR/VR requirements

Media creation

The literature review did not find specific definitions available related to the minimum connectivity requirements for professional creation of AR/VR content.

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[450] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

[451] Note that coverage will be use-case specific.

[452] Version 18.0.0 uploaded 2021-09-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3848

However, we believe that at a minimum, capacity requirements will be similar to those for generic ultra-high definition (UHD) video creation (see Section A.3), as video is typically the largest component of AR/VR capacity requirements. Similarly, given the lack of available information, we believe the latency and other requirements associated with UHD video creation are a good proxy. Coverage requirements will be limited to the local area where the studio creating the media is located. Typical connectivity requirements for media creation AR/VR use cases are shown in Figure A.8. It is noted that highly immersive applications would follow the same trend as described in the previous section, requiring higher capacity to enable the best quality of real-time user interaction.

Figure A.8: Typical connectivity requirements for media creation AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
At least 100–200 (UL) and 20 (DL)	≤10	Local	Very high reliability	Capacity likely to increase significantly as resolution increases, but compression technology may improve, reducing the values over time

Venues and events

The typical data requirements for AR/VR at events (Figure A.9) are not expected to differ from the generic use case requirements. Coverage will be local to the event/venue.

Figure A.9: Typical connectivity requirements for venues and events AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
10–50 (UL and DL)	Generally <20	Local	High reliability	Capacity likely to increase significantly over time

Health and social care

In hospitals, AR/VR might be used in future to assist surgery. According to the latest version of 3GPP specification 22.826 (Study on communication services for critical medical applications), which is for Release 17, AR-assisted surgery requires extremely stringent communication service performance, which is unlikely to be met by public networks. The 3GPP specification refers to using a “5G-LAN type service”, which we understand refers to a private 5G network specifically provisioned for this application; see Figure A.10.[453]

Figure A.10: Communication service performance requirements for AR-assisted surgery [Source: 3GPP, 2021]

Component	Bitrate (Gbit/s)	Maximum end-to-end latency (ms)	Target service availability	Service reliability (mean time between failure)
4K, 120fps, HDR, real-time video stream	Compressed: 12 UL and DL Uncompressed: 30 UL and DL	<0.75	>99.99999%	>1 year
3D, 10fps, ultrasound unicast data stream	4 UL	<10	>99.9999	>1 year

In comparison with the generic AR use case, the much higher bitrates given in Figure A.10 are likely the result of lower latencies and higher video frame rates or resolution, as described in Section A.3 for UHD video requirements for health and social care.

One method in which AR/VR can be used to assist in surgery is by allowing the visualisation of 3D models generated from medical scans as part pre-operation preparation. A paper published in March 2021 tested this use case, and used an average bandwidth of 60Mbit/s uplink and 90Mbit/s downlink.[454] This bandwidth is much lower than the values reported in Figure A.10 above, however it is specific to one particular use case of AR/VR in health and social care, and other use cases (such as an augmented field of view during surgery) may require more bandwidth due to higher resolutions and lower latencies (note that the value of these parameters were not reported in the paper so we cannot be certain of the exact requirements).

As there is limited information on current data requirements for AR/VR in the health and social care subsector, the typical requirements (Figure A.11) encompass a

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[453] Version 17.2.0 uploaded 2021-04-02; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3546

[454] https://www.frontiersin.org/articles/10.3389/fsurg.2021.657901/full

wide range, from the upper limit of the generic use case requirements to the values reported as potential Release 17 requirements.

Figure A.11: Typical connectivity requirements for health and social care AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
50–12 000 (UL and DL)	<10	Local	Ultra-high availability, high reliability, likely to require high security	Capacity is highly dependent on video quality and latency. It is likely that current values are towards the lower end of the range, but that over time they will increase significantly.

Education

The usage of AR/VR in education does not have any specific requirements beyond those of the generic use case. Coverage will be local to the school/university, and capacity will primarily be downlink-based (i.e. students using AR/VR rather than uploading content). Figure A.12 shows the typical connectivity requirements for AR/VR in education.

Figure A.12: Typical connectivity requirements for education AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
10–50 (DL)	Generally <20	Local	High reliability	Capacity likely to increase significantly over time

Emergency services

There is not much published information available on the specific requirements for future emergency services applications. However, for AR scenarios where the user mobility is required, which would likely be most scenarios for the emergency services, six degrees of freedom and 3D “free-viewpoint” data will be required. According to Qualcomm in 2020, bitrates of between 200Mbit/s and 5000Mbit/s may be required to support this.[455] There have been examples of this type of training solution being used in the UK, namely for the fire service[456] and for first-aid training.[457]

For in-field AR/VR that uses glasses or visors, mobility is important, but so is high-definition imagery. Data rates are thus likely to be much higher than for generic use cases. In 2020, Qualcomm published a white paper on the mobile future of extended reality, focusing on XR glasses that could be used by first responders. The white paper states that "5G enhanced mobile broadband is required for XR mass adoption",[458] and that "XR is here today, but it is still in its infancy".[459] It describes the XR requirements associated with enhanced 5G as "~200 to 5000Mbit/s, very low latency"[460] and that enhanced 5G is "next decade".[461] The white paper also mentions other technological advances that are required before glasses are really suitable and wireless, such as realistic lighting and improved battery lifetime.[462] For uses such as firefighting or policing, there are general personal protective equipment (PPE) standards that must also be met.

There are some prototype devices that are due to come onto the market soon, such as the Quake C-THRU,[463] but these are not yet readily available. Given the mission-critical nature of the emergency services, we assume there will be further regulation and testing needed before the public services are able to make use of such devices, which will take several years at least to define.

The typical requirements for connectivity for AR/VR in the emergency services sector (Figure A.13), stem from the generic AR/VR use case requirements, with amended capacity requirements in line with the sector- specific literature findings.

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[455] https://www.qualcomm.com/media/documents/files/vr-and-ar-pushing-connectivity-limits.pdf

[456] https://www.immersivelearning.news/2017/09/14/uk-fire-service-and-rivr-collaborate-on-vr-training-programme/

[457] https://emergencyservicestimes.com/virtual-reality-first-aid-training-now-part-training-courses-uk/

[458] https://www.qualcomm.com/media/documents/files/the-mobile-future-of-extended-reality-xr.pdf

[459] Ibid.

[460] Ibid.

[461] Ibid.

[462] Ibid.

[463] https://www.qwake.tech/prebook

Figure A.13: Typical connectivity requirements for emergency services AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
Up to 5000 (DL)	Generally <20	Local	High reliability	Once glasses/visors are being used in field, both UL and DL capacity will be required, there may be security requirements, and coverage will need to be ubiquitous

Energy/utilities – smart grid

In the smart grid context, AR/VR might be used for remote expert-type use cases. One simple remote expert solution on the market uses up to 2.5Mbit/s for a 1080p, 30fps video on a mobile phone.[464] However, for more complex AR/VR (higher resolution, glasses, and so forth) the generic capacity values may be more appropriate. Additionally, 3GPP specification 22.804 (Release 16) requires an end-to-end latency of less than 100ms to ensure remote support for plant maintenance up to 5000km between end points.[465] Hence the typical connectivity requirements for smart grid AR/VR (see Figure A.14) are the generic requirements, but with a slightly wider capacity range and a higher latency. We note that the remote expert capability would be needed across the footprint of the energy company's grid operations, which might include remote and hard-to-reach locations (potentially not within the coverage footprint of public cellular networks).

Figure A.14: Typical connectivity requirements for energy/utilities – smart grid AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
2.5–50 (UL and DL)	<100	Ubiquitous	High reliability	Capacity likely to increase over time as more data-intensive evolutions of remote expert emerge; latency may be lower for some applications.

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[464] https://librestream.com/media/LIB-platform-brochure-2021.pdf

[465] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

Energy/utilities – site operations

Site operations is also a remote expert use case, and as such will have similar requirements to the smart grid case above. However, in this instance coverage will be localised to the site, rather than being required across the footprint of the energy grid (see Figure A.15).

Figure A.15: Typical connectivity requirements for energy/utilities – site operations AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
2.5–50 (UL and DL)	<100	Local	High reliability	Capacity likely to increase over time as more data-intensive evolutions of remote expert emerge; latency may be lower for some applications.

Agriculture, forestry and fishing

Agriculture, forestry and fishing is also a remote expert use case, but coverage areas could be vast and include remote and hard-to-reach locations. As such, it will have similar requirements to the energy/utilities – smart grid use case (see Figure A.16).

Figure A.16: Typical connectivity requirements for agriculture, forestry and fishing AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
2.5–50 (UL and DL)	<100	Ubiquitous	High reliability	Capacity likely to increase over time as more data-intensive evolutions of remote expert emerge; latency may be lower for some applications.

Construction

A 2021 article on 5G in construction states that for the AR/VR use case to provide on-site views of 3D models and project drawings, 25Mbit/s and a latency of 1–10ms is required.[466] However, this is also a remote expert use case, localised to construction sites, and as such the typical requirements (see Figure A.17) will be similar to

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[466] https://www.mdpi.com/2079-9292/10/14/1713/htm

energy/utilities – site operations, with lower latencies to account for additional use cases.

Figure A.17: Typical connectivity requirements for construction AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
2.5–50 (UL and DL)	Generally <20	Local	High reliability	Capacity likely to increase over time as more data-intensive evolutions of remote expert emerge; latency may be higher for some applications.

Ports

A port AR/VR use case example was noted in the literature review: an Ericsson blog post from 2020. The post examines digital twins in port operations, specifically the Port of Livorno's digital twin. It states that the cameras used for AR transmit a continuous data flow of about 10Mbit/s in uplink, and that the end-to-end latency target is posed at 10ms.[467] The data rate falls within the generic values, and although the latency is lower, other port uses of AR/VR, such as a remote expert use case, may not have such stringent requirements. Thus the generic AR/VR requirements values (with a wider capacity range to account for simple remote expert use cases) are likely to be required (see Figure A.18). Coverage will be localised to the ports.

Figure A.18: Typical connectivity requirements for port AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
2.5–50 (UL and DL)	Generally <20	Local	High reliability	Capacity likely to increase significantly over time, some mission-critical applications may have lower latencies.

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[467] https://www.ericsson.com/en/blog/2020/12/digital-twins-port-operations

Smart factories and warehousing

3GPP specification 22.804 (Release 16) states that for AR in the context of factories of the future, the end-to-end latency should be 10ms or less and the service availability should be at least 99.9%.[468]

In ACIA 5G's white paper on 5G for automation in industry, AR in smart factories is identified as requiring 99% availability.[469]

Typical uplink and downlink capacities (Figure A.19) are likely to be similar to the generic use case values. Coverage will be local to the factories and warehouses.

Figure A.19: Typical connectivity requirements for smart factories and warehousing AR/VR use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
10–50 (UL and DL)	≤10	Local	High reliability, high availability (99.9%)	Capacity likely to increase significantly over time, some mission-critical applications may have lower latencies

A.3 UHD video

A.3.1 Generic UHD video requirements

UHD video falls into three generic categories; watching, creating and surveying.

We have compiled the recommended UHD video download speeds for a range of streaming services, as shown in Figure A.20.

Figure A.20: Streaming service recommended UHD video download speeds [Source: Various]

Streaming service	Download speed (Mbit/s)
Netflix[470]	25

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[468] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

[469] See https://5g-acia.org/wp-content/uploads/2021/04/5G-ACIA_5G-for-Automation-in-Industry-.pdf

[470] See https://help.netflix.com/en/node/306

Streaming service	Download speed (Mbit/s)
Disney+[471]	25
Apple TV+[472]	≥25
YouTube[473]	20
Google Play Movies and TV[474]	≥15
BT Sport[475]	25

According to an article published in 2018, "a video's start-up time – the gap between when the viewer hits Play and when their video starts – is seen as the most important factor in online video service provider success".[476] The article mentions a study conducted by Akamai which found that "a two-second increase in start-up time can result in as much as 50 percent of the audience giving up on playing the video altogether".[477] It also notes that the average video start-up time in 2017 was 4.84 seconds.

