FINAL REPORT

5G Infrastructure Requirements in the UK

On behalf of

NATIONAL INFRASTRUCTURE COMMISSION

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1 Executive Summary

The National Infrastructure Commission (NIC) has commissioned this report to understand the extent to which existing private and public telecommunications infrastructure in the UK is prepared for the next generation of fixed and wireless networks.

The study aims to consider the many facets of the telecommunications infrastructure within the UK. The study identifies the challenges and barriers associated with the necessary upgrades to existing infrastructure and deployment of new infrastructure. The telecommunications industry is diverse and complex with a wide range of issues to address including technical, regulatory, competition, economic and market related. The mobile and fixed telecoms market is a key contributor to the UK economy: Total reported annual operator revenue in 2014 was £37.4 billion. As well as being a positive economic contributor it is also a key enabler of growth and productivity for the UK. Revenues however, have been in decline since 2009, driven mainly by decreases in wholesale revenue. Therefore, both mobile and fixed sectors need to continue to grow their infrastructure investment in order to satisfy the increasing demands for connectivity by consumers, businesses, public institutions and many other services. This is not only to keep pace globally, but also to ensure continued and sustainable growth at a national level. Investment from both the EU and UK Government has been significant over recent years in recognition of the importance of the telecommunications sector to the economy.

Next generation technologies and networks need to be deployed to meet future demand and in particular our study has examined four key areas to gain a sense of the existing infrastructure's preparedness:

- Roadside infrastructure for connectivity to vehicles
- Railway trackside infrastructure for connectivity to trains and passengers
- Densification of small cell sites in urban are for very high throughput future networks and
- Rural connectivity to address the cellular mobile coverage gaps that remain across the UK

Below, we have provided a summary of the key messages and findings of the study across these four areas.

1.1 Key messages

The study found that there are significant gaps in capability between the existing telecommunications infrastructure and the aspirational requirements of future networks and technologies. Specifically, the study has explored:

- why there is still poor mobile coverage on parts of the motorways and major trunk roads;
- why it remains difficult to deploy infrastructure on the trackside;
- the challenges facing mobile operators deploying large numbers of smaller cells (densification) in urban areas, as needed to meet the continued surge in the use of mobile data amongst consumers and businesses; and
- mobile coverage gaps in rural areas.

The key messages from the study are as follows.

Access to motorway and major A road infrastructure (e.g. overhead gantries and bridges) and fibre presents an opportunity to enhance connectivity to vehicles on the roadside

- The telecommunications infrastructure deployed on the roadside consists of nationwide high speed data capacity through an optical fibre network on almost all of the motorways and to a much lesser extent on the major trunk roads. At present, it solely serves both safety and operational uses. We have found there is spare fibre capacity and duct space that could be readily used by third party operators to provide better wireless coverage and to deliver high speed connectivity to vehicles enabling numerous transport related applications
- Although there is no existing wireless infrastructure on the roadside, current connectivity to vehicles is provided by the mobile operators using land adjacent to the roadside. This land is typically privately owned (e.g. by farmers). As a result, 2G, 3G and 4G service is not available everywhere on all motorways and trunk roads because topographical challenges (such as cuttings, trees, embankments or landscaping) limit mobile coverage.
- Access to the physical structures such as gantries, bridges and road signs would be needed to enable future wireless networks. Also, connection into the high capacity roadside optical fibre network would be needed to meet the performance requirements of future networks.
- Deploying new mast sites or mobile infrastructure along the motorways and major trunk roads presents some practical challenges. Given the Health and Safety issues and disruption associated with road or lane closures, access to the roadside will have to follow the appropriate governance and procedures. This means specialist approved contractors are required for deployment projects. Supervision may also be required which is likely to increase implementation costs and timescales.

New trackside wireless infrastructure could offer very high capacity to train passengers

- In the case of trackside infrastructure, enabling high speed wireless connectivity for passengers would need brand new infrastructure including both wireless sites and fibre optic cable. Deployment of new sites would require identifying potentially thousands of suitable locations along the trackside that can readily mount to the fixed (non-telecoms) infrastructure.
- The provision of dedicated connectivity to passengers is dependent on the availability of suitable frequencies that can provide ubiquitous coverage and capacity along the rail corridors. This is essentially a backhaul architecture which means there is no dependence on access to mobile operator spectrum because the trackside masts could connect to the train antenna using a suitable frequency band subject to regulatory conditions.
- However, similar to the roadside, access to the certain trackside infrastructure presents a challenge for third parties. This is due to the essential safety qualifications engineers require to install any equipment at these potentially dangerous locations
- Deployment of a new wireless network will be costly and time consuming given the access limitations and therefore, any new infrastructure should be pre-equipped with the necessary capabilities to support the new mobile technologies that are being developed.

A significant increase in the number of small radio cells (located on street furniture, small masts, walls etc) is needed to meet the performance requirements of future networks in urban areas

- It should not be assumed that small radio cells will be cheaper and quicker to deploy. This is due to the significant backhaul requirements, and urban restrictions such as Local Authority permits and traffic management. The volume of sites required will be significant so strategic Government and Local Government support will be needed to ensure networks can expand to meet future requirements in dense urban areas.
- Most of these wireless cells will need to connect to the fixed telecommunications networks so operators will have to be prepared for large scale deployments. BT, for example has started testing the new software and virtualised network technologies in readiness for connecting the numerous wireless sites of future networks. These will likely become commercially available around 2019 coinciding with the completion of 5G standards and live trials.

The MNOs have committed to increased geographical coverage which will help to fill some of the coverage gaps in rural areas

- Low demand together with the backhaul challenges (including high backhaul costs) in rural areas has meant rural deployment has been a lower priority for the MNOs. This is because the investment and focus needed has been on programmes such as 4G deployment and network consolidation, thus many not-spots can still be found throughout the UK. This remains a highly political issue with national roaming recently proposed as a solution by Members of Parliament. Ofcom consulted industry on the merits of national roaming as an alternative solution for addressing the coverage issue. However, this has since been abandoned in favour of a legally binding agreement with MNOs to increase national coverage.
- Mobile network operators have committed to invest in further infrastructure to fill many of the remaining mobile coverage gaps that exist in rural areas. This commitment aims to raise the mobile coverage level to geographical (e.g. roads) as well as populated areas.
- Government has recently revised the Electronic Communications Code which regulates the relationship between electronic communications network operators and site providers in the UK. It underpins agreements to host and maintain communications apparatus on land and property. The Government wants to reform the Code to put in place modern regulation which fully supports the rollout of digital communications infrastructure. The intention is to make site deployment easier everywhere, including in rural areas but it isn’t yet clear how this will assist MNOs deploy quicker and easier.
- Government has also recently announced amendments to the Town and Country Planning (General Permitted Development) (England) Order 2015 that aims to speed up the deployment process. This only applies to England but there are ongoing discussions for Wales, Scotland and Northern Ireland.

We note from above there are a number of overarching requirements to consider for the deployment of new infrastructure to enable future networks. Site sharing, for instance is a common approach used by MNOs today and will be essential in future to support the varied multi-operator use cases. This is particularly apparent for trackside infrastructure, roadside infrastructure and new mobile masts.

Another consideration is the requirement for wide spread availability and access to suitable fibre in all relevant locations. However, challenges remain with the current state of access and condition of ducting in roads and footpaths. We provide a more detailed overview below of our findings from the study across the four key focus areas.

1.2 Opening up roadside telecoms infrastructure could pave the way for high speed mobile connectivity to vehicles

The telecommunications infrastructure deployed along the roadside, mainly the motorways and some major trunk roads, provides high capacity optical fibre connectivity for road transport specific operations. This is a private network (closed to non-road transport related users) which connects dedicated equipment such as CCTV cameras, information signage and message boards to gantries.

The study found that not all of this fibre is being fully utilized: Highways England's National Roads Telecommunications Service (NRTS) uses less than 20% of the fibre capacity to serve all today's needs on the Strategic Road Network (SRN). This presents an opportunity to deploy new dedicated wireless network infrastructure and connect it to the spare fibre.

We highlight a number of reasons why this opportunity would benefit future UK communications networks:

1) Opening up access to nationwide spare and available fixed bandwidth could unlock numerous future applications linked to connected car services with significant benefits to road safety and potential improved traffic flow.
2) The roadside fibre currently runs through parts of the country that is currently unserved by existing broadband providers. This could potentially open up new broadband markets in these remote areas if given the appropriate access.
3) There has been a considered amount of future proofing to ensure there is sufficient capacity for systems that may be more bandwidth hungry in future. The spare capacity could also be present an opportunity for future passenger connectivity enabling in-car multimedia entertainment and driver assistance also creating new network architecture and services models.

We conducted a network dimensioning analysis to understand the infrastructure capabilities needed to deliver future enhanced mobile broadband connectivity to road users. The following site numbers and costs have been estimated for both a dedicated roadside network and expansion of the MNOs network adjacent to the roadside.

1) To deliver the very high mobile broadband speeds that would be expected in 5G the number of sites needed along the motorway part of the SRN in Britain ranged from approximately 7300 to 18270.
2) Connecting these sites to the existing roadside fibre and fixed infrastructure along the motorway part of the SRN in Britain would cost between £183 million and £457 million.
3) The number of required sites increases to approximately 24300 - 60650 to cover all the SRN in Britain. However, new fibre would be needed in all non-motorway sections of the SRN to replace the existing copper cable.
4) Connecting these sites to the existing fibre and fixed infrastructure and newly laid fibre where it does not already exist would cost between £1.75 bn and £5.1 bn.
5) An alternative would be for MNOs to increase their sites along the roadside (assuming it is on the land adjacent to the roads). Our cost estimates based on MNO deployments ranges from £743 – £1.1bn for all motorways in GB. This increases to £4.1bn - £7.8bn for all the SRN in Britain.

However, there are a number of practical challenges, particularly in relation to accessing the roadside infrastructure by future network providers. There would be a requirement to build new sites on the roadside and mount equipment on existing signage, bridges and gantries. This requires access to both power and fibre at the desired locations, which at present is not possible. Furthermore, the stringent safety requirements to access the roadside means typical MNO installers may not be sufficiently qualified. This is likely to result in higher costs and potential delays in deployment. Furthermore, network roll out at the roadside will cause disruption to road users including lane closures and network downtime. Nevertheless, a new wireless network and architecture could enable an entire ecosystem of vehicle connectivity applications, operators and use cases.

Considering, in-car Wi-Fi today for example, connects directly to passengers' devices and uses the mobile operator network as the backhaul from the car to the internet. The service is patchy along some of the major roads in UK areas where there is lack of coverage. A dedicated roadside network would provide not just complete coverage of the SRN, but robust contiguous high speed mobile connectivity to vehicles. Besides the technical and practical challenges already identified, access to suitable additional spectrum would be needed. This could either use the MNOs spectrum and technology which means ensuring the infrastructure meets the MNO's technical requirements, or use some other technology and band such as 5 GHz. The infrastructure, therefore, would need to support the required amount of bandwidth and potentially multiple operators. In turn, specific radio receiving equipment would be needed for the vehicles to connect with new roadside infrastructure which adds further complexity, cost and time constraints.

Overall, any decision to invest in new roadside wireless infrastructure should be ready to support the full set of relevant 5G requirements for high speed throughput and low latency.

1.3 A new high capacity trackside infrastructure is the optimum approach to enabling ultra-high speed connectivity for rail passengers

The railway trackside network architecture is similar in some ways to the roadside. In the case of rail however, there is a mix of dedicated trackside fibre and a wireless network that provides safety critical communications to drivers and signallers. The trackside infrastructure does not provide connectivity to passengers. Wi-Fi on board trains today is provided through an onboard gateway that connects back to the internet via the MNOs networks but many locations on the rail routes are poorly served.

In the rail environment, there are already almost 2500 wireless sites providing secure voice and safety-related signaling functions. These sites form part of a European mandated system that connects into a dedicated optical fibre network, which runs along all routes managed by Network Rail. There are hundreds of thousands of other devices (CCTV cameras, trackside phones, signals) that connect to this fibre network, which has now become largely encumbered from the different legacy technologies in use. Subsequently, Network Rail has deployed an enhanced and much faster fibre network (known as FTN-X) with very high capacity creating a nationwide core network. The aim is to eventually transfer existing assets to this new network so that everything operates on a single telecommunications protocol, also known as Internet Protocol (IP). The access layer of this network is yet to be built and will take several years to do so, but once in place all existing equipment will be connected to it.

Our analysis found that given the major challenges of access and safety implications of the existing infrastructure, a completely new wireless network would be needed to support passenger broadband. Thus, we determined the number of new sites required to deliver the end user performance targets. The number of new sites required ranged from 3270 to around 8370, depending on the required mobile broadband speeds. In the lower bound case, the estimated new site costs to deliver mobile broadband (in the order of 500 Mbps per train) to passengers today would be approximately £135 million. This does not include upgrades to the existing GSM-R masts but new, smaller sites. These sites would need to connect to a new fibre network which would approximately cost £150 – £250 million. Therefore, total costs for a new wireless passenger network is in the range £285 – £385 million. To deliver the future network speeds expected for future 5G the cost estimates increase to £495 – £595 million. The costs are not much cheaper if upgrading GSM-R masts if less restrictive access were possible in future. It should be noted that these high level estimates are dependent on numerous assumptions relating to unit costs, track access, choice of technology and network architecture.

The challenges and complexities arise when third parties wish to deploy equipment on the trackside. Another major issue from Network Rail's perspective is the need to physically separate safety related network functions from other non-safety related communications traffic to avoid any potential impact on rail operations. However, in future with 5G's proposed virtualized network functions this may not be necessary as the technology is expected to handle the full mix of traffic requirements. Another challenge is the need to physically mount telecommunications equipment on existing non-telecoms infrastructure such as gantries and trackside poles. The risks from infrastructure deployment can include:

1) interference to the safety-related GSM-R network;
2) high cost to ensure equipment is suitable (or hardened) to operate within an electrically noisy rail environment
3) available trackside space to build in the 5G capabilities such as multi operator capability; and
4) stringent trackside access requirements for installation.

The very high and necessary safety requirements are mitigated by deploying a completely separate trackside communications network for passenger connectivity. This becomes less restrictive in terms of access enabling more commercial incentives for other operators to deploy equipment. However, usual safety practice such as line closures or speed restriction will still be required for network rollout which will mean reduced services on routes as the equipment is deployed.

1.4 Dense deployment of small cell sites is needed for future networks in urban areas

Mobile infrastructure in dense urban and urban areas are typically deployed on the rooftops of office blocks and residential buildings or on poles deployed in the street. These sites provide the key capacity layer for mobile broadband. The mobile broadband speeds provided by the MNOs, reached, on average, over 15 Mbit/s[1] download in UK cities at the end of 2014 which is similar to some home broadband services.

However, there is growing expectation and demand for this mobile connectivity to continue to increase to ultra-fast speeds (100 Mbps) while on the move. This will require a much increased density of new sites in dense urban areas to meet the mobile traffic capacity needs of future wireless networks, potentially thousands. For example, our study found that as many as 42,000 small cell sites could be needed to deliver the ultra-fast broadband speeds expected of future networks in an area the size of the City of London (based on certain spectrum and technology assumptions).

A number of significant challenges and issues emerge in order to achieve this. For example, access to sufficiently capable and available optical fibre is needed at locations where small cell sites will be deployed. New equipment will be deployed on existing street furniture such as lampposts, signs, sides of buildings at street level so the sites are closer to the users. It

[1] Ofcom publishes 4G and 3G mobile broadband speeds research, Nov 2014

remains uncertain how big, heavy or capable the new equipment will be and this may limit what future services and applications can be delivered from these site types.

Fixed telecommunications operators will also play a crucial role in these enabling of future networks. It is no longer just about laying more fibre in ducts but the formation of suitable arrangements amongst operators in terms of access flexibility, maintenance, sharing of contractual obligations and future deployment. BT, Virgin Media and Vodafone (formerly Cable & Wireless) already carry significant proportions of data traffic in the UK and thus will no doubt form part of the future ecosystem. The challenge however, is extending the reach and connecting into this fibre from non-typical locations, so that operators can roll out new sites in a cost effective and timely manner. Specifically, there are limitations in:

- the deployment of infrastructure in new buildings;
- the deployment of infrastructure within existing and potentially new ducting; and
- future access to poles and other public infrastructure.

Notably, there will be a need for access to street furniture by mobile operators. This requires collaboration with the landlords (e.g. local authorities) to handle the requirements for deploying telecommunications equipment on infrastructure that is not designed for that purpose. There is currently no common approach to this type of collaboration. The process tends to be fragmented across different local authorities and negotiations are often legally complex and protracted, thus MNOs have so far been reluctant to get deeply involved. Aspects such as planning policy, legislation for code powers, and guidelines relating to radiation hazards for deployment at street level will need addressing before dense site deployment can take place.

1.5 Addressing the coverage gaps in rural areas is needed before new technology can be deployed

There are approximately 40,000 mobile base stations deployed in the UK providing up to 98% outdoor voice coverage. However, there are still areas of poor coverage across the UK. Efforts from mobile operators to extend the coverage in challenging and costly locations (such as rural areas and minor roads) have been limited by a number of barriers. Government projects, such as the Mobile Infrastructure Project have had limited success in trying to address these issues but some barriers have been too difficult to overcome.

One common challenge is cost. MNOs have often found that deployment of rural sites tall enough to support multiple operators, cover a large enough area, and to have line of sight for microwave connectivity to sites with sufficient backhaul capacity (ideally fibre) can be prohibitively expensive. The business case for sites in these areas is very difficult. There are either insufficient subscribers or traffic in rural areas to generate sufficient revenue to pay for the investment. In cases where the site is deemed potentially economically viable, it may be at locations where planning permissions becomes a problem such as in Areas of Outstanding Natural Beauty. Obtaining planning permission in sensitive areas can be protracted as the MNO has to deal with objections from local residents, consultation meetings with Local Planning Authorities, conservation officers or wider interest groups. A successful outcome is by no means guaranteed and some compromise may be required to avoid rejection, in turn leading to reduced benefits of the business case.

These barriers are making the legally binding commitment made by MNOs to Government in December 2014, very challenging. The agreement was made on the basis of MNOs investing £5 Billion to improve mobile infrastructure and thus cover 90% of the UK's land mass (geography) by 2017. This agreement was made when Government was considering national roaming. Positive progress is, however, being made by programmes such as 'grow the grid' in which new cellular masts are deployed to address poor coverage.

Furthermore, the Government has introduced changes to Town and Country Planning and the Electronic Communications Code to speed up site deployment, mentioned earlier in this document to assist the MNOs.

Increased consolidation and infrastructure sharing is also well advanced amongst the MNOs with joint ventures operating between EE and Three (MBNL) and O2 and Vodafone (CTIL). Site sharing and consolidation helps reduce operational costs by sharing them between operators. The savings can then used for future investment in network roll out.

We note that the new Emergency Services Network (ESN) being built by EE and the Home Office will extend EE's coverage in rural areas. ESN is designed to meet the needs of the emergency services and whilst it may facilitate additional services to MNO customers in the future, this is not necessarily guaranteed. Furthermore, the challenging deployment timescales set by the Government may result in the deployment of smaller, more aesthetically sympathetic site designs to avoid Town and Country Planning objections and delays. This will ultimately result in fewer sharable structures, and sites with restricted capacity to share.

It is imperative that coverage gaps are addressed before mobile operators focus on offering new technology options in rural areas otherwise rural areas will not benefit from these advanced technologies as there will be inadequate infrastructure to support them.

1.6 Summary of the infrastructure requirements analysis

In considering the impact of 5G requirements on future networks, we have used a number of future 'use cases' to drive our analysis. These use cases consider a range of foreseen areas where future communications technologies are expected to play a role, from superfast consumer broadband to connected cars and critical communications.

It is against this backdrop that our examination of the UK's existing telecommunications infrastructure has been undertaken. With 5G and other future networks still under development it has meant many of the cost and site estimates are high level. These have been based on a set of justified and qualified assumptions such that a basic understanding of how the existing infrastructure might play a role in future networks has been gained. This will help identify areas where Government could intervene to help support future network roll out in a more coordinated and informed way.

2 Development of telecommunications infrastructure in the UK

2.1 An overview of fixed and mobile networks

A brief overview of the history, shape and size of UK's telecommunications infrastructure evolution is given below.

Consumer and business telephony and connectivity

Traditionally fixed telecommunications infrastructure, mainly for telephony, was deployed as a mix of telegraph poles to residential and business premises and more recently, below ground in ducts using copper and fibre cable. The copper telephone lines, used for voice calls and some very small amounts of data were rolled out firstly by the Post Office then BT.

In the late 1970's, early 1980's optical fibre was used to transport increasing voice and data traffic and it was the roll out of fibre which changed the landscape of telecommunications networks enabling very high speed connectivity across the UK and overseas. However, fibre deployment is notoriously expensive as it is deployed underground and any new connectivity requires digging roads and pavements which is expensive and disruptive.

Fibre to the cabinet and more recently fibre to the home has become more common as regulations have forced BT to open up access to its infrastructure (including ducts and poles) to other operators resulting in more competitive broadband services across the UK.

Two other nationwide telcom companies, Cable and Wireless (now Vodafone) and Virgin Media also have significant national infrastructure but still well below the presence and coverage of BT.

Cellular networks were created in the mid 1980's, which introduced independence from the fixed line operators. The first cellular masts were deployed in around 1985 by two mobile operators Racal Vodafone and BT Cellnet[2] using analogue and then GSM technology in the 900 MHz band. In the mid 1990's two additional mobile operators emerged (Mercury One2One and Orange) using 1800 MHz frequencies. By 2016, the four mobile operators have deployed around 40,000 mobile phone masts in the UK supporting 91.5 million mobile subscriptions[3] providing 3G coverage to 98% of the population and a growing percentage of 4G coverage.

The first masts used analogue technology and were deployed initially to serve car phones and sites were deployed along motorways and major trunk roads but with increases in voice and more recently data traffic (mobile broadband) and the expectation that mobile devices can be used anywhere has led to an increase in the number and location of cellular masts also ranging in size (macrocell/microcells).

Infrastructure for the roads, rail and utilities network:

A number of private networks have been built to meet specific user requirements which cannot normally be met by the public mobile networks. For example:

- Network Rail built its national private radio and cab secure radio network which was subsequently replaced by the GSM-R network for digital signaling and voice operations. At the core of its activities is Network Rail's FTN and the new FTNx provides enhanced backbone infrastructure to all Network Rail Telecom assets.

[2] Vodafone celebrates 30 years first UK mobile phone call, TechWeek Europe, 2015
[3] Ofcom telecommunications sector update – Facts & figures 2016

- Airwave built a dedicated digital voice and data network to meet the needs of the UK's emergency services.
- Utility companies throughout the UK have installed a variety of fixed and wireless networks to support services such as SCADA to monitor, control and supervise their operational equipment and networks.
- The National Road Telecommunications Service (NRTS) has deployed telecommunications infrastructure along the major highways and trunk roads in the UK. The network connects emergency telephones and other roadside devices to a number of regional control centres. Prior to the NRTS, a piecemeal of networks had developed over a 40 year period providing connectivity between thousands of roadside devices and 32 separate Police Control Offices across England.

Overall there is a lot of distinct telecommunications infrastructure distributed across the UK serving a multitude of disparate users. This study aims at identifying the arrangements of the existing infrastructure and the gaps in its capability to serve future networks. This includes upgrade or the addition of new infrastructure in order to meet the key performance requirements of future wireless networks.

2.2 Future of wireless networks

The growth of mobile networks in recent years has predominantly been driven by the intense increase in demand for mobile data by consumers, typically on smartphones. Forecasts and predictions for growth in mobile traffic vary, but most forecasters agree that growth in demand will continue for many years as indicated below in a report by the GSMA[4].

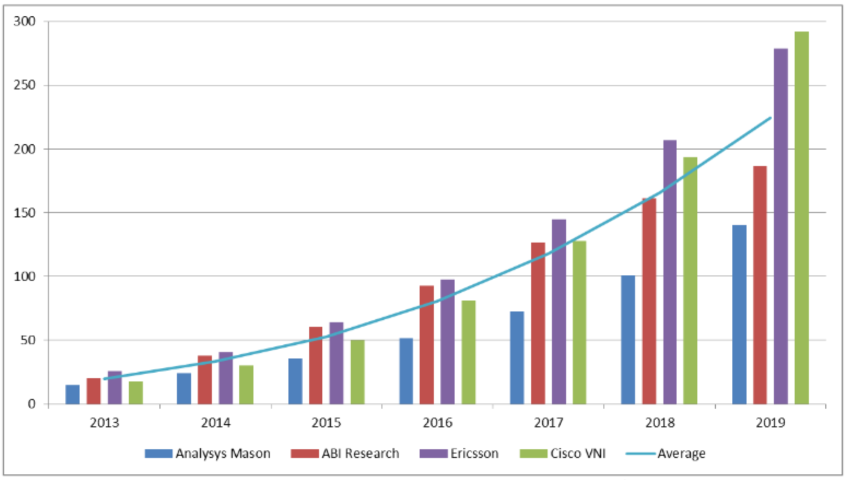


Figure 2: Annual global mobile data traffic (in Exabytes)

Figure 1: Global mobile data traffic growth. Source GSMA[4]

The impact of this traffic growth on the shape and size of the infrastructure is potentially problematic for mobile operators, as they will need to continually address the capacity needs within their networks. This traffic growth can be met in a three ways, namely by:

- Additional Spectrum – a limited resource – National policy determines cost
- Enhanced technology i.e. efficiency gains more bits per second per hertz of spectrum – which requires development of new technology
- Additional sites – smaller and smaller cells so as to re-use spectrum

[4] Data demand explained, GMSA, June 2015

Each method has an impact on cost/investment with some more than others but it is expected that operators will continue to investment in additional sites (often requiring higher backhaul connectivity speeds) which may or may not be suited to the longer term investment in future wireless networks.

Comparing the near term problems of mobile operators with other network infrastructure providers and operators and we identify some distinct differences, which are highlighted in the table below.

Operator type	Drivers for infrastructure development	Typical investment time horizon (estimate)	Impact on potential future wireless networks integration
Mobile Network Operator	Capacity crunch/growth mobile data traffic/technology refresh/ regulatory requirements (spectrum license conditions)	12 – 18 months based on regular upgrade and technology renewal	MED/HIGH
Wi-Fi operator	Capacity and traffic growth/Technology update	2-3 years based on technology refresh and end of life	LOW/MED
Private radio and fixed networks	Technology refresh/obsolescence	>10 years based on whole system life	MED
Fixed line networks	Technology refresh/growth in capacity	2-3 years based on technology refresh and end of life	MED

Table 1: Typical infrastructure investment horizon amongst operators

In parallel, we note the timeline for the evolution and expected roll out of 5G technology over the next 5 – 10 years[5]. It is imperative, therefore, to understand how MNOs intend to deploy infrastructure in future such that measures can be taken today by relevant parties to minimise the impact on enabling future wireless networks.

2.3 Structure of the report

The above summary demonstrates the extensive deployment of telecommunications infrastructure and mix of equipment deployed across the UK for a wide variety of services and applications. This highly fragmented industry would benefit greatly from convergence between fixed and mobile infrastructure, site sharing but also collaboration between telecommunications operators with similar technical and commercial motivations and incentives. In this study LS telcom UK Ltd in partnership with InterDigital Europe Ltd and WHP Telecoms Ltd have delivered a comprehensive analysis of the fixed and mobile infrastructure available in a representative set of geographical areas across the UK. We map the capabilities of the infrastructure in these locations relative to requirements of next generation networks to identify the gaps in infrastructure capability and what solutions would be needed to address them.

[5] 5G Vision The 5G Infrastructure Public Private Partnership: the next generation of communication networks and services, European commission, Feb 2015

The report is structured in the following way:

- Executive Summary – presents the key messages and overall findings of the study
- Chapter 2 – Developments of telecommunications infrastructure in the UK provides a brief overview of how telecommunications infrastructure has developed for both fixed and mobile networks over the years.
- Chapter 3 - Overview of UK telecommunications infrastructure presents a comprehensive description of the arrangements and context for all fixed and mobile telecommunications infrastructure relevant to the study
- Chapter 4 – 5G Technology Readiness describes the key future technologies and architectures that are being developed to enable next generation wireless networks that support specific use cases
- Chapter 5 - Digital infrastructure requirements in the UK provides the detailed findings from network dimensioning and cost analysis for the needs of road, rail, urban and rural areas
- Chapter 6 - The barriers and challenges of modern infrastructure deployment presents the key technical, regulatory and commercial challenges of deploying telecommunications infrastructure within each of the four focused environments
- Chapter 7 – Opportunities and barriers of infrastructure sharing to support 5G highlights the impact and importance of infrastructure sharing that will be needed to enable the specific use cases
- Chapter 8 – Conclusions from the main and key themes for site numbers and costs across the four focus areas analysis of the study.
- Chapter 9 – Appendix includes additional detailed information relating to the mapping analysis conducted in chapter 5

3 Overview of UK telecommunications infrastructure in the context of 5G

In this section we describe the current arrangements for existing telecommunications infrastructure in the UK for both fixed and wireless networks. The specific technical, commercial and practical details are captured for public and private network operators and owners of infrastructure.

The following key messages are provided:

- Mobile phone coverage is provided via a network of approximately 40,000 sites. Approximately 60% of these are owned by individual site landlords where a site specific agreement (lease or license) is in place. The deployment of additional and/or new equipment, to upgrade to 5G for example, has the potential to change the terms of that agreement. The work involved reviewing agreements and negotiating with landlords on many 000s of sites should not be underestimated.
- Infrastructure sharing by the UK Mobile Network Operators (MNOs) is already well advanced. Network consolidation between operators has increased the number of sites available for each individual operator (improving coverage) while driving down the total number of sites in the shared network (so reducing cost).
- Private radio networks have been deployed to meet the operational requirements of road, rail, utility and emergency service operators. Infrastructure has been deployed in specific locations to meet those needs. These are often deployed with minimal infrastructure and in locations (for example, railway trackside) making infrastructure sharing with MNOs difficult.
- The provision of mobile coverage in rural areas remains a challenge. The rollout of additional site infrastructure in more sparsely populated areas is often deemed uneconomic. The deployment of larger sharable structures to the reduce cost presents significant environmental challenges.
- While a number of fixed line operators continue to invest in fibre infrastructure, the deployment of Fibre to the Premises (FTTP) is not yet widespread. 5G technology will require the wide spread availability and access to fibre in both dense urban and rural locations. The sharing of existing fibre networks along the road and rail networks will be key.

3.1 Introduction

The section provides the overall context of the infrastructure in relation to how it may or may not be suited to enable future wireless networks.

UK telecommunications infrastructure providers can be divided broadly into four categories:

- **Mobile Network Operators**: Providing national mobile voice and data services to consumers using mobile 2G, 3G, 4G and Wi-Fi technologies.
- **Private and Fixed Radio Network Operators**: Providing voice and data services to a specific "closed" group of users – most often for business or commercial operations. Services are provided to meet the specific needs of the user group and for specific locations such as the main rail routes and Strategic Road Network.
- **Fixed Line Network Operators (Wholesale)**: Owners of ground based copper and fibre assets providing leased line, fixed data connectivity and wide area networking services.

- **Wi-Fi Operators**: Providing nomadic data services at specific "hot spot" locations using Wi-Fi technology.

These categories each serve a range of different geo-types/geography, population, end users, and end point equipment. In some cases there is overlap with both public and private network operators offering similar voice or data services to the same coverage area resulting in a duplication in infrastructure in roughly the same geographic location. This is brought about by differences in key attributes between public and private networks as highlighted Table 2.

Attribute	Public Network for example Cellular network (MNOs)	Private mobile networks, for example Rail and Emergency Services
End user	Mass market serving millions of public/consumer/business users.	Dedicated, specific small groups of users with a mix of fixed end point and mobile devices. Often specialised equipment needed.
Technology	Standardised, mass consumer devices.	Broadly standardised with modifications to meet specific conditions or uses.
Spectrum	Increasing amount of spectrum available from 700 MHz – 3.5 GHz which is harmonised with global allocations. Capacity and high bandwidth are often the key drivers.	Fragmented portions of narrow bandwidth available regionally or nationally but is often harmonised. Security and QoS are often the key drivers.
Coverage/ Geographic spread	Principally aimed at serving most profitable populated areas, residential, industrial, leisure and business premises. Population coverage is often the key driver.	Delivered to meet the specific needs of the relevant business or sector, for example, to meet the safety critical requirements for road, rail, utilities and emergency services. Geographic coverage is often the key driver.
Infrastructure	Mix of greenfield, rooftop, street works located near to power and transmission backhaul.	Dedicated sites developed at strategically placed locations to serve the end users and end user devices, for example, trackside, roadside, sub stations, and other remote locations. Safety critical applications demand high network resilience and availability.

Table 2: Key attributes between public and private networks

The following sections provide an overview of the infrastructure deployed in each category including the technology and spectrum used, the infrastructure site types in place and the coverage provided.

3.2 Mobile Network Operators (MNOs)

The UK's four MNOs (EE, O2, Three and Vodafone) own and operate their own wireless infrastructure operating under a licence which grants them exclusive access to a specific set of radio spectrum bands providing both wholesale and retail offerings to consumers and businesses. In return they are required to meet designated coverage obligations within their licence conditions.

Each MNO provides national mobile voice, text and data services (including Machine-to-Machine (M2M)) using a mixture of 2G, 3G, 4G and Wi-Fi technologies.

They also provide wholesale offerings to a number of MVNOs (Mobile Virtual Network Operators). While these provide similar end-user services to the MNOs, they do not own or operate their own wireless infrastructure. Some MVNO examples are shown in Table 3.

MNO	MVNO examples
EE	Virgin Mobile; ASDA Mobile; BT Mobile
Three	iDmobile; FreedomPop; The People's Operator
O2	Tesco Mobile; Lycamobile; Giffgaff
Vodafone	Lebara Mobile; TalkTalk Mobile; TalkMobile

Table 3: MVNO examples

3.2.1 Technology

MNO network infrastructure can be divided into two main elements simplified in Figure 2. The base station network provides coverage to customers via thousands of radio sites deployed in cities, towns and villages spread across the UK. Base station equipment costs tens of thousands of pounds and requires space and supporting civil infrastructure (towers, power, cooling etc.) and as such represents a significant investment for each MNO. Sites within the base station network deliver coverage via a number of architecture site types depending upon the coverage area required and the service (i.e., data speeds, quality) to be delivered.

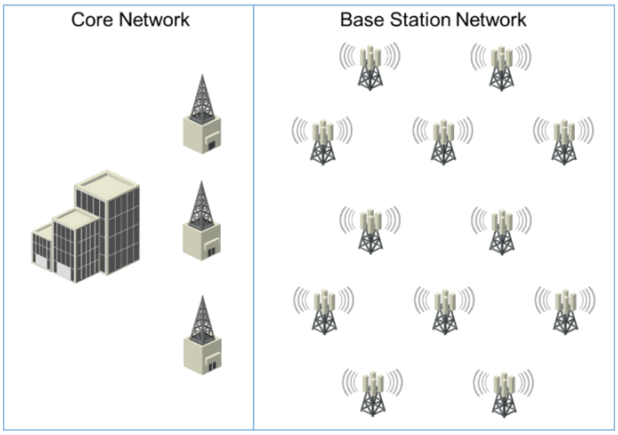


Figure 2: Simplified network infrastructure

Base station sites are connected back to the MNO core network using a mixture of point to point microwave or fixed "lease line" circuits ("transmission backhaul"). The choice between point to point microwave and lease line depends on a number of factors, for example:

- Speed of deployment: Microwave links tend to be quicker to deploy compared to leased lines.
- Cost: Upfront CAPEX and low OPEX for microwave in contrast to more expensive OPEX for lease lines.
- Operations: Microwave links are controlled by MNOs but must be managed. Leased lines are bought as a managed service and subject to various SLAs.

However, the rising demand for user data and deployment of 4G has driven the need for higher connectivity speeds at the base station with MNOs now deploying 1Gbps fibre connectivity in many cases. Fibre connectivity is supplied by a number of service providers for example, BT, Virgin Media, Cable & Wireless (now Vodafone) and City Fibre (see Section 3.3).

The availability of transmission is key for the deployment of sites in more rural areas. The cost of delivering fibre to remote sites or the need for multiple towers to provide microwave hop sites can prove uneconomic for public (MNO) operators.

The architecture site types are outlined in Figure 3 and described below.

Figure 3: Network architecture site types

a) Macrocell

A macrocell provides the main wide area radio coverage for a mobile network. The antennas for macrocells are mounted on ground-based masts, rooftops and other existing structures, at a height (typically between 10m and 40m) that provides a clear view over the surrounding buildings and terrain. Macrocells provide radio coverage over varying distances (including into buildings) dependent upon frequency capacity and clutter. Macrocell base stations can provide coverage for up to tens of km.[6]

b) Microcell

Microcells provide infill radio coverage and additional capacity where there are high numbers of users within urban and suburban environments. The antennas for microcells are mounted at street level (i.e. below the surrounding buildings and terrain) typically on the external walls of existing structures, lamp-posts and other street furniture. Microcell antennas can be smaller than macrocell antennas and when mounted on existing structures can often be disguised as building features. Microcells provide radio coverage over distances of, typically, between 300m and 1000m[7].

c) Picocell

Picocells provide more localised coverage than microcells (e.g., inside buildings) where coverage is poor or there are high numbers of users.[8]

d) Femtocells

Femtocells are very small low power consumer base stations and are typically used to improve coverage in the home or small business premises. The use of a domestic power supply and existing broadband connection helps minimise any MNOs infrastructure investment.

e) Small cells

Small cells is an umbrella term covering microcells, picocells and femtocells providing targeted (e.g., street level, indoor) high capacity coverage.

[6] http://stakeholders.ofcom.org.uk/sitefinder/glossary/jargon/
[7] http://stakeholders.ofcom.org.uk/sitefinder/glossary/jargon/
[8] http://stakeholders.ofcom.org.uk/sitefinder/glossary/jargon/

3.2.2 Spectrum

The radio spectrum for MNOs is exclusively licensed and in recent years mobile spectrum has been auctioned by the Radiocommunicaitons Agency (2.1 GHz in 2000) and Ofcom (800 MHz and 2.6 GHz in 2013). It is used across all site types and will depend on the requirements of a specific area with lower frequencies providing better wide area coverage and building penetration and higher frequencies offering better capacity. MNOs have traditionally deployed the lower frequency carriers on their macro cells to give the wide area coverage. However, a mixture of high and low frequency bands are needed to provide coverage in suburban and rural areas and capacity in town and city centres.

Total spectrum holdings for all MNOs is currently over 600 MHz across the 800MHz, 900MHz, 1800 MHz, 2100MHz and 2600MHz bands with each allocation shown in Figure 4.

