Spectrum Sandbox:
An economic assessment of spectrum sharing in the Upper 6 GHz and lower frequency bands

Final Report by London Economics for the UK Department for Science, Innovation and Technology (DSIT), March 2025

Table of contents

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London Economics is one of Europe's leading specialist economics and policy consultancies headquartered in London. We advise clients in both the public and private sectors on economic and financial analysis, policy development and evaluation, business strategy, and regulatory and competition policy.

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We would like to thank the organisers and participants at a number of online and in person workshops and events held during 2024 and early 2025 for their helpful comments and feedback on our early work. We would also like to acknowledge the contributions, inputs and advice provided by our Sandbox partners Telet, Durham University, TRL and, in particular, Ranplan Wireless for providing us with the simulations of infrastructure deployment underlying the economic analysis. Finally, we would like to thank DSIT and Ofcom for the ongoing support and input provided throughout the study.

Cover image source: ChatGPT

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Executive Summary

Objectives

This report focuses on the economic analysis of spectrum sharing in the Upper 6 GHz between mobile and Wi-Fi to deliver capacity to address peak demand in high density areas and in lower frequency bands (e.g. Band III and n77) to address poor network coverage in lower density areas. The aim is to contribute to an evidence base for the UK Government and Ofcom to determine whether more intensive spectrum sharing approaches should be adopted and under what scenarios.

This report is part of a broader 'Spectrum Sandbox' research project funded by the Department for Science, Innovation, and Technology (DSIT) to investigate the possibilities and implications of increased spectrum sharing between different users and service types within these bands.

Scope

This study assesses the economic benefits, costs, and regulatory and policy implications associated with spectrum sharing in two key spectrum bands using an approach consistent with HM Treasury's Green Book methodology:

- **Sharing between mobile and Wi-Fi in the Upper 6 GHz band:** to provide additional capacity in environments with a high density of simultaneous users at peak times, such as Dense Urban environments, and high-density sporting or entertainment events.
- **Sharing of other bands with propagation characteristics suitable for wide area provision in lower density areas (e.g. Band III or the n77 band):** to facilitate more accessible spectrum for existing MNOs or private network providers to address total and partial connectivity not-spots for mobile users in lower density and rural areas where current network extension is too expensive to deliver.

Benefits and costs are estimated for 'producers' (i.e. those immediately using spectrum to supply services) and 'consumers' (users who purchase data services from producers for personal consumption). The net benefit to consumers is estimated as the difference between the improvements to throughput that they experience and the costs for the new services that deliver these. The net benefits to producers is estimated as the difference between their earned revenues (equivalent to the costs faced by consumers) and the capital and operating expenditure of the networks required to deliver these services.

The analysis models networks in five small geographical archetype areas in the UK. Whilst we also provide an assessment of aggregate economic impacts at the UK level, this is based on the results from the small number of areas analysed. Extension of the number of geographic areas modelled is a potential area for further research beyond this Sandbox.

Key findings

Results

Spectrum sharing in the Upper 6 GHz

The table below summarises the total net present surplus of spectrum sharing over exclusive mobile or Wi-Fi allocation, which varies across use cases. Spectrum sharing is the policy option with the highest net present surplus for the High-Density Urban area (£11m compared to mobile only allocation, which is the next best) and for the Dense Urban area (£2m compared to mobile only allocation, which is the next best). For the Stadium, allocation of the Upper 6 GHz band to Wi-Fi has a slightly higher net present surplus (£0.6m) than spectrum sharing whilst for the less-Dense Urban area allocation of the Upper 6 GHz band to mobile has a slightly higher net present surplus (£0.4m) than spectrum sharing.

Table: Net present surplus of Upper 6 GHz spectrum sharing over exclusive mobile or Wi-Fi access by use case

Use case	10-year present value	
	Total net present surplus of spectrum sharing compared with Wi-Fi only allocation	Total net present surplus of spectrum sharing compared with mobile only allocation
Stadium	-£0.6m	£11m
High-Density Urban area	£51m	£4m
Dense Urban area	£11m	£7m
Low-Density Urban area	£1m	-£3m

Note: These estimates are for each of our very small area use case areas. Aggregate estimates at the Great Britain level are provided below.

The difference in net present surpluses across use cases is driven by variations in producer costs. Consumer surplus remains constant across scenarios 1-4 because both consumer benefits and costs are unchanged - consumers have the same willingness to pay for speed and incur the same expenses for those speeds. Since consumer costs and producer revenues are identical across scenarios, the only factor influencing net benefits is producer cost. This variation arises from differences in spectrum allocation, which impact the infrastructure costs for both mobile and Wi-Fi providers.

Aggregate impacts of **spectrum sharing in Upper 6 GHz band for urban areas in Great Britain**

The table below provides the estimated aggregate net present surpluses across Great Britain of spectrum sharing in the Upper 6 GHz band over i) exclusive allocation of the 6 GHz band to Wi-Fi and ii) exclusive allocation of the 6 GHz band to mobile. This shows that in this baseline assessment the greatest benefits are from spectrum sharing. These benefits are £0.2bn higher than the benefits from mobile only allocation, whereas the benefits of spectrum sharing are £3.3bn higher than the benefits of Wi-Fi only allocation of the band. This indicates that Wi-Fi only allocation of the band would be the least beneficial option of the three.