The latest version of 3GPP specification 26.825 for Release 16 (Typical traffic characteristics of media services on 3GPP networks), lists typical streaming/broadcast video and audio uplink bitrates, as shown in Figure A.21.[478] The values remain the same in the latest Release 17 version.[479]

Figure A.21: Typical streaming/broadcast video and audio bitrates [Source: 3GPP, 2021]

Video/audio	Resolution/ quality	Bitrate (Mbit/s)
Video	720p HD	2–5
Video	Full HD	3–12
Video	4K UHD	5–25

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[471] See https://help.disneyplus.com/csp?id=csp_article_content&sys_kb_id=beb5f45fdbaf849860f3eacb13961997

[472] https://support.apple.com/en-gb/HT207949

[473] https://support.google.com/youtube/answer/78358?hl=en

[474] https://support.google.com/googleplay/answer/7184994?hl=en

[475] https://www.bt.com/help/bt-sport/bt-sport-ultimate--what-it-is-and-how-you-can-watch

[476] https://www.streamingmedia.com/Articles/ReadArticle.aspx?ArticleID=124163

[477] Ibid.

[478] Version 16.0.0 uploaded 2020-03-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3533

[479] Version 17.0.0 uploaded 2021-09-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3533

Video/audio	Resolution/ quality	Bitrate (Mbit/s)
Video	8K UHD	20–80
Audio	Normal quality	0.024–0.048
Audio	High quality	0.024–0.512
Audio	Extreme quality	0.512

Both the Release 16 and Release 17 versions of 3GPP specification 26.825 also identify uplink bitrates ranging from 143Mbit/s to 24Gbit/s for wired connections within professional production environments, with uncompressed 4K video requiring 17.684Gbit/s. It should be noted that with the compression used for portable cameras equipped with wireless modules, the value is likely to be several magnitudes lower, based on the relative values for compressed and uncompressed 720p and 1080p (see Figure A.22).[480]

Figure A.22: Compressed and uncompressed video stream bitrates [Source: 3GPP, 2021]

Video format	Uncompressed video bitrate (Mbit/s)	Compressed video bitrates for wireless cameras (Mbit/s)
480p (480 vertical pixel resolution), 30fps or 576p, 25fps	221	2–9
720p, 50 or 60fps	982 or 1178	3–9
1080p, 50 or 60fps	2210 or 2650	Not specified
2160p, 50 or 60fps	8842 or 10 600	Not specified
2160p, 100fps (4K)	17 684	Not specified
4320p, 50 or 60 or 100fps (8K)	36 103 or 43 280 or 72 206	Not specified

3GPP specification 22.804 states that for professional video production in the context of Release 16, the uplink data rate target is 100–200Mbit/s, and the downlink data rate target is 20Mbit/s. The end-to-end latency should be 10ms or less and the packet error ratio should be 99.999% (i.e. one defect video frame per hour of operation).[481]

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[480] Version 16.0.0 uploaded 2020-03-24 and version 17.0.0 uploaded 2021-09-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3533

[481] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

In its 2022 discussion paper on mobile networks and spectrum, Ofcom states that "8K (UHD) video may require throughputs of 40Mbit/s"[482].

In a comparison of 4K UHD CCTV cameras for surveillance in 2017, Benchmark magazine listed the requirements for a selection of cameras, as shown in Figure A.23.[483]

Figure A.23: Comparison of bitrate and latency for six UHD CCTV cameras [Source: Benchmark magazine, 2017]

Camera	Bitrate (Mbit/s)	Latency
Bosch Dinion IP ultra 8000 MP	UHD image optimised profile: 28 (max 32) UHD bit-rate optimised profile: 6 (max 12) if lots of motion show initial signs of compression	Not specified but at least lower than 2s
FLIR: CF-6308	Max: 20, reducing to 8 only impacts image quality if scene is very busy	Not specified but at least lower than 2s
Hanwha Techwin: PNV-9080RP	20 gave clean sharp image, dropping to 10 did not degrade image quality	Not specified but at least lower than 2s
Hikvision: DS-2CD2385FWD-I	Max: 16, reducing to 8 did not impact image quality	1s
IDIS: DC-T1833WHR	Max: 18, dropping to 10 did not impact image quality	"Very low"
Panasonic:WV-SFV781L	20 has very good image quality, 12 does not impact image quality, 8 introduces small imperfections	2s

Based on the literature reviewed, the typical requirements for UHD video use cases are as shown in Figure A.24.

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[482] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

[483] https://benchmarkmagazine.com/cctv-test-4k-uhd-cameras-2/; accessed 10/12/2021

Figure A.24: Typical connectivity requirements for generic UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements[484]	Additional comments
Generic UHD video watching	Generally ≥25 (DL)	<5000	–	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.
Generic UHD video creation	100–200 (UL) and 20 (DL)	≤10	Very high reliability	Capacity may increase as video resolution increases, but compression technology may improve, reducing the values over time.
Generic UHD video surveillance	5–30	<2000	Likely to have strict security requirements	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

A.3.2 Sector-specific UHD video requirements

Media creation

This is the generic UHD video creation use case. Coverage will be localised to studios creating content except where media is being filmed on location and sent back to studios, when consistently higher levels of wide-area coverage would be needed (especially if filming from different locations). Media companies often have dedicated outside production equipment that they use for filming on location, which would fall under Ofcom's programme making and special events (PMSE) licensing framework.

Typical connectivity requirements for media creation UHD video use cases are presented in Figure A.25. Note that drones are beginning to be used for filming

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[484] Note that coverage will be use-case specific.

purposes in the media and creation category, however the connectivity requirements for the video component far outweigh the connectivity required to control the drone, hence the requirements captured below are sufficient.

Figure A.25: Typical connectivity requirements for media creation UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
100–200 (UL) and 20 (DL)	≤10	Local	Very high reliability	Capacity may increase as video resolution increases, but compression technology may improve, reducing the values over time. If transmitting data to another location wider coverage will be needed.

Venues and events

UHD video in venues and events might be used for live streaming of the event onto large screens on site. Professional cameras will be used and hence this is the generic UHD video creation use case. Coverage will be localised to the venues and events. Typical connectivity requirements for venues and events UHD video use cases are presented in Figure A.26.

Figure A.26: Typical connectivity requirements for venues and events UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
100–200 (UL) and 20 (DL)	≤10	Local	Very high reliability	Capacity may increase as video resolution increases, but compression technology may improve, reducing the values over time.

Health and social care

At a Healthcare Estates conference in 2021, a representative from Brandon Medical (a UK-based designer and manufacturer of technology solutions for operating theatres) discussed the design considerations for the modern operating theatre, including supporting the implementation of UHD medical video. In the presentation, the bandwidth requirements for video transmission were discussed (see Figure

A.27). HD was the most common format for medical videos, and fibre optics was presented for UHD 4K solutions.[485]

Figure A.27: Bandwidth requirements for medical videos [Source: Brandon Medical presentation, 2021]

Video type	Bandwidth requirements (Gbit/s)
SD 720p	1.45
HD 1080p	2.97
UHD 4K 30fps	11.14
UHD 4K 30fps	18

The latest version of 3GPP specification 22.826 (Study on communication services for critical medical applications), part of Release 17, for the use case of duplication of video on multiple monitors, states that a real-time, compressed, 8K, 120fps, HDR video stream:

- has a bitrate of 48Gbit/s uplink and downlink
- has a maximum end-to-end latency of <1ms
- requires >99.99999% communication service availability
- must have a mean time between failure >1 year.

However, for 4K video, the bandwidth required will be lower, as shown in Figure A.10 (Section A.2), where the real-time, compressed, 4K, 120fps, HDR video stream component of AR/VR surgery has a bitrate of 12Gbit/s uplink and downlink. For real-time, stereoscopic, compressed, 4K, 120fps, HDR video stream the bitrate is 24Gbit/s uplink and downlink, and latency must be <2ms.[486] These values are magnitudes greater than those for any generic UHD video use case, likely due to the ultra-low latency requirements.

Based on the literature review, the typical connectivity requirements for UHD video in health and social care are more stringent than any of the generic use cases (see Figure A.28).

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[485] https://vimeo.com/639445147

[486] Version 17.2.0 uploaded 2021-04-02; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3546

Figure A.28: Typical connectivity requirements for health and social care UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
10 000–25 000	<1	Local	Ultra-high availability, ultra-high reliability; also likely to have ultra-high security requirements	Capacity will increase as demand evolves towards higher resolutions, however the evolution of compression technologies may help to counteract this.

Education

UHD video in education falls under the generic UHD video watching category, so the typical education requirements (Figure A.29) will be the generic UHD watching requirements, and coverage will be localised to schools and universities.

Figure A.29: Typical connectivity requirements for education UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
Generally ≥25 (DL)	<5000	Local	–	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

Emergency services

A 2020 white paper by IDC indicates that remote emergency service use cases will require 50Mbit/s to transmit video of patients to the hospital.[487]

The latest version of 3GPP specification 22.826 (Study on communication services for critical medical applications), for Release 17, examines the use case of patient monitoring inside moving ambulances (see Figure A.30). It states that a real-time, compressed, 4K video stream of the ambulance requiring a latency of no more than 100ms would need a bitrate of 25Mbit/s uplink, and has high availability and reliability requirements. The accompanying high-quality audio stream only requires

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[487] See https://carrier.huawei.com/~/media/CNBGV2/russia/Images/KAIKeyArchitectureInedxWhitePaperbyIDCFinal.pdf

0.128Mbit/s uplink and downlink. For an uncompressed video scan (e.g. CT) stream, with higher resolution but lower fps, the bitrate is given as 670Mbit/s, however with compression this would likely be much lower. For the use case of remote, stationary, ultrasound and interventional support (Figure A.31), a real-time video stream has all the same requirements as that of the moving ambulance, bar a lower latency (maximum 20ms), and for the uncompressed ultrasound probe video stream the bitrate given is 160Mbit/s.[488]

Figure A.30: Potential new communication service requirements to support patient monitoring inside ambulances [Source: 3GPP, 2021]

Component	Bitrate (Mbit/s)	Max end-to-end latency (ms)	Target service availability	Service reliability (mean time between failure)
Compressed 4K (3840×2160 pixels), 12 bits per pixel, 60fps, real-time video stream	25 (UL)	<100	99.99%	>1 month
Uncompressed 2048×2048 pixels, 16 bits per pixel, 10fps, real-time video scan stream	670 (UL)	<100	99.999%	>1 month but <1 year
High quality audio stream	128 (UL and DL)	<100	99.99%	>1 month

Figure A.31: Potential new communication service requirements to support remote ultrasound and interventional support [Source: 3GPP, 2021]

Component	Bitrate (Mbit/s)	Max end-to-end latency (ms)	Target service availability	Service reliability (mean time between failure)
Compressed 4K (3840×2160 pixels), 60fps, 12 bits, real-time video stream	25 (UL)	<20	99.99%	>1 month
Uncompressed 512×512 pixels, 32 bits, 20fps, video	160 (UL)	<20	99.999%	>1 month, but <1 year

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[488] Version 17.2.0 uploaded 2021-04-02; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3546

Component	Bitrate (Mbit/s)	Max end-to-end latency (ms)	Target service availability	Service reliability (mean time between failure)
stream from ultra-sound probe				

Based on the literature reviewed, the typical requirements for UHD video use cases are as shown in Figure A.32.

Figure A.32: Typical connectivity requirements for emergency services UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
25–500	<20 if stationary, <100 if moving	Ubiquitous	High availability, high reliability, likely very high security	Note that these requirements stem mostly from Release 17 which is not due to come into force until 2022.

Energy/utilities – smart grid

The requirements for smart grid surveillance (Figure A.33) are likely to be similar to those discussed in the next subsection (Energy/utilities – site operations).

Figure A.33: Typical connectivity requirements for energy/utilities – smart grid UHD video use cases – per device [Source: 3GPP, 2021]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
3–5	<1000	Local	High reliability	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

Energy/utilities – site operations

3GPP specification 22.867 (Study on 5G Smart Energy and Infrastructure), as input to definition of Release 18, specifies that 3–5Mbit/s is required for HD surveillance cameras in energy substations. However, there is no key requirement for latency or availability as streaming protocols will allow for buffering in the event of changes of latency, and availability can be compensated for by local storage on site. It also specifies that HD is sufficient. For the case of video in an energy storage station the data rate is given as >5Gbit/s uplink and >0.1Gbit/s downlink per storage station, with <1000ms of latency and >99.9% reliability.[489] Coverage will be localised to the energy sites. Typical connectivity requirements for energy/utilities – site operations UHD video use cases are presented in Figure A.34.