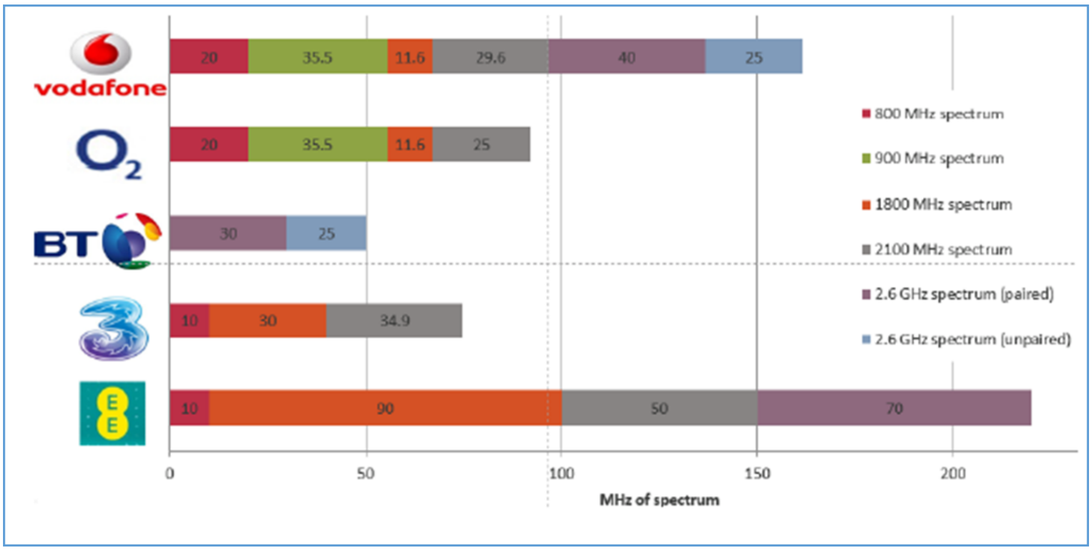


Figure 4: UK spectrum holdings after 4G auction and EE divestments in 1.8 GHz[9]

Additional spectrum in the 2.3 GHz and 3.4 GHz bands sourced from public sector spectrum holdings of the MOD has been planned for release for some time and is currently scheduled to become available through Ofcom auctions in 2017. A total of 190MHz will be released.

3.2.3 Site Infrastructure

The network architecture types identified above (for example macro and micro cell) are used to differentiate the cell ranges and where they might be deployed relative to each other. The physical site infrastructure upon which these architecture types are deployed are generally categorised as follows:

a) Greenfield Site

The term greenfield is used to describe a site where no existing infrastructure existed prior to development (e.g., a farmer's field). A greenfield site requires new accommodation (a cabin or cabinets) in which to house the base station equipment and a tower/mast to mount the radio

[9] https://www.techuk.org/component/techuksecurity/security/download/3773?file=UK_Spectrum_Policy_Forum_Report_-_UK_Spectrum_Usage__Demand.pdf UK Spectrum Policy Forum: UK Spectrum Usage and Demand

antennas at the required height. Greenfield site masts tend to be steel lattice or tubular monopole structures typically 15m to 60m tall.

Greenfield sites are typically found in suburban and rural locations due to the amount of space needed and provide the height required for wide area coverage and the deployment of macrocells.

A number of Wireless Infrastructure Providers (one of the largest being Arqiva) have portfolios of greenfield sites throughout the UK which are offered for sharing to all MNOs in exchange for an annual licence fee.

Given the size and nature of these site types it is common to find multiple operators sharing the passive infrastructure at these locations. There is usually sufficient space to mount additional antennas and house additional equipment.

Figure 5: Greenfield site examples

In a number of cases, especially where local authority planning dictates, existing non-telecoms structures are used. These include high voltage pylon sites owned by National Grid or one of the electricity Distribution Network Operators.

b) Rooftop Site

The term rooftop is used to describe a site where an existing structure (e.g., a building) can be used to house the base station equipment and mount the radio antennas.

Rooftop sites are typically found in suburban and urban areas and provide the height and location needed to provide macrocell coverage within, for example, town and city centres. Given current densification of macro cells, available rooftops sites are becoming increasingly more difficult to find in towns and cities with most prime locations being fully occupied. The ability for expansion at these sites is limited given the restricted space and potential additional costs applied by landlords.

Figure 6: Rooftop site examples

c) Streetworks Site

A term streetworks is used to describe a site, comprising base station equipment cabinets and tubular steel monopole (typically 15m to 20m) located in the pavement or verge of a local authority adopted highway.

Streetworks sites are typically found in suburban and urban areas. Their height tends to provide good infill coverage solution where greenfield or rooftop locations are not available and provide the operator with deployment and operational cost savings (for example, there is no ongoing rental charge for Local Authority streetworks deployment).

Due to their "street level" position, these sites are ideal for the deployment of smaller cells.

Figure 7: Streeworks site examples

Streetworks offer a cost effective and quicker to deploy alternative to other site types but are limited in the extent of coverage they can provide. This trade off will often require MNOs to deploy two or more streetwork solutions in order to match the coverage of a single greenfield or rooftop site.

d) Indoor Site

An indoor site is used to improve the coverage and capacity to a specific indoor location. These range from a single operator solution (e.g., to cover the offices of a corporate customer) to larger solutions (e.g., airport or shopping centre) involving the housing of base station equipment in a central location (a single equipment room for all operators or "base station hotel") and the deployment of a shared distributed antenna system.

Figure 8: Indoor site examples[10,11,12]

Indoor site solutions are a growing trend within large enterprises and buildings because they provide the required ubiquitous coverage that cannot be offered from an outside-in approach (MNOs largely depend on their lower frequencies to penetrate into buildings from sites outside). However, while indoor deployments have not been as prevalent as industry has

[10] Telefonica UK's LTE & Small Cell Trials, Telefonica, 2012
[11] Scalable Enterprise Small Cell System, SpiderCloud wireless
[12] http://www.wireless-mag.com/taxonomy/Airvana/209

expected in recent years, there is an expectation from the small cell industry of significant growth over the next few years as MNOs attempt to densify their networks to meet the indoor capacity demands[13].

The above infrastructure site types can provide a variety of coverage options. In general site types are deployed in to meet the various coverage/architecture requirements as shown in Figure 9:

	Network architecture site type				
Site deployment option:	Macrocell	Microcell	Picocell	Femtocell	Small cell
Greenfield	Yes	No	No	No	No
Rooftop	Yes	Yes	No	No	No
Streetworks	No	Yes	Yes	No	Yes
Indoor	No	No	Yes	Yes	Yes

Figure 9: Typical infrastructure capability

Infrastructure Sharing

Infrastructure sharing is already well advanced amongst the MNOs with joint ventures operating between EE and Three (“MBNL”) and O2 and Vodafone (“CTIL”). MBNL and CTIL are responsible for a balanced approach to both consolidation of existing sites and growing the portfolio of sites to meet the required coverage obligations of their MNO stakeholders. The key drivers for infrastructure sharing are two-fold:

- Operators gain access to sites in locations not previously accessed thereby improving the service offered to customers in those areas.
- Operators are able to consolidate the network in areas where both operator sites are present thereby reducing operational costs.

This is illustrated in Figure 10. It can be seen that while the number of sites for each individual operator increases (improving coverage) the overall number of sites in the shared network is lower (reducing cost).

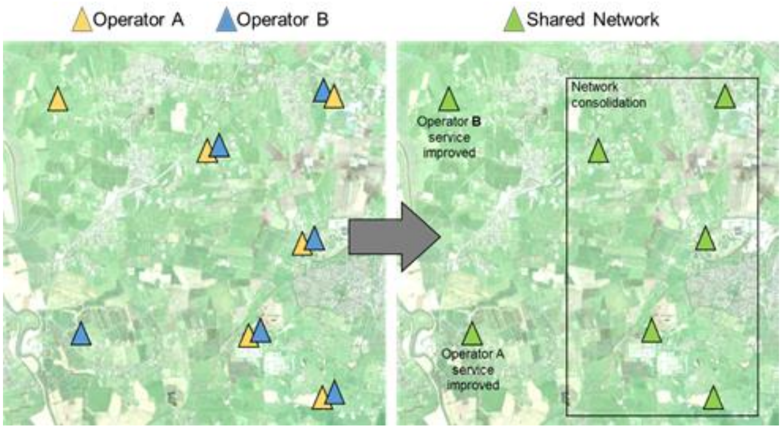


Figure 10: Infrastructure sharing key drivers

[13] 6 predictions for the small cell market, RCR Wireless, Feb 2016 http://www.rcrwireless.com/20160227/featured/6-predictions-for-the-small-cell-market-tag6-tag99

The MNO and shared network ownership is summarised below:

Operator	Joint Venture	Active Infrastructure	Passive Infrastructure
EE	MBNL	Operator retains ownership; Operational responsibility for 3G network with MBNL (2G & 4G with the operator although antenna & transmission sharing in place)	Operator retains ownership; MBNL manages deployment and sourcing of sites by 3rd party site providers
Three			
O_2	CTIL	Operator retains ownership; Operational responsibility split: Vodafone west; O_2 east	CTIL owns the passive asset, manages deployment and sourcing of sites by 3rd party site providers
Vodafone			

Table 4: MNO shared infrastructure ownership

Both Operator Joint Ventures utilise 3rd party sites upon which base station equipment can be installed. These 3rd party sites can be broken down into the following categories:

- Individual site landlords: A site specific agreement (lease or license) is contracted with the land or building owner.
- Other operators: One operator agrees to share a site with another operator. Equipment from both operators is installed on the same site.
- Wireless Infrastructure Providers (WIP): Provide access to a portfolio of existing structures. Example WIPs include:
  - Arqiva – Marketable portfolio of approximately 16,000 sites including 8,000 active cellular sites in the UK.[14]
  - WIG – Operates a network of over 2,000 shared communication infrastructure assets[15].
  - Shere[16] – Owns approximately 500 sites in the UK[17] with access to 4,150 potential sites on land belonging to United Utilities and Thames Water. [18]
- Other site portfolios: Agreement with owners of large site portfolios, for example, BT, City Councils, Police Authorities, utility companies, Network Rail and Government buildings.

There are approximately 40,000 base station sites from which mobile network coverage is provided by all MNOs. The approximate breakdown of site numbers into the above categories is shown in Figure 11. These are derived from stakeholder discussions, industry knowledge and outputs from the 2016 "TowerXchange" post event report.[19]

[14] https://www.arqiva.com/about-us/at-a-glance.html
[15] http://www.wirelessinfrastructure.co.uk/communication-towers/
[16] It should be noted that the Spanish company Cellnex has recently announced its acquisition of Shere http://www.globaltelecomsbusiness.com/article/3590503/Cellnex-expands-into-UK-with-393m-Shere-Group-acquisition.html#/.V_YpUY8rLIU]
[17] http://www.towerxchange.com/meetup/meetup-europe/towerxchange-meetup-europe-2016-post-event-report/
[18] http://www.sheregroup.com/about-us/ownership-and-group-structure
[19] http://www.towerxchange.com/meetup/meetup-europe/towerxchange-meetup-europe-2016-post-event-report/

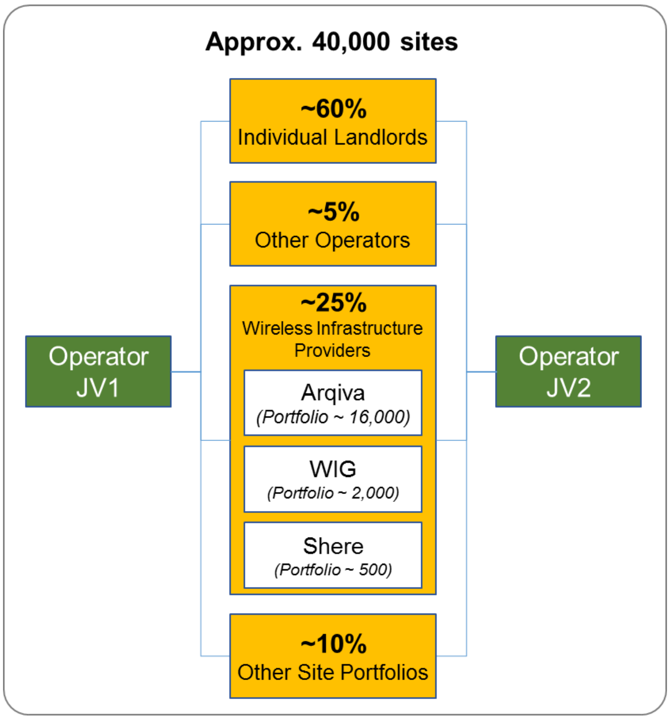


Figure 11: Base station site infrastructure breakdown

MNOs continue to invest in site infrastructure:

- Discussions with stakeholders have revealed that additional sites are being deployed in order to meet the 90% geographic voice coverage commitment and improvement in indoor data coverage (98% premises) (see later). For example, Vodafone and O_2's "Grow the Grid" initiative is expected to add 500+ sites to the network by 2017. Specific examples include the plan to install 5 new base station sites within the Cairngorms National Park[20].
- As part of the UK Government's new Emergency Services Mobile Communications Programme (ESMCP) EE will be building more than 500 additional 4G sites which will provide increased coverage for their mobile customers[21].
- Support of the UK Government's Mobile Infrastructure Project (MIP) to cover mobile not-spots – around 60 new masts (out of 600 potential sites identified) where completed, when the project closed at the end of the 2016 financial year[22].

The investment decisions made by MNOs are typically driven by a relatively short term view (12- 18 month time horizon). The need to deploy sites quickly to meet RoI, customer demands and regulatory requirements often result in MNOs deploying the minimum infrastructure required as opposed to the potential longer term needs of future technology or sharable infrastructure.

[20] Mobile Telecommunications Developments, Cairngorms National Park Authority, May 2016
[21] http://ee.co.uk/our-company/newsroom/2015/12/10/ee-selected-to-deliver-critical-new-4g-voice-and-data-network-for-britains-emergency-services
[22] http://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN07069

3.2.4 Mobile coverage and service provision

Mobile coverage is defined and reported in a number of ways to reflect the type of location where the mobile service is provided.

The type of coverage is often described in three ways:

Coverage Type	
Outdoor coverage	Outdoor coverage is deemed available when a mobile customer can use the service while located outdoors e.g., outside on the street.
Indoor coverage	Indoor coverage is deemed available when a mobile customer can use the service while located indoors e.g., within a building. Differences in building size and construction make indoor coverage difficult to predict. Assumptions are therefore made regarding the amount by which the signal will be reduced as the signal penetrates the building.
Incar coverage	Incar coverage is deemed available when a mobile customer can use the service while travelling by car. This will assume that no external aerial is fitted.

The amount of coverage provided is expressed as a percentage. Three measures are provided:

Coverage Measure	
% Premises Covered	Premises coverage is calculated from a base of almost 30 million UK postal delivery points (taken from the Ordnance Survey *AddressBase* dataset, Northern Ireland Pointer address database and the ONS National Statistics Postcode Lookup). This provides a good indication of the coverage provided at locations where people both live and work. The % Premises covered figure is often divided into two separate measures: ▪ % Indoor Premises Covered: The proportion of premises where the customer can use the service inside their home or office. ▪ % Outdoor Premises Covered: The proportion of premises where the customer can use the service stood outside their home or office.
% Geography Covered	Geographic coverage considers the land mass as a whole - everything from city centres to the most rural locations. This takes no account of where people live or work or the use to which that land is put. As such coverage measures are typically shown for Outdoor coverage only.
% Roads Coverage	Is similar to geographic coverage and is expressed as the % of the total road length. Coverage measures are calculated from road data taken from, for example, the Ordnance Survey *Meridian* and Northern Ireland Land and Property Services datasets.

Mobile coverage, and in particular the lack of, continues to be discussed by policy makers and the industry alike. The presence of "not spots" (where basic voice coverage is not available from any operator) and what should be done about them has been debated at all political levels.

The challenge to improve coverage is recognised across the mobile industry with the deployment of additional site infrastructure often deemed uneconomic in more sparsely populated areas. Coverage can be improved through a number of methods, for example:

- Spectrum/operating licence obligations. For example, O_2 has a coverage obligation in its 800 MHz licence to roll out 4G to cover at least 98% of the UK population (when indoors) by 2017 at the latest. This results in more than 99% coverage for 4G when outdoors. It should also be noted that other UK mobile operators have indicated they intend to match the 98% coverage figure. [23] [24]
- Strategic investment targeting rural areas. For example, the Government's Mobile Infrastructure Programmed (MIP) where public funds were utilised to build sharable telecoms masts to cover not spot locations.
- Increased collaboration between MNOs to increase network sharing or implement solutions such as national roaming.
- Technology solutions such as Wi-Fi roaming and Wi-Fi calling.
- The densification of sites through the deployment of small cells in urban environments to improve street level coverage and capacity.

In December 2014, the UK Government signed a binding agreement with the four network operators to improve mobile coverage. The agreement guarantees coverage of a mobile voice and text service from each operator to 90% of the UK's land mass (geography) by 2017. [25]

However, the British Infrastructure Group (BIG) report on mobile coverage[26] highlights a lack progress made by the sector in improving coverage since 2014. While publicly available data is limited it concludes that the sector is highly unlikely to meet these coverage obligations by the end of 2017.

The mobile voice coverage provided by each MNO is summarised in Figure 12. This uses a combination of 2G and 3G technologies and is expected to improve with the future availability of voice services over the 4G networks operating in the lower 800MHz band.

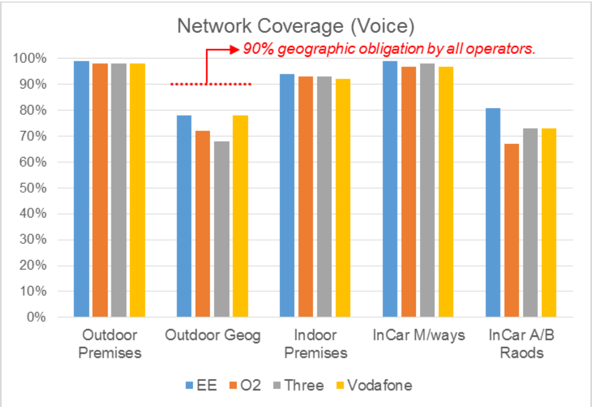


Figure 12: UK coverage for mobile voice services[27]

[23] [http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf]
[24] http://media.ofcom.org.uk/news/2015/mno-variations/
[25] https://www.gov.uk/government/news/government-secures-landmark-deal-for-uk-mobile-phone-users
[26] http://britishinfrastructuregroup.uk/wp-content/uploads/2016/10/Mobile-Coverage.pdf
[27] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf. Ofcom analysis of Operator Data

The mobile data coverage provided by each MNO is summarised in Figure 13. This uses a combination of 3G and 4G technologies. The deployment of 4G technology is ongoing with the 2015 level of outdoor premises coverage summarised in Figure 13.

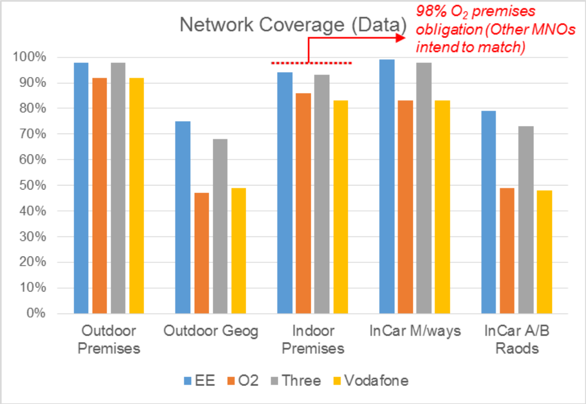


Figure 13: UK coverage for mobile data services based on combined 3G and 4G coverage[28]

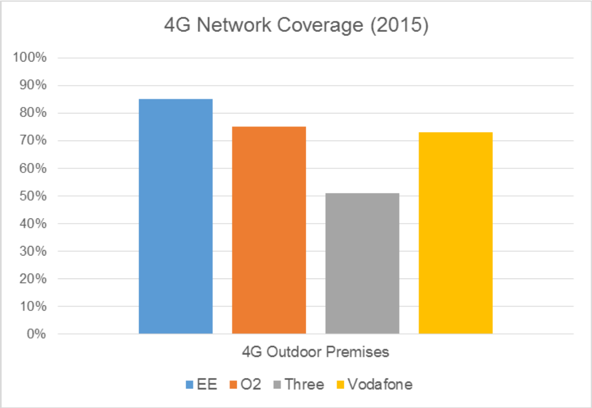


Figure 14: 2015 4G coverage[29]

While coverage data for both geographic and premises provides a good indication regarding the reach or availability of mobile voice and data services it provides an incomplete picture when it comes to mobile user experience.

A report (Consumer Experiences of Mobile Phone Calls) published by Ofcom in August 2014[30] and using data from independent mobile analytics firm RootMetrics[31], showed:

- Overall Call Completion Success Rate (CSSR – a combination of blocked and dropped calls to give an overall view) were between 93% and 97% nationally.

[28] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf
Ofcom analysis of Operator Data
[29] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf
Ofcom analysis of Operator Data
[30] http://stakeholders.ofcom.org.uk/binaries/research/telecoms-research/consumer-experiences-mobile-phone-calls/report.pdf
[31] http://www.rootmetrics.com/en-GB/home

- CCSRs was lower in rural areas compared to urban areas: In the case of some operators there are rural areas where as many as one in five call attempts failed. The same pattern was observed in each of the Nations.

A more recent study (April 2016) from Which? and independent mobile coverage experts OpenSignal[32] [33] found that mobile customers in the UK were only able to access 4G just 53% of the time on average across the four networks. While MNOs continue to deploy and make improvements in their network (in particular 4G) these reports together with anecdotal evidence suggests that network availability from a user perspective is lower than that suggested by overall coverage statistics. This points to the need to improve the mobile user experience which requires targeted cell densification in the areas most affected.

Details relating to the coverage of specific locations (via interactive maps) can be found on each MNO website. In 2015, Ofcom launched an interactive mobile coverage checker map[34] enabling a like-for-like comparison to be made of mobile voice and data coverage between each MNO.

In addition MNOs have used alternative platforms (typically in-building/local area solutions) to help enhance indoor coverage or offload traffic from the macro network, in particular to deliver targeted coverage to points of interest where location and high traffic density requires a special solution. For example, sports stadia, shopping centres, airports and corporate customer locations. A number of temporary solutions are also be deployed to cover specific time limited events, for example, Glastonbury and the British Grand Prix. Coverage is further enhanced with MNOs now offering Wi-Fi coverage to their customers, for example:

- O_2 provides access to a network of 13,000 hotspots nation-wide.
- EE and Vodafone provide access via the BT Wi-Fi network.
- Access to Virgin Media's Wi-Fi network covering some 150 London underground stations is provided to each MNO.

In addition to providing enhanced indoor mobile data coverage, all MNOs have launched a voice over Wi-Fi service which will help improve coverage in building where mobile signals are poor. However, this currently requires the use of a standalone smartphone app or availability of a handset with integrated Wi-Fi calling functionality.

Network densification through the deployment of small cells can be used to address specific coverage, capacity and service level requirements. However, while small cell technology is well developed and readily available its deployment has not yet been as prevalent as industry had expected.

This could be for a number of reasons including:

- Difficulty surrounding access to small cell infrastructure, for example, street furniture, and the deployment challenges associated with it (further details given in the section 6).
- Additional capacity/service gains obtained through more cost effective means such as existing site upgrade, optimization, technology (carrier aggregation) and use of additional spectrum bands.
- Other distractions: MNOs are still focused on 4G national deployment, network consolidation, site decommissioning (following consolidation), MIP, site churn (for example, Notice to Quit (NTQ)), with no/limited resource for "special projects".

[32] https://press.which.co.uk/whichpressreleases/uk-mobile-users-only-able-to-connect-to-4g-half-of-the-time/
[33] http://opensignal.com/reports/2016/03/uk/state-of-the-mobile-network/
[34] http://maps.ofcom.org.uk/check-coverage

- Scalability: Densification of the network (potentially tens of thousands of additional sites) requires an additional management overhead on the network and this requires advanced techniques to manage in terms of both OSS and BSS arrangements.

3.3 Private and fixed radio networks

In contrast to the MNO infrastructure private and fixed radio networks provide voice and data services to a specific "closed" user groups. Some of the larger national dedicated networks and users include:

- National Roads Telecommunications Services (NRTS) and Traffic Scotland: Provides national highways roadside device connectivity and vehicle traffic control and emergency telephony.
- Network Rail Telecom: Deployed a national trackside cellular network for train communications and signaling using GSM-R technology across all main rail routes in Great Britain.
- Airwave: Provides a nationwide TETRA network serving the emergency services and public safety agencies across the UK.
- Power Utilities: Regionally deployed networks providing operational telecoms, network monitoring, control and automation (including tele-protection).
- Sigfox/Arqiva: Currently deploying a network providing M2M/IoT connectivity.

Private mobile radio networks have evolved to meet specific user requirements which cannot normally be met, for example, by the public MNO networks. These requirements can be summarised at a high level below:

- Coverage – often high geographic coverage is needed including very remote areas.
- Availability – service to be available 24/7; near zero network downtime.
- Resilience – service is maintained in times of fault (for example power failure) or crisis (for example flooding).
- Performance – for example, the need for very low jitter and latency (<10ms) in Electrical supply tele-protection circuits.
- Security – encryption and segregation of traffic types (e.g., network control signalling from office IT).
- Functionality – specific requirements for example push to talk, group calling, prioritisation and pre-emption.

To understand these requirements in more detail the use of telecoms networks in the utility sector is explored further. Communications infrastructure is essential in order to allow the remote monitoring of gas, water and electricity plant throughout the UK. The status of a gas compressor, water pump or circuit breaker will normally be monitored at some centralised control centre to allow safe, reliable operation of the network. Not only is the status of these devices monitored remotely but control signals are also routinely employed to optimise the use of the network. An example is the ability of an electricity company to remotely disconnect and isolate a faulty section of cable or a transformer under fault conditions; ensuring that the smallest number of end users are affected by the fault.

The communications systems utilised for this purpose are hierarchical and comprise a mixture of fibre, copper and wireless technologies. Those installations with the most critical function in the network (e.g. a large pumping station or major substation) are generally connected by a highly reliable, resilient, secure combination of fibre and radio connections. Those more peripheral devices are likely to have a lower cost, less robust connection (possibly at the end of pair of copper wires via analogue voice circuits, ADSL or 3G data connection).

Without the ability to communicate remotely with their plant, Utility Companies would be unable to reliably provide the critical services to the UK and restoration times in the event of faults would likely be several orders of magnitude greater. Thus these types of networks are known as ‘critical national infrastructure’ and require the very high levels of reliability, availability and resilience.

3.3.1 Technology for private radio and fixed networks

The network infrastructure and split between radio and fixed networks will depend upon the operator. For example, the Airwave TETRA network is predominantly a secure nationwide radio based network; the NRTS is a fixed line based roadside network and Network Rail a combination of fixed and wireless deployed along the trackside. This is shown simplified in Figure 15.

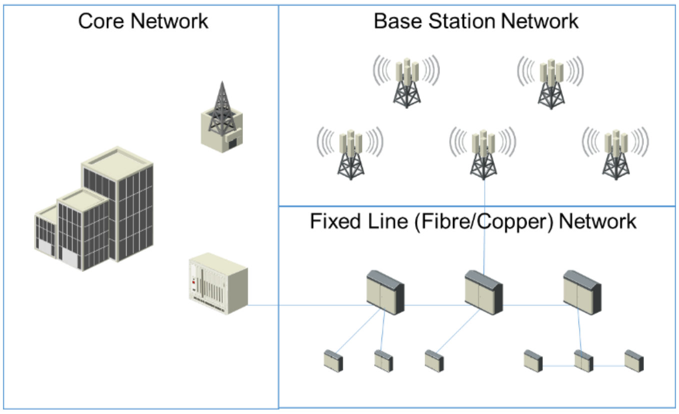


Figure 15: Simplified Private Radio/Fixed network architecture

Base Station Network

Sites within the base station network deliver radio coverage to end users or devices. Sites are deployed to meet specific network requirements, for example, located to provide coverage to a specific road/rail route or overlapping coverage to provide a level of resilience (i.e., coverage available from multiple sites).

The radio technology also varies depending upon the application. For example, the Airwave network uses the TETRA standard whereas Network Rail uses GSM-R. These standardised technologies were chosen based on their characteristics and functionality designed to serve the particular end user requirements.

Base station sites are connected back to the core network using a mixture of point to point microwave or fixed “lease line” circuits. Availability, resilience and performance are key drivers and so self-provide microwave links are often used supplemented by leased line circuits where microwave is not viable (i.e., no line of sight). Where neither solution is possible and the site is still required, for example, to meet the coverage needs of the Emergency Services, satellite backhaul connectivity has been provided despite its limitations in terms of cost, throughput and latency.

Fixed Line Network

Cable (fibre or copper) based networks provide direct point to point connectivity between key nodes in the network. Each node provides a point of user or device connection and/or forward connectivity to the rest of the network. Again, the location of network nodes are specific to meet the requirements of the network.

The traffic on these networks is dedicated to specific operational use and is designed and dimensioned accordingly. Flexibility in terms of large capacity growth, upgrade or support for a change in use is often limited by the need to provide continued support for legacy equipment. Specific examples are highlighted later.

3.3.2 Spectrum

Spectrum is licensed to different users on an exclusive and dedicated basis and only relevant to private operators with radio based networks. Spectrum can be nationally or regionally licensed and in the cases of transport, utilities and emergency services a national licence is required to operate the specific services as identified below:

Operator	Spectrum bands and bandwidth
Airwave	Spectrum: 380 to 400MHz; Bandwidth: 2 x 5MHz
Network Rail	Spectrum: 876 – 880 MHz UL 921-925 MHz DL; Bandwidth 2 x 4 MHz
Utilities	The Utilities sector in the UK holds a modest amount of dedicated radio spectrum in the VHF and UHF (450MHz-470MHz) frequency bands. Most of this radio spectrum is managed by the JRC (Joint Radio Company) - jointly owned by the UK Electricity and Gas sector. The Water industry equivalent is TAUWI (Telecommunications Association of the UK Water Industry). The spectrum held by these two organisations is generally split into narrow channels of either 12.5kHz or 25kHz. The majority of channels have been used for a mixture of Private Mobile Radio (PMR) (voice) and telemetry (data/SCADA) applications. Most PMR systems have now been decommissioned, with the vacated channels being used to support additional (very low rate) data communication with electrical plant; especially in rural areas. In addition to the dedicated UHF and VHF channels, the sector also makes use of several microwave bands for point to point communications. These include 1.4 GHz, 7.5 GHz, 13 GHz, 22 GHz, 26 GHz and 38 GHz bands. These links have a mixture of uses ranging from telemetry and inter-tripping (low data rate, low latency safety critical links) to high capacity, high availability routes for corporate networks. Each link is licensed on an individual basis through Ofcom.
Sigfox/Arqiva	Spectrum: Ultra Narrow Band in shared license free spectrum (868MHz) [35]

Table 5: Spectrum bands for private and fixed networks

[35] http://makers.sigfox.com/

3.3.3 Site Infrastructure

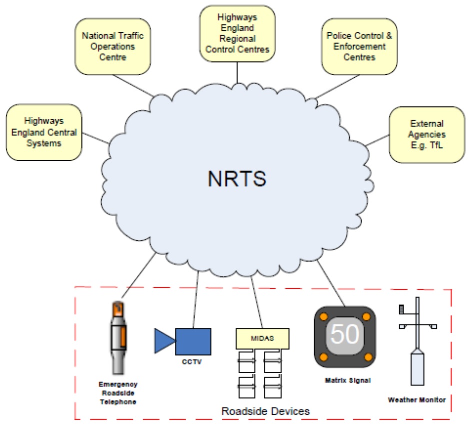
The site infrastructure used by each operator is specific to the application and outlined below:

Operator	Site infrastructure summary
NRTS & Traffic Scotland	NRTS: Approximately 3,650 km fibre and copper cabling with over 11,700 access points along 72 "A" roads and motorways.[36] Traffic Scotland: A mixture of fibre and copper cabling with over 794 access points along 16 "A" roads and motorways[37]
Network Rail	Approximately 2,800 base station sites including 16,000km of fibre and 22,000km copper cable carrying over 200,000 circuits.
Airwave	Approximately 3,500 base station sites with a mix of leased line and point to point microwave links.
Power Utilities	Approximately 2,250 base station sites (85% utility owned) [38] with a mix of fibre and copper cabling.
Sigfox/Arqiva	Utilises a network of existing Arqiva sites (Arqiva acting as Sigfox Network Operator in the UK).

Table 6: Summary of site infrastructure for private and fixed networks

Fixed infrastructure along the trackside and roadside

Highways England - NRTS



The National Roads Telecommunications Services (NRTS) PFI launched in 2004 has deployed approximately 3450 km of telecoms cabling (88% is fibre, the remaining 12% is copper) along the motorway section of the strategic road network (SRN). Given the full SRN in England is 7040km in total, which includes major trunk roads, this means 50% of the entire SRN is connected by varying levels of fibre. There are over 11,700 connection points along the 72 major trunk roads and motorways. The core network is divided into a 10Gbps national service and a number of regional 2Gbps networks which currently support CCTV, electronic message boards, emergency roadside telephone and weather stations, traffic counting and other applications. The current network could deliver as much as 100Mbps today from a single point based on existing technology on a smart motorway to less than 2 Mbps where the last mile is copper. There is no one single bandwidth figure given the fragmented nature along all the SRN

In terms of future opportunity, Highways England (HE) network is made up of a number of different fibre deployments ranging from legacy 1990s 12/24 core to 96 core fibre installed on the newest smart motorways sections of road. Depending on location there are levels of unused dark fibres with most capacity on the smart motorways sections, hence older deployments between 1990 and 2009 in lesser demanding areas of the network have reduced fibre capability.

[36] https://www.gov.uk/government/publications/public-sector-telecommunications-and-digital-infrastructure-maps-interim-publication
[37] https://www.gov.uk/government/publications/public-sector-telecommunications-and-digital-infrastructure-maps-interim-publication
[38] Represents a national extrapolation based on the number of sites within a typical DNO

The overall capability of the infrastructure today is mixed given the varying density of deployments across the SRN. On motorways with advanced infrastructure deployment, such as the M25, there is active infrastructure deployed typically every 500m to 1000m. These locations have power and connectivity available and as such could present an opportunity for future network providers. Motorways that have lower density of active infrastructure (such as the M5) typically every 3km to 5km, would require additional infrastructure for the very high data rate use cases and applications.

HE confirmed they plan to trial roadside infrastructure by providing more power and connectivity to the A2 M2 corridor. For example, there have been considerations within HE for the deployment of beacons every 200 m to 1000m along the 100 km stretch of A road and of motorway using microwave frequencies. By extrapolating the estimated cost across the whole motorway network the approximate deployment costs are within the same order of magnitude as our estimated costs for a dedicated roadside network (see section 5.2.1). This means power, physical structures and fibre to connect approximately these devices on the roadside are needed which could potentially deliver the very high data rates expected for the connected car use cases.

Highways England could use the sharing of infrastructure to fund expansion of smart motorway technology on the all-purpose trunk road (APTR) network and future 5G network. This means one organization could roll out infrastructure across the SRN at reduced cost as demonstrated on the motorway network by the NRTS PfI in 2004.

Third party access is considered with the current commercial model supporting a 50/50 arrangement in which profits are shared between third parties and HE. In the forthcoming NRTS 2 programme the arrangements will be different and understood to be done on a service delivery method. However, full contractual details are unavailable. Given this is a national public asset HE would need to charge market rates for access to the fibre but could also provide power and access to land.

HE operates a thin organisation, outsourcing and contracting out all major works including the management of large construction projects and maintenance to predominantly civil engineering companies and consultancies. To carry out a major national deployment of complex telecoms infrastructure would require a third party contractor with the necessary skills, expertise and capacity.

Network Rail

Network Rail sites range from 5 to 35m in height and usually comprise of both lattice and column masts. There are usually two antennas mounted on the top of the masts facing in either direction providing the coverage along as much of the rail route as possible. However, at junctions and other busy locations there are sometimes three or occasionally four antennas. Sites become more densely deployed at busy junctions, hub stations and urban areas to meet multiple service demands. GSM-R provides a mix of voice and data for signaling purposes to control the flow and management of rail (passenger and freight) traffic across all routes.

Figure 16: Example Network Rail site

There is a commitment from the supply industry to support GSM-R technology until 2030. There are now efforts within both the rail and telecommunications industry to determine what mobile technology is needed and suitable to continue to provide the service necessary to passengers and railway operations in future.

A typical Network Rail site is shown in Figure 16. These structures are deployed to meet a specific end user need i.e., a single user structure deployed trackside to optimize coverage of the train and trackside assets. While these structures are capable of supporting small form factor antenna (e.g., single mode/band antennas) it is unlikely that they are capable of supporting the additional antenna requirements seen on many MNO sites today.

The fixed trackside infrastructure consists of the Future Telecommunications Network (FTN) and the FTN-X which comprises 16,000km of fibre transmission capacity and 22,000km of copper supporting over 200,000 circuits[39].

The current network (running over the FTN) includes a number of STM-16 rings of 2.5Gbps capacity and STM-4 rings of 155Mbps capacity, deployed to connect all network rail system including the GSM-R network, CCTV network (circa 16,000 cameras), telephone systems, and depot connectivity etc. This is a highly encumbered network with a mix of different legacy access technologies which creates bottlenecks in different parts of the available fibre depending on the assets (signals, data networks, level crossing control) distributed along the routes. It is unlikely there will be much unencumbered fibre on the FTN and ultimately this will not be suitable to support future wireless networks given the throughputs needed for enhanced mobile broadband.

The FTN-X, is a recently deployed all IP MPLS core network. The FTN-X uses the same fibre infrastructure as the FTN. However, given the new technology it can support 8Tbps of capacity (80x100Gbps) based on 10% of the fibre being 48 available fibre cores and remaining 90% being 24-fibre cables. This network could support future wireless networks. While the network is now in place and operational the issue is that the FTN-X for both the access layer (which on the FTN, currently supports the GSM-R nodes) and the sub access layer (which supports the lineside emergency telephone, on the FTN) are barely deployed at all.

However, there are 'pockets' of access layer deployments on the FTN-X such as on the Glasgow-Edinburgh route where Project SWIFT[40] is running its wireless trackside trial. The trial has been able to deliver 500 Mbps capacity from each site along the route which is delivered as wireless backhaul to trains involved in the trial. The network is capable of delivering higher capacity if needed but the trial arrangements considered 500 Mbps represented the most pragmatic approach in protecting NR interests.