Table: Baseline net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive Wi-Fi allocation or exclusive mobile allocation for Great Britain

10-year present value	
Additional benefits of spectrum sharing compared to Exclusive Wi-Fi allocation	**Additional benefits of spectrum sharing compared to Exclusive mobile allocation**
£3.3bn	£0.2bn

Note: The baseline results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing). When these assumptions are relaxed the net benefits change significantly and, across the assumptions tested, can range from minus £2.5bn to plus £16.8bn for sharing versus mobile only and from plus £3.3bn to plus £22.7bn for sharing versus Wi-Fi only. In practice, the benefits of sharing relative to mobile only allocation are likely to be lower than this as take up of the Lower 6GHz band by Wi-Fi services increases over the time horizon.

Spectrum sharing in lower frequency bands for underserved areas

The net benefits of addressing underserved areas in the UK range from £50m to £300m net present value over 10 years[1]. Three scenarios are assessed, based on: i) a low cost high willingness to pay scenario, ii) a medium cost medium willingness to pay scenario, and iii) a high cost low willingness to pay scenario.

Table: Costs and benefits of addressing not-spots and underserved areas

Sensitivity	Willingness to pay (£)	Producer Costs (CAPEX + OPEX) (£)	Total surplus (£)	% not-spots with positive surplus
Lower (higher cost, lower WTP)	£103m	£50m	£53m	51%
Central (mid cost, mid WTP)	**£201m**	**£80m**	**£121m**	**75%**
Upper (lower cost, higher WTP)	£407m	£101m	£305m	94%

As areas are only included in the analysis when consumer willingness to pay exceeds deployment and operational costs (i.e., total surplus is positive), the percentage of not-spots that could feasibly be addressed decreases as cost increases and willingness to pay decreases. This is because with higher costs and lower willingness to pay, the cost of building and operating a network exceeds the total price consumers would be willing to pay for the service in more areas. With a negative total surplus, there is no rationale to build a network and additional government intervention would be needed to serve these areas.

Conclusions

Our analysis has demonstrated that there are net benefits from the adoption of shared spectrum for the Upper 6 GHz band between mobile and Wi-Fi users within several defined geographic contexts. Net benefits are achieved for both 'producers' of communications services and 'consumers' who use such services. We see positive and significant surplus for both groups, suggesting that there is both an

[1] Net present value is calculated using a 3.5% discount rate in line with the green book. The first year is considered a "build year" where there are only capex costs, and no opex or willingness to pay benefits.

incentive to provide these services and incentive to purchase them. This implies a new revenue earning opportunity for both existing suppliers and new operators.

We also see positive surplus across many of the lower density areas analysed, indicating that opportunities for network expansion through easier access to spectrum also exist in these use-cases e.g. through a permissive licensing scheme enabling use of appropriate lower bandwidth spectrum.

In the case of producers, these benefits reflect the value of supplying bandwidth to address minimum user requirements for the average user at market prices, and for consumers, these reflect the willingness to pay for additional coverage and faster data rates. We assume that the additional spectrum from the Upper 6 GHz band is used to optimise network architecture, in effect to lower CAPEX and OPEX, to address defined user requirements, in excess of what is delivered today. The main value of spectrum sharing therefore comes from the ability of producers to lower costs. These benefits exist even after accounting for the potential reservation of spectrum to mitigate interference between mobile and Wi-Fi users.

Furthermore, our results are driven by assumptions regarding indoor handover of mobile traffic to Wi-Fi and the level of indoor deployment expected in various scenarios. Spectrum sharing is most beneficial when the offloading of mobile traffic to Wi-Fi is maximised, and indoor mobile deployment is minimised in the counterfactual. This result arises because Wi-Fi access points are more cost-effective than mobile small cell at serving indoor traffic. In practice, the degree of indoor uptake of Upper 6 GHz-enabled Wi-Fi and the Wi-Fi offloading will depend on several factors, including: the incentives of private building owners and private network operators to deploy indoor solutions, the cost of Wi-Fi equipment, and ultimately the capacity of the 'last mile' connection to buildings (i.e. roll out of 'full fibre' connections).

The benefits of spectrum sharing are evident even under various sensitivities to key assumptions, including variation to the discount rate, throughput pricing, producer network costs, and consumer willingness to pay for improved throughput. Notably, increases in producer costs erode the economic advantage of spectrum sharing over Wi-Fi only allocations, whereas the economic advantage of spectrum sharing over mobile-only allocations is improved. This is because Wi-Fi infrastructure is less expensive to deploy than mobile, meaning that as costs increase, the savings from spectrum sharing in a Wi-Fi context become smaller, while the savings are larger for mobile.