Figure A.34: Typical connectivity requirements for energy/utilities – site operations UHD video use cases – per device [Source: 3GPP, 2021]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
3–5	<1000	Local	High reliability	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

Construction

No specific requirements for UHD video in construction were noted in the literature review. Video in construction is used for surveillance, and as such the generic UHD video surveillance use case requirements are likely to apply to this sector (see Figure A.35).

Figure A.35: Typical connectivity requirements for construction UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
5–30	<2000	Local	Likely to have strict security requirements	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

Roads

No specific requirements for UHD video on roads were noted in the literature review. In road-related use cases, UHD video is used for surveillance, and as such the generic UHD video surveillance use case are likely to apply to this sector (see Figure A.36).

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[489] Version 18.1.0 uploaded 2021-09-29; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3770

Figure A.36: Typical connectivity requirements for road UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
5–30	<2000	Local	Likely to have strict security requirements	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

Rail

3GPP specification 22.804 states that for Release 16, in the case of rail-bound mass transit, real-time CCTV requires at least 4Mbit/s, <500ms latency, >99.99% service availability, and high levels of security.[490] CCTV is the standard rail UHD video use case so these values are likely representative of the typical requirements for rail UHD video (Figure A.37).

Figure A.37: Typical connectivity requirements for rail UHD video use cases – per device [Source: 3GPP, 2020]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
>4Mbit/s UL	<500ms	Local	>99.99% service availability, high security	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time.

Air

No specific requirements for UHD video in airports were noted in the literature review. Video in airports is used for surveillance, and as such we assume the requirements for the generic UHD video surveillance use case as stated earlier in this annex should apply (see Figure A.38).

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[490] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

Figure A.38: Typical connectivity requirements for air UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
5–30	<2000	Local	Likely to have strict security requirements	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time

Ports

According to a Huawei white paper on smart ports, video surveillance requires 2–4Mbit/s, <200ms latency and 90% reliability.[491] CCTV is the standard port UHD video use case so these values are likely representative of the typical requirements for UHD video in ports (Figure A.39).

Figure A.39: Typical connectivity requirements for port UHD video use cases – per device [Source: Huawei, 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
2–4	<200	Local	Medium reliability (90%), likely to have strict security requirements	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time

Smart factories and warehousing

No specific requirements for UHD video in smart factories or warehouses were observed in the literature review. Video in smart factories and warehouses is used for surveillance, and as such the generic UHD video surveillance use case requirements are likely to apply to this sector (see Figure A.40).

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[491] https://www.huawei.com/en/download?rid=%7bEE93406C-B514-4433-AE39-D4057F0B8179%7d

Figure A.40: Typical connectivity requirements for smart factories and warehousing UHD video use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
5–30	<2000	Local	Likely to have strict security requirements	Capacity may increase as resolution increases, but compression technology may improve, reducing the values over time

A.4 Sensor networks

A.4.1 Generic sensor network requirements

3GPP specification 22.804 states that in the context of Release 16 and massive wireless sensor networks, typical monitoring requirements vary according to scenario, as shown in Figure A.41. Some examples of data generation per sensor are provided in Figure A.42. The specification also states that “the 5G system shall support high-bandwidth streams from a massive set of devices with a user experienced data rate of up to 100 Mbit/s”[492] and “the 5G system shall support a very high connection density of up to 10^6 connections per km^2”,[493] so if the former requirement was also for a square kilometre, the average data rate could be as low as 0.1kbit/s.

Figure A.41: Typical monitoring service requirements [Source: Source: 3GPP, 2020]

Scenario	End-to-end latency (ms)	Communication service availability
Condition monitoring for safety	5–10	> 99.9999%
Interval-based condition monitoring	50–1000	> 99.9%
Event-based condition monitoring	50–1000	> 99.9%

Figure A.42: Example of data generation per sensor [Source: 3GPP, 2020]

Measurement	Data generation (kbit/s)
Temperature	6

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[492] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

[493] Ibid.

Measurement	Data generation (kbit/s)
Acceleration	192–384
Audio WAV	2.4–4600
Audio MP3	8–320

A 2018 white paper by Keysight technologies discusses the throughput and delay of various applications enabled by future 5G standards (note that at the time Release 16 had not yet been released). In the paper, monitoring sensor networks is depicted as requiring <1Mbit/s throughput and 1000ms delay,[494] which agrees with the examples given by 3GPP and appears to be a good representation of the typical sensor network requirements (see Figure A.43).

Figure A.43: Typical connectivity requirements for generic sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements [495]	Additional comments
Generic sensor network devices	<1 (UL)	<1000	May require high availability	–

A.4.2 Sector-specific sensor network requirements

Health and social care

Sensors are used to monitor vitals in hospitals and in social care scenarios.

In a 2017 article in the *International Journal of Advance Computer Science and Applications (IJACSA)*, requirements are given for a selection of common sensor applications, as shown in Figure A.44.[496]

Figure A.44: Requirements for a selection of sensors used in healthcare [Source: IJACSA, 2017]

Sensor type	Data rate (kbit/s)	Latency
ECG	144	<250

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[494] https://www.keysight.com/gb/en/assets/7018-06129/white-papers/5992-2921.pdf?success=true

[495] Note that coverage will be use-case specific

[496] https://pdfs.semanticscholar.org/45b1/7f5e26ef5e8e7d503f80f0b0c4163f7f1400.pdf

Sensor type	Data rate (kbit/s)	Latency
EMG	300	<250
EEG	43.2	<250
Blood saturation	0.016	Not specified

A 2016 report by Real Wireless for the National Infrastructure Commission states that sensors used around the home, or body sensors used in assisted living services, have a “very low data rate” ranging from 1kbit/s to 10kbit/s. The same range is provided for sensors used in preventative health services.[497]

The latest version of 3GPP specification 22.826 (Study on communication services for critical medical applications), which is for Release 17, includes a table detailing requirements for several sensors used in healthcare, which is replicated in Figure A.45.[498]

Figure A.45: Requirements for a selection of sensors used in healthcare [Source: 3GPP, 2021]

Sensor type	Data rate (kbit/s)	Latency	PLR
Temperature	<10	<250	$<10^{-3}$
Blood pressure	<10	<250	$<10^{-3}$
Heart rate	<10	<250	Not specified
Respiration rate	<10	<250	Not specified
ECG	72	<250	Not specified
EEG	86.4	<250	Not specified
EMG	1536	<250	Not specified

While typically these sensors require less than 1Mbit/s of uplink, the latency requirements are slightly stricter than for generic sensor network use cases due to the potential risk to life involved (see Figure A.46).

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[497] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

[498] Version 17.2.0 uploaded 2021-04-02; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3546

Figure A.46: Typical connectivity requirements for health and social care sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	**Latency (ms)**	**Coverage**	**Other requirements**	**Additional comments**
<1 (UL)	<250	Ubiquitous	Likely to require high security, reliability and availability.	–

Emergency services

The 2016 report by Real Wireless for the National Infrastructure Commission states that sensors used in remote healthcare services "would typically require not more than 10kbit/s".[499]

A 2018 white paper by Keysight technologies discusses the throughput and delay of various applications enabled by future 5G standards (note that at the time Release 16 had not yet been released). Disaster alert is depicted as requiring <1Mbit/s throughput and 10ms delay.[500]

According to 3GPP Release 17 specification 22.826 (Study on communication services for critical medical applications), the physical vital signs monitoring the data stream from an ambulance requires 1Mbit/s uplink, <100ms of latency, 99.999% communication service availability and a mean time between failure of between a month and a year.[501]

The monitoring of firefighters' vital signs is likely to have similar requirements.

Typical connectivity requirements for emergency services sensor network use cases are shown in Figure A.47.

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[499] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

[500] https://www.keysight.com/gb/en/assets/7018-06129/white-papers/5992-2921.pdf?success=true

[501] Version 17.2.0 uploaded 2021-04-02; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3546

Figure A.47: Typical connectivity requirements for emergency services sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
≤1 (UL)	<100	Ubiquitous	Ultra-high availability, likely to require high security and reliability.	Some applications (e.g. disaster alerts) may require lower latencies.

Energy/utilities – smart grid

3GPP specification 22.862 (Release 14) states that in the context of a smart grid system, sensors should be able to reliably (99.999%) deliver 200 to 1521 bytes in 8ms.[502]

In a 5G Americas white paper published in 2017, massive IoT in smart grid/utilities is identified as requiring 1–100kbit/s uplink and downlink and 1–5ms latency.[503]

A paper published on smart grid communication in Computer Science Review includes a table on quality-of-service requirements for smart grid applications, all of which require high levels of security. The table is reproduced in Figure A.48.[504]

Figure A.48: Quality-of-service requirements for smart grid applications [Source: Computer Science Review, 2018]

Application	Bandwidth (kbit/s)	Latency	Reliability
Home energy management	9.6–56	300–2000ms	99–99.99%
Advanced metering infrastructure	10–100	2000ms	99–99.99%
Meter reading – on demand	0.1	<15s	>98%
Meter reading – scheduled manner	1.6–2.4	<4 hours	>98%

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[502] Version 14.1.0 uploaded 2016-10-04; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3014

[503] https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Network_Transformation_Final.pdf

[504] See https://www.researchgate.net/publication/327321554_Smart_grid_communication_and_information_technologies_in_the_perspective_of_Industry_40_Opportunities_and_challenges

Application	Bandwidth (kbit/s)	Latency	Reliability
Meter reading – collective manner	≥1000	<1 hour	99%
Wide-area situation awareness	600–1500	15–200ms	99%
Demand response management	14–100	500ms to several minutes	99%
Substation automation	9.6–56	15–200ms	99–100%
Outage management	56	2000ms	99%
Distribution management	9.6–100	100–2000ms	99–99.99%
Distribution generation	9.6–56	2000ms	99%
Control and data acquisition	56–100	2000–5000ms	99%
Asset management	56	2000ms	99%
Meter data management	56	2000ms	99%
Transmission line monitoring	9.6–64	1000ms	99%
Distributed energy resources and storage	9.6–56	300–2000ms	99–99.99%
Vehicle to grid	9.6–56	2000ms to 5 minutes	99–99.99%
Electrical vehicles	9.6–56	2000ms to 5 minutes	99–99.99%
Program/ configuration update	25–50	<5 minutes to 7 days	>98%
Firmware update	400–2000	<2 minutes to 7 days	>98%

3GPP specification 22.804 states that for Release 16, sensors involved in primary frequency control – controlling energy supply and end-to-end latency – should be in the order of 50ms, and for distributed voltage control it should be in the order of 100ms.[505]

The 2016 report by Real Wireless for the National Infrastructure Commission states that smart grid devices fall in the data range of 1–200kbit/s. Sensors used in remote healthcare services “would typically require not more than 10kbit/s”.[506]

A paper titled Network Coding in Smart Grids, states that “the data rates involved in smart grid communications are unlikely to exceed 10kbit/s”, and that “advanced metering functionalities are not time critical, they can occasionally suffer a delay”, but “require a very high level of reliability” and have security and privacy requirements.[507] It is noted that energy companies will have their own business needs for advanced connectivity – e.g. AR/VR for remote expert operations or for maintenance and fault diagnostics. These applications would require higher bitrates than the ones reported in these papers.

3GPP specification 22.867 (Study on 5G Smart Energy and Infrastructure), which is for Release 18, lists a variety of advanced use cases involved in smart grids, several of which relate to sensors, and are captured in Figure A.49. In particular, advanced metering requires <2Mbit/s uplink and <1Mbit/s downlink, <3000ms latency for general information data collection, and >99.99% reliability, all of which can be supported by existing 3GPP releases.[508] Given that the smart grid is a critical national infrastructure it is expected that some of these applications might require lower latencies in practice than those reported from the 3GPP below.