Airwave – Emergency Services Network (ESN)

In urban and suburban areas, the Airwave infrastructure is typically deployed on existing shared structures (MNOs, Police masts/rooftops, WIPs). To provide high levels of geographic coverage, more bespoke solutions are deployed in rural areas. A typical rural Airwave site is shown in Figure 17. These are often deployed with minimal infrastructure, for local authority planning purposes, and satellite backhaul. While these structures provide the coverage necessary for the ESN, it is unlikely that they are capable of supporting the additional antenna requirements seen on many MNO sites today.

Figure 17: Example rural Airwave site

[39] UK Railway Telecommunications Update, August 2015 The Rail Engineer
[40] https://cisco-create.squarespace.com/swift/

The Airwave service will be replaced over the next few years by a 4G based service provided by EE. This new ESN will utilise the same base station infrastructure as provided to other EE customers. A “slice” of the network will be provided for ESN using additional core network elements.

In order to deliver the mission critical ESN, EE said it will:

- Build a new, highly resilient dedicated core network for the Emergency Services.
- Build more than 500 new sites, expanding coverage in rural areas.
- Switch on low frequency 800MHz spectrum on more than 3,800 sites to enhance rural and indoor coverage.
- Implement the capability to afford network access priority to Emergency Services when required.
- Implement VoLTE (voice calls over 4G), and new LTE voice capabilities including 'push to talk'.
- Deploy a fleet of Rapid Response Vehicles to ensure maximum service availability.
- Implement satellite backhaul for Britain's most hard-to-reach areas.

In more remote areas – not included within the EE ESN scope and typically where there is no MNO coverage – the Home Office will deploy its own infrastructure upon which EE will install its equipment. The ESN “Extended Area Service” (EAS) comprises specific locations (typically roads) contained within the 38 remote areas shown in Figure 18.

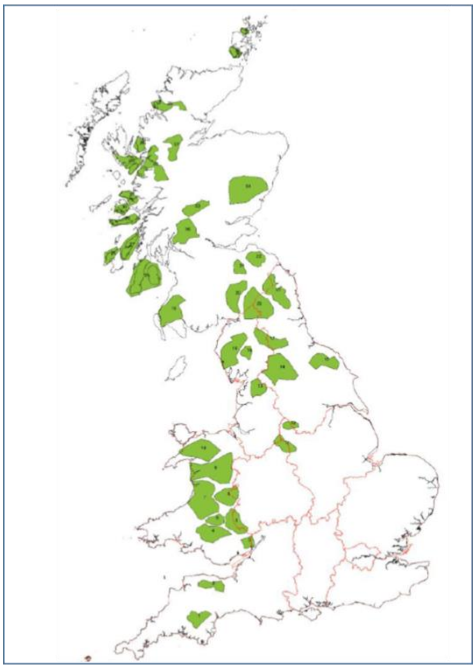


Figure 18: ESN Extended Area Service (EAS) Locations[41]

While there will be some overlap between the EE and EAS coverage, the use of infrastructure within the EAS areas will extend the geographic coverage to 97%[42]. However, it should be noted that this extension in coverage is designed to meet the needs of the emergency services

[41] http://bluelightinnovation.co.uk/wp-content/uploads/2015/11/11.30-Gordon-Shipley.pdf
[42] http://bluelightinnovation.co.uk/wp-content/uploads/2015/11/11.30-Gordon-Shipley.pdf

and while it may provide additional services to MNO customers in the future this is not necessarily guaranteed.

One of the benefits of choosing a standard technology such as 4G is the certainty in upgrade path for future communications. 4G will be upgraded iteratively providing additional functionality (e.g. 4.5G offering multi gigabit throughput) with each subsequent iteration of the standard. The mobile technology standards body (3GPP) is already incorporating critical communications functions (such as mission critical push to talk) into Release 13 of the standard which was frozen in March 2016 enabling vendors to start producing equipment.

However, it is not totally clear what will happen to the existing Airwave passive infrastructure, especially in more rural areas. As in the example above, in more remote places minimum/stealth installations are not capable of upgrade or re-use and would need to be re-developed for the installation of MNO equipment. The majority of the end user devices will likely become redundant due to their specialist nature being dedicated and configured for emergency service use. Furthermore, given the interoperability requirements between emergency services and other users it is unlikely there will be much interest in other users continuing to use the service. The technology, spectrum, need for minimal design and stealth solutions used by the Airwave network means that much of the existing infrastructure in rural and remote locations cannot be re-used.

In addition, the differences in spectrum between TETRA and cellular bands would result in a different radio plan and site locations i.e., existing Airwave sites providing coverage at 400MHz will not provide the same coverage at 900/1800/2600MHz due to the RF signal range limitations at higher frequencies.

Utility Companies

Historically UK utilities have utilised a mixture of self-provide and 3rd party communications solutions. Copper communications cables (pilot cables) have, for many years, been laid alongside new electricity cables in order to facilitate low data rate communication between electricity substations.

These networks were further enhanced during the 1990s when many of the privatised electricity companies began to establish their own telecommunications companies offering services to business customers. Examples include Torch (Yorkshire Electricity), Energis (National Grid), Scottish Telecom/THUS (Scottish Power), Norweb Telecom/ Your Communications (NORWEB/UU) and Surf (Western power Distribution).

These organisations allowed the electricity companies to utilise existing assets to establish, at relatively modest cost, hybrid fibre & radio networks offering services to compete with the likes of BT and Cable and Wireless/Mercury.

In addition to the installation of new switches and exchange equipment, there was a significant expansion in fibre networks, commonly on overhead power lines between key electricity substations.

Figure 19: Example Power Utility Site

Each of these new “telcos” served the internal communication requirements of its parent organisation and also deployed new fibre and ducts within the main population centres of its

Utility ‘footprint’. The new “telecos” had a limited amount of success and in most cases have been absorbed into other larger operators such as Cable & Wireless or Vodafone.

Many water, gas and electricity companies had operated their own hilltop radio site infrastructure from the 1950’s until the mid to late 1990s. The electricity companies in particular utilised these hilltop radio sites to rapidly expand the geographic coverage of their Telecoms subsidiaries beyond the boundaries of their limited fibre infrastructure. In the mid 1990’s there was an increasing move towards the sale of these assets to third party Wireless Infrastructure Providers who could market such assets to other users (including the growing cellular sector). Typically, the original Utility owner would rent back space on the radio site for a favourable fee and receive a share of any additional revenue generated through the promotion of the site to new users. An example power utility site located within a substation environment is shown in Figure 19. The site is shared with both Airwave and MNOs.

There were financial and regulatory incentives for this type of arrangement. Firstly the Utility Company could gain an immediate payment for the use of an under-utilised asset and secondly they could benefit from operational savings by removing the maintenance liability for these sites. Overall these ‘sale and leaseback’ arrangements worked well. There have been a number of challenges to renting out spare capacity on some of these structures to other users (the radio structures are commonly located within the compound of a water, electricity or gas installation) which have associated access restrictions connected with working safely in those environments. This has resulted in some sites being less utilised than others for the support of additional usage (the skillsets required to work safely in those environments introduces unacceptable costs and/or delays to potential third party users of the assets).

3.3.4 Coverage provided from private radio and fixed networks

The coverage from private radio and fixed networks are targeted to a mix of highly specific locations such as roads, rail and sub stations for utilities or for wide area critical national coverage for the emergency services.

While the coverage provided by private radio networks is expressed in similar terms to that provided by the MNOs (e.g., % geographic coverage) the networks cannot be compared on a like for like basis. For example, while the Airwave network provides coverage of 100% of roads its infrastructure is based on TETRA technology operating at 400MHz. This is not suitable for delivering mass consumer mobile telephony services. Deploying MNO equipment on the same infrastructure would not provide the same 100% level of coverage due to the higher frequency bands available.

a) Emergency Services Network - Airwave – Complete UK wide geographic coverage

The Airwave network covers 100% of roads and 99% landmass of Great Britain.

b) Rail network – Complete coverage of rail routes

The GSM-R network covers over 15,000km of railway lines. The location of the Network Rail infrastructure is shown in Figure 20. The network provides full operational coverage of along all the rail routes it serves from infrastructure deployed at the trackside.

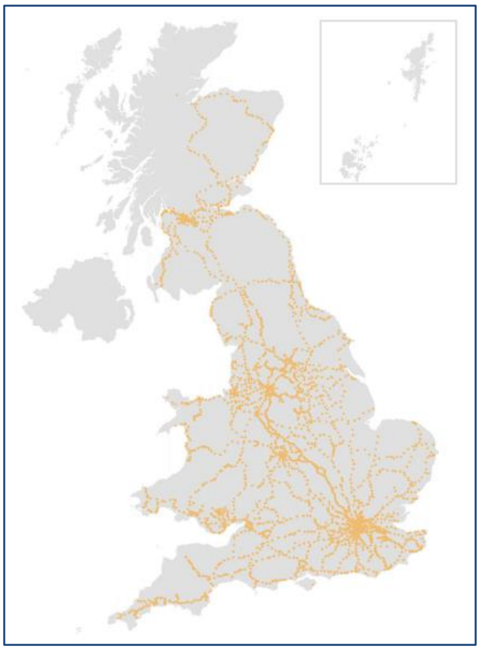


Figure 20: Network Rail Telecoms Infrastructure[43]

c) Energy sector – national strategic coverage for utilities

As explained in the previous section energy utility telecoms sites provide specific coverage and connectivity to specific locations within the energy network at remote locations usually outside of urban and suburban areas. The telecoms infrastructure is often located alongside the power infrastructure it supports and as such information regarding location (maps) is not readily available.

d) Roadside network delivered by nationwide infrastructure - NRTS

The location of the NRTS infrastructure is shown in Figure 21. It is nationally spread along the motorways and major trunk roads and includes a mix of copper and fibre fixed connectivity to points of presence at the roadside.

[43] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416995/FINAL-Telecommunications-and-Digital-Infrastructure-Maps-Second-Publication_v2.pdf

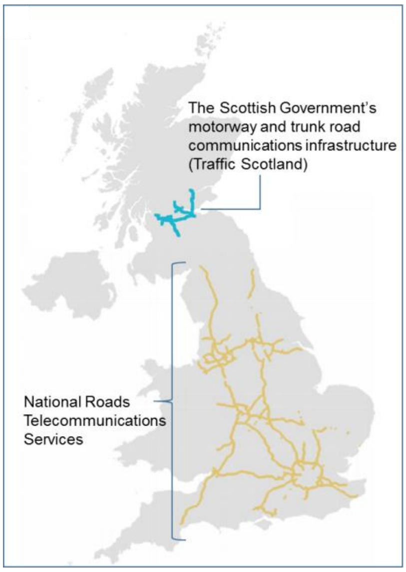


Figure 21: National Road Telecommunications Services[44]

e) Internet of Things network delivered by Sigfox/Arqiva collaboration

A new dedicated IOT network is being deployed to support the growing need to connect millions of devices in smart cities, or in residential and business premises throughout the UK. The French company Sigfox uses Arqiva as the network operator in the UK providing coverage of 10 major cities including Birmingham, Bristol, Edinburgh, Glasgow, Leeds, Leicester, Liverpool, London, Manchester, and Sheffield.[45] The current Sigfox coverage is shown in Figure 22. The service operates in licence exempt spectrum and serves low energy, low cost devices that are deployed across a wide geographical area.

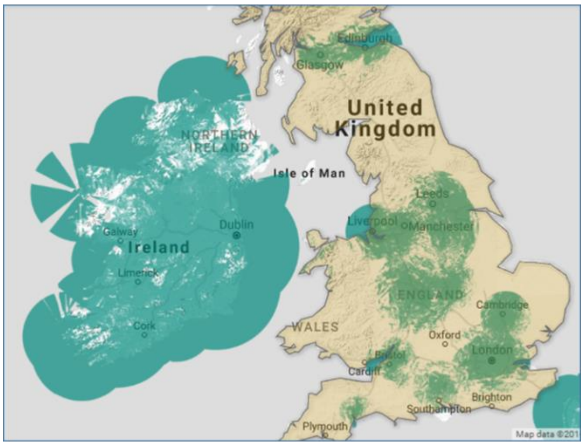


Figure 22: Sigfox/Arqiva coverage[46]

It should also be noted that a number of MNOs offer IoT solutions utilising their existing mobile network infrastructure.

3.4 Fixed Line Networks (Wholesale)

Fixed line networks provide the critical backbone of all communications networks within the UK. Wireless networks are largely dependent on fixed interconnection points to transport traffic back to their core networks and servers. Fixed line network operators provide leased line, fixed

[44] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416995/FINAL-Telecommunications-and-Digital-Infrastructure-Maps-Second-Publication_v2.pdf
[45] https://www.arqiva.com/news/press-releases/we-are-building-a-uk-network-dedicated-to-the-internet-of-things/
[46] http://www.sigfox.com/en/coverage

data and wide area networking services nationwide. While numerous providers operate within the UK, market consolidation has reduced the number of players owning fibre and copper infrastructure. Larger players in the UK include:

- BT Openreach
- Virgin Media
- KCOM
- COLT
- Vodafone

The Independent Networks Cooperative Association (INCA) represents a number of alternative network ("Altnets") providers, including for example:

- CityFibre
- Broadband for Rural North
- Gigaclear
- Hyperoptic
- ITS Technology Group

The picture of the fixed line network infrastructure is particularly complex given the commercial, regulatory and competitive environment. Access to the existing telecommunications infrastructure for the different service providers has improved over time based on Ofcom's efforts to de-regulate the infrastructure and open up access to the ducts and poles previously only used by BT. Efforts such as Local Loop Unbundling (LLU) which enables other providers to install equipment in BT exchanges to connect customers to their networks and the creation of OpenReach which is responsible for maintaining, investing and growing its network with the aim of enabling ubiquitous access to superfast Broadband throughout the UK.

The open wholesale telecommunications market offers direct access to the infrastructure so that service providers can compete on a level playing field and access infrastructure on a truly competitive basis. This compares to the retail market, which offers the differentiated consumer services, bundles and tariffs from the multitude of service providers that exist including Talk Talk, Sky, Plusnet and others.

3.4.1 Technology

Cable (fibre or copper) based networks provide direct point to point connectivity between key nodes in the network. Each node provides a point of user connection and/or forward connectivity to the rest of the network. This is shown simplified in Figure 23.

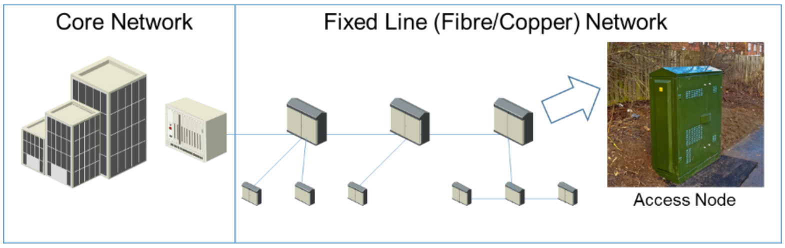


Figure 23: Fixed Line Network Infrastructure

Network infrastructure expansion is often costly due to the need to dig and install ducts along the proposed cable route. Access to existing ducts (e.g., BT Openreach) and the use of micro trenching techniques is helping to reduce cost and speed up deployment.

Superfast and Ultrafast broadband services are typically delivered using fibre optic cables terminated in street cabinets (FTTC) or directly to the premises (FTTP) as shown in Figure 24.

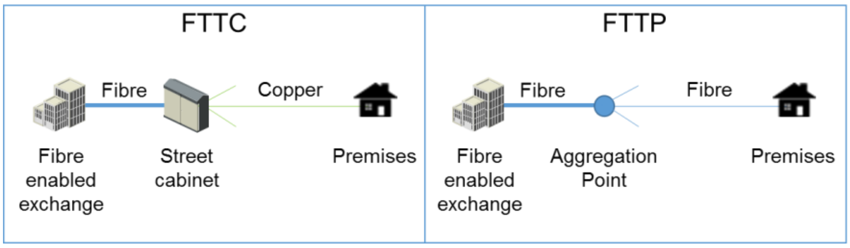


Figure 24: FTTC and FTTP

FTTC is typically used to deliver Superfast broadband speeds (>30Mbps). However, the distance between the premises and the street cabinet (i.e., the length of copper) currently has a major impact with superfast speeds only available at premises located within a few hundred metres of the cabinet. While future technology will help overcome the limitations of the copper network (for example G.Fast technology targets improvements of 300 to 500Mbps) speeds will remain distance constrained.

FTTP is typically used to deliver Ultrafast broadband speeds (>300Mbps). These higher speeds are available by replacing the copper with fibre from the exchange all the way to the premises. Provision of 1Gbps and 10Gbps services are now available on these networks.

A strategic programme launched by the Department for Culture, Media and Sport known as Broadband Delivery UK (BDUK), which is delivering superfast broadband and better mobile connectivity to the nation in specifically targeted and underserved locations.

3.4.2 Site Infrastructure

The infrastructure owned by each operator is summarised in the table below:

Operator	Description
BT Openreach	Has the largest network owning the UK's "last-mile" fibre and copper infrastructure. This network is made available to all retail service providers (such as Sky and TalkTalk) at regulated prices who in turn provide services to the end customer. The last mile copper and fibre infrastructure covers 30 million customers.
Virgin Media	Claims the largest privately built fibre optic network in the UK. The network has 38,000 breakout points, 186,000km of fibre-optic cabling and 330 Ethernet nodes.[47]
KCOM	Owns the "last-mile" fibre and copper infrastructure in the Hull and East Yorkshire area.
COLT	Provides a fibre based network in London (City; Docklands), Birmingham and Manchester.
Vodafone	Acquired Cable and Wireless in 2012 and with it their fibre network in the UK. The network includes some 20,500km of fibre-optic cables.[48]
INCA	INCA reports that in a June 2016 member survey Altnets passed 663,670 or 2.4% of UK premises with FTTP.[49]
City Fibre	Deploying ducts and fibre to support a number of Gigabit city projects across the UK. CityFibre have also entered into a joint venture with Sky

[47] http://www.virginmediabusiness.co.uk/why-virgin/our-technology/
[48] http://www.bbc.co.uk/news/business-17810568
[49] http://www.inca.coop/policy/building-gigabit-britain-report

	and TalkTalk to deploy fibre in the city of York. The network includes 1,100km of duct and fibre cabling and a 1,100km national network connecting these cities to major data centres and internet exchanges in London.[50] The network includes gigabit fibre networks in York, Peterborough, Coventry, Aberdeen, Edinburgh and Glasgow, and local access networks in a number of other UK towns and cities[51]. CityFibre's recent acquisition of network assets from Redcentric gives them networks in Cambridge, Portsmouth and Southampton and also bolsters its presence in Derby, Northampton, and Nottingham.[52]
Broadband for Rural North	Deploying fibre networks with over 800km of core network in Lancashire, North Yorkshire and Cumbria with over 1500 connected customers.[53]
Gigaclear	Deploying fibre networks in rural areas. The network passes over 20,000 properties and expects to double this by the end of the year across 15 counties.[54]
Hyperoptic	Deploying fibre in 13 UK cities including Greater London, Cardiff, Brighton, Bristol, Reading, Manchester, Leeds, Liverpool, Sheffield, Birmingham, Glasgow, Newcastle and Nottingham with network expansion plans to reach more than 300,000 homes in the next 3 years[55].
ITS technology group	Operates a number of local council concessions (including Nottingham and Bristol) providing access to ducts for the installation and extension of fibre networks.

Table 7: Fixed operator infrastructure

It should be noted that many operators make use of other provider's networks in the delivery of services outside their own network footprint.

Fixed line operators continue to invest in the fibre infrastructure helping the UK Government with its target to:

- Provide superfast broadband coverage to 90% of the UK by early 2016 and 95% by December 2017.
- Provide access to basic broadband (2Mbps) for all from December 2015.
- Explore options to provide superfast coverage to the hardest to reach parts of the UK.
- Encourage the take up of superfast broadband by SMEs to support growth through the Broadband Connection Voucher Scheme (now closed).
- Improve mobile coverage in remote areas by 2016.

More specifically:

- BT's investment in fibre of over £3bn (including both Broadband Delivery UK (BDUK) and commercial roll-outs). BT also continues to invest in its copper network with services such as "G.Fast" being trialled and initially offering speeds of up to 300Mbps.[56]

[50] https://www.cable.co.uk/news/-700001262/
[51] https://www.cable.co.uk/news/-700001262/
[52] CityFibre extends reach with Redcentric deal. Total Telecom; 26 Sept 2016
[53] http://b4rn.org.uk/about-us/
[54] http://www.gigaclear.com/gigaclear-story/
[55] https://www.hyperoptic.com/news/hyperoptic-to-expand-1gbps-network-withgbp-21-million-backing-from-eib/
[56] https://www.btplc.com/Thegroup/UKPublicAffairs/UK/Briefingnotes/151009broadbandupdatevFINAL.PDF

- Virgin Media's Project Lightning includes a £3bn investment to connect another 4 million homes.[57]
- City Fibre expansion plans to extend its footprint to 36 cities, serving more than 7,000 mobile cell sites, 24,500 public sector sites and 245,000 businesses.[58]
- INCA reports Altnets forecast that they will pass 4.9m premises (or 18% of UK premises) with FTTP by 2020.[59]
- BDUK continues to address the problem of poor broadband coverage particularly in rural areas as outlined below.

Superfast Broadband Programme

The Government's aim is to provide superfast broadband for at least 95% of UK premises and universal access to basic broadband (speeds of at least 2Mbps).

Government funding is stimulating private sector investment in broadband to ensure that the benefits of better broadband are available across the UK. There have been a number of UK Government interventions under the BDUK initiative to improve broadband access[60]:

- Rural Broadband Programme (Phase 1): A £530m scheme aimed at rural areas to achieve 90% coverage of superfast broadband (in this case defined as having a download speed faster than 24Mbps).
- Superfast Extension Programme (Phase 2): A £250m scheme aimed at extending superfast coverage to 95% of premises by 2017.
- Competitive Fund (Phase 3 pilots): A competition for a pot of £10m of funding to pilot potential solutions for the final 5% of premises not covered by phases 1 or 2.

In addition the Government is supporting seven Market Test Pilots to gain understanding of the challenges in rolling out superfast broadband to the hardest to reach areas of the UK. Emerging findings from the test pilots have been provided in a report from the Department of Culture, Media and Sport[61]. The seven pilot projects include a mixture of technology including:

- Superfast capable satellite (from Avanti and Satellite Internet)
- Fixed wireless (from Airwave, Quickline and AB Internet)
- Mix of fibre and fixed wireless (from Call Flow and Cybermoor)

The report concludes that after running for over a year the pilots are successfully providing good quality superfast broadband services to more remote households across the UK. The pilots have shown that:

- Non-fibre based technology suppliers can deliver reliable, superfast-capable broadband speeds and a quality of broadband service that satisfies the vast majority of customers.
- Suppliers can successfully mix technologies to deliver cost-effective superfast broadband solutions in hard to reach areas.
- Smaller suppliers can bid for, win and deliver open public procurements at competitive costs, including meeting the necessary EU-wide State Aid requirements for receiving public funding.

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[57] http://www.virginmediabusiness.co.uk/news-and-events/news/news-archives/2015/Virgin-Media-and-Liberty-Global-announce-largest-investment-in-UKs-internet-infrastructure-for-more-than-a-decade/
[58] https://www.cable.co.uk/news/-700001262/
[59] http://www.inca.coop/policy/building-gigabit-britain-report
[60] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf
[61] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/497369/BDUK_Market_Test_Pilots_-_Emerging_Findings_Feb_2016.pdf

3.4.3 Coverage Provided

The availability of Superfast and Ultrafast services can provide an indication of the overall fibre infrastructure coverage provided.

Superfast broadband coverage gives an indication of the number of premises in an area with a fibre enabled exchange and close to a fibre cabinet. Coverage for Superfast broadband is shown in Figure 25. However, availability in rural areas is significantly lower as shown in Figure 26.

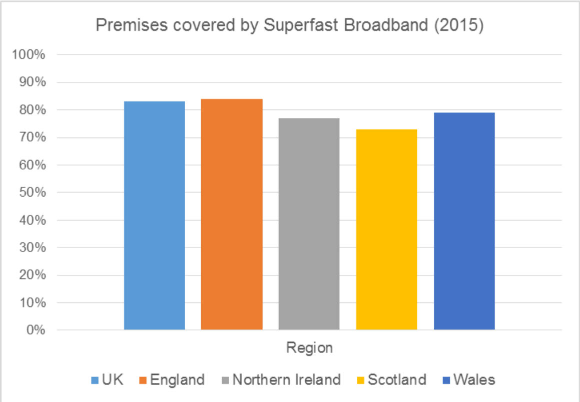


Figure 25: 2015 Availability of Superfast broadband – premises covered[62]

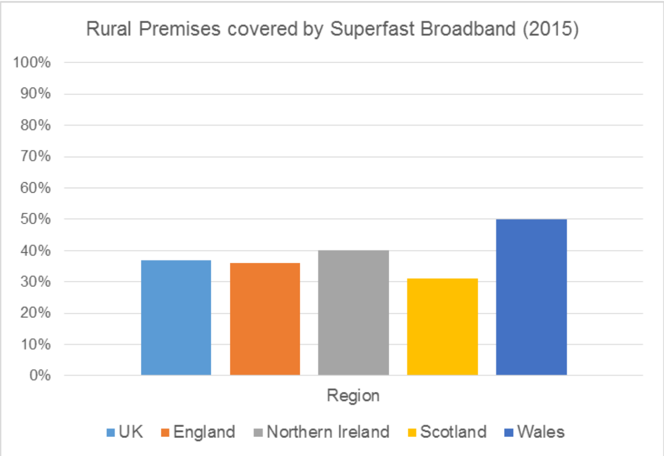


Figure 26: 2015 Availability of Superfast broadband in rural areas – premises covered[63]

Ultrafast broadband gives an indication of FTTP availability. Coverage for Ultrafast broadband is shown in Figure 27.

[62] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf. Ofcom analysis of Operator Data

[63] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf. Ofcom analysis of Operator Data

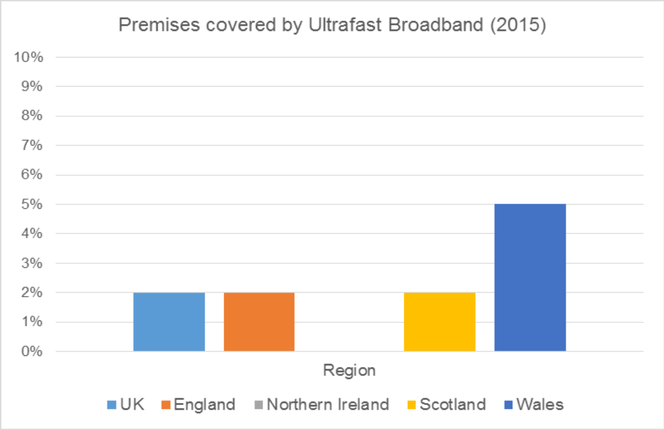


Figure 27: 2015 Availability of Ultrafast broadband – Premises covered[64]

Details relating to broadband availability at specific locations can be found on operator's website usually via a postcode search.

UK Communication Providers can gain access to BT Openreach Infrastructure Discovery Tool. This shows where existing duct and fibre node infrastructure is located and can be used to provide an indication of available fibre capacity.

Ofcom and BT are working to make duct and pole access easier for third parties with a view to improve FTTP deployment moving forward.

3.5 Wi-Fi Operators

The extensive use of smartphones and tablets and an increase in the number of Wi-Fi access points has driven a massive increase in mobile data traffic. Some estimates suggesting that more than 80% of the total traffic[65] is consumed indoors. To satisfy the continued demand for mobile data connectivity, Wi-Fi access points can now be found in many public places such as cafes, restaurants, shopping centres, train stations, hotels and airports.

While a number of individual business owners provide Wi-Fi access to their customers there are a number operators that own and operate networks across the UK including:

- BT Wi-Fi
- O2
- Sky ("The Cloud")
- Virgin Media (now including Arqiva[66])

A number of Wi-Fi operators provide wholesale access for MNO customers.

[64] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf. Ofcom analysis of Operator Data
[65] ABI Research Anticipates In-Building Mobile Data Traffic to Grow by More Than 600% by 2020, ABI Research, 2016
[66] 8/9/2016: Virgin Media acquires Arqiva's Wi-Fi business

3.5.1 Technology

Wi-Fi network infrastructure can be divided into two main elements simplified in Figure 28.

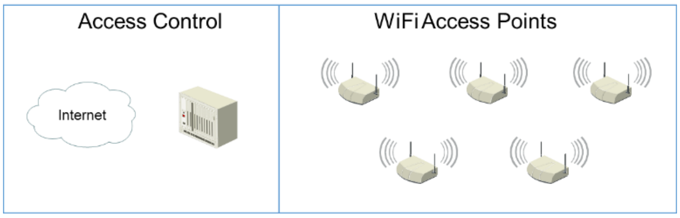


Figure 28: Simplified Wi-Fi network infrastructure

User coverage is provided by a network of Wi-Fi access points costing several hundred pounds each. While the supporting site infrastructure (power etc.) and installation requirements is relatively small each access point provides only localised “small cell” coverage; typically 10s of metres.

Wi-Fi access points are typically connected to the operator’s access control layer by fixed line/cable circuits or wide area network service (for example Ethernet provision) supplied by a number of service providers outlined in Section 3.4. The type of connectivity will depend upon the application with a number of access point devices having both copper and fibre interface options available.

Wi-Fi coverage may be extended through the use of mesh networking where some of the Wi-Fi spectrum (and hence capacity) is used to provide onward connectivity to other access points in the mesh. While this reduces the cost of deployment it comes at the detriment of end use bandwidth.

3.5.2 Spectrum

Wi-Fi networks utilise shared licence free 2.4GHz and 5GHz frequency bands. Each band offers a trade-off between capacity and coverage:

- 2.4GHz provides for a larger coverage area but is more susceptible to interference (from many non-communication device operating at 2.4GHz) and with only 3 x 20MHz non-overlapping channels its data throughput is limited.
- 5GHz provides 23 x 20MHz non-overlapping channels providing a much higher throughput. However, these higher frequencies have limited propagation characteristics and as such provide less coverage than at 2.4GHz.

3.5.3 Site Infrastructure

Public Wi-Fi access points provide a limited “small cell” range and as such are located close to the user. Both indoor and outdoor locations are used:

a) Indoor

The small physical size of the access point allows for wall or ceiling mounting. An example is shown in Figure 29.

Figure 29: Indoor small cell deployment

b) Outdoor

Outdoor access points can be mounted on the building facia or integrated within items of street signage or street furniture. Examples of small cell deployments are shown in Figure 30.

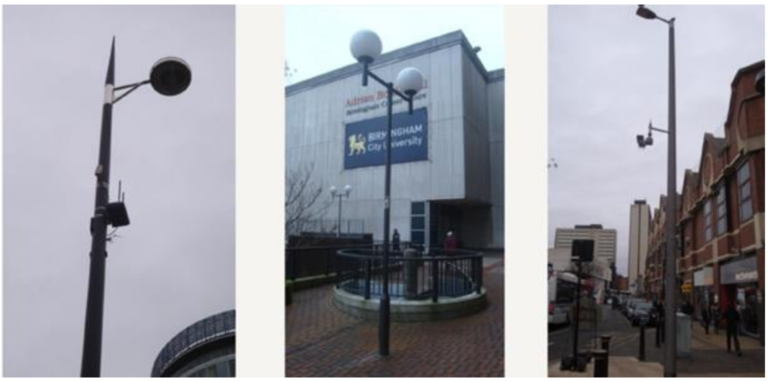


Figure 30: Outdoor street furniture small cells [Source: 3G4G Small Cells Blog] [67]

In addition to street furniture, small cells have been deployed in the pavement by Virgin Media in the UK and Swisscom in Geneva as shown in Figure 31.

Figure 31: Pavement deployment of small cells. Source: 3G4G Small Cells Blog [68]

Ofcom's Connected Nations document highlights a total number of 44,804 public Wi-Fi hotspots[69] deployed in 2015.

[67] http://smallcells.3g4g.co.uk/2013/02/small-cells-on-lamp-posts-and-other.html
[68] http://smallcells.3g4g.co.uk/2016/01/small-cells-wi-fi-in-pavements-roads.html
[69] http://stakeholders.ofcom.org.uk/binaries/research/infrastructure/2015/downloads/connected_nations2015.pdf

Specific examples by a selection of operators are outlined below:

BT Wi-Fi[70]

BT's Wi-Fi infrastructure includes a number of indoor and outdoor locations, for example:

- Thistle, Hilton and Hastings hotels.
- Starbucks, coffee shops, railway stations and shopping areas.
- Conference centres, exhibition venues and law courts.
- Airport lounges and terminals such as Etihad Airways, American Airlines and Flybe.
- Welcome Break motorway service stations.
- Major city centres or 'wireless cities', including Westminster in London, Birmingham, Liverpool, Cardiff, Glasgow and Newcastle.

In addition, BT provides its broadband customers access to its network of home and business customer Wi-Fi Hubs (with customer agreement) which when combined with the above provides for a network of 5 million hotspots across the UK.

O_2[71]

O_2 provides access to a network of 13,000 Wi-Fi hotspots across the UK, for example:

- McDonalds, Debenhams, Costa Coffee, Café Rouge.
- Debenhams, House of Fraser.

These are open to all and not restricted to O_2 customers. However, customers with a compatible handset benefit from a feature whereby the handset will be automatically connected to an O_2 Wi-Fi hotspot when it provides a stronger signal than the mobile network.

Sky ("The Cloud") [72]

Sky provides access to a network of 20,000 Wi-Fi hotspots across the UK, for example:

- Wetherspoon pubs, Caffe Nero, Eat, M&S, Pret a Manger.
- Train stations, and the London Overground.

These are open to all and free for Sky broadband customers.

Virgin Media

Virgin Media provides access to 150 London Underground stations. Access is available for all and free for customers of Virgin broadband, Virgin Mobile, and other MNOs.

Virgin Media's network is extended through agreements with Sky (The Cloud) and its recent acquisition of Arqiva's Wi-Fi business[73]. The network provides access to over 27,000 Wi-Fi hotspots across the UK[74] including:

- Over 1000 hotel rooms.
- 34 airports and 61 airline lounges.
- 1,300 street Wi-Fi hotspots across 11 London boroughs and other local councils. [75]

[70] http://www.btWi-Fi.com/
[71] http://www.o2.co.uk/connectivity/free-Wi-Fi
[72] https://www.thecloud.net/
[73] http://www.totaltele.com/view.aspx?C=0&ID=494898
[74] https://my.virginmedia.com/Wi-Fi/index.html
[75] https://www.arqiva.com/overviews/Wi-Fi/wireless-concessions/

- Wi-Fi infrastructure for businesses: Retail, pubs & restaurants, hotels, airports, banking, conference centres and venues.

Arqiva and Virgin Media have reportedly signed two partnerships including Arqiva providing indoor solutions to Virgin Media's Wi-Fi customers and Virgin Media using Arqiva street furniture for outdoor public Wi-Fi equipment. [76]

3.5.4 Coverage Provided

Coverage is provided at many indoor locations and more increasingly outdoors across a number of UK cities as described above.

In this constantly changing environment, Wi-Fi operators provide specific “hot spot finders” on-line or via smartphone apps allowing users to locate hotspots by location or postcode as per the examples shown in Figure 32.

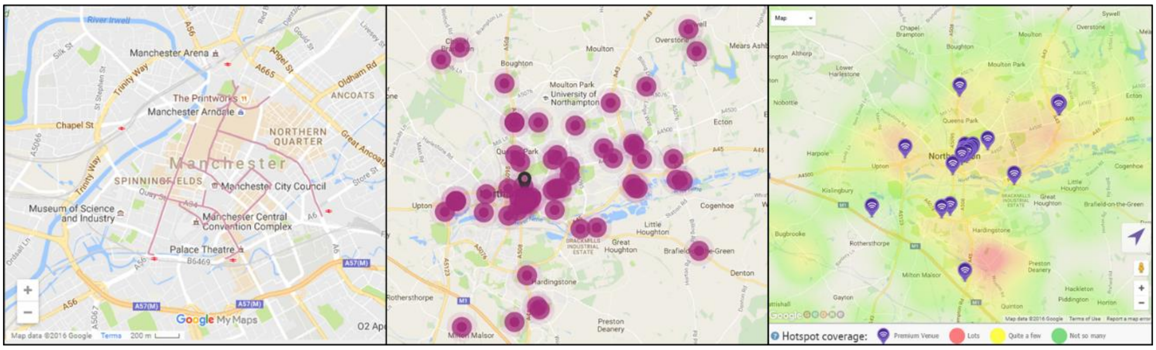


Figure 32: Example Wi-Fi hotspot finders

[76] http://www.totaltele.com/view.aspx?C=0&ID=494898

4 5G Technology Readiness

In this section we summarise the main aspects from a technology readiness perspective as follows:

- **Continued Densification**: Densification has been driving all generations of mobile technologies from 2G to now and this trend will only intensify, given the high network capacity gains needed for a number of the key use cases, as also confirmed in our discussions with several industry players. *Such densification will drive the need for increased site buildout*, similar to other technology generations, i.e., the availability of additional network attachment points, such as cellular access points or Wi-Fi access points, deployed close to end users. While we will provide insights into this aspect for each access network technology, we can already observe that the vast majority of capacity gains in wireless connectivity are achieved through site densification compared to innovations in radio access methods or availability of new spectrum. This relation is outlined in the figure on the right[77].

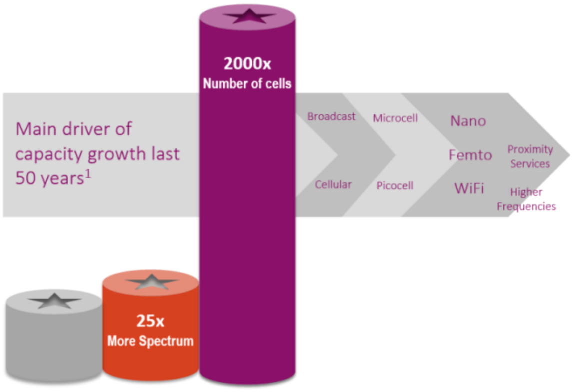


Figure 33: Densification of small cells

- **Need for Fixed-mobile convergence**: While increased site buildouts will contribute to the aforementioned densification, we also identify the need for fixed mobile convergence that goes beyond current efforts in the mobile industry. The chart on the right shows the relation of access technologies as being pushed by the two major standard bodies in this space, namely the 3GPP and IEEE. It can be seen that typical short link and WLAN connectivity has consistently outperformed 3GPP technology, used for wider area connectivity. *With this in mind, the increasing impasse in indoor coverage can largely be seen as a problem of providing proper fixed mobile convergence.*

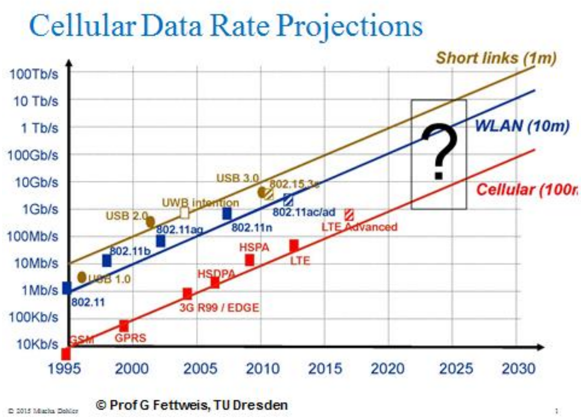


Figure 34: Cellular data rate projections

- **Need for localisation**: In order to achieve suitable experience for current services, the Internet is already heavily localising traffic through content delivery networks and local points of presence. This trend is going to increase significantly for enhanced Mobile Broadband (eMBB) but also to satisfy demands for future low latency use cases. Localisation can mean co-location of this storage and computing at cell sites or in regional data centres, where regions could be as small as street blocks, while also extending to parts of towns or boroughs. The desire to manage and control digital assets in smart city environments also drives the need for localisation of aggregation functions. Furthermore, the expected rise of body-worn cameras, as indicated by city councils like Bristol, will drive the need for storing and preprocessing the deluge of media content.

[77] Source: InterDigital, Inc.

- **Local capacity gain:** Even with heavily increased localisation, *local access technologies will still need to see a significant increase of local throughput*. This will drive new access technologies such as those deployed in mmWave bands and the resulting usage of new spectrum as well as refarming of existing spectrum (below 6GHz). In turn, new radio technologies will need to be deployed in the various mast sites (e.g., for narrowband IoT support). Such need for local capacity gain is not limited to wireless but also includes fibre-to-the-home rollouts due to the importance of these access types in converged scenarios. *Without a proper proliferation of fibre access in individual dwellings, we foresee a significant limitation of 5G capabilities in urban as well as rural environments*.

In terms of a timeline for readiness of key technologies, various standards activities point to 2019 as being the key year for early rollouts of 5G technologies and use cases.

4.1 5G Infrastructure Transition

We assess the transition of infrastructure towards 5G, and therefore the feasibility of infrastructure capability, by drawing up an architecture framework for 5G which sets a benchmark for the expected capabilities of future networks. Before doing so, we set out three key capabilities that will need to be supported by any future wireless network infrastructure.

- **Fixed mobile convergence**: The increasing impasse in indoor coverage can largely be seen as a problem of providing proper fixed mobile convergence. The proliferation of Wi-Fi calling capabilities is seen as a direct answer to such lack of indoor coverage, leading to *the requirement to integrate ANY access technology into the overall infrastructure.* In 5G, we see this need for convergence accelerating where services will use the most suitable access and network technology available that suits the purpose of the use case. Such convergence integration has so far largely focused on supporting various access types in user equipment (such as smartphones). For instance, WLAN capabilities in modern smartphones still allow mainly access to the general Internet with Wi-Fi calling capabilities through IP Multimedia Subsystem (IMS) still being rolled out and only offered by few (yet growing number of) operators, while non-traditional entities like Google are aggressively driving forward MVNO-like offerings[78] that heavily rely on Wi-Fi coverage for cost reduction.
- **Localisation**: In order to achieve typical ultra-mobile broadband capabilities, traffic will need to be localised to the largest extent possible and necessary for the use case. Such localisation is already in use in today's infrastructure through local points-of-presence (POPs) and content delivery networks (CDNs) that provide popular content to regional/local users, reducing the overall load on backhaul and core network infrastructure. However, *for a future mobile use case, such as mobile broadband along rail tracks, such traffic localisation will need increased computing and storage infrastructure support dedicated to these geographical build-outs to deliver the desired bandwidth.*
- **Flexibility**: While the selection of core use cases (of economic, national and/or societal interest) drives the early deployment of 5G, past infrastructure deployments have shown that the hardest use case to fulfil is the one that is unforeseen at the time of deployment planning. This issue is amplified by the wider span of vertical industries that 5G operators plan to support with their infrastructure. *This implies the capability must be available to provide a flexible modularisation of functionality with which infrastructure can be adjusted to the needs of the use*

> ***What is slicing?***
> *Slicing is a new terminology that enables virtual networks to coexist over a common shared infrastructure with services or entire businesses runing in such virtual networks, each providing their own connectivity, computing and storage resources.*

[78] https://fi.google.com/about/

case at hand. This capability is driven by the inefficiencies that would result in the roll-out of dedicated infrastructure solutions optimised to particular use cases only, regardless of the importance of said use cases at the time of deployment (since the socio-economic framework that ranked the importance of the use case at the time of deployment is likely to shift over time) – this is evidenced by current deployments of, e.g., broadband capabilities in areas of high economic value see section 5.1. *Slicing* capabilities have been identified by the NGMN[79] as an approach to achieving integration of vertical applications (e.g., healthcare or utilities) through isolating specific business offerings into isolated resource pools. In other words, network slicing is being positioned as an isolation technique that enables the establishment of a business function (e.g., smart parking) utilising the resources that are dedicated to the network slice by the mobile network operator. This enables vertical industries to effectively act as a Mobile Virtual Network Operators (MVNO) with radio assets being flexibly shared among a larger number of such MVNOs.

It is expected that the radio assets will be provided (and enabled) by the dedicated asset owners like MNOs as well as Network Rail, NRTS (Highways Agency), facility owners etc – assuming sufficient organisational flexibility and regulation is in place. While slicing-based offerings nowadays are provided manually, e.g., as a multi-site setup, these are likely to evolve to fully automated orchestration-based solutions. In terms of scalability for each slice, industry efforts such as the NGMN foresee a somewhat coarsely grained slicing only, with *templates* of slices being provided for service classes, such as eMBB or massive IoT. This is particularly driven by the costs of slicing in the radio access, which is currently seen as prohibitive by operators like BT. Furthermore, finely-grained slicing also increases costs in non-technical aspects like user engagement and cost of infrastructure. With this in mind, industry players such as operators only foresee templates for slicing, each template optimised for the needs of the specific industry vertical. Nonetheless, other propositions, such as those pushed by Internet players such as Google or Facebook, foresee a more fine-grained slicing (at least in the data centres at national and regional level), possibly down to the application level. It is unclear how these two views on slicing would be reconciled.

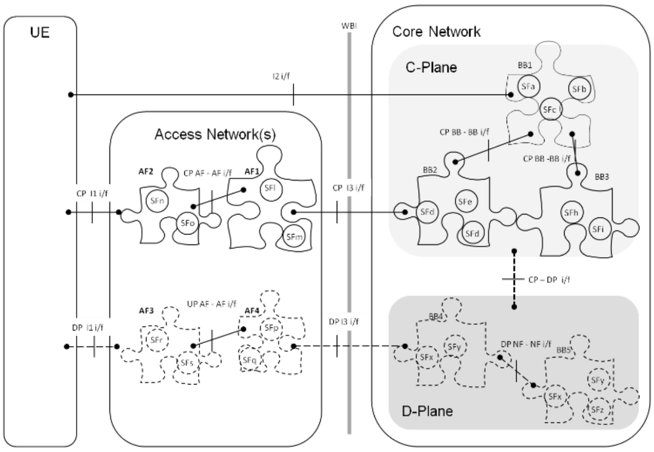


Figure 35: Template for 5G infrastructure architecture[80]

With the above core capabilities in mind, a cross-operator/vendor effort at European level[81] has provided a suitable architecture foundation for 5G that is currently being pushed into standards organisations such as 3GPP. Figure 35 outlines this high-level architecture framework. The key capabilities of this framework are to be (i) **access agnostic** (aiming at

[79] https://www.ngmn.org/uploads/media/160113_Network_Slicing_v1_0.pdf
[80] https://5g-ppp.eu/wp-content/uploads/2016/03/CONFIG-Brussels-Presentation-April-6th-v3.pdf
[81] http://www.5g-control-plane.eu/

FMC requirements), (ii) **modular** (aiming at flexibility requirements), (iii) **offered within network slices** (aiming at flexibility requirements) and (iv) **context-aware** (aiming at flexibility and localisation requirements). This framework has been designed specifically to address the wide range of cross-vertical use cases in 5G.

The existing 3G/4G framework is being integrated into this newly evolving infrastructure through the slicing concept. In other words, existing LTE offerings would be realised as backward compatible solutions in a single slice, while others will be dedicated to entirely new infrastructure offerings that fully utilise novel radio and core network capabilities. At the transport network level, such architecture assumes the integration with software defined networking (SDN) technology as well as network function virtualization (NFV) capabilities to address the extensive computing needs of many 5G use cases – see Section 4.2 on the readiness of these crucial enabling technologies.

As a specific aspect of multi-radio access technology (RAT) integration, we refer here to the proposition of *cloud-based radio access networks* (CRANs). In such radio access network (RAN) architectures, remote radio heads (RRHs) are directly connected via, often fibre, into a cloud-based baseband processing unit. Such proposition not only reduces CAPEX and OPEX for existing deployment scenarios but also facilitates new ones along, e.g., fibre-connected, geographic areas such as train lines where relatively simple RRHs are connected directly to wayside fibre cable with all baseband processing done remotely. If combined with a new RAT, such as mmWave based radio technology, high-speed mobile broadband can be achieved across a variety of use cases. Within our template architecture of Figure 35, CRANs are represented as a type of access network architecture on the left. As a commercial model, the owner of such CRAN assets would provide those to MVNOs for the purpose of delivering various use cases.

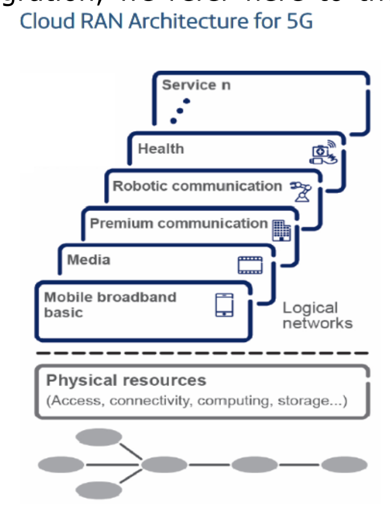


Figure 36: Cloud RAN architecture

4.2 Technology readiness

We divide aspects of technology readiness along two parts of the overall infrastructure, namely *access technology* and *transport network*. As mentioned in section 4.1, the readiness of the former is driven by two major organisations, namely the 3GPP and the IEEE. While 3GPP has been driving previous (and current) radio access technologies for wide area coverage (with LTE and LTE Advanced being the latest generation), the IEEE has been recognised for its development of high-speed LAN-type of connectivity solutions, such as WLAN (or Wi-Fi) on its various generations. Both standardization bodies have defined clear roadmaps for the ratification of suitable 5G radio technology standard recommendations, aligned with the plans for spectrum reconciliation in various markets, e.g., see 3GPP roadmap on the right[82].

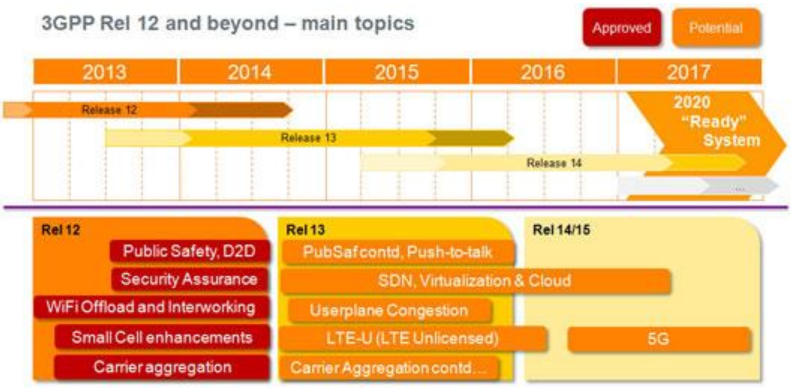


Figure 37: Standardisation timeline for SDN/NFV

[82] http://www.3gpp.org/news-events/3gpp-news/1614-sa_5g

A number of vendors have aligned their product announcements[83] [84] [85] with these roadmaps with the expectation to see 5G-ready access solutions to appear in 2018 and beyond. This is aligned with the expectation of operators like BT to see first 5G-enabled services to appear around 2019 in the UK market.

What is SDN?
Software-defined Networking (SDN) separates the control of networks from the forwarding of data. Such control can be realised in software, allowing for new control 'behaviours' to be deployed rapidly on top of commodity forwarding hardware. Such separation of control from forwarding is a key enabler for slicing of networks, each slice operating with its different control.

In the transport network space, we identify two key emerging technologies, namely **software defined networking** (SDN) and **network function virtualization** (NFV), with its main aspects being pursued in a number of standards organisations as well as open initiatives, such as Open Networking Foundation (ONF)[86].

SDN is being positioned as the evolution of current transport infrastructure away from specialised hardware components towards a largely commoditised software-based infrastructure. These SW-based components are governed by a set of simple rules that determine their behavior rather than requiring costly upgrades in cases of new services being deployed. Initiated through publicly funded research in the mid 2000s, SDN has been adopted by major standards and forum activities (see below) with product announcements of major manufacturers around the globe[87] [88] [89].

SDN provides a separation of control and data plane functionality, separating therefore the control over the forwarding rules from the act of physically switching a data packet in the network. Through such separation, flows and therefore entire networks can be isolated in their treatment (through different rules specific to a set of applications). Ultimately, such capabilities provide the basis for the aforementioned network slicing capability in future (5G) networks, while also being identified as key enablers for multi-site (corporate) VPN solutions as well as data centre interconnection by major operators like BT. Through the separation of control from data functions, new behavior and therefore new services can be easily deployed as pure software updates, while the slicing capability allows for such updates to be limited to only those services in need of such update. New innovations are therefore expected to arise enabled by SDN capabilities such as pure programmable whitebox switching through a centralised SDN controller and the possible slimming down of core network infrastructure through such SDN controller capabilities acting on simple but high-performance data forwarders, as confirmed through European research and standardization activities and discussions with BT. *In other words, SDN drives the desire to simplify the basic forwarding operations of the transport network, independent from the emergence of 5G use cases.* However, operators still foresee the need to integrate legacy transport networks (e.g., based on more traditional MPLS), with efforts existing at European[90] and international level to unify such integration under a single SDN umbrella. This need is driven by the sheer amount of existing transport infrastructure and the investment as well as organisational hurdles in upgrading this infrastructure in the near to mid-term future.

[83] https://networks.nokia.com/innovation/5g
[84] https://www.ericsson.com/5g?gclid=Cj0KEQjwx96-BRDyzY3GqcqZgcgBEiQANHd-nkMstpahHeGdwgWCoXVTWmMpUbRJmdwNQmBX-neSErkaAt-k8P8HAQ
[85] http://www.huawei.com/minisite/5g/en/
[86] https://www.opennetworking.org/about/onf-overview
[87] http://e.huawei.com/au/solutions/technical/sdn
[88] https://networks.nokia.com/solutions/software-defined-networking
[89] https://www.ericsson.com/networks/topics/sdn
[90] http://5g-crosshaul.eu/

NFV is a technology that allows for major network functions to be implemented in software environment, such as call processing, load balancing, firewalls, network translation and many others, in the core transport network. Functions of the network are interpreted as pure software modules, which are chained towards a larger service (such as automated call re-routing) through orchestration platforms and suites. The use of NFV allows for utilising commercial off-the-shelf (COTS) hardware platforms to be used and therefore reduces the need for proprietary hardware platforms that are often vendor specific, ultimately reducing Total Costs of Ownership (TCO). Virtualization solutions, such as virtual machines or virtual instances, enable the execution of network and service level functions as the aforementioned pure software modules, executed on COTS hardware.

Although originally positioned as a cost reduction tool (due to removing the dependency from proprietary hardware), *NFV is mainly seen as a tool for increasing flexibility in service deployment time down to a few days rather weeks or months today*. NFV also directly connects to the SDN evolution through NFV-provided SDN controller infrastructures, enabling scale and flexibility in programmable networks (slices). Cost reduction still plays a role in NFV deployments but only if such reductions are closer to specific technologies. Very often, however, such cost reduction attempts come with the need to re-tool an entire organisation within the mobile operator; an aspect that often results in a cost higher than the savings expected from the shift to NFV – an insight directly confirmed by Communication Service Providers (CSP) such as BT. Nonetheless, NFV is also seen as playing a role as an engagement tool with vendors and manufacturers in the stage of procurement and network planning, where the availability of SW functions eases testing and verification ahead of the actual physical deployment, ultimately also positioning NFV as a possible cost reduction tool (avoiding the test in real systems) and possible deployment time reduction tool.

A good indication of the readiness of NFV/SDN technology is the maturity of the key standards. While work is being undertaken in several fora, the key one for the telecom industry is ETSI with its NFV group which has reached some key milestones in 2016. Specifically, release 2 of the ETSI NFV standards is expected to occur by end of 2016, and planning has started for Release 3[91]. Furthermore, a large number (i.e., 40) of proof-of-concepts (PoCs) have been demonstrated (or will be by end of 2016)[92], largely based on open source platforms such as OpenStack platform[93]. Additionally, the first release of key open source software (ETSI Open Source MANO) for network operator management occurred in 2016[94]. Other activities of 5G relevance to operators like BT but also to digital infrastructure providers like city councils include the ETSI Mobile Edge Computing (MEC) activities with advanced standard maturity, moving currently from the initial Phase 1 to the Phase 2 of standards, while also moving to the phase of PoCs being presented[95].

What is MEC?
Mobile Edge Computing is a proposition in which computing and storage resides close to the end user at the edge of the network. It is seen as an enabler for massive IoT services as well as new virtual and augmented reality.

Surrounding SDN, a number of key standards have reached maturity, most prominently OpenFlow[96] with first products appearing in the market to support the latest V1.3 specifications. Several open source projects provide the necessary controller integration with

[91] http://www.etsi.org/news-events/news/1115-2016-07-news-etsi-nfv-renews-leadership-team-prepares-for-release-3
[92] http://www.etsi.org/technologies-clusters/technologies/nfv/nfv-poc
[93] https://www.openstack.org/
[94] http://www.etsi.org/index.php/news-events/news/1096-2016-05-news-open-source-mano-delivers-release-0-ahead-of-schedule
[95] http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing/mec-poc
[96] https://www.opennetworking.org/sdn.../openflow

active (operator and vendor) communities supporting OpenDayLight[97] and ONOS[98]. Although first deployments of SDN-based infrastructure is ongoing, e.g., see Section 4.4 or the efforts surrounding Bristol-is-Open as the first programmable smart city[99], operators such as BT do not expect widespread roll-outs before 2020 albeit expected in time for 5G roll-outs.

The role of UK industry in these standards is best exemplified by BT's role in the original ETSI NFV whitepaper[100], which was co-authored by BT employees. Furthermore, the following two quotes from BT's website[101] underline the role BT sees for itself in this technology area:

"BT has led the industry in researching the technical and operational benefits of NFV since mid-2011, including building several Proof-of-Concepts with our industrial partners to test the performance of NFV technology and validate the business benefits."

> *"We initiated and co-founded the ETSI NFV Industry Specification Group (NFV ISG) and are actively participating and steering its activities as chair of the network operator council."*

At this stage of technology readiness, it is fair to say that deployment rollout is still in the early phase. While a few operators (e.g., AT&T) have made some limited deployments in their live networks to get some experience, there have not been any large scale deployments of NFV/SDN in operator networks[102] with the implication that challenges and issues of these technologies in large-scale deployments are unlikely to be known at the time of initial 5G network rollouts.

With infrastructure in the future to be provided by more entities, including utility companies, Network Rail but also councils, the aspects of payments for services rendered is becoming increasingly important. While wholesale arrangements are likely to be dominant in areas of backhaul and core network, service-specific payment methods are being investigated, based on digital payment systems such as blockchain[103]. Outside the pure technology domain, thinking around new forms of compensation for the provisioning of and continuing investment into infrastructure is not only pursued in EU-funded research projects[104] but is also debated among policymakers and councils alike.

Payment, however, is only the monetary aspect of a clearing house for infrastructure. Councils such as Bristol highlight the importance of orchestration in general, which takes into account policy requirements (such as civic duty requirements for councils) for the access to infrastructure. As mentioned before, ETSI efforts in the MANO (management and operation) space are currently developing solutions for orchestration and management of infrastructure that takes such constraints into account with the ultimate goal to orchestrate the sharing of infrastructure at runtime rather than through possibly long negotiation at the business level.

Additionally, longer term studies in bodies like ETSI (e.g., on Next Generation Protocols, TCP revamping) or the ITU-T IMT2020 study groups[105] are investigating the readiness of enabling technologies from a longer term perspective beyond 2020. As indicated by their names, these activities have no clear timelines regarding the readiness of the technologies they investigate.

[97] https://www.opendaylight.org/
[98] http://onosproject.org/
[99] http://www.bristolisopen.com/
[100] https://portal.etsi.org/nfv/nfv_white_paper.pdf
[101] http://www.globalservices.bt.com/uk/en/point-of-view/nfv
[102] http://searchsdn.techtarget.com/answer/Where-does-NFV-deployment-stand-today
[103] A blockchain is a public ledger of all Bitcoin transactions that have ever been executed. It is constantly growing as 'completed' blocks are added to it with a new set of recordings. The blocks are added to the blockchain in a linear, chronological order. http://www.investopedia.com/terms/b/blockchain.asp
[104] https://rife-project.eu/
[105] http://www.itu.int/en/ITU-T/focusgroups/imt-2020/Pages/default.aspx

4.3 Capabilities of site infrastructure

In this section we address the capability of MNO, Wi-Fi, private mobile radio and fixed networks and fixed line networks infrastructure to enable future wireless networks based on the technology, equipment and deployment strategies in place today.

We have derived a set of criteria to assess, in each use case, whether new equipment, technology upgrade, spectrum or capacity is needed to meet the requirements of future networks. In such assessments, the specific considerations of asset owners, i.e., those who could possibly provide the physical access to required sites, manholes, ducts and more, needs to be taken into account, as specifically expressed as a concern by local authorities in our interviews.

In this study, the definition of future wireless as well as wired networks refers to a range of capabilities that could satisfy a mix of different use cases. It also means networks that are being designed and deployed today to support new and emerging services. An example of this is the new Emergency Services Network (ESN) programme. The ESN is essentially a technology upgrade to provide the three main emergency services (Police, Fire and Ambulance) with mobile broadband capability as the current network only provides limited data capability and secure voice. The chosen technology is 4G/LTE and will use EE's mobile network to provide the service. Therefore, the ESN network will actively be in use during the period of 5G network roll out and thus (inter)operate in parallel with other 5G networks.

In other words, some wireless networks may only meet some of the requirements of 5G networks whilst others will meet most/all of the requirements and this will be dependent on the use case, location, business case and services to be provided. In reference to the foreseen 5G system architecture, as presented in Figure 35, such partial support would be complemented with the ability for fixed-mobile convergence through integrating multiple RATs.

4.3.1 Enabling MNO infrastructure for future wireless networks

We expect MNO infrastructure to closely follow the technology developments in 3GPP, particularly for sub-6GHz technologies. As a consequence, MNO infrastructure will need to continue to support these future spectrum bands as well as upgrade to radio heads.

With the likely proliferation of CRAN deployments, e.g, along well-connected physical infrastructure such as train lines or in densely populated areas, we also expect to see a significant built-out of fibre backhaul as well as the proliferation of regional (in some cases down to city-level) CRAN data centres. The drive to CRAN propositions is likely to be accelerated by above 6GHz spectrum technologies, particularly in the mmW spectrum. Initially targeting high-density population scenarios, such as events, indoor coverage or coverage along well-connected physical structures, such as rail routes and roads, centralised processing power is expected to provide significant reductions in required investment levels, countering the necessary increase in densification of site deployments.

The necessary investment in such new enhanced base transmit stations (also known as eNodeB) and backhaul technology will be complemented by localised computing and storage capabilities, collocated with CRAN data centres or even directly collocated with eNodeB receivers, which in turn will need the necessary backhaul capacity for offloading functionality as well as additional physical space capacity to house the new equipment. Such computing/storage capabilities are likely to be based on COTS hardware, utilising NFV capabilities to integrate with the overall computing/storage environment of the operator. Such drive towards COTS equipment aims to reduce CAPEX as well as OPEX while benefitting from the developments of the IT industry in terms of developing more lightweight and energy-efficient hardware.

As an attempt to improve on indoor coverage, we expect an increased deployment of femto-cell technologies, together with MEC (Mobile Edge Computing) capabilities for localised communication within small areas of femto cells, as also confirmed by councils like Bristol and Newcastle. However, it is unclear how these deployments will co-exist with Wi-Fi (and evolved IEEE technology) deployments as well as how those deployments will be controlled as well as shared among MNOs or whether those will be treated like existing Wi-Fi access equipment that comes bundled into an ISP contract. While many operators have launched some form of femtocell offering, including AT&T, Sprint, Orange, Vodafone, EE, O2 and many others, the increasing convergence with IEEE technologies, e.g., through Wi-Fi calling capabilities, can be seen as encroaching on femtocell territory. Ultimately, we would expect a number of local access technologies to co-exist, all integrated into a 5G infrastructure that is generally access-independent. This would be in alignment within the envisioned infrastructure framework of Figure 35 as well as current industry efforts.

As indicated by operators like BT, the preparation of the MNO backhaul infrastructure for future demands poses a significant challenge. To address this challenge, we can already observe an increased deployment of fibre backhaul technology as well as regionalised data centres (see AT&T's software-driven network initiative).

Microwave and satellite technology have been traditionally used for backhauling and offloading tasks in current mobile network deployments, as shown on the right[106]. Typical applications of 3G/4G backhaul by satellite include broadband coverage extension in remote areas, backup of terrestrial broadband links, disaster recovery, handling of special events, and offload of microwave backhaul for peak hours traffic. While satellite backhaul for 2G networks was focused on reducing the bandwidth required to transport voice, optimization for 3G/4G focusses on data transmission, increasingly including solutions for header data compression, web performance enhancing proxies and support for fronthaul/backhaul caching.

Figure 38: Use of satellite in cellular networks

We expect the role of satellite technologies to increase, to further eliminate not-spots in coverage and also meet the overall capacity demands for 5G. Particularly, the buildout of low orbit solutions[107] will target flexible demand coverage, rural backhauling and remote connection forexample for agriculture purposes. With the increasing deployments of Ka-Band satellite solutions[108] and the expected costs for VSAT terminals to decrease further as a consequence, we would expect an increased reliance of satatellite-based fronthaul connectivity to remote sites, remote villages, and similar. In international deployments, supported by discussions with UK-based companies such as Avanti, rich caching solutions have been developed for supporting education and community use cases[109]; solutions that are equally applicable to rural and remote use cases in the UK.

For microwave-based backhaul networks, new spectrum bands (e.g., in 42GHz as well as 60GHz and above) will need to be supported in combination with microwave fronthaul solutions. Also, new solutions for microwave mesh backhauling are emerging, requiring additional deployment of backhaul repeaters.

106 http://www.cell-sat.com/en/solutions/3g-4g-mobile-backhaul-via-satellite.html
107 http://leosat.com/
108 http://www.itu.int/md/dologin_md.asp?id=R12-ITURKA.BAND-C-0008!!PDF-E
109 http://www.avantiplc.com/case-studies/connecting-communities-south-africa.html

The readiness in both technology areas goes hand-in-hand with the general densification need in order to meet the capacity demands. Specifically for microwave backhaul solution, we need to expect a significant increase of microwave backhaul build-out for those areas where fixed line backhaul capacity is sparse or non-existent (e.g., rural). Furthermore, the expected increase of devices as well as vertical use cases such as sensor deployments in agriculture or infrastructure monitoring, is likely driving the deployment of VSAT terminals.

4.3.2 Enabling private radio and fixed networks infrastructure

Wireless networks that have been deployed for a specific purpose, application and/or operation are typically designed and deployed in a way that complements their particular use rather than for the general public like a cellular network does. This is often because the needs, location and incentives of the business/operational users are different to the general public and consumers. This is exemplified by the GSM-R network, with masts only located trackside to provide coverage along the rail routes to provide voice and specific data services to trains. The same applies for other national infrastructure deployed to meet the specific needs of its constituent users. Another example is the Airwave TETRA network which operates at 380 – 400 MHz and has around 3500 base stations deployed in strategically placed locations so as to serve all the UK's land mass for digital secure voice and limited data connectivity for the emergency services. The ESN programme, already mentioned above, is going to replace this network using a public cellular network from EE and will likely make use of some existing Airwave sites where practical, cost effective and feasible.

Enabling these types of networks for future wireless capabilities will require key changes to the way private networks are deployed. Examples of GSM-R and other antennas mounted on the railway stanchion, as confirmed in discussions with rail stakeholders, demonstrates the potential to utilise existing built infrastructure to support current and future telecoms networks.

Coordination and collaboration amongst government departments will also be needed and between the users themselves. It is likely a proportion of the existing infrastructure within these networks could support upgrades to new technologies, addition of new equipment or identify suitable locations for densification within their network environment (e.g. trackside or along roads). Thus serving as new network locations, points of interconnect and configuration options for future networks.

The ESN is one example of a critical operational need being met by a modified public network and standard technology. This has required significant effort in addressing the many critical safety requirements of users (e.g. fire service) in addition to government investment in extending the coverage of the EE network to satisfy those operational needs. Therefore, enabling today's business radio and fixed networks to meet the needs and capabilities for future wireless networks will require inter departmental collaboration to understand the safety and business critical needs combined with recognition of the capability of existing infrastructure, site locations and upgradeability relative to the expected future needs and use cases expected for future wireless networks.

4.3.3 Fixed line networks infrastructure

Readiness of fixed line networks infrastructure is largely determined by the deployments of the major wholesale ISP in the UK, BT, with FTTP (fibre-to-the-premises) deployments significantly trailing other developed markets due to the chosen FTTC (fibre-to-the-cabinet) deployment option[110]. Due to this choice, fixed line network speeds for individual customers are currently

[110] FTTC delivers fibre only to the local street cabinet, then choosing VDSL2 over copper for the connection to individual homes and flats in apartment buildings, significantly relying on the quality of the very last link quality, often to the detriment of the final delivery speed.

limited to 24 to 76Mbit/s offerings for ISPs over BT's OpenReach infrastructure. Competitors like Virgin Media offer similar line speeds of 50Mbit/s, while local competitors like HyperOptics offer packages reaching to up to 1GBit/s per flat connection. With the introduction of G.Fast[111], BT aims at reaching similar speeds to premises in early trials in 2016, albeit carried over conventional copper lines and therefore promising cost advantages due to the utilisation of legacy infrastructure while being limited in support maximum bandwidth compared to full fibre deployments (with the latter support access speeds of many GBit/s). Investments in this space largely focus on the re-use of copper line infrastructure, while competitors like VirginMedia and HyperOptics are driving the facility-based competition with new rollouts that aim at flat/home-level line speeds that are comparable to those of international markets, as mentioned above.

However, as indicated in interviews with local councils such as Bristol, the lack of a national planning approach to new housing with respect to proper fixed line, even FTTC/H, access is likely to continue posing problems to the proliferation of fixed lines access speeds that will be competitive to other nations in terms of speed and availability to the population. For instance, new housing is still being pursued with inadequate ducting and planning for high-speed broadband access. Due to the expected utilisation of fixed line infrastructure for small cell or Wi-Fi backhauling in fixed-mobile convergence scenarios, such continuing lack of fixed-line capacity increase will likely impact the overall capacity buildout, possibly requiring another review of fixed line investments in preparation of 5G readiness, as being addressed in the challenges section.

4.3.4 Enabling Wi-Fi infrastructure

Wi-Fi infrastructure is traditionally less coupled to the longer investment cycles of MNOs since Wi-Fi is often deployed in small to medium-size premises. However, larger-scale managed Wi-Fi deployments have increased the proliferation of Wi-Fi as widespread access technology. The upgrade towards future, largely IEEE-driven, standards (including the support for future spectrum bands) will therefore be largely driven by an upgrade of the dedicated access points within the observed replacement cycles of 3 to 5 years. The upgrade of backhaul capacity is largely driven by the upgrade of the fixed line network infrastructure (see Section 4.3.3). The necessary investment is therefore limited to the average AP unit costs, while a premises upgrade will depend on the site footprint and expected occupancy particularly for larger enterprise sites (Large office blocks) and managed Wi-Fi networks.

In large managed Wi-Fi deployments, more investment is likely to be seen in the management infrastructure, handling, for instance, the band and power allocations for entire AP deployments, the flow handling in the overall access network, traffic prioritization etc. We expect a significant increase for this enabling aspect due to the expected larger proliferation of Wi-Fi as a high-bandwidth access technology for 5G (following our observation on capacity of 3GPP vs IEEE technologies in 4.2). Such managed deployments are already today the foundation for Wi-Fi operators like Sky, BT and others. In addition to management of the mobile communication infrastructure, we also expect the increase of edge computing capabilities, similar to femto cell deployments, allowing for localised communication and computation within regions of Wi-Fi access points. Existing ETSI MEC proof-of-concept prototypes112 already showcase the capabilities of largely existing Wi-Fi infrastructure in providing such localised communication, minimizing the support for such evolving solutions to SW upgrades of existing Wi-Fi access point hardware while supporting existing IP-based applications and end user devices.

[111] http://www.ispreview.co.uk/index.php/2016/03/bt-unveil-large-ultrafast-g-fast-broadband-pilot-fttp-trials.html
[112] http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing/mec-poc

4.3.5 Utility networks infrastructure

There is an increasing requirement for remote communication to devices at the edges of utility systems. This is particularly acute in the electricity sector.

Since the beginnings of public electricity networks, generation has been centralised at a number of large stations throughout the UK with power transmitted through a series of 400, 275 and 132 kV power lines and substations. Remote visibility of the status of devices at these locations has generally been possible through SCADA type systems connected back to centralised control rooms via a mixture of telecommunications protocols supported by a variety of mediums including radio, fibre, copper and some satellite technologies. This type of arrangement has provided the UK with the facility to monitor and control electricity infrastructure to a sufficiently robust level to ensure that the reliability of electricity supply in the UK is amongst the highest in world.

Whilst the existing arrangement has provided satisfactory for many decades, it does have some limitations. In particular the remote visibility of electrical plant further down the hierarchy of electricity transmission has been limited. Visibility of remote substations at the 33kV level is generally possible but with a lower level of detail and granularity than at the 132 kV level. Moving further away from the centralised core (11kV, 6.6 kV and LV), the visibility of equipment at secondary level has been even more restricted – with many pole mounted transformers, auto-re-closers and voltage regulators remaining without a connection to the centralised control centre.

With a centralised distribution model and large fossil fuelled / nuclear generation this has been an acceptable strategy. However the advent of distributed generation and, in particular, the move towards more renewable generation has brought about a real and pressing need to enhance visibility and detail of (eventually) hundreds of thousands of additional devices. Such distributed power generation could be accelerated through a larger number of wireless transmission sites with autonomous power generation where excess energy is pushed back into the overall utility system. Without effective control of the network at the edges, much of the renewable wind and solar generating capacity cannot be transmitted efficiently and is wasted as heat or disconnected. As the power generation mix between reliable fossil fuelled generation and more dynamic renewable generation moves in favour of the latter, it is essential to have real time visibility of the entire network in order to ‘keep the lights on’.

Not only has the advent of distributed renewable generation brought about the need for change, but the increasing success of plug-in electric vehicles is a further reason to enhance communications to the edge of the network. Other examples for needing to rethink such communication comes from the possibility of wireless sites being temporarily being integrated into the overall communication network in cases of (local) demand surges. Without significantly more granular control of the distribution network, such increased edge usage will seriously affect load balancing and voltage regulation throughout the UK. In addition to the very significant number of additional devices which need to be connected to the network, there is also a step change in the data throughput required to each. Currently, communication with most utility devices very low data rate digital signals i.e. is a circuit breaker open or closed? This level of functionality can be delivered using low throughput systems (300 or 1,200 baud). However, new systems will be required to send information in real time regarding voltage, temperature, pressure and potentially video signals – driving the required throughput to tens or hundreds of kilobits per second.

Major enhancements to Utility sector communications systems are a pre-requisite to further adoption of smart grid technology. 5G and IOT / M2M solutions will play an important part in solving the communications challenges which the utilities sector is facing. However, it is important to note that there is still likely to be a very significant role for a dedicated, utility grade communications system which will provide services at a sufficiently high level of reliability, security and throughput to support critical national infrastructure in the UK.

4.4 Comparison with international developments

As briefly mentioned in Section 4.2, international operators have started trialing relevant 5G technology. Most prominently, AT&T has recently called for action[113] [114] to fully utilise the potential of SDN and NFV technologies. Through their ECOMP orchestration software suite, AT&T is pushing for handling 75% of all users' traffic through their virtualised mobile core by 2020, aggressively moving orchestration functionality as well as SDN deployment at scale into its core network. Pushing beyond this SDN proliferation, AT&T is also the leading operator in the OpenFog consortium[115], together with other industry players such as Intel, Microsoft and GE, pushing for an adoption of open, next generation edge computing standards. However, clear deployment timelines for this set of technologies are still missing.

In Asia, much 5G momentum is focused on the two large-scaled events that align with the overall 5G timeline, namely the Korean 2018 Winter Olympics and the Japanese 2020 Summer Olympics. For instance, early announcements for the 2018 event foresee holographic VR services and so-called Sync view services for immersive audiovisual experiences across up to 250000 devices[116] [117], while early trials for the Japan 2020 Summer Olympics[118] showcase LTE-Advanced up to 2200mbps with projections to move towards massive MIMO technologies at 5tbps throughput in stadium scenarios for providing multi-angle 4k video experiences. However, while such event-focused deployments will undoubtedly fuel press releases and marketing around 5G, there are few indications for a large-scale deployment of the underlying (mostly radio) technologies at national scale.

Specifically on the spectrum side, there has been growing international momentum between core countries like Korea and Japan to position mmWave solutions in the 28GHz spectrum band with the danger of creating non-harmonised deployments on these technologies, piggybacked on the exposure of the aforementioned Olympic events in 2018 and 2020.

On the infrastructure build-out side, international activities in the space of fibre built-out have long been ongoing in many developed markets with countries like South Korea, Japan and Spain reaching and exceeding 60% of FTTP coverage. In contrast, the UK within the current regulatory environment, has been unable to compete with these countries in terms of fibre roll outs to the premise. This is mainly due to dominant incumbent copper infrastructure laid to the premise many decades ago and ambitions from the major operators such as BT continuing to focus on development in copper technology rather than focus on fibre to the premise. We explain the current situation for fixed line deployments in the UK further in section 3.4.