Figure A.49: Performance requirements for sensors involved in a variety of smart grid use cases [Source: 3GPP, 2021]

Use case	Data rate (kbit/s)	Latency (ms)	Availability
Data collection for distributed energy storage	>128kbit/s (UL), >100kbit/s (DL)	<1000	>99.9%
Advanced metering	<2000 (UL), <1000 (DL)	<3000	>99.99%
Distribution automation	9.6–100	100–2000	99–99.99%

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[505] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

[506] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

[507] http://www.yphulpin.eu/Papers/SGC2011_Phulpin2.pdf

[508] Version 18.1.0 uploaded 2021-09-29; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3770

Use case	Data rate (kbit/s)	Latency (ms)	Availability
Demand response	14–100	500–3000	99–99.99%
Distributed generation	9.6–56	20ms to 5 minutes	99–99.99%
State estimation (insight into operation state of power network)	~5 (UL)	100–3000	99.99%
Power control	<100 (UL)	<30	99.99%
Load generation and prediction	0.1	Not critical	99.9%

This literature agrees with the generic sensor network capacity requirements identified in Figure A.43. Latency, however, seems to be even less critical, although it is expected that specific emergency alarm-type sensors may require low latencies. Typical connectivity requirements for energy/utilities – smart grid sensor network use cases are shown in Figure A.50.

Figure A.50: Typical connectivity requirements for energy/utilities – smart grid sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
≤1 (UL)	<3000	Local	High reliability, and very high availability and high security	Sensors involved in emergency alarms may require lower latencies

Energy/utilities – site operations

The typical requirements for sensor networks in site operations in the energy/utilities sector (Figure A.51) are likely to be similar to the requirements identified in Figure A.50 for sensor networks in energy/utilities – smart grid.

Figure A.51: Typical connectivity requirements for energy/utilities – site operations sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
≤1 (UL)	<3000	Local	High reliability, and very high availability	Sensors involved in emergency alarms may require lower latencies

Agriculture, forestry and fishing

In a 5G Americas white paper published in 2017, massive IoT in agriculture is identified as requiring 1–100kbit/s uplink and downlink and 1–5ms latency.[509] This value is likely applicable to sensor networks in this subsector, however it falls within the range of the generic use case requirements, and due to the limited information found in the literature review, the generic sensor network use case requirements are likely to apply to sensor networks in agriculture, forestry and fishing (see Figure A.52).

Figure A.52: Typical connectivity requirements for agriculture, forestry and fishing sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	**Latency (ms)**	**Coverage**	**Other requirements**	**Additional comments**
<1 (UL)	<1000	Ubiquitous	May require high availability	–

Smart cities

In a 5G Americas white paper published in 2017, sensor networks in smart cities are identified as requiring 1–100kbit/s uplink.[510]

3GPP specification 22.804 states that for Release 16, in the context of sensors involved in building automation, “the 3GPP system shall support an end-to-end latency of 10ms with a [99,9999%] communication service availability for data transmission”.[511]

These values fall within the range of the generic use case, albeit towards the lower end of the range, and due to the limited information found in the literature review, the generic sensor network use case requirements are likely to apply to smart city sensor networks (see Figure A.53).

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[509] https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Network_Transformation_Final.pdf

[510] https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Network_Transformation_Final.pdf

[511] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

Figure A.53: Typical connectivity requirements for smart city sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1 (UL)	<1000	Local	Ultra-high availability	–

Construction

The literature review did not find any specific data requirements for sensors used in construction. As such, the generic sensor network use case requirements are likely to apply to sensor networks in the construction subsector (see Figure A.54).

Figure A.54: Typical connectivity requirements for construction sensor network use cases – per device [Source: Analysys Mason, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1 (UL)	<1000	Local	May require high availability	–

Roads

In a 5G Americas white paper published in 2017, sensor networks for connected roads are identified as requiring 1–100kbit/s uplink.[512] However, this refers to data exchange between vehicles, and between vehicles and infrastructure for the purposes of conveying speed, traffic and route information, rather that the data speeds needed to drive a vehicle autonomously.

A 2011 research paper on wireless sensor networks in road transportation application states that in most wireless sensor network applications, the data rate is limited to 10–250kbit/s.[513] Again this relates to messaging between vehicles and with infrastructure. CAVs driven autonomously would require ultra reliable, low latency connectivity (URLLC).

These sensor network values fall within the capacity range of the generic use case, and due to the limited information found by the literature review, the generic sensor network use case connectivity requirements are likely to apply to road sensor networks (see Figure A.55).

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[512] https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Network_Transformation_Final.pdf

[513] Available at https://www.researchgate.net/publication/252020517_Wireless_sensors_networks_in_road_transportation_applications/link/5547664b0cf249186bb0f399/download

For fully autonomous driving, 5G-like speeds of 1Gbit/s are envisaged to be required, such as demonstrated through the Millbrook trials funded via DCMS's 5G test beds and trials programme.[514]

Figure A.55: Typical connectivity requirements for road sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1 (UL)	<1000	Local	May require high availability	–

Rail

In a 5G Americas white paper published in 2017, sensor networks for connected railways are identified as requiring 1–100kbit/s uplink.[515]

3GPP specification 22.804 states that for Release 16, in the case of rail bound mass transit, train diagnostics require at least 0.1Mbit/s, <1000ms latency, >99.99% service availability, and high levels of security.[516]

In the 2016 Real Wireless report for the National Infrastructure Commission, telemetry in railway use cases is identified as having "very low [bandwidth] per device" and requiring an estimate 300kbit/s per train.[517]

All of these data points support the values identified in the generic use case, and thus the generic requirements can be applied to the rail subsector (see Figure A.56).

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[514] https://www.automotivetestingtechnologyinternational.com/news/cavs/5g-enabled-mobile-network-launched.html

[515] https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Network_Transformation_Final.pdf

[516] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

[517] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

Figure A.56: Typical connectivity requirements for rail sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1	<1000	Local	Very high service availability, and high security	–

Air

The literature review did not find any specific data requirements for sensors in airports. As such, the connectivity requirements for generic sensor network use cases are likely to apply to the air subsector (see Figure A.57).

Figure A.57: Typical connectivity requirements for air sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1 (UL)	<1000	Local	May require high availability	–

Ports

The literature review did not find any specific data requirements for sensors in ports. As such, the connectivity requirements for generic sensor network use cases are likely to apply to the ports subsector (see Figure A.58).

Figure A.58: Typical connectivity requirements for port sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1 (UL)	<1000	Local	May require high availability	–

Smart factories and warehousing

3GPP specification 22.862 (Release 14) states that industrial process automation requires sensor devices to have a PLR of $<10^{-5}$, and a latency between 100ms and

1s, however, “data rates can be rather low since each transaction typically comprises less than 100 bytes”.[518]

3GPP specification 22.804 (Release 16) gives potential requirements for three categories of sensor installed in plants, and for three types of condition-monitoring sensor, as shown in Figure A.59.[519]

Figure A.59: Typical monitoring service requirements [Source: 3GPP, 2020]

Sensor category	End-to-end latency (ms)	Communication service availability
Closed-loop control	10	>99.9999%
Process monitoring	50–1000	99.99%
Plant asset management	1000	99.99%
Condition monitoring for safety	5–10	>99.9999%
Interval-based condition monitoring	50–1000	>99.99%
Event-based condition monitoring	50–1000	>99.99%

The literature review did not find any specific requirements relating to capacity, and the specific latency requirements support the generic findings, so the generic sensor network use case requirements are likely to capture the typical smart factory and warehouse sensor network requirements (see Figure A.60).

Figure A.60: Typical connectivity requirements for smart factories and warehousing sensor network use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1 (UL)	<1000	Local	Ultra-high reliability and availability	–

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[518] Version 14.1.0 uploaded 2016-10-04; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3014

[519] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

A.5 Remote machine manipulation

A.5.1 Generic remote machine manipulation requirements

The 2016 report by Real Wireless for the National Infrastructure Commission states that remote machine operation requires <50Mbit/s, <1ms of latency and >99.9% availability.[520]

According to Qualcomm's 2018 document on VR and AR, "interactive remote experiences often range from 40 to 300ms of latency, and feedback below 5ms will enable novel uses of multi-sensory remote tactile control".[521]

A 2018 white paper by Keysight technologies depicts the throughput and delay of various applications enabled by future 5G standards (note that at the time Release 16 had not yet been released). Tactile internet is depicted as requiring 100–1000Mbit/s throughput and 1ms delay, however device remote controlling is depicted as requiring 1–10Mbit/s throughput and 100ms delay.[522]

The IEEE TI standards working group released a paper which defines the requirements and traffic characteristics for key TI use cases, one of which is teleoperation. The information from this paper is presented in Figure A.61.[523]

Figure A.61: KPI requirements and traffic characteristics for TI teleoperation [Source: IEEE, 2019]

Component	Average data rate (Mbit/s)	Latency (ms)	Reliability
Haptics	Not specified	1–10	99.999%
Video	1–100 (UL)	10–20	99.999%
Audio	0.005–0.512 (UL)	10–20	99.9%

A 2020 research paper entitled "Tactile Internet in the Beyond 5G Era" identifies the key challenges for the realisation of tactile internet in future wireless applications

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[520] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

[521] https://www.qualcomm.com/media/documents/files/vr-and-ar-pushing-connectivity-limits.pdf

[522] https://www.keysight.com/gb/en/assets/7018-06129/white-papers/5992-2921.pdf?success=true

[523] https://ieeexplore.ieee.org/document/8605315

as ultra-low latency (<1ms), high reliability (>99.99%) and high data rates for some applications (in the order of Gbit/s to Tbit/s).[524]

3GPP specification 22.847 (Study on supporting tactile and multi-modality communication services) lists the quality-of-service requirements for multi-modal streams involved in teleoperation of devices, as shown in Figure A.62. It also lists the potential key performance requirements that Release 18 should support for remote-control robots. These are shown in Figure A.63.[525]

Figure A.62: Typical quality-of-service requirements for multi-modal streams [Source: Analysys Mason, 2022]

Component	Throughput (Mbit/s)	Delay (ms)	PLR
Haptics	0.512–1.024	≤50	≤10%
Video	2.5–40	≤30	≤10%
Audio	0.064–0.128	≤30	≤1%

Figure A.63: KPIs for remote-control robots [Source: 3GPP, 2021]

Component	Data rate (Mbit/s)	Latency (ms)	Reliability
Haptic feedback	0.0008–0.2	20–100	99.99%
Video	1–100	5	99.9%
Audio	0.005–0.5	5	99.9%
Sensing information	<1	5	99.999%

In general, the video component of remote machine operation is the most capacity-heavy component. The literature review indicates that this typically requires 1–100Mbit/s (although this could increase significantly over the next few years as higher resolution is demanded). Typical latency values vary depending on the component, but the strictest requirement tends to be for the haptic/tactile element. Typical connectivity requirements for generic remote machine manipulation use cases are shown in Figure A.64.

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[524] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9034103

[525] Version 18.0.0 uploaded 2021-09-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3848

Figure A.64: Typical connectivity requirements for generic remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements [526]	Additional comments
Generic remote machine manipulation	1–100	1–10	High availability, ultra-high reliability	Latency may be higher if haptics are not required, and over time capacity is likely to increase as demand for higher-quality video increases.

A.5.2 Sector-specific remote machine manipulation requirements

Health and social care

Remote machine operation is used for so-called robotic surgery,[527] also known as telesurgery, either with the operator located in the same hospital, or based remotely.

An overview of 5G mobile communication applications for surgery identified two early examples of remote surgery. The first was the 2001 Lindbergh operation, which used the ZEUS robotic system to perform a surgery at a distance of 6000km, using a fibre-optic connection with a guaranteed 10Mbit/s connection, with latency measured at 155ms. The second was a series of 22 surgeries performed in 2003 at a distance of 400km, also using the ZEUS system, but using internet protocol at a bandwidth of 15Mbit/s with latency of 135–140ms.[528]

A 2015 paper on real-time AR for robotic-assisted surgery stated that the latest [at the time] *da Vinci* robotic surgery system required a data rate of 1.5Gbit/s.[529]

A 2018 article discusses the first robotics coronary surgery conducted remotely, where a cardiologist placed a stent in a patient at a distance of 32km. The article

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[526] Note that coverage will be use-case specific.

[527] Note that despite the name, this is classified as remote machine manipulation as the ‘robot’ is being controlled by a surgeon.