[113] https://www.business.att.com/enterprise/Family/network-services/network-functions-on-demand/
[114] https://about.att.com/innovationblog/031516sdncall
[115] https://www.openfogconsortium.org/
[116] http://telecoms.com/427991/kt-targets-5g-rollout-for-2018-winter-olympics/
[117] http://www.netmanias.com/en/post/korea_ict_news/8494/5g-kt/kt-s-5g-trials-for-world-s-first-5g-olympics
[118] http://www.phonearena.com/news/Japans-NTT-DoCoMo-shares-its-plans-to-deliver-5G-in-time-for-the-Olympics-in-2020_id72473

5 Digital infrastructure requirements in the UK

5.1 Mapping digital infrastructure in strategic geographical areas

In this section, we summarise the findings from the network mapping exercise which determined whether existing digital telecommunications infrastructure can satisfy the coverage/service requirements of particular demanding use case scenarios. We have conducted a telecoms network mapping exercise that demonstrates how existing telecommunications infrastructure site capabilities and their location can fulfil the potential for enabling future wireless networks. We determined the size of the gap in capability and densification requirements in order to meet the desired performance targets and also the costs.

Our infrastructure dimensioning analysis was conducted across the four focus areas the strategic road network, rail routes across Britain, urban and rural areas.

Infrastructure requirements for the Strategic Road Network (SRN)

There is no dedicated roadside wireless infrastructure in place on the SRN. Therefore, our analysis focused on upgrade to MNO sites deployed on adjacent land, how much new and additional fibre is needed and the number of dedicated roadside sites along different parts of the SRN. This included the motorway parts in England and Great Britain (GB) and the entire SRN in England and GB.

There is 3,025 km of fibre within the 3,450 km of cabling of the NRTS core network. The remaining cabling is copper. Therefore, if all the SRN were to require fibre in GB then an additional 9,106 km of fibre is needed.

The number of new sites needed to meet the range of different use cases (vehicle management to driver assistance) ranged from 6716 for all motorways in England up to 60,655 new dedicated roadside sites across 12,131km of the SRN in GB.

We estimated the cost for MNOs to deploy adjacent to the roadside was more than double the cost of a dedicated roadside network. The overall costs for a dedicated roadside network ranged from £153 -£457 million using existing fibre on the motorways in England/GB, up to £1.75 - £5Bn for a new dedicated roadside fibre network and new roadside equipment across the entire SRN in GB.

Infrastructure requirements for the rail routes in Britain

A similar approach to the roads was used for the analysis of the rail routes infrastructure. A breakdown of the numbers of sites and lengths of fibre needed to meet the performance criteria for different use cases.

We compared a current mobile broadband service (e.g. 500 Mbps per train) with a future mobile broadband service (e.g. 100 Mbps per user) to estimate the number additional sites needed along all rail routes in GB. We estimated approximately 8,300 additional sites would be needed for a future network compared to approximately 3,270 for a mobile broadband solution based on today’s technology.

Although, there is a sufficiently high capacity fibre core along the rail routes this is encumbered with safety critical equipment and applications and thus cannot feasibly be used for a passenger connectivity network. We therefore determined that £150 -250 million would be needed to deploy a separate dedicated fibre access layer in parallel with Network Rail’s operationally focused access layer. Adding the new dedicated trackside sites for future enhanced mobile broadband passenger connectivity the cost ranges from £495 – 595 million. These costs reduce to £285 – £385 million if deploying a less dense network based on today's wireless technology.

Infrastructure requirements for urban areas

We assessed the number of sites required for dense urban areas across the UK. We estimated that around a total of 15000 small cell sites could be required if two separate network are deployed this is reduced to 7600 sites for a multi operator solution. This was based on the assumption of using 24 GHz spectrum with a cell range of 80m. This would deliver a future enhanced mobile broadband service of up to 100 Mbps per user. Comparing this to an area the size of the City of London this would require 170 – 290 sites.

Infrastructure requirements for rural areas

We estimated the number of sites required nationwide for rural areas. The total number of sites needed for a mobile broadband and machine type communications service is between 14600 to 15000 sites. Comparing to the Downham Market area we assessed in detail the number of additional sites ranged from 22 for multi operator solution to 33 sites for a single operator solution. This was using 3.5 GHz machine type communications service. The impact of choice of spectrum band was key to the number of sites in the rural area. Using the 700 MHz band limited the number of additional sites to three for the Downham Market analysis.

5.1.1 Objectives

The objectives of the exercise were to examine a number of representative geographical areas by plotting existing wireless sites from across the MNOs, Network Rail, Arqiva, WIG, Shere and onshore windfarms and estimate the extent of coverage provided based on a set of different cell ranges. The cell ranges were driven by the use case categories which are discussed in more detail below.

In order to identify the feasibility of each of the sites types we conducted a desktop survey of the existing infrastructure so that we could score the upgrade potential with respect to the need to meet the future use cases. For example, the desktop site survey included an assessment of:

- Site types (rooftop, greenfield, or streetworks) and ability for site, mast and equipment expansion in each case.
- Space around the site to determine if the site type is conducive to mast upgrade with additional antennas and cabling that would support new frequency bands.
- Capability for integration of new technologies into the existing owned infrastructure could be handled.

Calculate any additional sites that would be needed, based on the outcome of the gap analysis. The exercise determined how many more sites will be needed to meet the use case requirements. In particular, for the road and rail areas estimate the network infrastructure capex.

5.1.2 Input parameters

The key input parameters used for conducting the analysis are identified below:

- Mobile mast sites: These are built specifically for their purposes and there are a number of different network operator sites considered, namely;

- Mobile Operator mast sites based on source data from Ofcom sitefinder and discussions with MNOs today.
- Majority of third party mast sites based on source data from the Arqiva sitefinder database and WIG data.
- GSM-R sites across England/Wales based on source data from Ofcom sitefinder and discussions with NRT.
- Electricity pylons and on shore windfarms based on source data from Arqiva (pylons) and Cabinet office web site (on shore windfarms).

- Geographical areas selected for the detailed analysis are shown in the table below. More detailed rationale for the choice of the different areas is given in sections 9.3 in the Appendix.

Geographical area	UK location chosen
Strategic road network	M4 stretch Cardiff/Newport (27 km)
Primary rail routes	Glasgow to Edinburgh (75km)
Dense Urban	City of London (2km x 2km)
Small urban city	Exeter (5km x 5km)
Suburban	Cardiff/Newport area (defined by Suburban clutter class)
Rural/not spot location	Downham Market area of Norfolk (30km x 30km)

Table 8: Representative locations for the geographical areas

5.1.3 General assumptions and key statistics

Given the inputs identified in the previous section, we have made the following relevant assumptions in order to conduct the mapping exercise:

Mobile mast/tower assumptions:

- If the tower is a purpose built mast for multiple tenants then we assume it can be upgraded to support additional infrastructure and technology have sufficient space for upgrading and expansion. This is based on third sites typically accommodating multiple operators on a single site.
- If the tower is built for a single purpose like for utilities or GSM-R only (single mini lattice tower or pole) then we assume it cannot be upgraded with new equipment without a new stronger lattice tower or strong network sharing (C-RAN) everyone uses the tower and same antennas.
- We assume dedicated small cell type equipment can be mounted on single poles or existing mast lattice towers (e.g. GSM-R).
- In the case of trackside (for rail) and roadside (for vehicle) backhaul is provided directly into the trackside or roadside fibre network.
- We have assumed that sites will be further consolidated over time thus reducing the total number of sites and based on the site numbers data available we have taken the average across the MNOs site portfolio.
- We assume there will be some instances where for practical, commercial and political reasons upgrades will not be permitted.

Street works sites:

- We assume these can be upgraded but dependent on access and space available at the site. Some operators share streetworks (e.g. O2 and Vodafone). However, for the type of expected upgrade for future wireless networks we assume new antennas would be needed and swap out of the whole deployment.

Rooftop sites:

- These may be able to be upgraded if there are multiple operators already on the site. Might be issues with adding more equipment as many buildings are already crowded with multiple operators. This also means there is a willing landlord.

Onshore wind farms and electricity pylons:

- These are capable of supporting multiple operator equipment including antennas and base stations and have access to sufficient backhaul.

Dedicated roadside and trackside sites:

- We assume that the expected inter site distances for rail will be in the range 1.2km to 4.8km (see Table 19) depending on the use case. This is based on discussions with industry and scenarios developed within the European 5GPPP research and other studies[119].
- Connections and deployment into available fibre/ducting/troughing and power can be made at the required level of regularity along both the road and track side
- We assume that in future the infrastructure will provide the backhaul connectivity to the train/vehicle mounted antennas and not direct connectivity to passengers.

Fibre backhaul:

- We have assumed there is and will be sufficient fibre backhaul infrastructure available along the roadside and trackside and that new sites will be connected to the fibre. This is based on Ofcom's database - Connected Nations[120] assumes Superfast BB and Ultrafast broadband is available in the postcodes in urban and suburban areas of our geographic areas.
- MNO sites connect to sufficient backhaul where it is available for new site locations. Additional fibre would be needed in remote rural areas currently unserved.
- Fibre availability per postcode from BT. Fibre or other high speed infrastructure is available in the area close to the wireless site we assume it can be supportable to next generation networks.
- Site numbers generated in these results are purely estimates as the approach is statistically based on linear site coverage for roads and rail and circular per site coverage area ($\pi r2$) relative to the size of the gap area for urban, suburban and rural areas. No consideration has been given to terrain, clutter or propagation models.

5.1.4 Assumptions for use case cell ranges and service platforms

Below are the technical assumptions gathered from the parallel study by Real Wireless on future use cases used to derive the cell ranges and the use case performance criteria. The table below is extracted from the output of Real Wireless' analysis[121] and shows the range of use cases that apply across each of the service platforms. In this study we considered the automotive connected cars, public transport railways and media and business cloud platforms.

[119] Mobile Hotspot Network System for High-Speed Railway Communication using Millimeter Waves, C Sungwoo et al, ETRI journal, 2016

[120] Connected Nations 2015, Ofcom

[121] Details of the how the numbers were derived can be found in Real Wireless' report

Use Cases and Service Platforms		Automotive - Connected Cars			Public Transport - Railways			Healthcare Services			Utility & Supply Chain		Media and Business Cloud		
		Entertainment	Driver Assistance	Vehicle Mgmt	Passenger Broadband	Command & Control	Telemetry	Assisted Living	Remote Healthcare	Preventative Health	Smart Utility	Road Haulage	AR/VR Gaming	4K anywhere	Mobile Office
Mobile Broadband	MBB	✓	(✓)	(✓)	✓	(✓)	✗	✓	✓	✓	✗	✗	✓	✓	✓
Machine Type Communications	MTC	(✓)	✗	✓	✗	(✓)	✓	✓	✓	✓	✓	✓	✗	✗	(✓)
Mission Critical Communications	MCC	✗	✓	✗	✗	✓	✗	(✓)	✗	✗	(✓)	✗	✗	✗	✗
Indoor Wireless Systems	IWS	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓

Table 9: Service platforms and use cases

The cell ranges have been derived by the parallel Real Wireless study across frequency bands 700 MHz, 3.5 GHz and 24 GHz for urban, suburban and rural areas. In each case there is a cell range for massive machine type communications (mMTC), ultra reliable low latency mission critical communications (URLLMCC) and mobile broadband (eMBB). These can then be related back to the different specific use cases in the table above.

Cell Ranges (km)		mMTC	URLL MCC	eMBB
700 MHz	Urban	4.30	0.65	0.59
	Suburban	7.00	0.82	0.80
	Rural	12.50	2.69	2.62
3.5 GHz	Urban	0.47	0.09	0.09
	Suburban	2.09	0.17	0.17
	Rural	5.65	0.65	0.62
24 GHz	Urban	0.48	0.08	0.08
	Suburban	0.97	0.13	0.13
	Rural	1.52	0.17	0.16

Table 10: Cell ranges across different frequency bands and clutter types

The cell ranges for the roadside and trackside deployments differ slightly as we assume line of sight conditions along the majority of the routes particularly in suburban and rural areas. We assumed non Line of Sight largely occurs in urban areas. This means we can use longer cell ranges, compared to those in Table 10 at the millimeter wave frequency bands such as 24 GHz. The tables below provide the cell ranges assumed for roadside and trackside deployments.

Cell ranges (km)	ULLMCC (700 MHz)	MBB 500 Mbps (5 GHz)	eMBB (24 GHz)
Urban	2.0	2.4	0.6
Suburban	3.0	2.4	1.0
Rural	4.0	2.4	1.0

Table 11: Cell ranges for different frequency bands for trackside deployments

Cell ranges (km)	Dedicated roadside (low - high)	MNO deployed (close to roadside)
Urban	0.1 – 0.25	0.25
Suburban	0.1 – 0.25	0.25
Rural	0.1 – 0.25	0.50

Table 12: Cell ranges for different frequency bands for roadside deployments

The table below shows the expected user and network performance characteristics across each of the service platforms.

Service Platform	Device Density	Mobility (km/h)	User Data Rate	Typ. Cell Edge Rate	Latency	Network Availability
Mobile Broadband	1k – 10k /km^2	Static – 300 km/h	50 – 100 Mbps	50 Mbps DL, 25 Mbps Ul	10 – 50 ms	99%
Machine Type Communications	10k – 1m / km^2	Static – 300 km/h	1 – 100 kbps	100 kbps DL, 50 kbps UL	>50ms	99%
Mission Critical Communications	Up to 10k/km^2	Static – 300 km/h	Up to 10 Mbps	10 Mbps DL and UL	1 – 50 ms	99.9% - 99.999%

Table 13: Service platform performance criteria

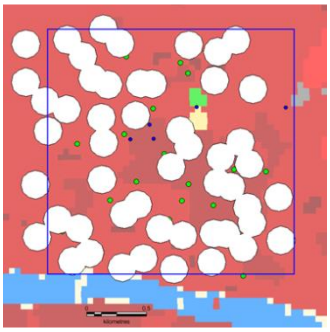
In each geographical area we consider how the existing digital infrastructure available across the different networks could meet the minimum service/coverage requirements for the different use cases. The analysis considered the following scenario per geographic area.

Geographic area	Use cases		
	mMTC	**ULLMCC**	**eMBB**
Strategic road network	Vehicle Management	Driver assistance	Passenger entertainment
Rail network	Telemetry	Command and control	Passenger broadband
	Use cases		
	mMTC	**eMBB**	
Dense Urban	Smart Utility	4K anywhere	
Urban	Smart Utility	4K anywhere	
Suburban	Smart Utility	4K anywhere	
Rural	Smart Utility	4K anywhere	

Table 14: Different use cases within the geographic areas

We describe the approach to the telecoms network mapping exercise in more detail in Appendix A section 5.1.5.

5.1.5 Infrastructure gap analysis methodology



In our gap analysis, we identify for each geographical area the gaps in potential coverage based on existing infrastructure locations and compared against the density expected from the use case scenarios. A summary of the gap analysis approach is given below:

- The existing infrastructure locations in each area set the baseline coverage for the network.
- Determine the min, max and average inter site distance, site density and number of gaps depending on the size of the gaps within the area (e.g. number of gaps of less than 1km, gaps of between 1-2km and so on).
- Determine, where possible, the gaps between existing sites – for strategic road and rail these are linear gap sizes – for the areas we assess the number and size of gaps based on coverage buffer zones for each of the use cases.
- Calculate the area of no coverage statistically based on the remaining unserved areas (see image right with non-white areas having no coverage inside the blue box).
- We compare the size and number gaps for each site and within each geographic area against all the cell ranges for each of the use cases to determine whether the existing sites can deliver the minimum services expected today (e.g. minimum cell range for connected car telematics is 5.65 km and infotainment is 500m).
- We will apply the following criteria depending on the outcome of the comparison analysis:
  - Calculate how many site upgrades are needed to fulfil the use case criteria. This includes new technology, base station, antennas, masts.
  - Calculate how many additional sites are needed, if any, to meet the use case performance criteria based on the number of gaps that exceed the minimum cell range of the particular use case.

Site deployment criteria

Sites are deployed based on a rudimentary gap analysis algorithm. Each cell is assumed to serve the area within its buffer with no consideration for path loss, propagation losses, or attenuation or terrain. Therefore, the results are purely estimates to illustrate the orders of magnitude required for additional sites. The impact of the propagation and terrain losses could have a material impact on the outcome of the number of sites. However, we have verified our results with the expected coverage predictions from the Ofcom mobile coverage checker (2G and 4G) and then further cross checked with practical reality from anecdotal data of coverage in the given geographical area.

Setting minimum cell ranges and service levels from the use cases

The use case criteria have been developed by a parallel study that has examined future use cases for mobile telecommunications networks. A report has been produced which outlines the approach to deriving the use cases and the technical network architecture and performance criteria to set the minimum service level thresholds and cell ranges.

The desired cell ranges provide the ideal coverage and achievable user throughput from all the site types which we assume has taken account of available spectrum bands, bandwidth and technology. However, we note a more detailed network dimensioning exercise would be needed to derive more precise cell ranges for the different clutter types.

Analysis of the Strategic Road/Rail Network

- Consider a representative stretch of strategic highway/railway in the UK and plot existing wireless sites that are within 200m of the road or railway line. Examples include MNO sites, Arqiva, and WIG sites by their nature will be adjacent to the roadside and all streetworks/rooftop sites can serve its closest roads/streets based on its cell range.
- Visual inspection of the map and calculate site density and inter site distance within our road and rail study areas.
- Validate site locations with a survey review using Google maps and Streetview.
- Test the minimum service level requirements of the existing infrastructure with that needed for the use case (connected cars or broadband for railways).
- Determine if the existing infrastructure can meet the use case requirement: a) Yes, fully; all sites in the right place and can achieve the desired min service level b) Partially, depending on exact site locations might get some level of service increase so gets close to what is needed but not the full service 3) No, cannot get close to the service and additional infrastructure is needed.

Urban/Suburban and rural areas

- Cut a map tile for each of the main geographical areas to ensure it is sufficiently representative in size and existing telecom infrastructure availability.
- Plot on each geographical area the location for all the existing wireless masts for MNOs, Arqiva, WIG, GSM-R, utilities, wind farms.
- Survey each individual site by checking the specific aspects linked to the infrastructure capability namely provide a mapping reference, i.e. near the M1 northbound, close to trackside/junction, rooftop site with sufficient access and capability for upgrade.
- Provide a physical upgradeability score based on the criteria i.e. a score of 1 a site can be upgraded for future networks, through to 5 where a site cannot be upgraded at all. Complete the table for all infrastructure types. This determines what aspects of the site can be upgraded to meet the needs of the use case. For example, new technology may require new antennas, base station equipment, processing equipment etc.

5.2 Capital costs and infrastructure requirements for nationwide road and rail routes

In this section we present the capital costs and infrastructure requirements required nationwide for the strategic road network and the rail network across Britain.

The national infrastructure requirements for the rail and road environments derived in following sub sections provide the size of the gap between existing infrastructure and the potential size of next generation networks needed to meet the various future use cases. Given the public investment already made in road and rail telecoms infrastructure there is merit in estimating the potential costs of the additional capital equipment needed that could enable future networks. In both cases, upgrades to existing sites, such as new technology or masts are needed, and in other cases additional telecommunications equipment such as new masts, antennas, cabling, civils and base station transmitters or small cells/access points.

In preparing the cost estimates in both the roadside and trackside bases, we have taken account of the general costs of the provision of the infrastructure and equipment. However we are aware that the installation of equipment in both environments is made more complex by the safety environment in which installers and other staff have to operate. It is often difficult to estimate these additional costs on safety grounds because it is not certain where the necessary equipment will need to be installed and the extent to which this would require either roadside or trackside permission or imply the need for safety-qualified staff. As such, we believe these costs to be a reasonable representation of the underlying costs of the implementation of such a service, but we recognise that there may be significant additional overheads associated with gaining access to both the roads and railway.

Details of the infrastructure requirements results for each of the specific portions of road and rail considered are given in section 9.1.1 and of Appendix A. These specific areas were used to extrapolate and determine the nationwide picture. In section 9.2 details of the capital costs for infrastructure along the roadside and trackside are given.

5.2.1 Capital costs and infrastructure requirements for the Strategic Road Network

Based on the extrapolated findings from the analysis in section 9.1.1, we have determined the extent of network infrastructure needed along the motorway and SRN in England and also for motorways and SRN in Great Britain.

In this study we considered the fixed telecoms (e.g. fibre optic cable) and non-telecoms infrastructure (e.g. overhead gantries) deployed along the roadside. This existing infrastructure could be used to mount dedicated wireless equipment and connect to existing fibre backhaul along the motorways. We have also assumed there will be continued growth in coverage of the major roads from existing MNO sites deployed adjacent to the roadside. The infrastructure that ultimately gets deployed must be able to deliver the expected user performance for in-car entertainment and driver assistance use cases. Table 15 below shows different lengths of the strategic road network (motorways and/or major trunk road), length of fibre, currently only deployed on the motorways and existing MNO sites adjacent to the roadside for each deployment option.

<table>
<tr><th>Deployment option</th><th>Length of road[122]</th><th>Length of fibre (Mway only)</th><th>Existing MNO site upgrades single operator</th><th>Existing MNO site upgrades multi operator</th></tr>
<tr><td>All motorways England</td><td>3,056</td><td rowspan="4">3,025</td><td>1,497</td><td>2,131</td></tr>
<tr><td>All motorways GB</td><td>3,654</td><td>1,790</td><td>2,548</td></tr>
<tr><td>All strategic roads England</td><td>7,192</td><td>3,524</td><td>5,015</td></tr>
<tr><td>All strategic roads GB</td><td>12,131</td><td>5,944</td><td>8,460</td></tr>
</table>

Table 15: road and fibre length statistics and existing MNO sites

We have used the data above to determine the total number of required sites to meet each of the connected car use cases. The first four columns of total GB sites in Table 16 are based on the inter site distances 500m for urban and suburban portions of the SRN and 1km for rural portions assuming 3.5 GHz for MNO sites adjacent to roadside. This is based on a line of sight environment similar to that of rail (See section 5.1.4 for the different cell ranges). The fifth

[122] Table RDL0201 road length (kilometres) by road type and region and country in Great Britain, Department for Transport

column assumes a two cell ranges. The lower cell range is 100m for a highly dense network deployment and a higher cell range of 250m for less dense network deployment that takes into account practical line of sight aspects of the environment. The cell ranges translate into an inter site distance of 200m and 500m respectively. In practice the number of sites would vary according to the expected demand along each part of the road.

Deployment options	Total GB MNO sites				Total GB dedicated roadside sites
	Additional MNO sites (Single operator)	Additional MNO sites (multi operator)	Total MNO infrastructure requirements (single operator)	Total MNO infrastructure requirements (multi operator)	All new sites deployed roadside only (200m - 500m)
All motorways England	3435	4875	4923	7006	6112-15280
All motorways GB	4389	6246	5886	8377	7308-18270
All strategic roads England	11017	15680	12514	17811	14384-35690
All strategic roads GB	19611	27912	21108	30043	24262-60655

Table 16: Estimate of total sites needed for different deployment options for motorway and SRN in England and across Great Britain

We compare the numbers in the table above to a future (5G) densely deployed network that does not rely on existing MNO infrastructure but solely uses the roadside infrastructure. The number of sites needed to support an inter site distance of 200m for example, requires approximately 15,280 sites for all motorways in England and up to 60,655 sites for all SRN in Britain. The expectation is this type of network could deliver a low latency mission critical and/or a high definition media streaming service to vehicles/passengers based on our assumed use case category cell ranges. The possible deployment options differ depending on whether MNOs deploy on the roadside sites (and use their spectrum) or if Highways England procure a managed neutral host operator and use alternative spectrum bands. The key enabler will be to ensure access to the existing roadside fibre that has the suitable technology to support the expected capacity.

In turn, based on the above site numbers we have developed high level cost estimates for the required equipment investment. The capital costs have been determined based on a number of key equipment cost assumptions which are shown in Table 17 below.

Site type	Acquire, design and build	Assumption	Reference source
Greenfield	£110,000	Assumes 15m mast with 3 sectors and 4 transmitters	Real Wireless study on future use cases
Rooftop	£95,000	Assumes 3 sectors and 4 transmitters	Real Wireless study on future use cases
Street furniture	£40,000	Assumes 12m high column with 3 sectors and 4 transmitters	Real Wireless study on future use cases
Small cell	£13,000	Assumes street furniture option	Real Wireless study on future use cases
Rooftop upgrade	£36,000	Assumes tech upgrade e.g. 3G to LTE plus additional 3 sectors	Real Wireless study on future use cases
Roadside equipment deployment	£25,000	Assumes sub 10m mast, or gantry access, new antennas and access points, site design and civils, interconnection with existing infrastructure and the internet	Discussions with HE and sector knowledge
Fibre deployment costs road per km	£135,000 – £420,000	Assumes civils, planning, surveys, terminal equipment, fibre cable, road closures and connection	Discussions with HE and sector knowledge, BT OpenReach price list indicators for carriageways

Table 17: Costs for new telecommunications equipment and upgrades for MNOs and dedicated roadside deployment

We have multiplied the required mix of technology upgrade costs, fibre costs and additional site costs, with the respective number of upgradable sites and additional sites in both the road and rail environments to yield total estimated costs for different deployment options. The total cost estimates for the future road infrastructure are shown in Table 18 below.

Deployment options	Range of estimated costs for new MNO sites, fibre and roadside equipment (£m)	
	Wireless roadside equipment (existing fibre)	New/upgrade MNO sites
All motorways England	153 - 382	580 – 825
All motorways GB	183 – 457	743 – 1,058
All strategic roads England	918– 2,636	2,229 – 3,408
All strategic roads GB	1,750-5,076	4,118 – 7,792

Table 18: Estimated site cost for connecting wireless equipment deployed along the motorway versus MNO site costs on all Strategic Road Network in England and Great Britain

Table 18 shows the low and high cost range based on the number of sites given the different inter site distances comparing a dedicated roadside deployment against a potential MNO deployment on land adjacent to the roadside. The infrastructure costs increase as the length of strategic road to be served increases for England and GB.

We compare the costs in Table 18, between the dedicated roadside deployment connecting into existing fibre and MNO upgrades of sites along roads and any new sites to meet the future use cases. Our estimates show that it would be more than twice as expensive for the MNOs to serve the motorways compared to a dedicated network. This is mainly due to the large number of costly new sites and upgrades needed, plus costs of laying new fibre connecting these sites in both rural and urban/suburban areas. The cost difference reduces to 1.5 times more expensive for deployment of MNO sites along all SRN. This is due to similar commercial challenges of deployment in urban, suburban and rural areas for non-motorway (major trunk) roads particularly as new fibre would need to be laid in a similar fashion across the remaining non-motorway portion of the SRN.

Cleary, the dedicated wireless roadside network connecting to existing fibre is the most cost effective. However, in order to deliver a nationwide network the costs increase significantly to lay fibre and deploy sites along the remaining non-motorway sections of the SRN (See section 9.2 for more details). In the case of MNOs, infrastructure costs savings can be made where sharing sites between multiple MNOs[123], compared to a single operator network.

Furthermore, the lower cost of the range for each configuration, is driven by larger inter site distances between sites. Thus resulting in a less dense network which may potentially mean lower performance capability given the different use cases but still the most economic.

5.2.2 Capital costs and infrastructure requirements for rail routes in GB

The infrastructure requirements to cover all 15,700km of Britain's rail routes can be determined in a number of ways based on the type of services to be delivered. For example, the current GSM-R service provides full coverage of the rail routes it serves based on approximately 2800 trackside sites using sub 1 GHz frequencies.

In order to meet the future use case performance targets such as enhanced mobile broadband to passengers, we have estimated the total number of sites needed for all routes shown in the table below. The site numbers are based on the inter site distance used from Project Swift (See section 3.3.3 for more details) and enhanced MBB use case cell ranges.

Use case	Min inter site distance	Total GB sites needed
Mobile broadband for 2016 (500 Mbps)	4.8 km average across all GB routes (5 GHz)	3271
Future enhanced Mobile Broadband for passengers	1.2 km (24 GHz Urban) 2.0 km (24 GHz Suburban, Rural)	8367

Table 19: Estimate of site number needed for all rail routes in Britain

Our analysis focuses on rail passenger connectivity due to the current political attention of this issue[124] and the potential for new networks and technologies to deliver much improved user

[123] Multi operators refers to all operators sharing the same network

[124] Government promise of fast, cheap Wi-Fi on trains goes off the rails, The Guardian, Nov 2016 https://www.theguardian.com/business/2016/nov/21/rail-network-fast-cheap-wi-fi-trains-internet-access

data rates along the rail corridor. However, the rail industry is also currently considering new technologies as a replacement for its existing safety/operational GSM-R network[125].

Therefore, we consider the total number of sites needed in order to deliver a future enhanced Mobile Broadband (eMBB) service compared to typical Mobile Broadband service achievable today. The number of new sites for eMBB is almost double that of a MBB service today. However, the likely frequency bands to be used in future to support the very high data rates of 5G applications will be in the millimeter wave bands such as 24 GHz. As a consequence this means the new sites will have smaller cells ranges and thus, as shown in the table above, more sites will be needed.

The issue with considering smaller cell ranges in urban and suburban areas applies to traditional radio planning rules to fill hotspot gaps whereas the demand for traffic is relatively well known and largely predicable for rail. Therefore, a more precise level of dimensioning is needed according to the predictable pattern of traffic. For example, there are usually lower levels of traffic/demand at the start of a journey when travelling towards a hub station in a city as there are fewer passengers and the train becomes busier the closer it gets towards its destination, particularly for commuter routes. This differs compared to high speed lines, when the train is quite highly occupied throughout the whole journey. Therefore, the dimensioning should differ according to the traffic demand locations and thus the total number of sites could range from around 6500 - 8400 depending on the use case need. Whether the values prove to be reflective of a real life network, it is clear that the amount of infrastructure that will be required far exceeds that which is currently deployed.

Based on the above site numbers we have developed high level cost estimates for the required equipment investment. The capital costs have been determined based on a number of key equipment cost assumptions which are shown in Table 20 below.

Site type	Acquire, design and build	Assumption	Reference source
New trackside site	£41,250	Assumes Network Rail approved unit for trackside (£55k without discount for economies of scale) with integral directional antenna plus installation on sub 10m mast and connection into existing infrastructure and the internet.	Discussions with industry, commercial costs of telco equipment plus data from a report for the European Union Agency for Railways http://www.era.europa.eu/Document-Register/Documents/Annexes%20v27%2001%202015.pdf
New trackside fibre costs	£150m – £250m	See details below	Discussions with Network Rail

Table 20: Costs for new telecommunications equipment and upgrades along the trackside

We have assumed that brand new fibre infrastructure will be deployed trackside for providing passenger connectivity. In addition, it will provide a national high capacity and secure backbone network that support service innovation. This is because infrastructure that is completely separate from safety critical and operational needs of the railway will be open and more accessible on a commercial basis compared to connecting into spare capacity on existing fibre that supports the FTN and FTNx. Furthermore, we found from discussions with Network Rail that the costs of deploying fibre on the trackside are considerably cheaper (around 25% of the cost) compared to the costs incurred by typical (non-rail) commercial telecoms operators.

125 The future of GSM-R, Railway Engineer, Nov 2015 http://www.railengineer.uk/2015/11/11/the-future-of-gsm-r/

This is because deployment at trackside does not require wayleaves or ducting which is usually required for laying fibre elsewhere and also that power is readily available along rail the corridor. Therefore, on that basis our forecast range for one-off costs to deploy fibre for national primary routes is estimated at a range of £150m - £250m.

The total estimated costs of deploying a brand new telecommunications infrastructure on the trackside for passenger connectivity is shown in Table 21 below. We have multiplied the new site costs from Table 20 and fibre costs with the respective number of new sites (from Table 19) needed along the rail corridor for a current mobile broadband service and a future enhanced mobile broadband service.

Trackside deployment options	**Estimated costs for total GB sites per use case (£m)**	
	Current mobile broadband service (e.g. Project Swift delivering 500 Mbps)	**Future eMBB connectivity to passengers**
New sites	135	345
New fibre (access layer)	150 – 250	
Total costs	285 – 385	495 – 595

Table 21: Estimated site cost for brand new sites and fibre cable along all rail routes in Britain

It can be seen that a denser future eMBB network deployment is almost twice the cost of the network architecture based on today's wireless technology capabilities. Specific aspects to consider however for such new networks are the uncertainties. This includes access to new mmWave spectrum practical deployment given the need to deploy comparatively much larger numbers of sites. The costs may also increase if there is a requirement to access existing mast infrastructure (see section 9.2.2 on GSM-R masts upgrade costs). This is because these sites are used for the safety related and operational aspects of the railways and as such requires the necessary additional safety related arrangements to consider which includes Network Rail related costs.

Fundamentally, access to existing fibre capacity and GSM-R masts at the trackside presents too many restrictions at a, technical, commercial and practical level. Thus, deployment of brand new wireless infrastructure along the trackside for a passenger connectivity service would need to be mounted on existing non-telecom fixed infrastructure such as gantries and poles. This will have its own challenges particularly given the planning and management requirements and the practical and commercial feasibility to deploy approximately 8300 new sites along all GB routes, although would likely be the most efficient and economic approach. We also note other costs that have not been taken into account in this study are the fitment and/or upgrade of equipment on board the trains. New on board equipment (antennas and radio access points) would be required and the costs likely to be borne by the train operating companies.

We discuss the technical and practical challenges of deploying infrastructure along the trackside in section 6.

5.3 Telecommunications infrastructure requirements mapping results – representative populated areas types

In this section we present the results from our infrastructure requirements analysis in which we determine the size of the gap in network capability for urban, suburban and rural areas. The objective was to map existing telecommunications infrastructure to determine its capability to meet the specific use case cell range performance targets.

Details of the results from our analysis are given in section 9.3 of Appendix A which provides a description of the specific geographical areas listed below:

- Dense Urban – City of London
- Urban – Exeter
- Suburban – Cardiff/Newport area
- Rural – Area around Downham Market

The results from the analysis present the number of upgrades needed for existing sites and additional sites for each of the specific areas. The figures from the representative geographical areas have each been extrapolated to determine a nationwide picture for urban and rural areas. This is because these areas present some of the most significant technical, commercial and regulatory challenges.

There are some large gaps in infrastructure densification requirements in dense urban/urban environments. Based on our high level statistical analysis, which focuses on filling coverage gaps using cell ranges of specific use case capabilities, we expect there will be a need for many hundreds of thousands of small cell sites in urban areas in the UK. These sites are typically deployed at street level to meet the expected capacity requirements of future mobile broadband users in dense urban areas nationwide. The large densification numbers are predominantly driven when using the 24 GHz frequency band but could deliver ultra-fast broadband up to 100 Mbps per user at any location in a mix of low and very high speed mobile environments.

In the sections below we present the infrastructure requirements required nationwide.

5.3.1 Infrastructure densification requirements for UK extrapolation for MNO and other network infrastructure sites

We have estimated the numbers of sites needed at a national level for each clutter class extrapolated from the results of the specific dense urban, urban, suburban and rural areas analysis shown in section 9.3. The large urban and suburban numbers are driven higher by the limited samples of clutter data used for the specific area exercises. Furthermore, the small cell ranges, i.e. 80m drive the site densities beyond what may be considered economical or manageable by commercial operators. However, shared infrastructure numbers are within the expected orders of magnitude for small cell deployments in densely populated urban and suburban areas according to other studies[126].

[126] Techno-Economical Analysis and Comparison of Legacy and Ultra-dense Small Cell Networks, Tampere University of Technology, Finland and Elisa Corportation, 2014

	Estimated total number of sites needed for UK	
Use case (cell range)	**Dense urban (two single operator networks)**	**Dense urban (Multi operator)**
Machine Type Comms (500m)	3663	3170
Mobile Broadband 1 (80m)	15109	7616
Use case with (cell range)	**Urban (two single operator networks)**	**Urban (Multi operator)**
Machine Type Comms (500m)	24276	18382
Mobile Broadband 1 (80m)	369324	186732
Use case (cell range)	**Suburban (two single operator networks)**	**Suburban(Multi operator)**
Machine Type Comms (2090m)	19358	20809
Mission Critical (170m)	140514	75866
Mobile Broadband (80m)	610667	309014
Use case (cell range)	**Rural (three single operator networks)**	**Rural (Multi operator)**
Machine Type Comms (12,500m)	14673	15041
Mission Critical/Mobile Broadband (2620m)	14692	15042

Table 22: Estimate of total number of sites extrapolate from dense urban, urban, suburban and rural areas of the UK

Comparing the multi operator infrastructure locations with two single operator networks generally shows a reduced total number of sites needed. This demonstrates why site sharing with multi-operator capability will be needed for future networks. These results also show there is still a lot of densification still required specifically in urban and suburban areas to meet some of the modest cell ranges. Therefore, there is a need to focus on how this level of densification can be achieved economically to deliver the enhanced mobile broadband speeds envisaged for 5G.

An anomaly appears in rural areas because a similar number (to that of a single MNO portfolio for the area) of additional non-MNO sites were considered. This scenario assumed a greater use of utilities sites or pylons which increased the number of multi operator sites serving the area. Therefore, we multiplied the number of single operator sites by three.

For example, a detailed review of using the 1145 public buildings[127] to support densification would help determine what use they could be to support the future wireless networks. Given the level of densification shown above it is unlikely that the number of public buildings will be able to offer much support in this regard. This is possibly because there are too few buildings clustered where the sites are needed. However, a more detailed review of their locations relative to areas of high mobile traffic demand would be needed.

[127] Telecommunications & Digital Infrastructure Maps: Supporting Data, March 2015, DCMS

Further examination of other available infrastructure such as street furniture, in dense urban/urban/suburban environments would reveal whether the type of densification required is feasible in towns and city centers or if additional street works will be needed. This examination would also reveal how much additional fibre infrastructure is needed.

Therefore, addressing the challenges of identifying feasible infrastructure now will be critical to the successful deployment of future wireless networks within all populated areas of the UK.

6 The barriers and challenges of modern infrastructure deployment

Telecommunications infrastructure is an essential provision to the UK economy. Reliable, available and ever increasingly faster connectivity is needed to support long-term economic growth[133]. Research in the challenges of finding, enabling and accessing new infrastructure will be paramount to support this growth.

We have already discussed the varying nature of the arrangements in the telecommunications landscape due to the different operators and ownership structures, network capabilities and interconnectivity potential.