[528] https://www.wjgnet.com/2689-7164/full/v2/i1/1.htm

[529] https://core.ac.uk/reader/60639080

states that “the experts said that even though the network connectivity of 100 Mbps was used to carry out this surgery, the required bandwidth is only 20 Mbps”.[530]

A 2018 paper on 5G-enabled tactile robotic telesurgery collates quality-of-service requirements for various components of robotic telesurgery, as shown in Figure A.65.[531]

Figure A.65: Quality-of-service requirements for telesurgery [Source: Zhang, Qi, et al., Towards 5G Enabled Tactile Robotic Telesurgery, 2018]

Component	**Data rate (Mbit/s)**	**Latency (ms)**	**PLR**
Real-time multimedia stream – 2D camera flow	<10	<150	$<10^{-3}$
Real-time multimedia stream – 3D camera flow	137–1600	<150	$<10^{-3}$
Real-time multimedia stream – audio	0.022–0.2	<150	$<10^{-2}$
Physical vital signs – temperature	<0.01	<250	$<10^{-3}$
Physical vital signs – blood pressure	<0.01	<250	$<10^{-3}$
Physical vital signs – heart rate	<0.01	<250	$<10^{-3}$
Physical vital signs – respiration rate	<0.01	<250	$<10^{-3}$
Physical vital signs – ECG	0.072	<250	$<10^{-3}$
Physical vital signs – EEG	0.0864	<250	$<10^{-3}$
Physical vital signs – EMG	1.54	<250	$<10^{-3}$
Haptic feedback – force	0.128–0.5	3 – 10	$<10^{-4}$
Haptic feedback – vibration	0.128–0.4	<5.5	$<10^{-4}$

A 2020 white paper by IDC states that real-time command and control for remote surgery requires 10ms end-to-end latency and 99.9999% reliability.[532]

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[530] https://www.indiawest.com/news/india/doctor-performs-worlds-first-in-human-remote-robotic-coronary-surgery/article_e6536028-f97c-11e8-83ed-93c9cbc97fd5.html

[531] Paper available at https://www.researchgate.net/publication/323694408_Towards_5G_Enabled_Tactile_Robotic_Telesurgery

[532] See https://carrier.huawei.com/~/media/CNBGV2/russia/Images/KAIKeyArchitectureInedxWhitePaperbyIDCFinal.pdf

The latest version of 3GPP specification 22.826 (Study on communication services for critical medical applications), which is for Release 17, includes a table detailing requirements for robotic aided surgery, which is shown in Figure A.66.[533]

Figure A.66: Release 17 communication service performance requirements for robotic aided surgery [Source: 3GPP, 2021]

Component	Bitrate (Mbit/s)	Maximum end-to-end latency (ms)	Service availability (target value)	Service reliability (mean time between failure)
Stereoscopic uncompressed 8K, 120fps, HDR, real-time video stream	240 000 (UL and DL)	<2	>99.99999%	>1 year
Stereoscopic 4K, 120fps, HDR, real-time video stream with lossless compression (an acceptable alternative to the above)	24 000 (UL and DL)	<2	>99.99999%	>1 year
Uncompressed 8K, 120fps, HDR, real-time video stream	120 000 (DL)	<50	>99.99999%	>1 year
4K, 120fps, HDR, real-time video stream with lossless compression (an acceptable alternative to the above)	12 000 (DL)	<50	>99.99999%	>1 year
Motion-control data stream	2 (UL), 16 (DL)	<2	>99.999999%	>10 years
Haptic feedback data stream	16 (UL), 2 (DL)	<2	>99.999999%	>10 years

The capacity requirements for remote machine operation in the health and social care subsector stem from the quality and latency of the video used to guide the surgeon. Current values are in the region of tens of megabits to several gigabits with tens or hundreds of milliseconds of latency for video. However, as demand for higher resolution, increased frame rate, and lower video latencies develops, capacity will increase dramatically, as demonstrated by 3GPP's potential network requirements for Release 17 (Figure A.66, above), and in UHD video requirements for health and social

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[533] Version 17.2.0 uploaded 2021-04-02 available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3546

care. Typical connectivity requirements for health and social care remote machine manipulation use cases are presented in Figure A.67.

Figure A.67: Typical connectivity requirements for health and social care remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
10–2000	1–10	Local	Ultra-high reliability and availability. Given the nature of the use case, likely to require ultra-high security too.	Latency may be higher (10–150ms) if haptics are not required. Capacity is likely to increase significantly over time (up to tens or hundreds of Gbit/s) with increasing demand for higher-quality videos at lower latencies (<2).

Emergency services

Remote machine operation in emergency services might be used for bomb disposal, rescue at sea, and so forth. The literature review found no specific data requirements for these use cases, so we assume the requirements for the generic remote machine operation use case are likely to apply to emergency service remote machine operation (see Figure A.68).

Figure A.68: Typical connectivity requirements for emergency services remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Ubiquitous	High availability, ultra-high reliability, likely to require high security	Latency may be higher if haptics are not required, and over time capacity is likely to increase as demand for higher-quality video increases.

Energy/utilities – site operations

The literature review did not find any specific data requirements for remote machine manipulation in energy/utilities – site operations. As such, the generic remote machine manipulation use case requirements are likely to apply in the energy/utilities – site operations subsector (see Figure A.69).

Figure A.69: Typical connectivity requirements for energy/utilities – site operations remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	High availability, ultra-high reliability, likely to require high security	Latency may be higher if haptics are not required, and over time capacity is likely to increase as demand for higher-quality video increases.

Agriculture, forestry and fishing

The literature review did not find any specific data requirements for remote machine manipulation in agriculture, forestry and fishing. As such, the generic remote machine manipulation use case requirements are likely to apply to the agriculture, forestry and fishing subsector (see Figure A.70).

Figure A.70: Typical connectivity requirements for agriculture, forestry and fishing remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Ubiquitous	High availability, ultra-high reliability, likely to require high security	Latency may be higher if haptics are not required, and over time capacity is likely to increase as demand for higher-quality video increases.

Construction

A 2021 article on 5G in construction states that the main challenges posed by the use case for remotely and autonomously controlled machinery are:

"[T]he need to transmit and receive information at very low latency, between 1 and 10ms, the high availability of the services, higher than 99.9999%, the reliability in the communication, which should be at least 10^{-6}, and the need for a secure link. In those cases where the data collected by the machinery are video, a high bandwidth is also needed, at least a data rate of 10 Mbps per connected machine being required".[534]

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[534] https://www.mdpi.com/2079-9292/10/14/1713/htm

This supports the findings for the generic remote machine manipulation use case connectivity requirements, so those requirements may be applied to this subsector (see Figure A.71).

Figure A.71: Typical connectivity requirements for construction remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	Ultra-high availability, ultra-high reliability, high security	Over time, capacity is likely to increase as demand for higher-quality video increases.

Ports

According to a Huawei white paper on smart ports, remote control of a gantry crane requires 5–16 30Mbit/s video channels (thus 150–480Mbit/s bandwidth in total), and a latency of <30ms. Quayside cranes have more than 20 cameras per crane, with an uplink bandwidth of 200Mbit/s (thus 4000Mbit/s bandwidth in total). In general, the white paper describes the requirements for remote control as 30–200Mbit/s (per video stream) plus 50–100kbit/s for remote control signalling, with a latency of <30ms and a reliability of 99.999%.[535] This typical capacity (see Figure A.72) is much higher than in the generic use case, but that is to be expected given the larger machines and increased number of moving parts.

Figure A.72: Typical connectivity requirements for port remote machine manipulation use cases – per device [Source: Huawei, 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
150–4000	<30	Local	Ultra-high reliability, also likely to require ultra-high availability and high security	Over time, capacity may increase as demand for higher-quality video increases.

Smart factories and warehousing

The literature review did not find any specific data requirements for remote machine manipulation in smart factories and warehousing. As such, the generic remote

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[535] https://www.huawei.com/en/download?rid=%7bEE93406C-B514-4433-AE39-D4057F0B8179%7d

machine manipulation use case requirements are likely to apply to remote machine manipulation in this subsector (see Figure A.73).

Figure A.73: Typical connectivity requirements for smart factories and warehousing remote machine manipulation use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	High availability, ultra-high reliability, likely to require high security	Latency may be higher if haptics are not required, and over time capacity is likely to increase as demand for higher-quality video increases.

A.6 Robotics

A.6.1 Generic robotics requirements

3GPP specification 22.804 states that in the context of Release 16 and ‘control to control’ (i.e. for machine handovers), cyclic traffic should have a response time <4ms and acyclic traffic should have a response time <10ms. Communication service availability should exceed 99.9999%.[536]

In a 2016 article in the Ericsson Technology review, [537] a trial used non-industrial robots to produce a completely automated logistics process. During the trial, round-trip latency was measured at 40ms. This latency was sufficient for stable navigation and control of robotic arms, and the bandwidth available to each robot (7–25Mbit/s) was sufficient to transfer data collected from the camera and sensors.

According to a 2017 paper on latency-critical IoT applications in 5G, process automation requires 50–100ms latency, and a PLR of 10^{-3}–10^{-4}.[538]

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[536] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

[537] https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/cloud-robotics-5g-paves-the-way-for-mass-market-automation

[538] https://www.vodafone-chair.org/media/publications/philipp-schulz/Latency_Critical_IoT_Applications_in_5G_Perspective_on_the_Design_of_Radio_Interface_and_Network_Architecture.pdf

Factory automation in a smart factory demands a reliability of approximately 99.999% for about 1ms latency, according to a paper published in 2020.[539]

A review article on the Internet of Robotic Things (IoRT) states that “total latency needs to be <20ms for average IoRT applications”.[540] The article goes on to say that “IoRT applications’ connectivity technologies need further development to meet the high demands for ultra-high reliability, very low-latency, high-bandwidth signal quality, and data rates”, and mentions that safety and mission-critical IoRT capabilities will not be widely available before 2025–30.

The latest version of 3GPP specification 22.847 (Study on supporting tactile and multi-modality communication services), Release 18, outlines the communication service performance requirements for skillset-sharing robots (Figure A.74).[541]

Figure A.74: Communication service performance requirements for skillset-sharing robots [Source: 3GPP, 2021]

Use cases	Bitrate (Mbit/s)	Latency (ms)	Reliability
Low dynamic robotics – video	1–100	10	99.999%
Low dynamic robotics – audio	0.005–0.512	10	99.9%
Low dynamic robotics – haptics	0.0008–0.2 (UL and DL)	5–10	99.999%
Highly dynamic/ mobile robotics – video	1–10	1–10	99.999%
Highly dynamic/ mobile robotics – audio	0.1–0.5	1–10	99.9%
Highly dynamic/ mobile robotics – haptics	0.0008– 0.2 (UL and DL)	1–5	99.999%

Similarly to generic remote machine control, video is the largest component in robotics, with a current typical capacity of 1–100Mbit/s, although this may increase as higher-quality video becomes available. Low latency, and ultra-high reliability and service availability are also critical for safe and effective robotics (see Figure A.75).

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[539] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9034103

[540] https://www.frontiersin.org/articles/10.3389/frobt.2020.00104/full

[541] Version 18.0.0 uploaded 2021-09-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3848

Figure A.75: Typical connectivity requirements for generic robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements[542]	Additional comments
Generic robotics	1–100	1–10	Ultra-high reliability and availability	Capacity may increase as more complex robots are introduced

A.6.2 Sector-specific robotics requirements

Health and social care

The literature review did not find any specific data requirements for robotics in health and social care. Currently robots in health and social care have simple use cases, such as dispensing medicines[543] and cleaning operating theatres.[544] Fully robotic surgery (which might require higher capacity and lower latency) is unlikely to be commercially available in the next decade due to regulatory barriers and safety concerns, and hence connectivity is potentially not the most significant barrier. As such, the connectivity requirements for generic robotics use cases are likely to apply to robotics in health and social care (see Figure A.76).

Figure A.76: Typical connectivity requirements for health and social-care robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	Ultra-high reliability and availability, likely to require ultra-high security too	Capacity may increase as more complex robots are introduced into the sector

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[542] Note that coverage will be use-case specific

[543] https://www.azorobotics.com/Article.aspx?ArticleID=312 and https://www.guysandstthomas.nhs.uk/news-and-events/2019-news/february/20180201-new-pharmacy-with-hi-tech-robot-opens-at-guy's-Hospital.aspx

[544] https://en-uk.ecolab.com/news/2021/02/uk-or-premium-uvd-robots

Emergency services

The literature review did not find any specific data requirements for robotics in emergency services. As such, the connectivity requirements for generic robotics use cases are likely to apply to robotics in emergency services (see Figure A.77).

Figure A.77: Typical connectivity requirements for emergency service robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	Ultra-high reliability and availability, likely to require ultra-high security too	Capacity may increase as more complex robots are introduced into the sector

Energy/utilities – site operations

The literature review did not find any specific data requirements for robotics in energy/utilities – site operations. As such, the connectivity requirements for generic robotics use cases are likely to apply to robotics in energy/utility site operations (see Figure A.78).

Figure A.78: Typical connectivity requirements for energy/utilities – site operations robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	Ultra-high reliability and availability	Capacity may increase as more complex robots are introduced into the sector

Construction

The literature review did not find any specific data requirements for robotics in construction. As such, the connectivity requirements for generic robotics use cases are likely to apply to construction robotics (see Figure A.79).

Figure A.79: Typical connectivity requirements for construction robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	Ultra-high reliability and availability	Capacity may increase as more complex robots are introduced into the sector

Ports

The literature review did not find any specific data requirements for robotics in ports. As such, the connectivity requirements for generic robotics use cases are likely to apply (see Figure A.80).

Figure A.80: Typical connectivity requirements for port robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–10	Local	Ultra-high reliability and availability	Capacity may increase as more complex robots are introduced into the sector

Smart factories and warehousing

The 2016 report by Real Wireless for the National Infrastructure Commission states that factory automation requires <50Mbit/s, <1ms of latency and >99.9% availability.[545]

According to a 2017 paper on latency-critical IoT applications in 5G, factory automation requires 0.25–10ms of latency and a PLR of 10^{-9}. The paper includes four examples (manufacturing cell, machine tools, printing machines and packaging machines) that require latencies and PLRs that reflect the above-mentioned requirements.[546]

In the context of mobile robots (also referred to as automated guided vehicles), an ACIA 5G white paper on service-level specifications (SLSs) for 5G technology-enabled connected industries identifies several attributes. End-to-end latency is listed as 100ms, communication service availability is 99.9999% and

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[545] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

[546] *https://www.vodafone-chair.org/media/publications/philipp-schulz/Latency_Critical_IoT_Applications_in_5G_Perspective_on_the_Design_of_Radio_Interface_and_Network_Architecture.pdf*

communication service reliability is 1 year (mean time between failures). Similarly, the paper identifies SLSs for motion control systems (responsible for controlling moving parts of machines) as 1ms latency, 99.9999% availability and 10 years as the mean time between failures.[547]

Qualcomm's white paper on ultra-reliable low-latency 5G for industrial automation outlines the availability and latencies required in various industrial automation use cases, as shown in Figure A.81.[548]

Figure A.81: Industrial automation performance requirements for 5G [Source: Qualcomm, 2018]

Use case	Latency (ms)	Availability
Motion control – printing machine	<2	>99.9999%
Motion control – machine tool	<0.5	>99.9999%
Motion control – packaging machine	<1	>99.9999%
Mobile robots – co-operative motion control	1	>99.9999%
Mobile robots – video-operated remote control	10–100	>99.9999%
Mobile control panels – assembly robots	4–8	>99.9999%
Mobile control panels – mobile cranes	12	>99.9999%
Process automation	>50	>99.99%

3GPP specification 22.804 states that in the context of Release 16, mobile robots require a communication service availability >99.9999%, and for applications requiring real-time streaming data transmission (video data), the communication system should support at least 10Mbit/s per mobile robot.[549]

Only a few capacity values were found in construction-specific literature. These values fall within the generic robotics capacity range, and hence that range is preserved. There was, however, more literature available suggesting a wider range

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[547] https://5g-acia.org/wp-content/uploads/5G-ACIA_Guaranteed-Service-Level-Specification-SLS-for-5G-technology-enabled-connected-industries_2021.pdf

[548] https://www.qualcomm.com/media/documents/files/read-the-white-paper-by-heavy-reading.pdf

[549] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

of potential latencies depending on the specific robot. We therefore suggest a typical latency of 1–100ms for smart factory and warehouse robots (Figure A.82).

Figure A.82: Typical connectivity requirements for smart factories and warehousing robotics use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–100	1–100	Local	High – ultra-high availability and reliability, likely to have security concerns too	Capacity may increase as more complex robots are introduced into the sector

A.7 Drones

A.7.1 Generic drone requirements

3GPP specification 22.862 (Release 14) indicates that unmanned aerial vehicles (UAVs) falling into the higher-reliability and lower-latency category will require a latency of 50–100ms and a packet loss ratio of less than 10^{-5} and, for supporting video, a latency of 10ms.[550]

According to 3GPP specification 36.777 (Release 15), command and control (which includes telemetry, waypoint update, and so forth) requires a 60–100kbit/s uplink and downlink, a latency of 50ms, and a packet error loss rate of 10^{-3}. Application data (which includes video streaming, images and other sensors data) requires an uplink of up to 50Mbit/s.[551]

A 2021 paper published in *Results in Engineering* lists typical bandwidth requirements for various components of drone operation. Command and control requires 100–400kbit/s, video data requires up to 16Mbit/s, and more bandwidth is required for uncompressed depth and thermal imaging (compressed values are likely to be significantly lower than those listed). These typical bandwidth requirements are shown in Figure A.83.[552]

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[550] Version 14.1.0 uploaded 2016-10-04; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3014

[551] Version 15.0.0 uploaded 2018-01-06; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3231

[552] https://www.sciencedirect.com/science/article/pii/S2590123021000025

Figure A.83: Typical bandwidth requirement for various services used for operating a drone [Source: Results in Engineering, 2021]

Service	Bandwidth (Mbit/s)
C2 – Futaba SBUS protocol	0.1
C2 – MAVLink control stream	0.4
Video (front-person-view camera)	1–2
Video (1080p, 30fps)	6
Video (4K, 60fps)	16
RAW thermal (480p, 30fps)	137
RAW depth (720p, 30fps)	400

A Qualcomm report on LTE unmanned aircraft systems from 2017 states that command-and-control bandwidth is <10kbit/s, and that telemetry has relatively low requirements (10s of kilobits per second), and that reliability and latency requirements depend on the use case. For real-time video, the report says that bandwidth depends on resolution and frame rate, but is typically 1–10Mbit/s for high-quality video, and that if the video stream is used for navigation and situation awareness, sub-second latency is needed.[553]

The literature review also noted several drones that advertised their data rates and latencies for particular components. Examples of drones and their data requirements are presented in Figure A.84.

Figure A.84: Examples of drones and their data requirements [Source: Various, 2021]

Drone	Uses	Component	Data rate (Mbit/s)	Latency (ms)
Mavic 2 Enterprise[554]	Search and rescue, firefighting, law enforcement, emergency response, powerline inspection, cell tower inspection, bridge inspection	Live video stream	40	120–130
Anafi Ai[555]	Inspection and mapping	Real-time video transmission	8–12	300

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[553] https://www.qualcomm.com/media/documents/files/lte-unmanned-aircraft-systems-trial-report.pdf

[554] https://www.dji.com/uk/mavic-2-enterprise

[555] https://www.parrot.com/assets/s3fs-public/2021-11/white-paper-anafi-ai-v1.6.pdf

Drone	Uses	Component	Data rate (Mbit/s)	Latency (ms)
Mavic Air 2[556]	Filmography	Video transmission	12	120–130

According to a survey on 6G frontiers, UAVs require a data rate of 10–100Mbit/s, a latency of 1–10ms and a medium level of security.[557]

There is a limited amount of quantifiable information on drone data requirements, and the limited data on this topic that was accessed does vary to a notable degree. Broadly, there are two levels of requirement:

- for drones that only need command and control (i.e. those that store data collected for later retrieval, or have payloads that require simple communication)
- for drones that need to live stream video back to the controller.

Within each of these categories the available data is varied. This is reflected in the large ranges captured in the typical requirements in Figure A.85.

Figure A.85: Typical connectivity requirements for generic drone use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements[558]	Additional comments
Generic command and control	0.1–0.5	1–100	High reliability, medium security	Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority[559]
Generic application data (typically video streaming)	1–50	1–100	High reliability, medium security	Capacity will vary depending on the application, resolution and frame rate. This use case also includes the command and control captured above, hence latency might be lower than that required for specific video applications as the command and control

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[556] https://www.dji.com/uk/mavic-air-2

[557] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9397776

[558] Note that coverage will be use-case specific.

[559] https://publicapps.caa.co.uk/docs/33/CAP%201861%20-%20BVLOS%20Fundamentals%20v2.pdf

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements [558]	Additional comments
				latency takes precedent. Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority[560]

A.7.2 Sector-specific drone requirements

Emergency services

Drones in emergency services are used for search and rescue, firefighting, and so forth. The Mavic 2 Enterprise is marketed for search and rescue, firefighting, law enforcement, and emergency response, and its requirements are encapsulated in the generic application data use case. The generic application data use case is the relevant use case as these applications require live video streaming, and other drones may not have exactly the same requirements as the Mavic 2 Enterprise but will likely fall within the generic range. Given the nature of the sector, security requirements are likely to be high. Missing persons, fires or other emergency incidents could be located anywhere in the country so ubiquitous coverage is required.

Typical connectivity requirements for emergency services drone use cases are presented in Figure A.86.

Figure A.86: Typical connectivity requirements for emergency services drone use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–50	1–100	Ubiquitous	High reliability, high security	Capacity will vary depending on the application, resolution and frame rate. Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

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[560] https://publicapps.caa.co.uk/docs/33/CAP%201861%20-%20BVLOS%20Fundamentals%20v2.pdf

Energy/utilities – smart grid

Drones in energy/utilities – smart grid are used for equipment inspection, potentially in the event of an emergency. The Mavic 2 Enterprise is marketed for powerline and cell tower inspection, and its requirements are encapsulated in the generic application data use case. The generic application data use case is the relevant use case as this application requires live video streaming, and other drones may not have exactly the same requirements as the Mavic 2 Enterprise but will likely fall within the generic range (see Figure A.87). Given the nature of the sector, security requirements are likely to be high. Incidents could occur anywhere in the smart grid area, and hence ubiquitous coverage across the energy grid (i.e. nationwide) would be required.

Figure A.87: Typical connectivity requirements for energy/utilities – smart grid drone use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–50	1–100	Ubiquitous	High reliability, high security	Capacity will vary depending on the application, resolution and frame rate. Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

Agriculture, forestry and fishing

Drones used in agriculture, forestry and fishing only require the generic command-and-control requirements. These drones are typically pre-programmed with flight paths, can collect data for later analysis, have simply operated payloads, are operated within line of sight, and do not require live video streaming.

Typical connectivity requirements for agriculture, forestry and fishing drones use cases are presented in Figure A.88.

Figure A.88: Typical connectivity requirements for agriculture, forestry and fishing drones use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
0.1–0.5	1–100	Ubiquitous	High reliability, medium security	Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

Smart cities

Drones are used for deliveries in smart cities. These drones do not require live video streaming and can operate using telemetry and pre-programed flight paths. Therefore the generic command-and-control requirements are likely to be sufficient (see Figure A.89).

Figure A.89: Typical connectivity requirements for smart city drones use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
0.1–0.5	1–100	Ubiquitous	High reliability, medium security	Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

Construction

Drones used in construction are used for site surveys, equipment inspection, security and tracking progress and would fall under the generic data application use case (see Figure A.90). A 2021 article states that 25Mbit/s per device is required for drones in construction to be able to transmit video, and that for control, latency should be between 1ms and 10ms.[561] This falls within the range of data rates expected, albeit with a more stringent latency.

Figure A.90: Typical connectivity requirements for construction drone use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–50	1–100	Local	High reliability, medium security	Capacity will vary depending on the application, resolution and frame rate. Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

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[561] https://www.mdpi.com/2079-9292/10/14/1713/htm

Ports

In the context of ports, drones are used for site surveys, equipment inspection and security, and so they require live video streaming and as such would likely have the same requirements as the generic data application use case (see Figure A.91).

Figure A.91: Typical connectivity requirements for construction drone use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–50	1–100	Local	High reliability, medium security	Capacity will vary depending on the application, resolution and frame rate. Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

Smart factories and warehousing

In factories, drones can be used for simple automated tasks such as inventory and delivery of objects, and for tasks requiring live video streams such as equipment inspection and security. As such, although command and control may be sufficient in some instances, the generic data application use case is more representative of the range of potential requirements (see Figure A.92).