In this section, we identify where the key strategic challenges lie for modern infrastructure deployment in the four focus areas of the study, namely;

- Roadside infrastructure
- Rail infrastructure
- Small cell densification in urban areas
- Deployment of infrastructure in rural areas

In the case of roadside and trackside infrastructure there are limitations in terms of access which is restricted to qualified personnel only. This increases costs and adds delays to deployments. Other complexities on the trackside include the safety related considerations which requires only certified products to be deployed which impose additional design constraints on size, weight and other physical properties for equipment.

Furthermore, connection into existing trackside and roadside fibre is challenging given the limited access both in terms of number of physical connection points but also current usage which limits available capacity vital for future high speed networks.

A key challenge of enabling future infrastructure in urban areas is the access to suitable sites and availability of fibre at these locations. This includes deployment on street furniture, sides of buildings and other street works. Street furniture in particular means negotiating with local authorities who either sometimes have no processes or lengthy and complex processes which differ nationwide. This presents a challenge to MNOs and WIPs who have to separate negotiations with each individual local authority which is costly and time consuming.

In rural areas, the challenges are the building of suitably tall sites that provide sufficient wide area coverage, support multiple operators and economic enough to deploy in highly remote areas. Planning applications are lengthy and communities often disapprove of unsightly and tall sites in the countryside which are rejected and reapplied for at a more suitable location. The process can take many months and adds further costs which results in a less optimal deployment location.

6.1 Challenges for enabling infrastructure on roadside

Technical challenges relating to sites, availability, access and equipment

There are major challenges regarding access to Highways England owned infrastructure. Only qualified and cleared personnel can install and maintain equipment on gantries and other equipment that cross the highways.

In the case of NRTS infrastructure there are restrictions for access on health and safety grounds.

The densification of the roadside network to enable future network capabilities raises a number of challenges namely:

- Direct access and installation to roadside infrastructure by MNOs or WIPs would be needed particularly if mobile frequencies are to be used. At present this is not currently permitted
- Limited interaction and understanding of the full requirements given the few successful deployments between MNOs and HE to collaborate on site sharing and access to roadside infrastructure;
- Limited clarity on commercial incentives between different government departments (DfT, Ofcom, HE) and differences in local planning, regulatory.

There are varied and complex limitations in accessing fibre ducts and poles for future network expansion. We provide some examples of these limitations that may exist on the roadside infrastructure such as:

- Space; some of the existing ducts have limited space given the fibre that has already been deployed for NRTS. The available space may not be able to support future demand if it were a requirement for future wireless networks deployed on the roadside.
- Access risks; if accessing a third party duct with existing live services, there is a risk that the existing services could be compromised while new cables are pulled.
- Condition; Ducts can deteriorate over years. On the road the conditions are harsh and ducts can become fragile and unstable. A method to 'prove' the duct, is a process for checking the duct for damage or collapse. When collapsed ducts are located civil works are required to either repair or bypass the duct.
- Access to potential additional space for new equipment for functions such as local computing and storage that may be needed for enabling future network functions such as low latency and high reliability. Although this could be mitigated by a centralised RAN architecture (see section 4.2) in which the processing is all done centrally requiring only remote radio heads deployed along the roadside.

Commercial challenges

Deployment on Highways England land is expensive given the additional health and safety restrictions for accessing infrastructure. MNOs current practice is to deploy new sites on private land adjacent to the roadside often to meet the minimum backhaul requirements. Improved and more convenient access by third parties to roadside infrastructure (ducts, poles, overhead gantries) and the fibre network, would enable direct access to the high capacity required for future networks to support connected car use cases including vehicle management, passenger entertainment and driver assistance.

HE said that if an operator required a new IP circuit on the side of the road, new fibre would be laid from new equipment to nearest joint, with new cabinet, power and roadside routers, providing up to 100 Mbps. However, they also confirmed it is costly to do this and most often third parties choose DSL for the last few kilometers over existing copper and then join the fibre network at the next available point.

Other issues relating to the 'higher costs' include additional paper work and general administrative overhead. MNOs are required to adhere to these additional requirements when accessing the land owned by Highways England. Stakeholders informed us that it is more straightforward and less time consuming and thus cheaper to deploy sites on the adjacent private land than to have to negotiate with Highways England for access.

In the case of future network roll out, which would be technically possible, remaining issues would need to consider who maintains and controls the assets after installation and where priorities sit with respect to access and fault fixing. This demonstrates some of the uncertainties with future infrastructure roll out on the SRN.

Regulatory challenges

We found few regulatory challenges that would affect the deployment of infrastructure on the roadside. Regulatory challenges would arise if there were significant competition issues when allowing public operators to access public telecommunications assets such as the fibre infrastructure.

At present there are no dedicated frequencies used for vehicle to infrastructure applications in the UK. However, systems such as Dedicated Short Range Communications (DSRC) can be used at toll booths for automatic fee collection. Spectrum solutions for connecting broadband to vehicles are under development globally but as yet it is uncertain which bands will be used.

6.2 Challenges for enabling infrastructure trackside

Technical challenges relating to sites, availability, access and equipment

There are numerous technical challenges that would need to be overcome for enabling future wireless networks along rail routes.

At present there are a distinct number of mobile coverage 'not-spots' along the rail routes. These are the gaps in mobile coverage that appear due to many of the MNO site locations not optimised to serve the challenging rail environment terrain.

We have discussed earlier that the optimum technical solution is the deployment of infrastructure at the trackside to ensure there are no gaps in coverage. This presents a number of practical and technical issues relating to the physical deployment of new sites on the trackside.

The deployment of the GSM-R network, which was only completed in 2013, serves as an example of the technical challenges that must be overcome for such a solution. There is no previous example of deploying a wireless network for passenger connectivity on Network Rail land access before Project Swift.

Some of the technical and practical challenges that arise from the need to deploy a dense trackside network to enable future network capabilities include:

- Particular approaches to integration and methods of working are necessary to safeguard operational and safety principles, leading to costs and timescales which can exceed those in non-critical environments. Similar to the highways, only trained and qualified personnel are allowed to access the fixed and wireless trackside equipment.
- The environment at trackside is both electrically noisy (equipment subject to high voltage spikes) and subject to large vibrations. This means all equipment must be certified to a

minimum standard of acceptance by Network Rail[128]. This adds further cost to deployment of equipment only certified equipment is allowed to be deployed trackside.

- Ready access to power; There is no straightforward access to power new equipment at any point along the track. There are only limited power supplies at certain points which could be used otherwise, new power supplies at the correct voltages, will be needed at all necessary locations to power all the new sites.
- Sharing/access to existing GSM-R masts requires careful design work and planning to minimise potential interference and to ensure masts can support additional equipment such as antennas on the masts, additional feeder cables and space in the cabins/cabinets
- Limited interaction/collaboration, given the few successful deployments between MNOs and NRT to collaborate on site access to connectivity into trackside fibre;
- Limited clarity on commercial incentives between different government departments (DfT, Ofcom, NRT) and differences in local planning, regulatory.

Further challenges arise if there is a requirement to deploy new fibre cabling. The existing cabling arrangements are complex as there is a mix of power and telecommunications cabling present either laid trackside or elevated on posts beside the track. The concrete troughing already used for cable routes is already well occupied with existing fibre and power cables. There is a limit to new cable installation. The default situation is that new cables are installed along existing routes which requires a survey to determine the availability of space. The proportion of existing cable, upgrade, refurbishment and route clearance must be determined before new cable can be installed. Similar to deployment on the roadside the following common challenges apply on the trackside:

- Space; many of the existing ducts have limited space given the fibre that has already been deployed for FTN and FTN-X. The available space may not be able to support future demand if it were a requirement for future wireless networks deployed on the roadside.
- The existing fibre network, FTN, is largely encumbered by existing usage from connecting all the necessary operational equipment to the fibre network. This includes equipment such as GSM-R masts, trackside phones, signals and CCTV cameras. This means many of the fibres are used for operational purposes and thus become unavailable for any spare capacity. Furthermore, the legacy technology used for this equipment (such as Asynchronous Transfer Mode) would make connecting future high speed broadband equipment unusable as it will use IP-based technology.
- Access risks; if accessing a third party duct with existing live services, there is a risk that the existing services could be compromised while new cables are pulled.
- Condition; Concrete troughing is used that can deteriorate over years. There is risk of water ingress and cable deterioration too.
- There are limitations to potential additional space for new equipment for functions such as local computing and storage on existing masts. This would be needed for enabling future network functions such as low latency and high reliability. Although this could be mitigated by a centralised RAN architecture (see section 4.2) in which the processing is all done centrally requiring only remote radio heads deployed along the trackside.
- To manage the EMC risk to critical signalling systems, Network Rail also applies restrictions on emitted field strengths and the use of 900MHz spectrum by MNOs

[128] Network Rail product acceptance web page http://www.networkrail.co.uk/aspx/3262.aspx

Commercial challenges

One of the major commercial challenges in enabling infrastructure along the trackside relate to the cost of equipment. All equipment deployed trackside must be approved and accepted by way of certification from Network Rail. This process adds costs to standard commercial off the shelf equipment. The purpose of the approvals is to ensure that the equipment is safe, compatible, reliable, fit for purpose and does not generate unacceptable risks to NR infrastructure.

Once the equipment is certified, there are additional costs of gaining access to the site including permits, expensive engineers with the appropriate trackside qualifications.

Furthermore, if a new network/technology is to be deployed that integrates into the existing safety critical network then a new safety case would be needed. This would also generate significant costs to the overall process.

There are additional costs that also relate to the deployment of cabling on the trackside. For example, in our analysis we consider the option to deploy a new fibre network for the purposes of serving passengers with high speed connectivity. In this case there is added complexity in terms of new surveys and compensation for the third party infrastructure owners. They would need to move their cables out of the troughing and placing them back if they are being reused.

Assuming one of the deployment models of future networks requires one or MNOs to provide infrastructure, there are issues relating to the 'higher costs' (e.g. additional paper work and general administrative overhead) to MNOs when accessing the land owned by Network Rail. Stakeholders informed us that it is more straightforward and less time consuming and thus cheaper to deploy sites on the adjacent private land than to have to negotiate with Network Rail for access.

Regulatory challenges

There are significant regulations for rail operations that fall to the Office of Rail and Road (ORR) but with limited scope on telecommunications.

The main telecommunications licenses owned by Network Rail are for the operation of its GSM-R network. The GSM-R system is a mandate under European law and thus, currently can only be changed within the European Commission decision[129].

The spectrum licences are issued by Ofcom to Network Rail that allows them to operate the GSM-R network trackside infrastructure and train equipment. Only operational and safety related traffic is permitted on the GSM-R network. There is currently no possibility of using the frequencies (876 – 880 MHz paired with 921 – 925 MHz) for providing connectivity to passengers.

6.3 Challenges for the densification of wireless networks

Technical challenges relating to sites, availability, access and equipment

Site location availability is one of the most significant challenges facing mobile operators today. MNOs are continuously seeking new site locations to either extend coverage, densify the network in capacity constrained areas, or find replacement sites where an existing site is no longer available (e.g., because a site cannot be upgraded or the landlord requests removal of equipment). There is limited availability specifically of macro sites in urban areas and this trend is increasing. In urban areas the main rooftop sites have been occupied by MNOs for several years as they were used to deploy their initial coverage. Rooftop space is becoming

[129] European Commission Decision 2012/88/EU

crowded with prime sites already occupied by all operators. However, for future networks, equipment upgrades and enhanced capabilities will be required such as additional antennas and cabling and more space, power and cooling for processing type equipment. Furthermore, changes of use at existing sites may lead to increased rent demands and the likelihood of insufficient space on these rooftop sites to accommodate all additional new equipment may lead to increased site churn.

Availability of sufficient backhaul especially for an ultra dense network environment is also going to present a challenge to operators of 5G networks. Traditionally, commercial fixed line operators deploy infrastructure where there is demand so that a positive business case can be established. For example, BT and Virgin Media's strategies apply to connecting Superfast Broadband to the cabinet and premises and not 'future locations' where wireless operator masts might be deployed. The challenge, therefore, will be to bridge the gap between fixed operators and wireless operators plans so that access to sufficient backhaul at the locations where it is needed can be addressed.

Fixed microwave (radio) links offers an often quicker and cheaper alternative to fibre transmission but technology (in particular bandwidth) and spectrum availability will become limited; there is also an impact on site acquisition, given the additional load requirements of microwave dish antennas and the additional design and planning requirements.

Town and Country Planning rules also requires extensive Local Planning Authority and local community consultation which typically results in a compromise (e.g., to locate a tower on the side of the hill rather than the top of the hill), or smaller tower (a non-shareable structure), or a tower located within trees (improving visual aesthetics but reducing its coverage). Pylon sites can provide cover in rural locations and are marketed by a number of Wireless Infrastructure Providers. While the physical structure and location may be suitable, there are specific issues to consider including:

- Limited availability to low voltage power resulting in additional cost and complex power design (for example the need for additional equipment to ensure isolation of high and low voltage apparatus).
- Site provider rentals are not always clear e.g., a licence to operate on the tower is required plus a separate lease for any ground based equipment.
- Ongoing operational issues e.g., climb access to these highly hazardous sites is a limiting factor.

The availability/condition of ducts (access to fibre) and poles presents a number of varied and complex limitations for future network expansion. Some examples of these limitations include:

- Space; many existing ducts have limited space and are unable to address current market demand.
- A lack of accurate records means that available duct space can often only be ascertained through physical site survey adding time and cost.
- Access risks; if accessing a third party duct with existing live services, there is a risk that the existing services could be compromised while new cables are pulled.
- Wayleave; A wayleave is a right of way granted by the land owner to the owner of the duct. Usage rights similarly to those on mobile masts, could be restricted because the grantor wishes to generate further revenue in the future or in some cases, the duct is for a special concession which the grantor has an interest in. For example, a major City Council recently looked into the viability of using tram ducts to provide fibre connectivity to the surrounding council properties. When the wayleaves were researched, usage limitations were identified and the wayleave grantor wanted significant remuneration to extend the

usage clause from transport communications to council and other uses (as the council was also hoping to use it for commercial use).

- Condition; Ducts can deteriorate over years. When Openreach plans a new fibre run through existing ducts they first have to 'prove' the duct, checking the duct for damage or collapse. When collapsed ducts are located civil works are required to either repair or bypass the duct. The decision on which remedy to apply can be influenced by Local Authority restrictions on digging in certain areas, for example, operators are often prevented from digging up the road for a period of between three to five years after the road has been resurfaced or reconstructed.

Future wireless networks require a high density of sites to meet the proposed performance requirements. Access to, for example, lampposts, poles, ducts, street furniture, public buildings and other sites will be needed to enable expansion and densification. There is a complex and fragmented process to access this type of infrastructure as discussed above.

Small cell "street" deployments have increased in some markets (such as the US) but have failed to make a big impact in the UK[13]. One of the challenges linked to this is the fragmented deployment requirements and interpretation of planning rules by local authorities across the UK. Access to the street furniture requires permit to work, symology and traffic and pedestrian management (especially for road or lane closures). The process is seen as protracted leading to delays and additional cost (with local authority charging often seen as revenue generating).

The Independent Networks Cooperative Association (INCA) report that the barriers to FTTP deployment are often bureaucratic with network builders having to give 3 months' notice for work on all roads, even minor, limiting restrictions on working hours, and a lengthy embargo (up to 5 years) when it comes to deployment on recently laid footpaths and roads.[130]

Furthermore, the majority of street furniture in towns and cities is not capable of supporting communications networks i.e. there is no existing backhaul provision and limited ability to support large or heavy antennas. In some cases, the need to use existing contracted Local Authority (LA) suppliers to carry out deployment or maintenance work on street furniture creates duplication, additional cost and coordination delays. There is no standard approach and as such, MNOs and Wireless Infrastructure Providers will need to deal with each LA on a case by case basis. The lack of availability or suitability of existing street furniture could lead to operators deploying their own street infrastructure either as street works or on the side of buildings.

Another issue that occurs in the ultra dense, small cell environment is the potential for interference. The increased number of cells that are deployed in the coverage area of a macro cell will generate high levels of interference emissions from the mobiles in the small cell coverage area. While technical solutions exist[131] additional network management overhead and detailed network planning of capacity sites will be needed to ensure the quality of service and needs of users (within a 5G environment) can be satisfactorily met.

Finally, mass deployment of base stations can stir a public reaction to potential radiation hazards. To address concerns about radiation from masts, deployed in residential areas, or close to schools, mobile operators adhere to ICNIRP (International Commission on Non-Ionising Radiation Protection) regulations. ICNIRP is an independent scientific organisation, whose aims are to provide guidance and advice on the health hazards of non-ionizing radiation exposure (NIR). ICNIRP considerations are part of every mobile site design. In practice, this limits the location of certain types of antenna and dictates what needs to be done in terms of operational maintenance processes to maintain safe working practices. This can also limit the

130 http://www.inca.coop/policy/building-gigabit-britain-report
131 Network Densification: The Dominant Theme for Wireless Evolution into 5G, Qualcomm Technologies, 2014

location and types of antennas in an environment where lots of people can come in close proximity to the antenna.

Commercial challenges

The commercial challenges of infrastructure deployment relate to the availability of capital and investment, contractual terms and arrangements between landlord, tenants and operators, competition and markets, and wider economic policy.

The majority of MNO sites are leased from individual landlords. Changes to the requirements on site (for example, the need to install additional equipment) can raise the need to re-negotiate leases on thousands of sites. Understanding what can be done from an MNO perspective under an existing site lease is not always clear and is often site specific. Different lease durations, termination clauses, limited rights, and leases that have expired and held over can create a massive upgrade issue. This can also impact sites offered by WIPs who in turn may have their own landlords to negotiate with.

The telecoms rental market is now very mature. Site landlords and agents representing even small site portfolios are well informed limiting the MNO's negotiating power. Site providers often push for usage restrictions (for example, to deploy to new technology) in order to generate further revenue in the future. As such lease negotiations become protracted or an alternative, often sub-optimal, location is sought as the MNO does not want to set a cost precedent for thousands of sites.

Regulatory challenges

The regulatory challenges are focused on aspects such as planning permissions, operator code powers, limitations of site deployments, exclusivity in type of use, and any impact to the provision or limitation of access to electronic communication services by citizens.

Planning permissions and accessibility restriction for mast upgrade and changes are one of the major barriers to site acquisition and development. Planning may still be required depending upon location but can take time and vary depending on the local authority planning department and its application of planning regulations. Proposed legislation increasing the minimum height for permitted development will help but does not remove the need for consultation in some areas such as national parks and AONBs. In the new ECC proposals MNOs will be:

> *"encouraged to engage with local authorities and communities as a matter of best practice, and they will have to sign up to a code of practice on the siting of this infrastructure, to ensure that that is handled sensitively"*.

Some local authorities proactively support the aims of the ECC, to make site deployment and infrastructure access more straightforward, particularly if there are benefits to citizens and increased social inclusion. Newcastle City Council for example, has been actively engaging with mobile operators and neutral host operators to understand the requirements to enable the use of street furniture for wireless connectivity. A successful procurement of a wireless concession resulted in BT deploying a wireless network in the city centre including the use of public buildings around wide Newcastle-upon-Tyne district.

One particular report worth noting is a report by the INCA[132] (published in 2016) which identified the role Alternative Network providers (AltNets) could play in helping to build 'GigaBit Britain' using fibre networks from non-incumbent operators. The report highlights some specific findings relating to barriers currently in place when deploying fibre:

- New Roads and Street Works Act and Electronic Communications Code:

[132] INCA - Independent Networks Cooperative Association http://www.inca.coop/policy/building-gigabit-britain-report See page 27/28 of the report.

- Many INCA members report that the barriers to FTTP deployment are not financial, but bureaucratic, with rules relating to planning, permissions and permits holding back scheduled builds. Altnets report significant frustrations with a number of aspects of the New Roads and Street Works Act.
- It is usual for network builders to have to give 3 months' notice for work on all roads, even minor roads where works undertaken would not cause significant delay.
- Permits often impose very limiting restrictions on working hours, reducing the number of metres that can be dug in a day, and are required in circumstances where disruption from the build is likely to be minimal.
- The current approach to building on recently laid footpaths and roads also causes considerable delay because of the length the embargo, which can be up to 5 years, and a disjointed approach to agreeing with Local Authorities.

The new Electronic Communications Code (ECC) however includes new proposals:

> "*that provide an automatic right for network operators to upgrade and share apparatus without prior agreement or payment to landowners where there is minimal adverse visual impact as recommended by the Law Commission*".

This change will help MNOs and neutral host operators make the necessary upgrades and changes to their infrastructure when new technologies arrive without the additional cost and burden that was applied by the landowners. Currently leases have a typical 10-20 year lifespan and as such these recent changes may not help in the short term.

Any increase in bias towards the operator or potential for lower site rents raises the risk of increased site churn (through a landlord Notice to Quit (NTQ) – where the landlord serves notice on the MNO to remove its equipment). Increased property values and other commercial interests such as potential redevelopment opportunities become a more attractive option than the revenue from telecoms. Constant site churn or NTQ could impact the processes for enabling future wireless networks as MNOs often have to move quickly in order to find alternative locations. The process can lead to uncertainty, additional cost and in some cases an impact on consumer quality of service (e.g., loss of coverage). One mobile operator confirmed a landlord can issue a NTQ with no future certainty of regaining access to the developed site.

The need for densified networks on street furniture and the potential "land grab" where a single operator or neutral host procures exclusive access rights to use street furniture in towns and cities can both create and resolve issues. Where access processes are streamlined, already in place, and commercially attractive, third party operators will benefit. If not, the operators will look for alternatives (deploying their own street furniture or reaching agreement with building owners).

There are regulatory challenges that remain in relation to the UK's current fibre deployment status. The market structure and incentives for long-term investment may not encourage other private operators to invest in more fibre infrastructure. There are diverse strategies amongst operators on investment in future fixed infrastructure. For example, BT continues to pursue the development of copper-based technologies compared to CityFibre who are growing their fibre to the premise (FTTP) network as an alternative to incumbent offerings.

According to a parliamentary report on fibre future[133], access to BT's ducts and poles has proven a challenge for competitors due to restrictive access, current charging structures and costly surveys. UK Government and Ofcom have been developing ways to provide competitive

[133] Establishing world-class connectivity throughout the UK, DCMS, July 2016
http://www.publications.parliament.uk/pa/cm201617/cmselect/cmcumeds/147/14708.htm

options for other telecommunications operators, particularly proposals within Ofcom's Digital Communications Review to help facilitate further access.

The report makes some recommendations, namely:

- Easy access to BT's passive infrastructure on reasonable terms is vital in order to allow network builders to come to better investment decisions.
- Openreach providing online access infrastructure maps so that providers can plan their deployments.
- Pricing will also need to be regulated in a way to encourage investment.
- Openreach's processes must be realistic and flexible to meet alternative network builders' needs and not just those of BT.
- Openreach must demonstrate a willingness to deliver access arrangements that are flexible and encourage take up.
- Ofcom must treat this issue with much more urgency and should set out a programme of work to facilitate take-up of access to Openreach's ducts and poles facilities by non-BT providers.
- Access arrangements will need to be supported by an Alternative Dispute Resolution process to resolve any problems, perhaps in line with the mechanisms used to support effective functioning of the Electronic Communications Code.
- Conduct a review of business rates to determine where they may not be fit for purpose.
- Determine whether access to the broadband investment fund would be necessary.
- Identify the most efficient use of public subsidies in network infrastructure investment.

6.4 Challenges of deployment of infrastructure in rural areas

Technical challenges relating to deployment of rural sites

The technical challenges of rural site deployment are mainly related to the need to build tall sites in remote areas (that provides wide area coverage) with limited access to power and backhaul. MNO infrastructure sharing and network consolidation means new planned site deployments particularly in rural areas are likely to be shared sites. As already discussed in section 3.2 MNOs plan to extend coverage to fill many of the remaining not spots in the UK which will be shared sites. However, site sharing with other operators remains a challenge and is often more costly and protracted process than initially thought, for example:

- Despite the LPAs preference to utilise existing structure, to save money and time, sites are often deployed to meet MNO "minimum" requirements and not necessarily built with sharing in mind.
- Collaboration between Wireless Infrastructure Providers is limited given the potential reduction in available revenue.
- MNOs have implemented their networks based on varying business objectives and investment criteria which does not necessarily align with other operators objectives and investment decisions. This misalignment can be a challenge to resolve if increased levels of sharing are to be considered.

Town and Country Planning rules also requires extensive Local Planning Authority and local community consultation which typically results in a compromise (e.g., to locate a tower on the side of the hill rather than the top of the hill), or smaller tower (a non-shareable structure), or a tower located within trees (improving visual aesthetics but reducing its coverage). Pylon sites can provide cover in rural locations and are marketed by a number of Wireless Infrastructure Providers. While the physical structure and location may be suitable, there are specific issues to consider including:

- Limited availability to low voltage power resulting in additional cost and complex power design (for example the need for additional equipment to ensure isolation of high and low voltage apparatus).
- Site provider rentals are not always clear e.g., a licence to operate on the tower is required plus a separate lease for any ground based equipment.
- Ongoing operational issues e.g., climb access to these highly hazardous sites is a limiting factor.

In the case of rural areas most site deployments would be greenfield or upgrade to existing rural sites. There are a number of practical limitations of rural site deployment including limited access to backhaul and power sources, and the construction of long access tracks and stronger towers due to higher wind-speeds. In the more remote areas, e.g. Dartmoor and Pennines, where there is sparse population, it is extremely challenging to find any power and backhaul close to the potential sites.

This means many new site deployments require newly built access tracks, site compounds, long trenches for power and backhaul and tall masts which in some cases prove too uneconomic to build.

Commercial challenges

The commercial challenges in rural areas are predominantly based on the high costs of the large site build and the civils. Rural sites therefore should be built to support multiple operators to minimise the number of planning applications and the sites themselves which communities typically disapprove of being deployed in the countryside.

However, to minimise cost and accelerate deployment many new greenfield sites are built with minimal expansion in mind. The compounds are typically big enough to house the necessary equipment in a cabin or cabinets, and with cable trays just big enough to support the limited number of feeder cables for the antennas. In future networks, any upgrade to antennas or additional equipment for processing and storage, will require potentially stronger masts and larger equipment footprints. Space to expand the equipment at existing sites may require additional site provider or Local Planning Authority (LPA) agreements resulting in delays and additional cost since landlords seek to capitalize on these changes.

There are further limitations in the deployment of infrastructure in sensitive areas such as Conservation Areas, Listed Buildings and Areas of Outstanding Natural Beauty (AONB). The lower population densities in these areas, offer a diminishing return and as such a questionable return on investment for mobile operators.

Regulatory challenges

The regulatory challenges are focused on aspects such as planning permissions, operator code powers, limitations of site deployments, exclusivity in type of use, and any impact to the provision or limitation of access to electronic communication services by citizens.

Planning permissions and accessibility restriction for mast upgrade and changes are one of the major barriers to site acquisition and development. Planning may still be required depending upon location but can take time and vary depending on the local authority planning department and its application of planning regulations.

Proposed legislation increasing the minimum height for permitted development will help but does not remove the need for consultation in some areas such as national parks and AONBs. In the new ECC proposals MNOs will be:

> *"encouraged to engage with local authorities and communities as a matter of best practice, and they will have to sign up to a code of practice on the siting of this infrastructure, to ensure that that is handled sensitively"*.

Some local authorities proactively support the aims of the ECC, to make site deployment and infrastructure access more straightforward, particularly if there are benefits to citizens and increased social inclusion. Newcastle City Council for example, has been actively engaging with mobile operators and neutral host operators to understand the requirements to enable the use of street furniture for wireless connectivity. A successful procurement of a wireless concession resulted in BT deploying a wireless network in the city centre and public buildings around Newcastle.

Future networks, including the sites in rural areas, will depend on access to high speed fibre and as discussed in section 3.2. The AltNets, as described earlier, could play a useful role in the rural areas as they plan to connect cities. However, the same challenges apply in rural as in urban and suburban areas and therefore revisions and improvements in planning consents would help with more efficient and potentially more economic deployments.

The infrastructure requirements analysis in section 5.1 has shown a dependency on access to specific spectrum bands to achieve the particular inter site densities. There is a push from the mobile industry to ensure that all the spectrum bands required for 5G will be available and there is no certainty of this. The challenge with spectrum is the global and harmonised nature by which it becomes available. The regulatory challenge arises from the successful conclusion of coexistence and other technical and regulatory analysis, forward planning and preparation to ensure the desired spectrum and bandwidth is identified and made accessible to the diverse mix of operators in a way that supports the future frequency assignment regimes and the proposed network architecture.

6.5 Possible solutions to the infrastructure challenges

Collaboration and joined up thinking between government departments, regulators and planning authorities, such as DfT, BIS, DCMS, Home Office and Ofcom is one strategy that could be used to raise awareness of the potential use of all existing telecommunications infrastructure holdings and how they might play a role in supporting future networks.

The consideration of telecommunications infrastructure integration at the early stages of development for all infrastructure providers and operators would also raise awareness of forthcoming developments. For example, prior to a national/regional infrastructure deployment (e.g. HS2) a consultation or study on the future communications needs of not just the service being provided, such as rail, but the wider provision of telecommunications to the surrounding roads, towns, villages or industrial or utilities sectors.

Encouraging more active sharing of radio base station equipment, spectrum and other common telecoms equipment will demonstrate cost efficiencies and maximize network coverage which could lead to consumer benefits in improvements in quality of service.

Government led policy to enable local authorities to offer street furniture and other public assets to third party telecommunications operators in a common and flexible way so that operators need only consider one or two approaches rather than each local authority using its own specific approach.

7 Opportunities and barriers of infrastructure sharing to support 5G

There are several options for infrastructure sharing which can be seen in Figure 39 right. In the UK MNOs have extended into RAN sharing from initial passive sharing arrangements. 2G/3G/4G RAN sharing is becoming more common and thus yielding greater cost benefits in reducing the amount of active equipment needed at sites. The other options, such as network roaming are particularly complex or induce additional complexity in terms of technical implementation and operational costs.

There are more advanced infrastructure sharing techniques on fixed networks such as core network sharing which involves either transmission ring sharing or core network logical entity sharing. In transmission ring sharing one operator obtains access to the spare capacity on another operators' core network by way of leased lines.

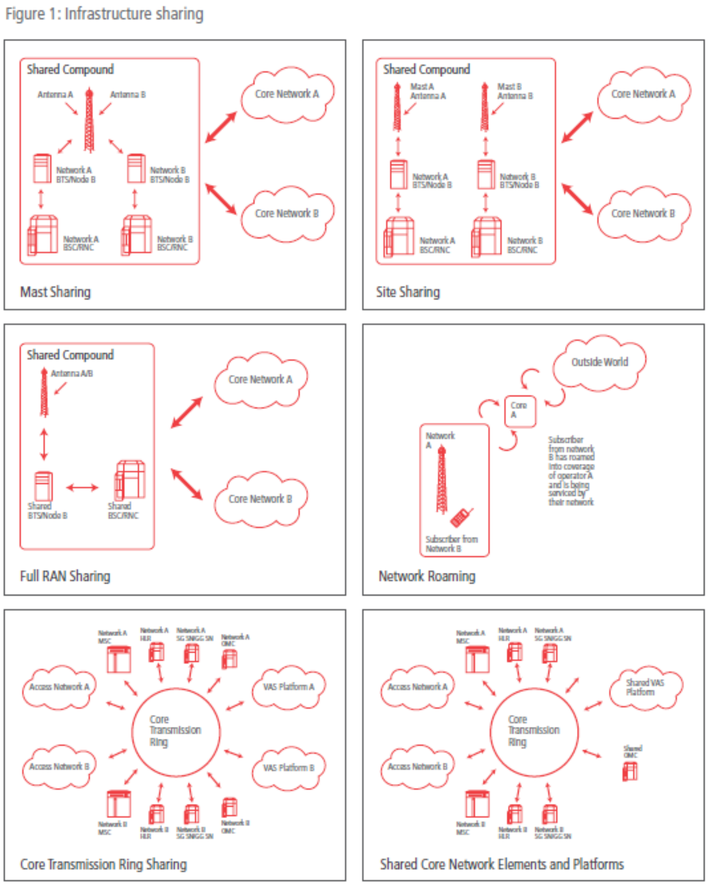


Figure 39: Infrastructure sharing options. Source: GSMA[134]

7.1 Opportunities for site sharing

As described in Section 3.2.3 the key driver for infrastructure sharing is largely commercial with site consolidation increasing in recent years following the formation of MNO joint ventures such as CTIL and MBNL. A significant amount of network consolidation has taken place removing duplicate sites and thus saving both capex and opex. There is an immediate benefit in capex saving through the need to deploy equipment (for example, when upgrading a site to 4G) on only a single shared site or the need to build site as a result of churn. Significant opex benefits are also seen with a reduction of site rentals, business rates, transmission and operational costs. However, many of these cost savings are longer term and reliant network decommissioning and existing site lease termination clauses.

In addition, site sharing it has presented opportunities for operators to deploy network assets in new locations improving the service offered in that area. Deployment timescales (particularly acquisition and build) can also be improved but this is heavily dependent on the capability of the shared structure (see below).

[134] Mobile Infrastructure Sharing, GSMA

In the case of supporting future networks site sharing will enable:

- Increased service coverage with access to additional sites and a lowering of the RoI barrier in new locations due to shared capex and opex across multiple mobile operators.
- A reduced overall capex/opex creating the potential for greater investment in innovation and improve MNOs ability to meet the more challenging 5G KPIs.
- Further opportunities driven by the technologies under development within 5G standards community. For example, network slicing, multi-domain orchestration and Infrastructure as a Service are new.
- Innovations in the use of small form factor and low energy equipment.
- Lessons learned from complex deployment arrangements of co-existence of multiple technologies on shared infrastructure (e.g. Broadcast, cellular and TETRA on the same mast).

7.2 Barriers preventing sharing of infrastructure

There are several barriers to site sharing which can be attributed to a number of key technical constraints. However, commercial relationship between MNOs, wireless infrastructure providers and landlords is often the most significant factor in many of the site sharing deals that have taken place. An overview of some of the technical and commercial barriers is given below:

- **Infrastructure capability –** site sharing is heavily dependent on the capability of the "receiving" infrastructure.
  - The existing site lease has to be examined to ensure that additional equipment can be accommodated and work done within existing rights and with or without landlord consent. Any issues in this area will result in an often lengthy and costly negotiation process with the site provider.
  - The existing site should have sufficient space and any mast checked to ensure it can withstand any additional antenna loadings. Issues in this area will lead to costly tower strengthening and/or site redevelopment costs.
  - A knock on impact of any redevelopment work e.g., the need for a new larger tower, is the need to gain planning permission. The process can be lengthy and will depend upon the work to be carried out and the geographic location of the site (e.g., industrial vs AONB).
  - While the consolidation of operators on a shared site provides the opportunity to share transmission backhaul this would need to have sufficient capacity. An upgrade of the link (e.g, to deliver fibre to site) can involve additional costs and timescales. For example, the need to change microwave dish configuration could involve additional lease negotiations and tower strengthening and the need for fibre may involve additional wayleaves.
  - Suitability of ducts in the ground poses issues with access for future technologies. Many of the ducts are old and often full with high risk of collapse. Lengthy and costly duct surveys and remedial measures may lead a new entrants to seek alternative solutions and new routes.
  - Capability issues can be overcome when future sharing or expansion is designed into the initial deployment. However, as described earlier, introducing this additional "scope" upfront will result in additional costs and timescales and so an operator is often reluctant to do so. This is particularly prevalent on non-MNO sites (for example, Network Rail, Airwave and local authority street furniture) which have been deployed to meet a

specific minimum need. Infrastructure sharing of these sites would invoke all the issues mentioned above.

- **Access and safety constraints** – access restrictions often create barriers for deployment, upgrade, optimization, operations and maintenance – e.g., Network Rail, where sites are often trackside and require specially trained and certified personnel to gain access. MNOs require 24/7 access to sites and this may be difficult if the right people are not available or if a track closure is needed. The same would apply to sites located on the SRN or on local authority street furniture given the need for road closures in many cases.

  There are access constraints to ducts, cabinets and poles from the fixed network perspective since many are owned by incumbent operators and access can be protracted and costly process.

- **Technology constraints** – Potential interference issues can also create a barrier when it comes to the spectrum and technology used on a site. Network Rail for example, does not allow deployment of MNO 900MHz technologies on its trackside and anything installed must meet certain field strength criteria – which must be tested before being switched on.
- **Limited resilience** – Site sharing limits the potential resilience for network operators since if a shared site goes down, this may impact all operators instead of just one. Efforts to ensure maximum availability and resilience will be key in future networks.
- **Regulatory/planning constraints;** There are a number of regulatory and planning constraints for mounting equipment on lampposts or side of buildings that may contravene local planning laws. Furthermore, the interpretation of these laws can vary between the different local authorities resulting in any potential operator having to negotiate multiple access agreements, deployment and operational processes and procedures.

Barrier preventing sharing	5G solution	Other practical solution	Barrier preventing sharing removed?
Infrastructure Capability	Small form factor equipment, smaller antennas for mmWave bands, low energy equipment	Coordination between parties in the assessment of future public infrastructure deployments to determine potential sharing opportunities Common processes and policy on de-minis form factor to ease installation process	Partial
Access and safety constraints	Innovations such as C-RAN will allow larger physical separation between active equipment and antennas reducing the need for access to “sensitive” areas	A review of current policies and procedures to minimize the barriers to sharing while maintaining a safe working environment. More transparency in the access process, willingness on all parties to work together including landlords better understanding of the issues. Develop dispute resolutions in policy, understanding of the backhaul requirements by enterprise and public building infrastructure	Partial. Since these aspects do not directly remove the barriers but rather help support the case for more sharing

Barrier preventing sharing	5G solution	Other practical solution	Barrier preventing sharing removed?
Technology constraints	Network slicing, multi-tenancy, multi domain orchestration, adaptive allocation of network functions		Yes
Limited resilience	Network slicing, multi-tenancy, multi domain orchestration, adaptive allocation of network functions	Additional site level investment to provide power and transmission resilience and increased security	Yes
Regulatory and planning constraints	Small common form factor, smaller antennas, low energy equipment	Additional guidance or mandate from central government on the interpretation of planning regulations Highlighting the benefits of giving telecoms operators the same powers as utilities	Yes

Table 23: Barriers preventing sharing versus 5G solutions to remove barriers

The above 5G solutions and key technological advancements expected to emerge could potentially help remove some of the barriers to wider site and infrastructure sharing. However, similar to the deployment of in-building small cells, raising awareness of the benefits and issues with building owners, infrastructure owners and shift in culture in terms of supporting densification and allowing site sharing will help to meet the requirements of future networks in a more coordinated and timely way. These solutions will vary in terms of complexity and cost. However, the overall impact of infrastructure sharing as seen in Figure 39 shows how increased sharing can help to significantly reduce costs. These figures are from a European 5GPPP study, 5G NORMA which examined the cost impact of deploying multi-tenancy network elements for macro cells and small cells to serve a 37km^2 area of Central London. Cost savings are already being delivered through the level of sharing currently seen in the UK. However, further sharing would offer greater savings in capex/opex but would require additional effort in terms of reducing barriers at the early stages of network design and deployment planning in order to ensure efficiencies and potential cost savings can be achieved.

Operator sharing options	NPV of network costs (2020-2030)	NPV as % of not sharing case
4 x 1 operators not sharing	£292 million	100%
2 x 2 operators sharing	£212 million	73%
1 x 4 operators sharing	£172 million	59%

Table 24: Example access network costs based on sharing scenarios. Source: 5G NORMA[135]

[135] Deliverable D2.2 Evaluation methodology for architecture validation, use case business models and services, initial socio-economic results, 5G NORMA, European Commission H2020 study, August 2016

8 Conclusions

We have conducted an extensive analysis of the capability of existing telecommunications infrastructure in the UK that could help enable future wireless networks. In particular, we have found that tens of thousands of kilometers of fibre and copper have been laid and tens of thousands of wireless sites have been deployed across the UK, all by different operators/owners and all serving a variety of business, consumer and operational users. Given this amount of deployed infrastructure, there are still major gaps in the UK's telecommunications capability to support some of the key 5G use cases such as enhanced mobile broadband or mission critical communications.

This is because of the way in which these networks have been designed and built, specifically for the purposes of serving their end users and customers. The public telecommunications operators such as BT, Virgin and the MNOs have the most flexible networks since the infrastructure is deployed in locations of greatest demand and commercial interest and the largest concentration of the population. However, we found there are some significant opportunities to deliver future 5G services if access to private network infrastructure such as high capacity fibre along the roadside including access to gantries and similar along the rail routes.

We provide our overall conclusions in the following sections with a focus on enabling connectivity to the existing roadside infrastructure, trackside infrastructure, densification in urban areas and filling coverage gaps in rural areas.

8.1 Key messages

The study found that there are significant gaps in capability between the existing telecommunications infrastructure and the aspirational requirements of future networks and technologies. Specifically, the study has explored:

- why there is still poor mobile coverage on parts of the motorways and major trunk roads;
- why it remains difficult to deploy infrastructure on the trackside;
- the challenges facing mobile operators deploying large numbers of smaller cells (densification) in urban areas, as needed to meet the continued surge in the use of mobile data amongst consumers and businesses; and
- mobile coverage gaps in rural areas.

The key messages from the study are as follows.

Access to motorway and major A road infrastructure (eg overhead gantries and bridges) and fibre presents an opportunity to enhance connectivity to vehicles on the roadside

- The telecommunications infrastructure deployed on the roadside consists of nationwide high speed data capacity through an optical fibre network on almost all of the motorways and to a much lesser extent on the major trunk roads. At present, it solely serves both safety and operational uses. We have found there is spare fibre capacity and duct space that could be readily used by third party operators to provide better wireless coverage and to deliver high speed connectivity to vehicles enabling numerous transport related applications
- Although there is no existing wireless infrastructure on the roadside, current connectivity to vehicles is provided by the mobile operators using land adjacent to the roadside. This land

is typically privately owned (e.g. by farmers). As a result, 2G, 3G and 4G service is not available everywhere on all motorways and trunk roads because topographical challenges (such as cuttings, trees, embankments or landscaping) limit mobile coverage.

- Access to the physical structures such as gantries, bridges and road signs would be needed to enable future wireless networks. Also, connection into the high capacity roadside optical fibre network would be needed to meet the performance requirements of future networks.
- Deploying new mast sites or mobile infrastructure along the motorways and major trunk roads presents some practical challenges. Given the Health and Safety issues and disruption associated with road or lane closures, access to the roadside will have to follow the appropriate governance and procedures. This means specialist approved contractors are required for deployment projects. Supervision may also be required which is likely to increase implementation costs and timescales.

New trackside wireless infrastructure could offer very high capacity to train passengers

- In the case of trackside infrastructure, enabling high speed wireless connectivity for passengers would need brand new infrastructure including both wireless sites and fibre optic cable. Deployment of new sites would require identifying potentially thousands of suitable locations along the trackside that can readily mount to the fixed (non-telecoms) infrastructure.
- The provision of dedicated connectivity to passengers is dependent on the availability of suitable frequencies that can provide ubiquitous coverage and capacity along the rail corridors. This is essentially a backhaul architecture which means there is no dependence on access to mobile operator spectrum because the trackside masts could connect to the train antenna using a suitable frequency band subject to regulatory conditions.
- However, similar to the roadside, access to the certain trackside infrastructure presents a challenge for third parties. This is due to the essential safety qualifications engineers require to install any equipment at these potentially dangerous locations
- Deployment of a new wireless network will be costly and time consuming given the access limitations and therefore, any new infrastructure should be pre-equipped with the necessary capabilities to support the new mobile technologies that are being developed.

A significant increase in the number of small radio cells (located on street furniture, small masts, walls etc) is needed to meet the performance requirements of future networks in urban areas

- It should not be assumed that small radio cells will be cheaper and quicker to deploy. This is due to the significant backhaul requirements, and urban restrictions such as Local Authority permits and traffic management. The volume of sites required will be significant so strategic Government and Local Government support will be needed to ensure networks can expand to meet future requirements in dense urban areas.
- Most of these wireless cells will need to connect to the fixed telecommunications networks so operators will have to be prepared for large scale deployments. BT, for example has started testing the new software and virtualised network technologies in readiness for connecting the numerous wireless sites of future networks. These will likely become commercially available around 2019 coinciding with the completion of 5G standards and live trials.

The MNOs have committed to increased geographical coverage which will help to fill some of the coverage gaps in rural areas

- Low demand together with the backhaul challenges (including high backhaul costs) in rural areas has meant rural deployment has been a lower priority for the MNOs. This is because the investment and focus needed has been on programmes such as 4G deployment and network consolidation, thus many not-spots can still be found throughout the UK. This remains a highly political issue with national roaming recently proposed as a solution by Members of Parliament. Ofcom consulted industry on the merits of national roaming as an alternative solution for addressing the coverage issue. However, this has since been abandoned in favour of a legally binding agreement with MNOs to increase national coverage.
- Mobile network operators have committed to invest in further infrastructure to fill many of the remaining mobile coverage gaps that exist in rural areas. This commitment aims to raise the mobile coverage level to geographical (e.g. roads) as well as populated areas.
- Government has recently revised the Electronic Communications Code which regulates the relationship between electronic communications network operators and site providers in the UK. It underpins agreements to host and maintain communications apparatus on land and property. The Government wants to reform the Code to put in place modern regulation which fully supports the rollout of digital communications infrastructure. The intention is to make site deployment easier everywhere, including in rural areas but it isn't yet clear how this will assist MNOs deploy quicker and easier.
- Government has also recently announced amendments to the Town and Country Planning (General Permitted Development) (England) Order 2015 that aims to speed up the deployment process. This only applies to England but there are ongoing discussions for Wales, Scotland and Northern Ireland.

We note from above there are a number of overarching requirements to consider for the deployment of new infrastructure to enable future networks. Site sharing, for instance is a common approach used by MNOs today and will be essential in future to support the varied multi-operator use cases. This is particularly apparent for trackside infrastructure, roadside infrastructure and new mobile masts.

Another consideration is the requirement for wide spread availability and access to suitable fibre in all relevant locations. However, challenges remain with the current state of access and condition of ducting in roads and footpaths. We provide a more detailed overview below of our findings from the study across the four key focus areas.

8.2 Opening up roadside telecoms infrastructure could pave the way for high speed mobile connectivity to vehicles

The telecommunications infrastructure deployed along the roadside, mainly the motorways and some major trunk roads, provides high capacity optical fibre connectivity for road transport specific operations. This is a private network (closed to non-road transport related users) which connects dedicated equipment such as CCTV cameras, information signage and message boards to gantries.

The study found that not all of this fibre is being fully utilized: Highways England's National Roads Telecommunications Service (NRTS) uses less than 20% of the fibre capacity to serve all today's needs on the Strategic Road Network (SRN). This presents an opportunity to deploy new dedicated wireless network infrastructure and connect it to the spare fibre.

We highlight a number of reasons why this opportunity would benefit future UK communications networks:

1) Opening up access to nationwide spare and available fixed bandwidth could unlock numerous future applications linked to connected car services with significant benefits to road safety and potential improved traffic flow.
2) The roadside fibre currently runs through parts of the country that is currently unserved by existing broadband providers. This could potentially open up new broadband markets in these remote areas if given the appropriate access.
3) There has been a considered amount of future proofing to ensure there is sufficient capacity for systems that may be more bandwidth hungry in future. The spare capacity could also be present an opportunity for future passenger connectivity enabling in-car multimedia entertainment and driver assistance also creating new network architecture and services models.

We conducted a network dimensioning analysis to understand the infrastructure capabilities needed to deliver future enhanced mobile broadband connectivity to road users. The following site numbers and costs have been estimated for both a dedicated roadside network and expansion of the MNOs network adjacent to the roadside.

1) To deliver the very high mobile broadband speeds that would be expected in 5G the number of sites needed along the motorway part of the SRN in Britain ranged from approximately 7300 to 18270.
2) Connecting these sites to the existing roadside fibre and fixed infrastructure along the motorway part of the SRN in Britain would cost between £183 million and £457 million.
3) The number of required sites increases to approximately 24300 - 60650 to cover all the SRN in Britain. However, new fibre would be needed in all non-motorway sections of the SRN to replace the existing copper cable.
4) Connecting these sites to the existing fibre and fixed infrastructure and newly laid fibre where it does not already exist would cost between £1.75 bn and £5.1 bn.
5) An alternative would be for MNOs to increase their sites along the roadside (assuming it is on the land adjacent to the roads). Our cost estimates based on MNO deployments ranges from £743 – £1.1bn for all motorways in GB. This increases to £4.1bn - £7.8bn for all the SRN in Britain.

However, there are a number of practical challenges, particularly in relation to accessing the roadside infrastructure by future network providers. There would be a requirement to build new sites on the roadside and mount equipment on existing signage, bridges and gantries. This requires access to both power and fibre at the desired locations, which at present is not possible. Furthermore, the stringent safety requirements to access the roadside means typical MNO installers may not be sufficiently qualified. This is likely to result in higher costs and potential delays in deployment. Furthermore, network roll out at the roadside will cause disruption to road users including lane closures and network downtime. Nevertheless, a new wireless network and architecture could enable an entire ecosystem of vehicle connectivity applications, operators and use cases.

Considering, in-car Wi-Fi today for example, connects directly to passengers' devices and uses the mobile operator network as the backhaul from the car to the internet. The service is patchy along some of the major roads in UK areas where there is lack of coverage. A dedicated roadside network would provide not just complete coverage of the SRN, but robust contiguous high speed mobile connectivity to vehicles. Besides the technical and practical challenges already identified, access to suitable additional spectrum would be needed. This could either use the MNOs spectrum and technology which means ensuring the infrastructure meets the MNO's technical requirements, or use some other technology and band such as 5 GHz. The infrastructure, therefore, would need to support the required amount of bandwidth and potentially multiple operators. In turn, specific radio receiving equipment would be needed for the vehicles to connect with new roadside infrastructure which adds further complexity, cost and time constraints.

Overall, any decision to invest in new roadside wireless infrastructure should be ready to support the full set of relevant 5G requirements for high speed throughput and low latency.

8.3 A new high capacity trackside infrastructure is the optimum approach to enabling ultra-high speed connectivity for rail passengers

The railway trackside network architecture is similar in some ways to the roadside. In the case of rail however, there is a mix of dedicated trackside fibre and a wireless network that provides safety critical communications to drivers and signallers. The trackside infrastructure does not provide connectivity to passengers. Wi-Fi on board trains today is provided through an onboard gateway that connects back to the internet via the MNOs networks but many locations on the rail routes are poorly served.

In the rail environment, there are already almost 2500 wireless sites providing secure voice and safety-related signaling functions. These sites form part of a European mandated system that connects into a dedicated optical fibre network, which runs along all routes managed by Network Rail. There are hundreds of thousands of other devices (CCTV cameras, trackside phones, signals) that connect to this fibre network, which has now become largely encumbered from the different legacy technologies in use. Subsequently, Network Rail has deployed an enhanced and much faster fibre network (known as FTN-X) with very high capacity creating a nationwide core network. The aim is to eventually transfer existing assets to this new network so that everything operates on a single telecommunications protocol, also known as Internet Protocol (IP). The access layer of this network is yet to be built and will take several years to do so, but once in place all existing equipment will be connected to it.

Our analysis found that given the major challenges of access and safety implications of the existing infrastructure, a completely new wireless network would be needed to support passenger broadband. Thus, we determined the number of new sites required to deliver the end user performance targets. The number of new sites required ranged from 3270 to around 8370, depending on the required mobile broadband speeds. In the lower bound case, the estimated new site costs to deliver mobile broadband (in the order of 500 Mbps per train) to passengers today would be approximately £135 million. This does not include upgrades to the existing GSM-R masts but new, smaller sites. These sites would need to connect to a new fibre network which would approximately cost £150 – £250 million. Therefore, total costs for a new wireless passenger network is in the range £285 – £385 million. To deliver the future network speeds expected for future 5G the cost estimates increase to £495 – £595 million. The costs are not much cheaper if upgrading GSM-R masts if less restrictive access were possible in future. It should be noted that these high level estimates are dependent on numerous assumptions relating to unit costs, track access, choice of technology and network architecture.

The challenges and complexities arise when third parties wish to deploy equipment on the trackside. Another major issue from Network Rail's perspective is the need to physically separate safety related network functions from other non-safety related communications traffic to avoid any potential impact on rail operations. However, in future with 5G's proposed virtualized network functions this may not be necessary as the technology is expected to handle the full mix of traffic requirements. Another challenge is the need to physically mount telecommunications equipment on existing non-telecoms infrastructure such as gantries and trackside poles. The risks from infrastructure deployment can include:

1) interference to the safety-related GSM-R network;
2) high cost to ensure equipment is suitable (or hardened) to operate within an electrically noisy rail environment
3) available trackside space to build in the 5G capabilities such as multi operator capability; and
4) stringent trackside access requirements for installation.

The very high and necessary safety requirements are mitigated by deploying a completely separate trackside communications network for passenger connectivity. This becomes less restrictive in terms of access enabling more commercial incentives for other operators to deploy equipment. However, usual safety practice such as line closures or speed restriction will still be required for network rollout which will mean reduced services on routes as the equipment is deployed.

8.4 Dense deployment of small cell sites is needed for future networks in urban areas

Mobile infrastructure in dense urban and urban areas are typically deployed on the rooftops of office blocks and residential buildings or on poles deployed in the street. These sites provide the key capacity layer for mobile broadband. The mobile broadband speeds provided by the MNOs, reached, on average, over 15 Mbit/s[136] download in UK cities at the end of 2014 which is similar to some home broadband services.

However, there is growing expectation and demand for this mobile connectivity to continue to increase to ultra-fast speeds (100 Mbps) while on the move. This will require a much increased density of new sites in dense urban areas to meet the mobile traffic capacity needs of future wireless networks, potentially thousands. For example, our study found that as many as 42,000 small cell sites could be needed to deliver the ultra-fast broadband speeds expected of future networks in an area the size of the City of London (based on certain spectrum and technology assumptions).

A number of significant challenges and issues emerge in order to achieve this. For example, access to sufficiently capable and available optical fibre is needed at locations where small cell sites will be deployed. New equipment will be deployed on existing street furniture such as lampposts, signs, sides of buildings at street level so the sites are closer to the users. It remains uncertain how big, heavy or capable the new equipment will be and this may limit what future services and applications can be delivered from these site types.

Fixed telecommunications operators will also play a crucial role in these enabling of future networks. It is no longer just about laying more fibre in ducts but the formation of suitable arrangements amongst operators in terms of access flexibility, maintenance, sharing of contractual obligations and future deployment. BT, Virgin Media and Vodafone (formerly Cable & Wireless) already carry significant proportions of data traffic in the UK and thus will no doubt form part of the future ecosystem. The challenge however, is extending the reach and connecting into this fibre from non-typical locations, so that operators can roll out new sites in a cost effective and timely manner.

[136] Ofcom publishes 4G and 3G mobile broadband speeds research, Nov 2014

Specifically, there are limitations in:

- the deployment of infrastructure in new buildings;
- the deployment of infrastructure within existing and potentially new ducting; and
- future access to poles and other public infrastructure.

Notably, there will be a need for access to street furniture by mobile operators. This requires collaboration with the landlords (e.g. local authorities) to handle the requirements for deploying telecommunications equipment on infrastructure that is not designed for that purpose. There is currently no common approach to this type of collaboration. The process tends to be fragmented across different local authorities and negotiations are often legally complex and protracted, thus MNOs have so far been reluctant to get deeply involved. Aspects such as planning policy, legislation for code powers, and guidelines relating to radiation hazards for deployment at street level will need addressing before dense site deployment can take place.

8.5 Addressing the coverage gaps in rural areas is needed before new technology can be deployed

There are approximately 40,000 mobile base stations deployed in the UK providing up to 98% outdoor voice coverage. However, there are still areas of poor coverage across the UK. Efforts from mobile operators to extend the coverage in challenging and costly locations (such as rural areas and minor roads) have been limited by a number of barriers. Government projects, such as the Mobile Infrastructure Project have had limited success in trying to address these issues but some barriers have been too difficult to overcome.

One common challenge is cost. MNOs have often found that deployment of rural sites tall enough to support multiple operators, cover a large enough area, and to have line of sight for microwave connectivity to sites with sufficient backhaul capacity (ideally fibre) can be prohibitively expensive. The business case for sites in these areas is very difficult. There are either insufficient subscribers or traffic in rural areas to generate sufficient revenue to pay for the investment. In cases where the site is deemed potentially economically viable, it may be at locations where planning permissions becomes a problem such as in Areas of Outstanding Natural Beauty. Obtaining planning permission in sensitive areas can be protracted as the MNO has to deal with objections from local residents, consultation meetings with Local Planning Authorities, conservation officers or wider interest groups. A successful outcome is by no means guaranteed and some compromise may be required to avoid rejection, in turn leading to reduced benefits of the business case.

These barriers are making the legally binding commitment made by MNOs to Government in December 2014, very challenging. The agreement was made on the basis of MNOs investing £5 Billion to improve mobile infrastructure and thus cover 90% of the UK's land mass (geography) by 2017. This agreement was made when Government was considering national roaming. Positive progress is, however, being made by programmes such as 'grow the grid' in which new cellular masts are deployed to address poor coverage.

Furthermore, the Government has introduced changes to Town and Country Planning and the Electronic Communications Code to speed up site deployment, mentioned earlier in this document to assist the MNOs.

Increased consolidation and infrastructure sharing is also well advanced amongst the MNOs with joint ventures operating between EE and Three (MBNL) and O2 and Vodafone (CTIL). Site sharing and consolidation helps reduce operational costs by sharing them between operators. The savings can then used for future investment in network roll out.

We note that the new Emergency Services Network (ESN) being built by EE and the Home Office will extend EE's coverage in rural areas. ESN is designed to meet the needs of the emergency services and whilst it may facilitate additional services to MNO customers in the future, this is not necessarily guaranteed. Furthermore, the challenging deployment timescales set by the Government may result in the deployment of smaller, more aesthetically sympathetic site designs to avoid Town and Country Planning objections and delays. This will ultimately result in fewer sharable structures, and sites with restricted capacity to share.

It is imperative that coverage gaps are addressed before mobile operators focus on offering new technology options in rural areas otherwise rural areas will not benefit from these advanced technologies as there will be inadequate infrastructure to support them.

8.6 Summary of the infrastructure requirements analysis

In considering the impact of 5G requirements on future networks, we have used a number of 'use cases' to drive our analysis. These use cases consider a range of foreseen areas where future communications technologies are expected to play a role, from superfast consumer broadband to connected cars and critical communications.

It is against this backdrop that our examination of the UK's existing telecommunications infrastructure has been undertaken. With 5G and other future networks still under development it has meant many of the cost and site estimates are high level. These have been based on a set of justified and qualified assumptions such that a basic understanding of how the existing infrastructure might play a role in future networks has been gained. This will help identify areas where Government could intervene to help support future network roll out in a more coordinated and informed way.

9 Appendix – Support material for mapping exercise

9.1 Mapping results for specific road and rail sections

9.1.1 Infrastructure requirements for a portion of the Strategic Road Network

There is a total of 83 sites along this stretch of motorway which includes 28 MNO sites, 3 Arqiva sites and 52 gantry sites. Based on just the use of the 28 MNO sites, some of which overlap, the vehicle management, connected car use case could be provided to vehicles. This assumes existing technology (4G) delivered by sub 1 GHz spectrum connecting to vehicle mounted antennas from these existing mast locations. There would be no requirement for upgrade to infrastructure, however, there would be a cost to add the relevant vehicle equipment.

In order to deliver a driver assistance and passenger entertainment service to vehicles from the roadside infrastructure, we would need to upgrade and in some cases enable most of the available sites along this stretch of motorway with more advanced technology than today's 4G. This would include some features of 5G such as localisation technology. Some of the gantries although densely located, overlap in some instances and would not be used.

Given the average site density the gap between sites is typically no greater than 400m and there are only three gaps greater than 1500m (for 3.5 GHz rural deployments). We estimate that 31 upgrades (to MNO and non MNO sites) and 16 additional sites are needed excluding the gantries. If gantries are used then 31 upgrades are needed, 31 gantries enabled and three additional sites are needed.

Connected Car use cases	Existing site upgrades (excluding gantries)	Additional sites (excluding gantries)	Number of gantries to enable	Additional sites (Including gantries)
Vehicle Management	0	0	0	0
Entertainment/ Driver Assistance	31	16	31	3

Table 25: Number of sites for connected car use case

We observe that this stretch of motorway is representative of a relatively high site density area and enabling the gantries with telecoms equipment, the density increases dramatically. In areas of lower site density additional sites will be needed as there will be an increased number of large gaps that require additional sites.

Therefore, we have extrapolated the site requirements at a national level for the motorways and full strategic road network for England and Great Britain based on the site density along the M4 stretch of motorway demonstrated above.

9.1.2 Infrastructure requirements along national rail routes

MNO sites located near to the railway already provide cellular backhaul for train operating companies, as exemplified by the EE/Chiltern Railways deal[137]. Therefore, we expect some of the existing cellular coverage to provide a good level of connectivity to trains (approximately 60 Mbps in a good service area[138]) on a 75km stretch of rail route between Glasgow and Edinburgh. There are 56 existing sites along the route including 11 GSM-R sites and 45 MNO sites which could potentially be used to support the rail telemetry service. There would be a need to upgrade the GSM-R sites in this case, however due to their location, which are all separated by an average distance of 7-8km, which is less than the minimum inter site distance of 16 km (the cell range for urban sites at 700 MHz), the rail telemetry use case could be supported by just the existing MNO sites.

In the case of command and control for trains (mission critical) and passenger broadband (mobile broadband) use cases, a higher density of site deployments is needed to meet the performance criteria. We assumed, therefore that 3.5 GHz provides sufficient bandwidth and cell range to support these higher throughput rail specific services. We calculated the proportion of urban, suburban and rural clutter along the rail route to determine how many additional sites would be needed based on the different cell ranges for each environment. This also enabled us to extrapolate for all routes in Britain. We assumed that site sharing between MNOs, upgrade of GSM-R masts and other trackside infrastructure will be required for the high levels of densification.

Figure 40: Map of Glasgow to Edinburgh rail route

Clutter type	Glasgow – Edinburgh (%)	All GB routes (%)
Urban	4	10
Suburban	14	27
Rural	82	63

Table 26: Percentage of clutter type for Glasgow – Edinburgh route and all GB routes

The table above shows the proportion of urban, suburban and rural types for the Glasgow to Edinburgh route and all routes in Britain. Given the largely rural area of the Glasgow-Edinburgh route, a larger cell range is used (600m) and the remaining urban and suburban track uses a smaller cell range is used (100- 200m).

We have calculated that an additional 147 sites would be needed to provide a command and control and passenger broadband service based along the 75 km route yielding an average

[137] Chiltern Railways and EE set to transform onboard Wi-Fi experience for thousands of commuters with revolutionary continuous connectivity, Chiltern Railways, Feb 2016, https://www.chilternrailways.co.uk/news/chiltern-railways-and-ee-set-transform-onboard-wi-fi-experience-for-thousands-commuters
[138] Assuming a single train can simultaneouslyconnect to the four MNOs networks with average use download speeds (15.1 Mbit/s) per operator. Ofcom publishes 4G and 3G mobile broadband speeds research, Nov 2014

inter site distance of 500m. This means a dedicated point of interconnection into an all-IP access layer will be needed along the route.

Use case	Existing site upgrades (excluding MNO)	Existing site upgrades (including MNO)	Additional sites trackside
Telemetry (700 MHz only)	11	0	0
Command & Control and Passenger Broadband (3.5 GHz only)	11	56	147

Table 27: Estimate of site numbers for use cases along Glasgow-Edinburgh route

On this particular route the infrastructure used has been enabled to support an all-IP network. This has enabled Project Swift[139] the Innovate UK funded project to be conducted along the Glasgow-Edinburgh route. As discussed in section 3.3.3 the project is intending to deliver dedicated trackside backhaul connectivity to trains so that high speed broadband can be provided to passengers with the potential to support other operational services. The 31 sites have been IP-enabled to access the FTN-X so that it can deliver 500 Mbps to each train on the route.

Furthermore, we observe this rail route is representative of a typical commuter line which runs through a mix of urban, suburban and rural clutter terminating at hub stations and thus requires a mix of site densities. This means that for this particular route the densification of sites will vary depending on where demand is greatest.

We found from Ofcom's coverage checker there is both good 2G coverage and in some cases patchy 4G coverage from the MNOs along the route. See section 9.4 for extracted coverage maps of the area.

9.2 Details of capital costs for roadside and rail infrastructure

In the following sections we provide more details of the capital costs for deploying new and upgrading existing infrastructure on the roadside and trackside.

9.2.1 Further details of capital costs for roadside infrastructure

Based on the lengths of road and number of sites given in section 5.2.1 we have calculated the following fibre deployment costs in Table 28 below.

- A completely new roadside fibre network for all motorways and the SRN
- Additional fibre to replace existing copper which is only non-motorway sections largely

In the same table we calculated the total costs for the following mix of infrastructure by multiplying the number of sites by the unit costs shown in Table 17 of section 5.2.1 and including the costs for the relevant lengths of fibre:

139 Project Swift (Superfast Wi-Fi In-carriage for Future Travel) https://cisco-create.squarespace.com/swift/

- Wireless roadside equipment connecting to existing fibre which can support each of the connected car uses cases
- Wireless roadside equipment connecting to new fibre which can support each of the connected car use cases
- New/upgraded MNO sites

The reason for the additional detail shown in the table below compared to the table in section 5.2.1 is based on the possibility that the existing fibre is too restrictive to access and/or provides insufficient bandwidth to support future use case requirements. However, the cost of deploying a new fibre network relative to using the existing fibre is increased by over four times. Furthermore, laying an entirely new fibre network it is the costliest option compared to the deployment by MNOs. However, the costs become slightly more balanced for all SRN this is due to similar commercial challenges of deployment in urban, suburban and rural areas for non-motorway (major trunk) roads particularly as new fibre would need to be laid across the remaining non-motorway portion of the SRN.

Deployment options	Range of estimated costs for new MNO sites, fibre and roadside equipment (£m)				
	New roadside fibre network (power, poles, civils)	Additional fibre (replacing existing copper)	TOTAL COSTS		
			Wireless roadside equipment (existing fibre)	Wireless roadside equipment (new fibre)	New/upgrade MNO sites
All motorways England	413 - 1,284	0	153 - 382	565 – 1,665	580 – 825
All motorways GB	493 – 1,535	0	183 – 457	676 – 1,991	743 – 1,058
All strategic roads England	971 – 3,021	558 - 1,737	918– 2,636	1,331 – 3,919	2,229 – 3,408
All strategic roads GB	1,638 – 5,095	1,144 – 3,560	1,750-5,076	2,244 – 6,611	4,118 – 7,792

Table 28: Estimated costs for new MNO sites, fibre and roadside equipment

9.2.2 Further details of capital costs for trackside infrastructure

In this section we consider the option of including upgrades to existing GSM-R masts and the deployment of a new ultra reliable low latency mission critical communications network. This would support a future wireless safety and operational network. As discussed in section 5.2.2 a new trackside fibre access layer would provide the most efficient and cost effective solution to support passenger connectivity given the physical separation from expensive access to incumbent networks and service.

In Table 29 we estimate the number of additional sites needed if existing GSM-R sites are upgraded to support future network capabilities. The additional sites are calculated from the total sites to serve all national rail routes (as shown in Table 21, section 5.2.2) and subtract the number of existing GSM-R masts. Although, this means the total number of sites across the network is the same for a brand new network the costs of upgrades are slightly cheaper.

Use case	Min inter site distance	Existing sites (to be upgraded)	Additional GB sites needed
Mobile broadband for 2016 (500 Mbps)	4.8 km average across all GB routes (5 GHz)	2500	771
Future enhanced Mobile Broadband for passengers	1.2 km (24 GHz Urban) 2.0 km (24 GHz Suburban, Rural)	2500	5,867
Future train command and control	4.0 km (700 MHz Urban) 6.0 km (700 MHz Suburban) 8.0 km (700 MHz Rural)	2500`	0

Table 29: Site ranges for trackside infrastructure deployments

In Table 30 it shows the costs of new site deployment, GSM-R upgrade and new fibre access layer. We assumed the GSM-R upgrades are slightly cheaper than a brand new site build given this infrastructure is designed to support telecommunications equipment.

Site type	Acquire, design and build	Assumption	Reference source
New trackside site	£41,250	Assumes Network Rail approved unit for trackside (£55k without discount for economies of scale) with integral directional antenna plus installation on sub 10m mast and connection into existing infrastructure and the internet.	Discussions with industry, commercial costs of telco equipment plus data from a report for the European Union Agency for Railways http://www.era.europa.eu/Document-Register/Documents/Annexes%20v27%2001%202015.pdf
GSM-R upgrade	£39,000	Assumes tech upgrade e.g. GSM-R to LTE plus feeders, additional 3 sectors	35% of the cost of new greenfield site
New fibre access layer	£150 – £250 million	See section 5.2.2	See section 5.2.2

Table 30: Trackside infrastructure costs

This marginal cost difference can be seen in the total costs in Table 31 below when we multiply the number of GSM-R upgrades and new sites with the unit costs. It can be seen that a brand new network is only £6 million more expensive than upgrading GSM-R masts and deploying 771 or 5867 sites additional sites for either a mobile broadband service deployed today or future enhanced MBB network. In the ultra reliable low latency mission critical use case (for command and control), we assumed 700 MHz band would be sufficient due to the wide coverage area and lower bit rate requirements. This means, only upgrades of existing GSM-R sites would be needed and thus estimate costs at £97.5 million.

Trackside deployment options	Estimated costs for total GB sites per use case (£m)		
	URLL Mission Critical Comms (command and control)	Current mobile broadband service (e.g. Project Swift delivering 500 Mbps)	Future eMBB connectivity to passengers
Brand new sites for all routes	0	135	345
New fibre (access layer)	150 – 250		
GSM-R upgrades and additional sites	97.5	129	340
TOTAL COSTS			
Total costs (New sites and new fibre)	N/A	285 – 385	495 - 595
Total costs (New sites, GSM-R upgrades and new fibre)	N/A	279 – 379	490 – 590
Total costs (New sites, GSM-R upgrades and existing fibre)	97.5	N/A	N/A

Table 31: Estimated capital costs for trackside infrastructure

We note the unit cost and total figures are estimates and potential for increased precision of the site numbers. Therefore, a more detailed network dimensioning exercise would consider the optimised placement of new sites either upgrading existing GSM-R sites or not which may turn out to be more cost effective.

9.3 Mapping results for extracted urban/suburban/rural areas

In this section we provide our estimates of the number of sites required for a set of representative dense urban, urban, suburban and rural geographical areas. We gathered the MNO and non-MNO site data and plotted them on to maps to establish the size of the gaps in future wireless network capability. The MNO sites were broken into two distinct configurations either single operator or multi operator. The use of Arqiva, WIG or other infrastructure is used where it could help fulfil the gaps in site density, we refer to this as 'multi operator'.

We assess the number of additional sites needed for a machine type communications use case which could support smart utility networks and also two enhanced mobile broadband configurations for different frequency bands:

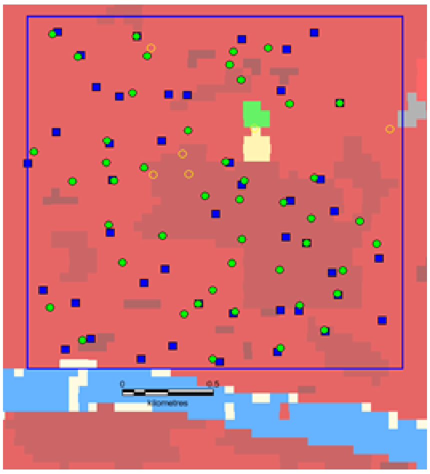
For urban and suburban:

- MBB/MCC – Mobile Broadband option using 3.5 GHz

For rural:

- MBB/MCC – Mobile Broadband option using 700 MHz

9.3.1 Enhanced Mobile Broadband in dense urban areas (City of London $4.21km^2$)



The City of London was chosen as an example area of where mobile capacity congestion will continue to grow given the high population density on a typical day at rush hour (100,000 people per square kilometer[140]). The image right shows the 79 existing MNO roof top sites either shared or individual sites amongst all four MNOs. Our assessment of coverage from existing infrastructure assuming a 500m cell range indicated no additional sites were needed. Furthermore, given the mobile broadband download speeds of around 15.1 Mbit/s is available in London (and other cities) today according to Ofcom's mobile broadband performance research[141], the issue is not coverage in dense urban areas but throughput (Mbps) performance. Densification of networks on the scale expected within the timescales of 5G (around early 2020's) will require the use of mmWave bands deployed at street level rather than rooftop level to serve the very high capacity hot spots. Therefore, the expected density in dense urban areas can range from hundreds to thousands of cells per square kilometer as exemplified by a research study in Finland that examined the technical and economic impact of ultra-dense small cell networks[126].

The table below shows the number of existing sites and additional sites needed to meet the high capacity future use case requirements from the parallel study. Single operator refers to a single individual mobile network and multi operator takes into account all sites available for more than one operator. We have estimated that between 456 and 492 additional small cell sites will be needed, in addition to the 79 existing sites, to meet both the mobile broadband and mission critical use cases within the City of London.

Use case	Existing site upgrades (single operator)	Additional sites (single operator)	Existing site upgrades (multi operator)	Additional sites (multi operator)
MTC at 3.5 GHz (500m radius)	46	0	79	0
MBB/MCC at 3.5 GHz (80m radius)	46	92	79	69

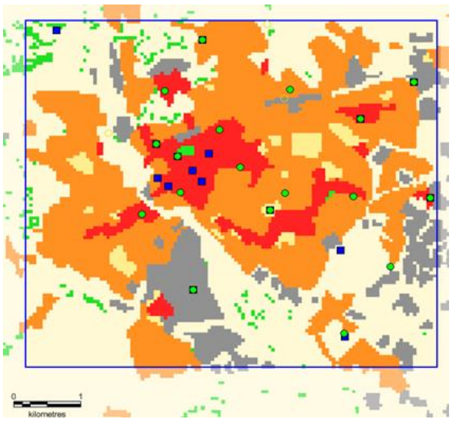
Table 32: Estimate of site number for the City of London

We observe only marginally fewer additional sites are needed in the multi operator case compared to the single operator. However, the multi operator provides a single grid for more than one operator and when comparing with the single operator the number of additional sites must be multiplied the equivalent number of operators supported. This shows the reduced requirement multi operator environment compared to more than one separate network.

[140] 4G Capacity Gains study, Real Wireless on behalf of Ofcom, 2011
[141] 4G and 3G mobile broadband speeds research, Ofcom November 2014

Our results confirm that in order to meet the expected user data rates from the 5G performance requirements this sample dense urban areas will need to increase infrastructure density by at least 10x. We provide further details of the analysis are shown in Appendix A.

9.3.2 Enhanced Mobile Broadband and machine type communications in urban areas (Exeter 33km^2)



The city of Exeter was the choice for the urban analysis because it was representative of mid to low rise and distributed clutter, has a good mix of residential, agricultural and education and commerce. Furthermore, the Southwest has recently received additional investment in infrastructure[142] and provides a potentially interesting case for future investment for high speed networks.

The total area within the blue polygon is 33km^2 (see right) and the size of the urban (red) and industrial (grey) clutter area is 6.4km^2. Our analysis considered 29 sites for the multi operator configuration within the urban and industrial clutter area of Exeter and 17 sites for the single operator network. There were only three non-MNO sites which did not greatly impact the densification requirements.

Use case	Existing site upgrades (single operator)	Additional sites (single operator)	Existing site upgrades (multi operator)	Additional sites (multi operator)
MTC at 3.5 GHz (500m radius)	17	29	29	24
MBB 1 at 3.5 GHz (100m radius)	17	1033	29	1021
MBB 2 at 24 GHz (50m radius)	17	4181	29	4169

Table 33: Estimate of site number for the urban area of Exeter

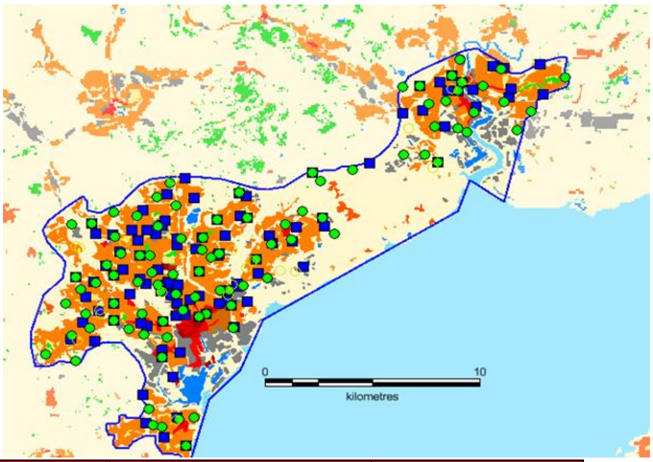
The table above shows that 24 additional sites would be needed to deploy a Machine Type Communications (MTC) network assuming full site sharing amongst MNOs and a cell range of 500m using 3.5 GHz spectrum. If using 700 MHz from the shared sites no additional sites are needed for the MTC use case.