Figure A.92: Typical connectivity requirements for smart factories and warehousing drone use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–50	1–100	Local	High reliability, medium security	Capacity will vary depending on the application, resolution and frame rate. Beyond visual line-of-sight, operation currently requires permission from the civil aviation authority

A.8 Smart tracking

A.8.1 Generic smart tracking requirements

3GPP specification 22.862 (Release 14) states that “[t]he system shall support location estimation of user equipment in less than 10 seconds when the information is requested by user”.[562]

3GPP specification 22.836 (Release 17) lists the data requirements for three types of smart tracking, as shown in Figure A.93.[563]

Figure A.93: Performance requirements for smart tracking [Source: 3GPP, 2019

Use case	Typical message size	Typical frequency (per day)
Containers	200 bytes	24
Wagons	200 bytes	24
Pallets	300 bytes	24

Figure A.94 summarises these typical smart tracking connectivity requirements.

Figure A.94: Typical connectivity requirements for generic smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements [564]	Additional comments
Generic smart tracking	4×10^{-7}–7×10^{-7} [565]	<10 000	–	–

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[562] Version 14.1.0 uploaded 2016-10-04; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3014

[563] Version 17.1.0 uploaded 2019-12-20; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3559

[564] Note that coverage will be use-case specific

[565] $(200/10^{6})/(60\text{x}60) = 4.44\text{x}10^{-7}$ and $(300/10^{6})/(60\text{x}60) = 6.66\text{x}10^{-7}$

A.8.2 Sector-specific smart tracking requirements

Agriculture, forestry and fishing

The literature review did not note any specific data requirements for smart tracking in agriculture, forestry and fishing. As such, the generic smart tracking use case requirements are likely to apply (see Figure A.95).

Figure A.95: Typical connectivity requirements for agriculture, forestry and fishing smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7}– 7×10^{-7}	<10 000	Ubiquitous	–	–

Construction

The literature review did not note any specific data requirements for smart tracking in construction. As such, the generic smart tracking use case requirements are likely to apply (see Figure A.96).

Figure A.96: Typical connectivity requirements for construction smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7}– 7×10^{-7}	<10 000	Local	–	–

Roads

The literature review did not note any specific data requirements for smart tracking in road environments that differed from those of the generic smart tracking use case, thus the latter requirements are likely to apply (see Figure A.97).

Figure A.97: Typical connectivity requirements for roads smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7}– 7×10^{-7}	<10 000	Ubiquitous	–	–

Rail

The literature review did not note any specific data requirements for smart tracking in rail. As such, the generic smart tracking use case requirements are likely to apply (see Figure A.98).

Figure A.98: Typical connectivity requirements for rail smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7}– 7×10^{-7}	<10 000	Ubiquitous	–	–

Air

The literature review did not note any specific data requirements for smart tracking in air. As such, the generic smart tracking use case requirements are likely to apply (see Figure A.99).

Figure A.99: Typical connectivity requirements for airport smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7}– 7×10^{-7}	<10 000	Local	–	–

Ports

The literature review did not find any specific data requirements for smart tracking in ports. As such, the generic smart tracking use case requirements are likely to apply (see Figure A.100).

Figure A.100: Typical connectivity requirements for port smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7}– 7×10^{-7}	<10 000	Local	–	–

Smart factories and warehousing

The literature review did not find any specific data requirements for smart tracking in smart factories and warehousing. As such, the generic smart tracking use case requirements are likely to apply (see Figure A.101).

Figure A.101: Typical connectivity requirements for smart factories and warehousing smart tracking use cases – per device [Source: 3GPP, 2016 and 2019]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
4×10^{-7} – 7×10^{-7}	<10 000	Local	-	-

A.9 Autonomous vehicles

A.9.1 Generic autonomous vehicle requirements

In 2015, connected cars generated more than 25Gbit/hour of data traffic,[566] according to a white paper by Hitachi.

The 2016 report by Real Wireless for the National Infrastructure Commission classified connected vehicles as requiring 50–100Mbit/s, 10–50ms of latency and >99% availability. The report also broke down the data rate required for entertainment service (0.5–25.5Mbit/s per car), driver assistance (10–100kbit/s for vehicle to infrastructure (V2I) per car) and vehicle management (gathering performance data: 10–100kbit/s per car).[567]

In a 5G Americas white paper published in 2017, connected vehicles require 1–5Mbit/s uplink and downlink, and 1–5ms of latency.[568]

A 2018 white paper by Keysight technologies depicts the throughput and delay of various applications enabled by future 5G standards (note that at the time Release 16 had not yet been released). Autonomous driving is depicted as requiring approximately 10Mbit/s throughput and 1ms delay.[569]

A 2018 article on six key connectivity requirements of autonomous driving outlines how “the demand for high-speed data will only increase”.[570] It provides five example applications of increasing autonomous performance and increasing data rates (see Figure A.102). The article also states that “in addition to being real-time, data sensing and transmission must be 100% reliable”.

Figure A.102: Data rates for five example applications (autonomous driving) [Source: TE Connectivity, 2018]

Application	Data rate (Mbit/s)
In-vehicle networks (e.g. apps, traffic, vehicle health report)	150
Legacy entertainment systems/ dashboard/ touch screens	1000

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[566] https://wheels.report//Resources/Whitepapers/659cef37-a227-48d5-8f9a-3fb9c2d82903_hitachi-white-paper-internet-on-wheels.pdf

[567] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

[568] https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Network_Transformation_Final.pdf

[569] https://www.keysight.com/gb/en/assets/7018-06129/white-papers/5992-2921.pdf?success=true

[570] https://spectrum.ieee.org/6-key-connectivity-requirements-of-autonomous-driving

Application	Data rate (Mbit/s)
Infotainment (e.g. full HD video)	3000
Advanced infotainment/ uncompressed advanced driver assistance system (ADAS) sensor data (e.g. 4K video, camera connectivity)	12 000
Uncompressed ADAS sensor data (Level 3–4 Autonomy)	24 000

The latest version of 3GPP specification 22.886 (Study on enhancement of 3GPP Support for 5G V2X Services), Release 16, identifies performance requirements for platooning (vehicle convoys), advanced driving and extended sensors (Figure A.103).

Figure A.103: Performance requirements for platooning, advanced driving and extended sensors (range dependent on component and level of automation) [Source: 3GPP, 2021]

Component	Data rate (Mbit/s)	Maximum end - to-end latency (ms)	Reliability
Platooning	50–60	10–500	90–99.99%
Advanced driving	10–53	3–100	90–99.999%
Extended sensors	10–1000	3–100	90–99.999%

Security is also an important requirement - according to a paper published in 2020, “ensuring security is a critical issue” for co-operative automated driving.[571]

According to a survey on 6G frontiers, connected and autonomous vehicles (CAVs) require a data rate of 1–10Gbit/s and medium security, and full CAV capability requires extremely high reliability, exceptionally low latency (0.1ms) and extremely high throughput.[572]

5G Americas released a white paper on vehicular connectivity in 2021 which includes a table of example use cases and their service requirements, which is reproduced in Figure A.104.[573]

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[571] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9034103

[572] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9397776

[573] https://www.5gamericas.org/wp-content/uploads/2021/09/Vehicular-Connectivity-C-V2X-and-5G-InDesign-1.pdf

Figure A.104: Service requirements for vehicular connectivity [Source: 5G Americas, 2021]

Use case	Use case type	Data rate (Mbit/s)	End-to-end latency	Reliability
Co-operative traffic gap	Safety	2	50ms	99.9%
Interactive vulnerable road users crossing	Safety	0.064	100ms	99.9%
Software update of reconfigurable radio system	Vehicle operation management	200MB (delay tolerant)	Delay tolerant (hours)	99%
Automated valet parking	Convenience	0.016	500ms	99%
Awareness confirmation	Convenience	0.04	20ms	99.9%
Co-operative curbside management	Convenience	Few kbit/s	100–5000ms	99%
Co-operative lateral parking	Convenience	27	10–100ms	99.9%
In-vehicle entertainment	Convenience	Up to 250	20ms	99%
Obstructed view assist	Convenience	5	50ms	99%
Co-operative lane merge	Autonomous driving	0.012	20ms	99.9%
Co-operative manoeuvres of autonomous vehicles for emergency situations	Autonomous driving	0.048	10ms	95%
Co-ordinated, co-operative driving manoeuvres	Autonomous driving	64	20ms	99.9%
Vehicle platoon in steady state	Autonomous driving	0.024	50ms	99%
Automated intersection crossing	Autonomous driving	~0.064	10ms	99.9999%
HD map collecting and sharing	Autonomous driving	16	100ms	99%
Infrastructure assisted	Autonomous driving	4–80	100ms	99.99%

Use case	Use case type	Data rate (Mbit/s)	End-to-end latency	Reliability
environment perception				
Infrastructure-based tele-operated driving	Autonomous driving	0.4	50ms	99.999%
Tele-operated driving	Autonomous driving	36 (UL) 0.4 (DL)	100ms (UL) 20ms (DL)	99.999%
AV disengagement report	Autonomous driving	26.7	10 minutes	99.99%
Bus lane sharing request/ revocation	Traffic efficiency and society	0.04	200ms	99%
Continuous traffic flow via green light co-ordination	Traffic efficiency and society	0.02	100ms	95%
Group start	Traffic efficiency and society	0.02	10ms	99.999%

In a 2020 interview, Christian Renaud, an analyst at 451 Research, said that data generated by autonomous vehicles depends on a number of factors, but:

"if you assume all systems (multiple LIDARs, multiple long and short range radar, multiple ultrasonics, multiple cameras etc) operating for a typical consumer two hour duty cycle per day […] then you're in the neighbourhood of 12–15TB per day". Robert Bielby (senior director of automotive system architecture at Micron) said data rates can range from 3 to 40Gbit/s based on components such as LIDAR (20–100Mbit/s) and 6–21 high resolution cameras (500–11 000Mbit/s). Thaddeus Fortenberry, who spent four years working on autopilot architecture at Tesla said his "near term estimate is ~1.6TB per car per day – without LIDAR".[574]

The latest version of 3GPP specification 22.847 (Study on supporting tactile and multi-modality communication services), Release 18, states that "the onboard sensors in today's automated driving vehicles generate data flows up to 8Gbit/s".[575]

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[574] https://blocksandfiles.com/2020/02/03/autonomous-vehicle-data-storage-is-a-game-of-guesses/

[575] Version 18.0.0 uploaded 2021-09-24; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3848

Note that these much larger, gigabit values are the amount of data that will need to be processed, not the volume that would be uploaded to the cloud (as only anomalous data will be uploaded, it will likely only be a tiny fraction of the total data processed).[576]

There is a wide range of reported capacity requirements, likely due to the variety of stages of autonomy in vehicles, as explained in the summary of typical autonomous vehicle connectivity requirements (see Figure A.105).

Figure A.105: Typical connectivity requirements for generic autonomous vehicle use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Use case	Capacity (Mbit/s)	Latency (ms)	Other requirements [577]	Additional comments
Generic autonomous vehicles	1–1000	10–100	Ultra-high reliability and security	As the level of autonomy in autonomous vehicles increases, capacity is likely to increase and latency decrease. Additionally, although volumes of data generated will increase significantly, this may not be representative of the data requirements due to local processing.

A.9.2 Sector-specific autonomous vehicles requirements

Roads

Autonomous vehicles used on roads are the same ones captured in the generic use case, as summarised in Figure A.106 below.

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[576] https://www.analysysmason.com/research/content/articles/autonomous-vehicles-entertainment-rdme0/

[577] Note that coverage will be use-case specific.

Figure A.106: Typical connectivity requirements for road-based autonomous vehicle use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–1000	10–100	Continuous along roads	Ultra-high reliability and security	As the level of autonomy in autonomous vehicles increases, capacity is likely to increase and latency decrease. Additionally, although volumes of data generated will increase significantly, this may not be representative of the data requirements due to local processing.

Rail

3GPP specification 22.804 states that in the context of Release 16 and in the case of rail-bound mass transit, mass transit train control (MTTC) requires <1Mbit/s, <100ms latency, >99.999% service availability, and the highest security. It also states that “the maximum bit-error ratio for control messages, e.g., MTTC messages, is 10^{-6}”.[578]

In the 2016 Real Wireless report for the National Infrastructure Commission, command and control in railway use cases is identified as requiring 200kbit/s, 10ms of latency and needing high availability (99.999%).[579]

Typical connectivity requirements for rail autonomous vehicle use cases are presented in Figure A.107.

Figure A.107: Typical connectivity requirements for rail autonomous vehicle use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
<1	<100	Continuous along railways	Ultra-high availability, reliability and security	–

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[578] Version 16.3.0 uploaded 2020-07-11; available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3187

[579] Report available at https://nic.org.uk/studies-reports/connected-future/future-use-cases-for-mobile-uk-real-wireless-report/

Air

The literature review did not note any specific data requirements for autonomous vehicles in airports other than those of the generic autonomous vehicles use case, as shown in Figure A.108.

Figure A.108: Typical connectivity requirements for airport autonomous vehicle use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–1000	10–100	Local	Ultra-high reliability and security	As the level of autonomy in autonomous vehicles increases, capacity is likely to increase and latency decrease. Additionally, although volumes of data generated will increase significantly, this may not be representative of the data requirements due to local processing.

Ports

According to a Huawei white paper on smart ports, autonomous trucks and intelligent guided vehicles used in ports require 10–20Mbit/s, <50ms latency and 99.9% reliability.[580]

Typical connectivity requirements for port autonomous vehicle use cases are presented in Figure A.109.

Figure A.109: Typical connectivity requirements for port autonomous vehicle use cases – per device [Source: Huawei, 2021]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
10–20	<50	Local	High reliability, likely high security	As the level of autonomy in autonomous vehicles increases, capacity is likely to increase and latency decrease. Additionally, although volumes of data generated will increase significantly, this may not be

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[580] https://www.huawei.com/en/download?rid=%7bEE93406C-B514-4433-AE39-D4057F0B8179%7d

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
				representative of the data requirements due to local processing.

Smart factories and warehousing

The literature review did not note any specific data requirements for autonomous vehicles in smart factories and warehousing beyond those identified in the autonomous vehicles use case (see Figure A.110).

Figure A.110: Typical connectivity requirements for smart factories and warehousing autonomous vehicle use cases – per device [Source: Analysys Mason based on literature review – see bibliography in Section A.10, 2022]

Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Additional comments
1–1000	10–100	Local	Ultra-high reliability and security	As the level of autonomy in autonomous vehicles increases, capacity is likely to increase and latency decrease. Additionally, although volumes of data generated will increase significantly, this may not be representative of the data requirements due to local processing.

A.10 Overview

Figure A.111 overleaf summarises the key results identified above.

Figure A.111: Sector connectivity requirements and possible technologies that might deliver on those requirements [Source: Analysys Mason based on literature review – see bibliography in Annex A.10, 2022]

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
1. Media and entertainment	1.a. Media creation	AR/VR	At least 100–200 uplink (UL) and 20 downlink (DL)	≤10	Local	Very high reliability	5G
		UHD video	100–200 (UL) and 20 (DL)	≤10	Local	Very high reliability	5G
	1.b. Venues and events	AR/VR	10–50 (UL and DL)	Generally <20	Local	High reliability	5G, Wi-Fi 6
		UHD video	100–200 (UL) and 20 (DL)	≤10	Local	Very high reliability	5G
2. Public services	2.a. Health and social care	AR/VR	50–12 000 (UL and DL)	<10	Local	Ultra-high availability, high reliability, likely to require high security	5G
		UHD video	10 000–25 000	<1	Local	Ultra-high availability, ultra-high reliability, also likely to have ultra-high	5G (mmWave)

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
						security requirements	
		Sensor networks	<1 (UL)	<250	Ubiquitous	Likely to require high security, reliability and availability	4G, 5G, NB-IoT, LTE-M, LoRaWAN
		Remote machine manipulation	10–2000	1–10	Local	Ultra-high reliability and availability. Given the nature of the use case, likely to require ultra-high security too.	5G (mmWave)
		Robotics	1–100	1–10	Local	Ultra-high reliability and availability, likely to require ultra-high security too.	5G
	2.b. Education	AR/VR	10–50 (DL)	Generally <20	Local	High reliability	4G, 5G, Wi-Fi, Wi-Fi 6
		UHD video	Generally ≥25 (DL)	<5000	Local	–	4G, 5G, Wi-Fi 5 or 6, satellite (LEO)
		AR/VR	Up to 5000 (DL)	Generally <20	Local	High reliability	5G (mmWave)

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
	2.c. Emergency services	UHD video	25–500	<20 if stationary, <100 if moving	Ubiquitous	High availability, high reliability, likely very high security	5G
		Sensor networks	≤1 (UL)	<100	Ubiquitous	Ultra-high availability, likely to require high security, and reliability.	4G, 5G, LTE-M
		Remote machine manipulation	1–100	1–10	Ubiquitous	High availability, ultra-high reliability, likely to require high security	5G
		Robotics	1–100	1–10	Local	Ultra-high reliability and availability, likely to require ultra-high security too.	5G
		Drones	1–50	1–100	Ubiquitous	High reliability, high security	4G, 5G, satellite (LEO)
3. Energy and utilities	3.a. Energy and utilities – smart grid	AR/VR	2.5–50 (UL and DL)	<100	Ubiquitous	High reliability	4G, 5G, satellite (LEO)

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
		UHD video	3–5	<1000	Local	High reliability	4G, 5G, Wi-Fi 5 or 6, satellite
		Sensor networks	≤1 (UL)	<3000	Local	High reliability, and very high availability	4G, 5G, Wi-Fi 5 or 6, LTE-M
		Drones	1–50	1–100	Ubiquitous	High reliability, high security	4G, 5G, satellite (LEO)
	3.b. Energy and utilities – site operations	AR/VR	2.5–50 (UL and DL)	<100	Local	High reliability	4G, 5G, Wi-Fi 5 or 6, satellite (LEO)
		UHD video	3–5	<1000	Local	High reliability	4G, 5G, Wi-Fi 5 or 6, satellite
		Sensor networks	≤1 (UL)	<3000	Local	High reliability, and very high availability	4G, 5G, Wi-Fi 5 or 6, LTE-M
		Remote machine manipulation	1–100	1–10	Local	High availability, ultra-high reliability, likely to require high security	5G
		Robotics	1–100	1–10	Local	Ultra-high reliability and availability	5G

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
4. Rural industries	4.a. Agriculture, forestry and fishing	AR/VR	2.5–50 (UL and DL)	<100	Ubiquitous	High reliability	4G, 5G, satellite (LEO)
		Sensor networks	<1 (UL)	<1000	Ubiquitous	May require high availability	4G, 5G, LTE-M, satellite
		Remote machine manipulation	1–100	1–10	Ubiquitous	High availability, ultra-high reliability, likely to require high security	5G
		Drones	0.1–0.5	1–100	Ubiquitous	High reliability, medium security	4G, 5G, satellite (LEO)
		Smart tracking	4×10^{-7}–7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
5. Smart urban	5.a. Smart cities	Sensor networks	<1 (UL)	<1000	Local	Ultra-high availability	4G, 5G, Wi-Fi 5 or 6, LTE-M, satellite (LEO)
		Drones	0.1–0.5	1–100	Ubiquitous	High reliability, medium security	4G, 5G, satellite (LEO)

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
	5.b. Construction	AR/VR	2.5–50 (UL and DL)	Generally <20	Local	High reliability	4G, 5G, Wi-Fi 6
		UHD video	5–30	<2000	Local	Likely to have strict security requirements	4G, 5G, Wi-Fi 5 or 6, satellite
		Sensor networks	<1 (UL)	<1000	Local	May require high availability	4G, 5G, LTE-M, Wi-Fi 5 or 6, satellite
		Remote machine manipulation	1–100	1–10	Local	Ultra-high availability, ultra-high reliability, high security	5G
		Robotics	1–100	1–10	Local	Ultra-high reliability and availability	5G
		Drones	1–50	1–100	Local / wide area	High reliability, medium security	4G, 5G, satellite (LEO), Wi-Fi 5 or 6
		Smart tracking	4×10^{-7} – 7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
6. Transport	6.a. Road	UHD video	5–30	<2000	Local	Likely to have strict security requirements	4G, 5G, Wi-Fi 5 or 6, satellite

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
		Sensor networks	<1 (UL)	<1000	Local	May require high availability	4G, 5G, LTE-M, Wi-Fi 5 or 6, satellite
		Smart tracking	4×10^{-7}–7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
		Autonomous vehicles	1–1000	10–100	Vehicle to vehicle connections would use low-power wireless technology (e.g. 5.9GHz ITS) but vehicle operations could be supplemented by either network connectivity or roadside infrastructure (e.g. for the purposes of conveying safety messages to vehicles or for other data	Ultra-high reliability and security	5G

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
					updates). Roadside infrastructure deployment would be subject to government policy concerning delivering digital roads[581]		
	6.b. Rail	UHD video	>4Mbit/s UL	<500ms	Local	>99.99% service availability, high security	4G, 5G, Wi-Fi 5 or 6, satellite
		Sensor networks	<1	<1000	Local	Very high service availability, and high security	4G, 5G, LTE-M, Wi-Fi 5 or 6, satellite
		Smart tracking	4×10^{-7}–7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
		Autonomous vehicles – messaging between	<10	<100	Continuous along railways	Ultra-high availability, reliability and security	4G, 5G, Wi-Fi 5 or 6

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[581] https://nationalhighways.co.uk/industry/digital-data-and-technology/digital-roads/#customers

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
		track and train					
	6.c. Air	UHD video	5–30	<2000	Local	Likely to have strict security requirements	4G, 5G, Wi-Fi 5 or 6, satellite
		Sensor networks	<1 (UL)	<1000	Local	May require high availability	4G, 5G, LTE-M, Wi-Fi 5 or 6, satellite
		Smart tracking	4×10^{-7}–7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
		Autonomous vehicles	1–1000	10–100	Local	Ultra-high reliability and security	5G
	6.d. Ports	AR/VR	2.5–50 (UL and DL)	Generally <20	Local	High reliability	4G, 5G, Wi-Fi 6
		UHD video	2–4	<200	Local	Medium reliability (90%), likely to have strict security requirements	4G, 5G, Wi-Fi 5 or 6, satellite (LEO)
		Sensor networks	<1 (UL)	<1000	Local	May require high availability	4G, 5G, LTE-M, Wi-Fi 5 or 6, satellite

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
		Remote machine manipulation	150–4000	<30	Local	Ultra-high reliability, also likely to require ultra-high availability and high security	5G, Wi-Fi 6
		Robotics	1–100	1–10	Local	Ultra-high reliability and availability	5G
		Drones	1–50	1–100	Local / wide area	High reliability, medium security	4G, 5G, satellite (LEO), Wi-Fi 5 or 6
		Smart tracking	4×10^{-7}–7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
		Autonomous vehicles	10–20	<50	Local	High reliability, likely high security	4G, 5G, Wi-Fi 5 or 6, satellite (LEO)
7. Manufacturing	7.a. Smart factories and warehousing	AR/VR	10–50 (UL and DL)	≤10	Local	High reliability, high availability (99.9%)	5G
		UHD video	5–30	<2000	Local	Likely to have strict security requirements	4G, 5G, Wi-Fi 5 or 6, satellite

Sector	Subsector	Use-case category	Capacity (Mbit/s)	Latency (ms)	Coverage	Other requirements	Possible wireless technologies
		Sensor networks	<1 (UL)	<1000	Local	Ultra-high reliability and availability	4G, 5G, LTE-M, Wi-Fi 5 or 6, satellite
		Remote machine manipulation	1–100	1–10	Local	High availability, ultra-high reliability, likely to require high security	5G
		Robotics	1–100	1–100	Local	High – ultra-high availability and reliability, likely to have security concerns too	4G, 5G, Wi-Fi 5 or 6, satellite (LEO)
		Drones	1–50	1–100	Local / wide area	High reliability, medium security	4G, 5G, satellite (LEO), Wi-Fi 5 or 6
		Smart tracking	4×10^{-7}–7×10^{-7}	<10 000	Ubiquitous	–	Sigfox, LoRa, NB-IoT, LTE-M
		Autonomous vehicles	1–1000	10–100	Local	Ultra-high reliability and security	5G

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