The situation changes dramatically when considering smaller cell ranges for the two mobile broadband use cases. We assume for these cases in an urban area, either 3.5 GHz, or mmWave bands (e.g. 24 GHz) will be used at street level and therefore the number of additional sites estimated ranges from 1021 to 4169 assuming multi operator shared sites for the Exeter area considered. Similar to the dense urban area, multiply the number of sites (from the single operator case) by the number of operators assumed and the number of required sites increases considerably. The magnitude of these numbers is driven by the distributed urban clutter area around Exeter and the need to meet the relatively large geographical capacity density. Further details of the analysis are shown in Appendix A.

[142] South West fibre broadband coverage passes the 2 million mark, My News Desk, Oct 2015

9.3.3 Enhanced Mobile Broadband and machine type communications in suburban areas (Cardiff/Newport 178 km^2)

The suburban area of Cardiff and Newport were chosen given the widely distributed residential areas which span the city of Cardiff and nearby town of Newport. This area was thought to be challenging to cover given the mixed topography, terrain, clutter, highly suburban, wide mix of available infrastructure. We created a total area of 178 km^2, however the sites of interest were deployed in 59km^2 of suburban clutter. A total of 200 sites were deployed from the multi operator configuration. The single operator case considered 101 sites. There were 22 non-MNO sites found to be useful for supporting the densification requirements.



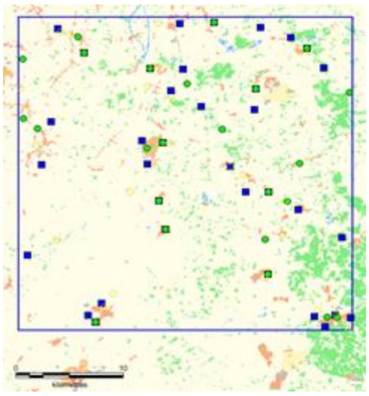
Use case	Existing site upgrades (single operator)	Additional sites (single operator)	Existing site upgrades (multi operator)	Additional sites (multi operator)
MTC at 3.5 GHz (1500m radius)	101	4	200	2
MBB 1 at 3.5 GHz (200m radius)	101	1321	200	1247
MBB 2 at 24 GHz (100m radius)	101	5569	200	5481

Table 34: Estimate of site numbers for suburban areas of Cardiff and Newport

The assessment of coverage from existing sites, assuming a 1500m radius for a Machine Type Communications (MTC) network, generated a requirement of 2 additional sites in the multi operator case and 4 additional sites in the single operator case as shown in the table above. The analysis assumed 3.5 GHz spectrum, however, if 700 MHz is used (cell range 7 km) from the multi operator sites portfolio no additional sites are needed for the MTC use case.

Similar to urban, the situation changes dramatically when considering smaller cell ranges for the two mobile broadband use cases. We assume for these cases in a suburban area both 3.5 GHz bands and 24 GHz bands may be deployed at rooftop and street level and therefore the number of additional sites estimated ranges from 1247 to 5481 based on the multi operator case. The infrastructure requirement increases 2-6% if the single operator case is considered. However, similar to the dense urban/urban areas, multiply the number of sites (from the single operator case) by the number of operators assumed and the number of required sites increases considerably. These numbers are driven by the wide spread nature of suburban clutter area around Cardiff and Newport and the need to meet the relatively large geographical capacity density. Further details of the analysis are shown in Appendix A.

9.3.4 Enhanced Mobile Broadband and machine type communications in rural areas (Downham Market 961 km^2)



The area around Downham Market was selected for rural type because of the particular not spot nature of the area. The area is poorly served by 2G/3G/4G coverage and has widely distributed residential and commercial area which is a commercial challenge to serve both from a fixed and wireless perspective. We created a total area of 961 km^2 (shown in the blue square), within which the sites of interest were deployed across a mix of residential, village, park and open in urban clutter types. A total of 73 sites were considered for the multi operator case and 30 site considered for the single operator case. There were 23 non-MNO sites found to be useful for supporting the densification requirements.

Use case	Existing site upgrades (single operator)	Additional sites (single operator)	Existing site upgrades (multi operator)	Additional sites (multi operator)
MTC at 3.5 GHz (2400m radius)	30	33	73	22
MBB 1 at 700 MHz (4600m radius)	30	3	73	1
MBB 2 at 3.5 GHz (600m radius)	30	100	73	25

Table 35: Estimate of site numbers for rural area near Downham Market

The assessment of coverage from existing sites using 700 MHz, assuming a 4600m radius for a MBB 1 use case, requires only 1 new site in the multi operator case and 3 additional sites in the single operator case. Shifting the frequency band to 3.5 GHz and the cell range to 600m 25 additional sites are needed for multi operator 100 additional sites for single operator case.

The table above shows that 22 to 35 additional sites would be needed to deploy a Machine Type Communications (MTC) service assuming full site sharing amongst MNOs and a cell range of 2400m using 3.5 GHz spectrum.

The technical assumptions for the rural area were chosen based on the likely use of frequency and infrastructure by MNOs in sparsely populated areas. MNOs tend to use macro cell type towers and lower frequency bands for coverage in rural areas as this is considered the most economic solution. Furthermore, densification is not a typical deployment strategy in rural areas due to the sparse and wide spread population and premises. However, deployment of 'meadow cells[143]' in small towns and villages is considered a viable strategy by organisations in the Small Cell community. The situation for broadband fixed telecoms infrastructure such as fibre deployments is uncommon and expensive in rural areas, therefore, limiting the opportunity for dense networks. The large cell ranges drive the low infrastructure requirements but the underlying assumption is that MNOs will use sub 1 GHz spectrum such as 700 MHz for new 5G networks when deploying in rural areas limiting the need for much densification. Further details of the analysis are shown in Appendix A.

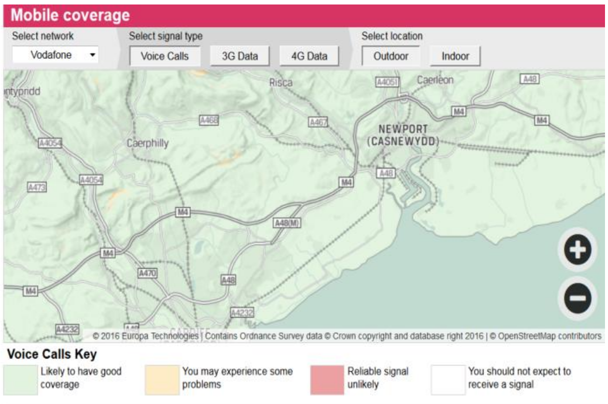
[143] Meadow cells are similar to streetworks sites that can be deployed in small villages in rural areas

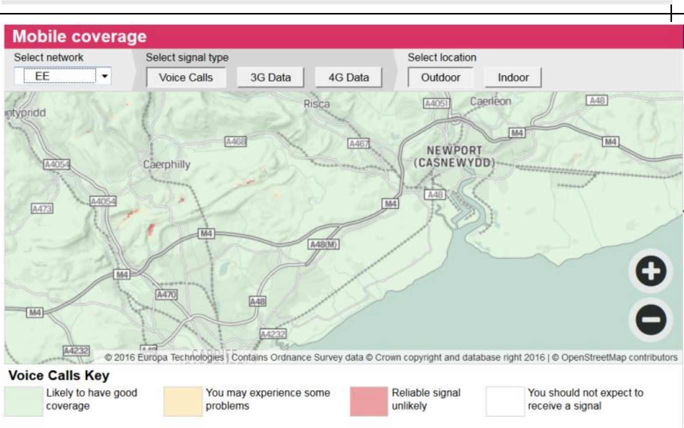
9.4 Coverage checker maps for geographical areas

The following tables show 2G and 4G coverage maps extracted from Ofcom's coverage checker for each of the geographical areas analysed in the study. These maps validate the assumed coverage provided from the existing sites plotted in the mapping exercise in section 5.1.

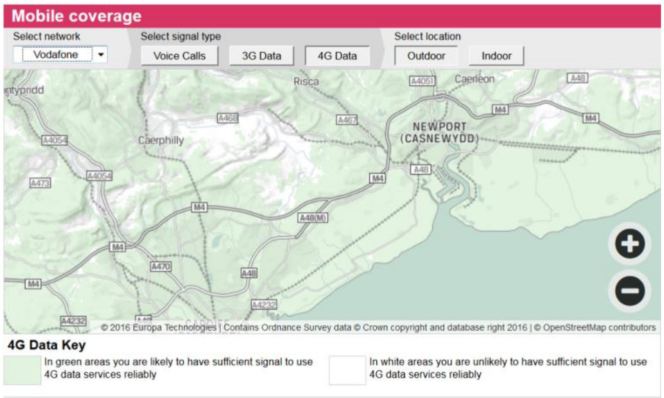
9.4.1 Strategic Road Network – Stretch of M4 between Cardiff and Newport

2G Coverage



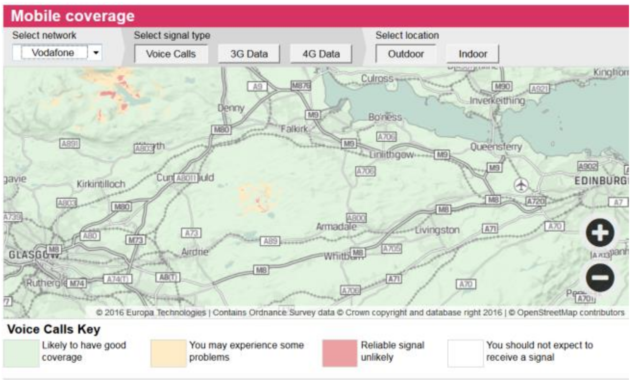


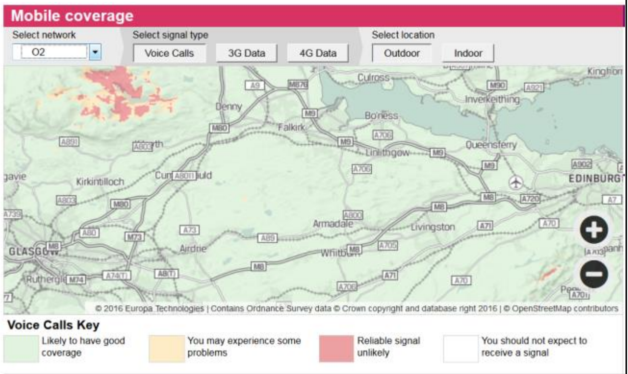
4G Coverage

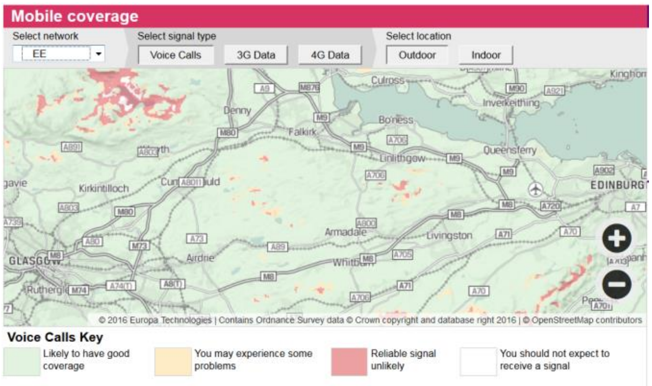


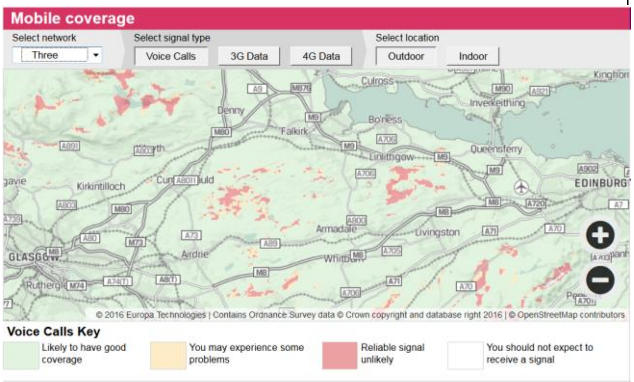
9.4.2 Strategic rail network – Glasgow to Edinburgh

2G Coverage

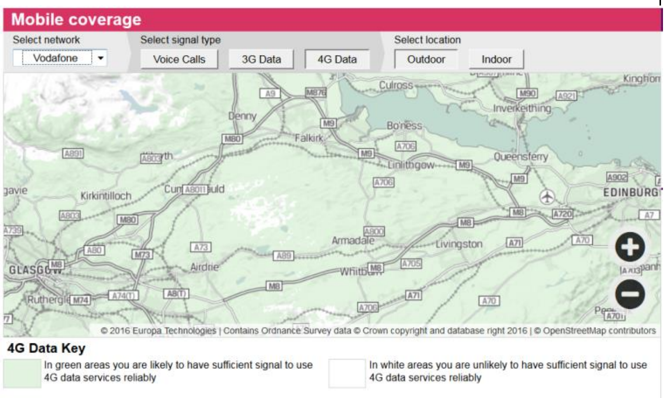


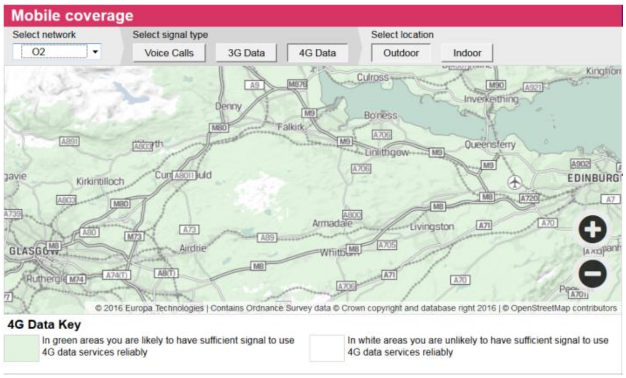


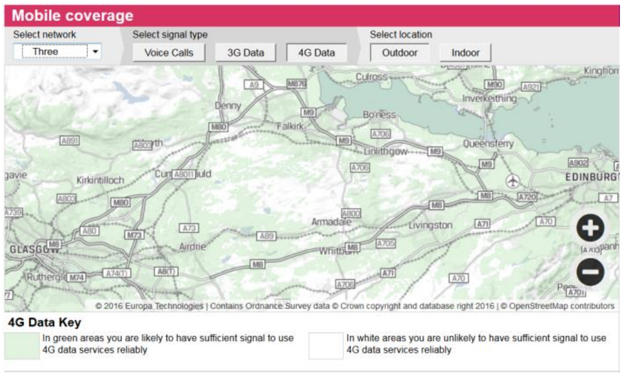




4G Coverage

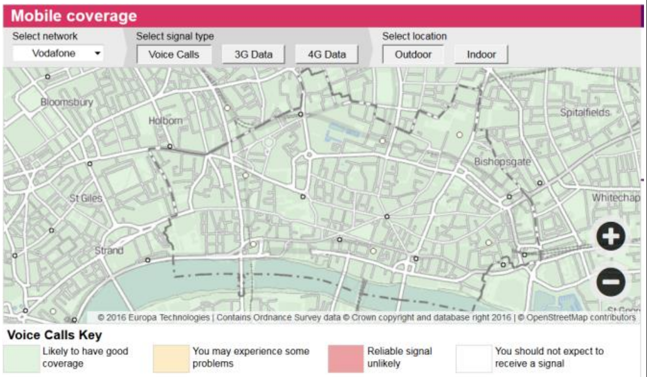


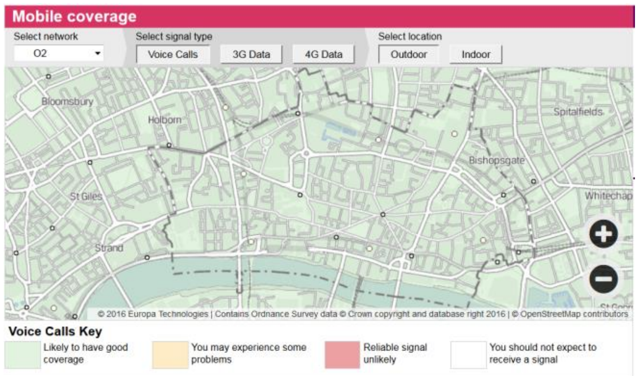


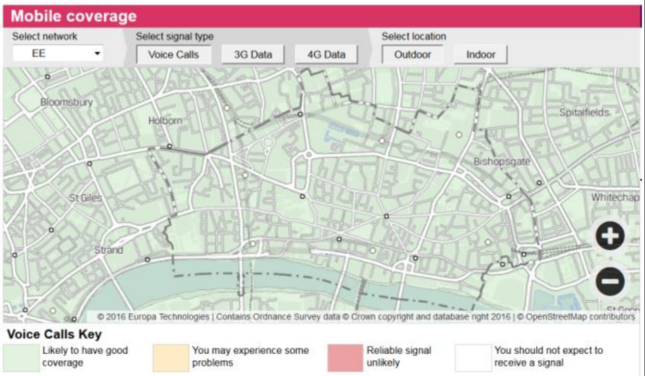


9.4.3 Dense urban – City of London

2G Coverage






Mobile coverage
Select network
EE
Select signal type
Voice Calls
3G Data
4G Data
Select location
Outdoor
Indoor
Bloomsbury
Holborn
Spitalfields
Bishopsgate
St Giles
Whitechap
Strand
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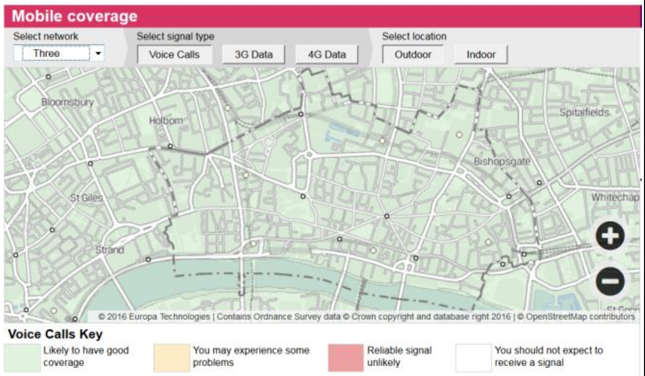
Voice Calls Key
Likely to have good coverage
You may experience some problems
Reliable signal unlikely
You should not expect to receive a signal


Mobile coverage
Select network
Three
Select signal type
Voice Calls
3G Data
4G Data
Select location
Outdoor
Indoor
Bloomsbury
Holborn
Spitalfields
Bishopsgate
St Giles
Whitechap
Strand
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Voice Calls Key
Likely to have good coverage
You may experience some problems
Reliable signal unlikely
You should not expect to receive a signal

4G Coverage


Mobile coverage
Select network
Vodafone
Select signal type
Voice Calls
3G Data
4G Data
Select location
Outdoor
Indoor
Bloomsbury
Holborn
Spitalfields
Bishopsgate
St Giles
Whitechap
Strand
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4G Data Key
In green areas you are likely to have sufficient signal to use 4G data services reliably
In white areas you are unlikely to have sufficient signal to use 4G data services reliably


Mobile coverage
Select network
O2
Select signal type
Voice Calls
3G Data
4G Data
Select location
Outdoor
Indoor
Bloomsbury
Holborn
Spitalfields
Bishopsgate
St Giles
Whitechap
Strand
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4G Data Key
In green areas you are likely to have sufficient signal to use 4G data services reliably
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Mobile coverage
Select network
EE
Select signal type
Voice Calls
3G Data
4G Data
Select location
Outdoor
Indoor
Bloomsbury
Holborn
Spitalfields
Bishopsgate
St Giles
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Strand
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Mobile coverage
Select network
Three
Select signal type
Voice Calls
3G Data
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Select location
Outdoor
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4G Data Key
In green areas you are likely to have sufficient signal to use 4G data services reliably
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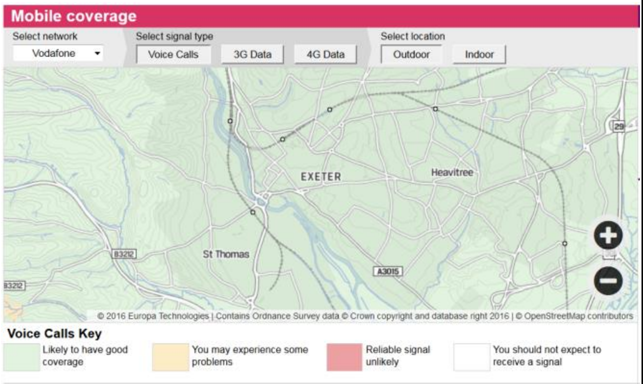
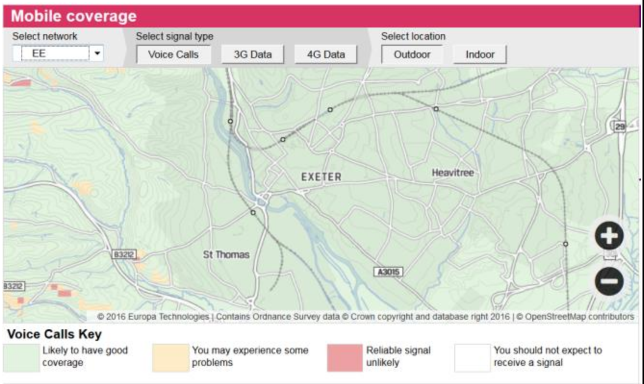
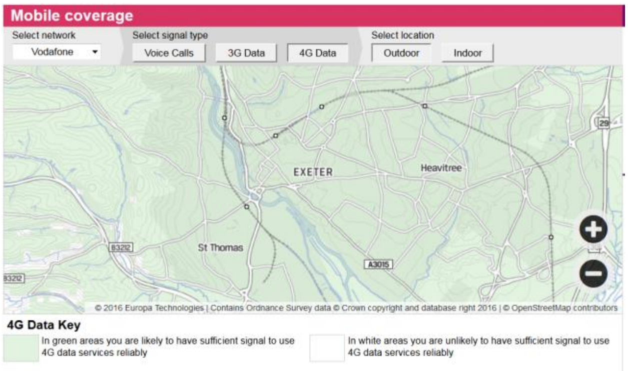
9.4.4 Urban - Exeter

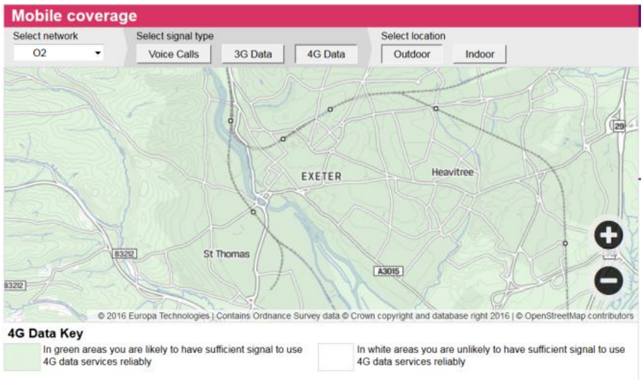
2G Coverage

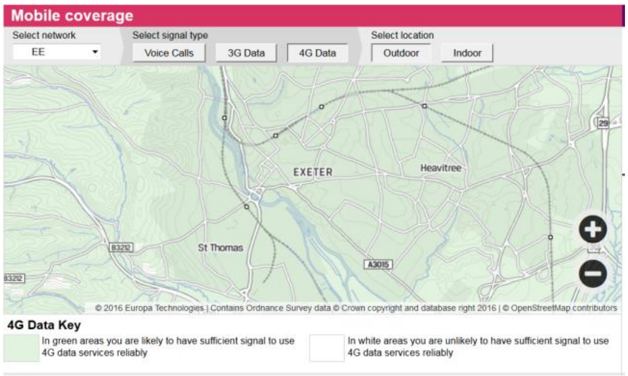
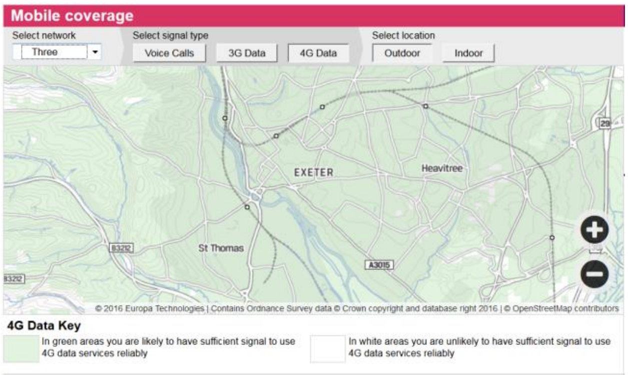




4G Coverage

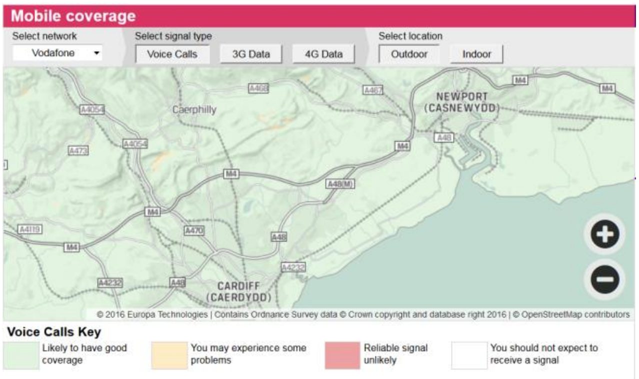


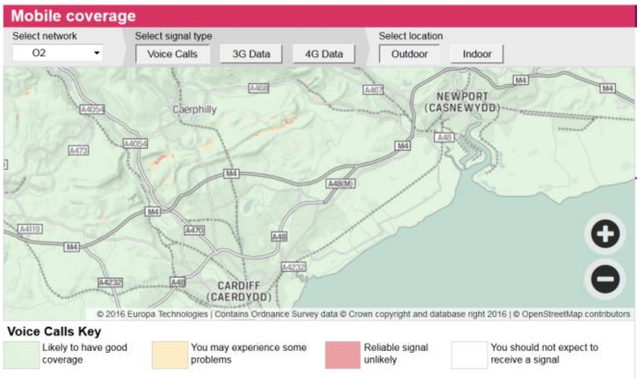


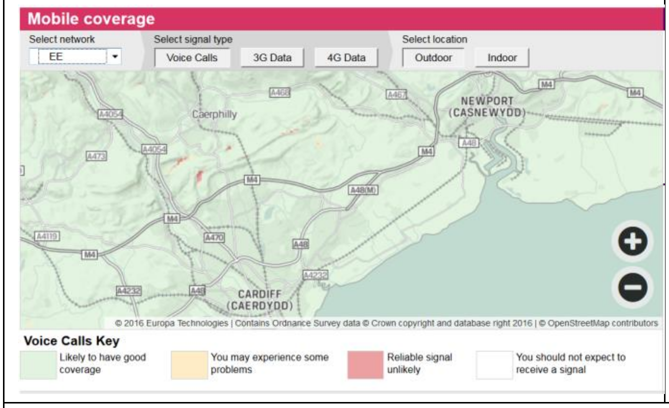
	

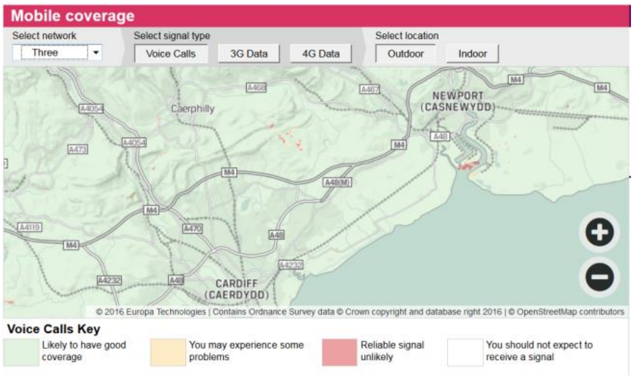
9.4.5 Suburban – Cardiff/Newport

2G Coverage

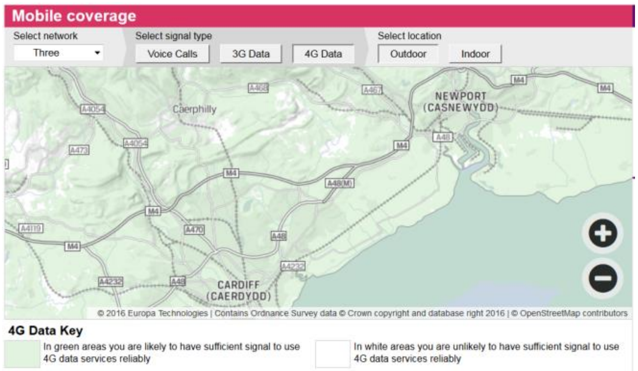






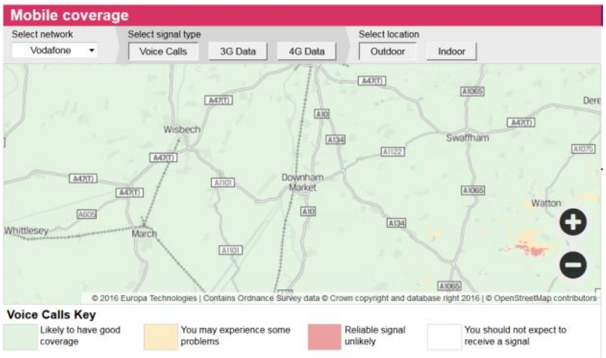


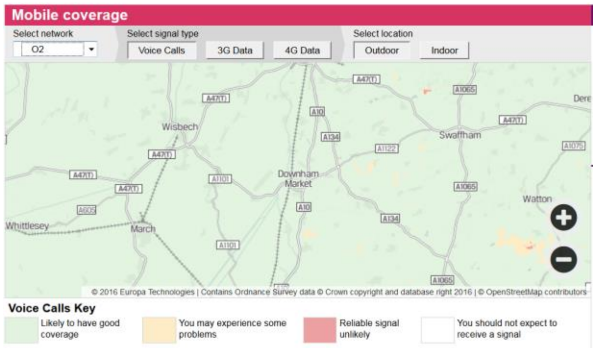
4G Coverage

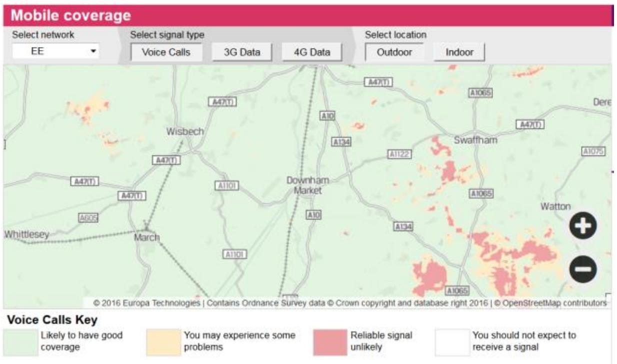


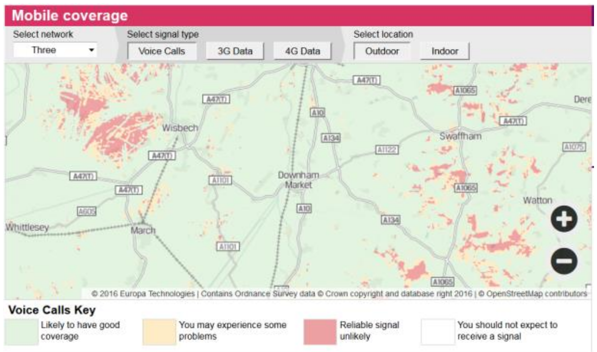
9.4.6 Rural – Downham Market

2G Coverage









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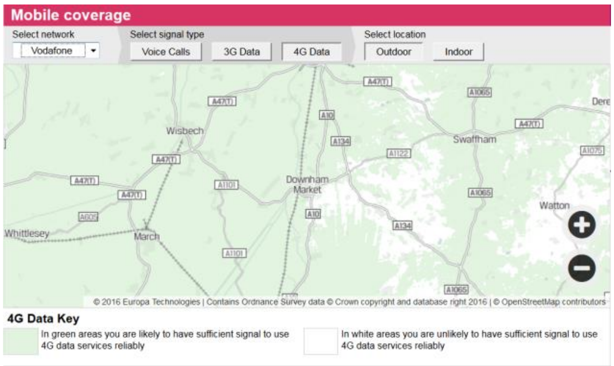
Mobile coverage
Select network
Vodafone
Select signal type
Voice Calls
3G Data
4G Data
Select location
Outdoor
Indoor
Wisbech
Swaffham
Downham Market
Watton
Whittlesey
March
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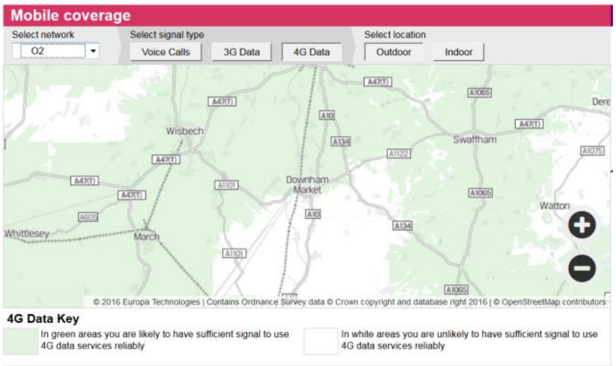
4G Data Key
In green areas you are likely to have sufficient signal to use 4G data services reliably
In white areas you are unlikely to have sufficient signal to use 4G data services reliably


Mobile coverage
Select network
O2
Select signal type
Voice Calls
3G Data
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Outdoor
Indoor
Wisbech
Swaffham
Downham Market
Watton
Whittlesey
March
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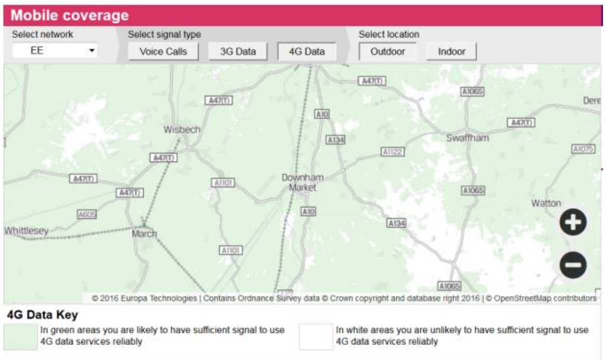
Mobile coverage
Select network
EE
Select signal type
Voice Calls
3G Data
4G Data
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Wisbech
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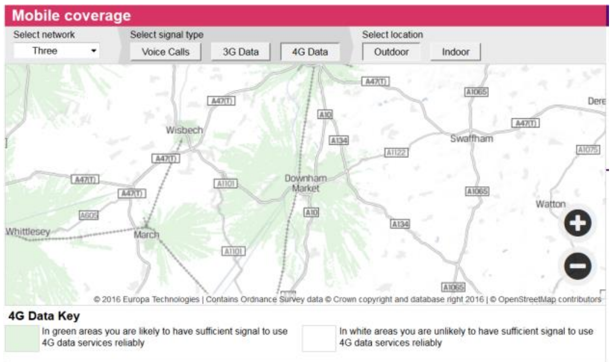
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Select network
Three
Select signal type
Voice Calls
3G Data
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Select location
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Wisbech
Swaffham
Downham Market
Watton
Whittlesey
March
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4G Data Key
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10 Glossary of terms

2G	Second Generation mobile communications standard, predominantly voice and text messages with some basic data capabilities
3G	Third Generation mobile communications standard, aimed at enabling mobile broadband and improving user data rates. This standard includes voice services.
3GPP	Third Generation Partnership project a special global group set up to develop mobile communications standards
4G	Fourth Generation mobile communications standard, an evolved solution compared to 3G with enhanced radio access techniques and all IP approach with flatter architecture
5G	Fifth Generation mobile communications standard, aimed at converging fixed and mobile network to not just deliver ultra-high speed user data rates everywhere, but also massive machine type connectivity, critical communications, low latency and high availability all from a single perceived network
APTR	All-purpose trunk road
BSS	Business Support Systems in relation to telecommunications networks
CCSR	Call Completion Success Rate
CDN	Content Delivery Networks
COTS	Commercial off the Shelf refers to equipment that is readily available from a that does not require specific or bespoke functions
CRAN	Cloud/Centralised Radio Access Networks
CWDM	Coarse Wave Division Multiplexing is a fibre access technology
DNOs	Distribution Network Operators are providers of power infrastructure
DSRC	Dedicated Short Range Communications
DWDM	Dense Wave Division Multiplexing is a fibre access technology
ECC	Electronic Communications Code
eMBB	Enhanced Mobile Broadband
ESN	Emergency Services Network is the new 4G network being procured by the Home Office to replace the existing Airwave TETRA network
FMC	Fixed Mobile Convergence
FTN	Fixed Telecommunications Network
FTTC	Fibre to the Cabinet
FTTP	Fibre to the Premises
GSMA	GSM Association
GSM-R	Global Systems for Mobile Communications - Railways
IMS	IP Multimedia Subsystem
IOT	Internet of Things is a term which refers to connectivity of different device types

IP	Internet Protocol
LTE	Long Term Evolution which is the fourth generation mobile technology or 4G
MANO	Management and Operation
MBB	Mobile Broadband refers to very high speed connectivity to mobile devices for consumers and businesses. The types of mobile broadband speeds within 5G ranges from 100 Mbps to 1 Gbps per user
MEC	Mobile Edge Computing is the latest term for processing the baseband signals at the equipment located at the edge of the network
MIP	Mobile Infrastructure Project government project to extend mobile coverage
mMTC	Massive Machine Type Communications will provide communications to potentially millions of devices on the network
MNO	Mobile Network Operator, e.g. EE, Vodafone, O2, Three
MPLS	Mulitprotocol Label Switching
M2M	Machine-to-Machine Communications refers to communications between devices
MVNO	Mobile Virtual Network Operators examples include Virgin Mobile and Tesco Mobile
NFV	Network Function Virtualisation
NRTS	National Road Telecommunications Services
OSS	Operational Support Systems in relation to telecommunications networks
OTT	Over the Top which comprise different applications that are accessed via different platforms
RAN	Radio Access Networks
RAT	Radio Access Technologies
RRH	Remote Radio Heads are small pieces of radio equipment that can be readily mounted on existing infrastructure
SCADA	Supervisory Control and Data Acquisition used predominantly by utility and rail network operators
SDN	Software Defined Networks
SRN	Strategic Road Network consists of England's motorways and major trunk roads
Symology	Submission to the council informing them of proposed streetworks
TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TETRA	TErrestrial TRunked RAdio is a digital voice and communications technology specifically aimed at emergency and mission critical communications
URLLMCC	Ultra Reliable Low Latency Mission Critical Communications will be used by operators that require high availability, reliability and low latency from their networks
VoLTE	Voice over LTE