In certain cases, the existence of positive consumer surplus (and total overall surplus) and negative producer surplus indicates a potential market failure – there are clear overall benefits and benefits to consumers but no producer incentive to supply. In such cases, there is an argument for sharing the surplus, suggesting that higher prices can be accommodated in markets that would otherwise be unserved.

We also identified areas where benefits are possible, though costs exceed total surplus. In these cases, additional government intervention, or a further reduction in costs of service provision - would be needed to address under-provision. Such costs reductions may be achieved if spectrum sharing is adopted at scale, whereby market signals to equipment suppliers and economies of scale can help achieve lower unit costs of network equipment.

While this analysis suggests value in spectrum sharing, a pre-requisite for truly ubiquitous connectivity – the main objective of future telecommunications policy - is for seamless handover of user devices between network typologies (e.g. between Wi-Fi, mobile, and private networks). This requires investment in device level capabilities and agreement between operators for standards which can be enable this, as well as potential regulatory adjustments too.

Recommendations

To move forward effectively, several key recommendations have emerged:

1. Robust technical standards must be developed to manage interference between coexisting technologies, including dynamic spectrum access and cross-technology signalling protocols where necessary. Clear rules for access prioritisation during interference events must also be developed to reduce regulatory uncertainty.
2. Industry-wide standardised frameworks should be established to delineate the appropriate circumstances for exclusive versus shared spectrum use.
3. Policymakers should consider introducing incentives—such as reduced licensing costs or expedited licensing procedures—to encourage spectrum sharing from a broader policy perspective. Our analysis shows that operators achieve positive surplus from both 6 GHz network deployment and spectrum sharing over exclusive spectrum allocation scenarios, even assuming discount rates in line with UK telecom industry benchmarks. Incentives to encourage
4. Current spectrum management decisions need to be aligned with future technology roadmaps, particularly for emerging technologies like 6G, ensuring that the integrity of high-capacity channels is maintained for long-term innovation.
5. Policies makers should support policies that incentivise private building owners and private network operators to deploy indoor solutions. These policies can be supported by broader infrastructure development initiatives such as full fibre roll outs to ensure that last mile connectivity is not a bottleneck to Upper 6 GHz enabled Wi-Fi.
6. Policymakers should incentivise development in device-level capabilities, network interworking technologies, and standards to enable seamless handover between network technologies and therefore truly ubiquitous connectivity of mobile devise.
7. Full realisation of the benefits of spectrum sharing implies significant network expansion of both Wi-Fi and mobile. Policymakers should send a clear market signal to equipment manufacturers to undertake investments to lower unit costs and reduce potential bottlenecks in deployment.

In summary, while Mobile Network Operators perceive interference management challenges from spectrum sharing of the Upper 6 GHz band, a reformed regulatory environment that encourages spectrum sharing could offer significant long-term advantages for the broader digital landscape. Achieving a balance between exclusive access for high-performance mobile networks and the potential for broader spectrum availability will require careful technical, regulatory, and economic planning—a challenge that future policy and standardisation efforts must address.

Suggested areas for further research

Further research beyond the scope of the sandbox to further enhance the results of the economic analysis could include:

- Refining breadth and precision of analysis with more use-cases and archetype areas
- Extension to non-consumer users and more specific scenarios
- Refining sensitivities through additional simulations
- Assessing the value of spectrum sharing for other technology pairs, such as between mobile and satellite Direct to Device (D2D).

Caveats and limitations

The research has been conducted by a team of independent professional economists with specialist knowledge of economic modelling, technology, and telecommunications, using best practice and best judgment. The methodology used, and assumptions made, are described in this report in a transparent manner, with caveats noted as required. Nonetheless, the reader should bear in mind the following high-level limitations and caveats of this study throughout:

1) The economic modelling presented in this report is heavily dependent on the network simulation modelling undertaken as a part of WP2 of this Sandbox. We provide an overview of some relevant elements of the WP2 modelling in this report, but more detail is available from the relevant WP2 report. Specifically:
   - The network modelling is limited by the need to assume that technologies (Wi-Fi, mobile) only have access to one spectrum band per simulation. This is addressed in the modelling through assumptions about offloading to other bands, but with newly available spectrum bands evidence for offloading assumptions is not available. For example, the modelling assumes that indoor Wi-Fi uses the 5GHz band only. Recently the Lower 6GHz band has also been allocated to Wi-Fi and, while low at present, take up of this band by Wi-Fi is likely to increase over the next ten years. This affects interpretation of the modelling results.
   - Ofcom is currently consulting on proposals to enable satellite Direct to Device (D2D) services which could in future improve connectivity for consumers in areas currently underserved by terrestrial networks and provide back-up services. Our analysis of the potential of spectrum sharing in underserved areas does not address the potential interaction between improved services from spectrum sharing and improved services from D2D services, though this is an area for potential future research.
   - The spectrum sharing mechanism assumed by Ranplan Wireless in WP2 is a combination of an indoor/outdoor split which uses building entry losses to isolate mobile and Wi-Fi networks, and adjustments to the power of mobile base stations to reduce the overlap between mobile and Wi-Fi networks further. Estimates of the net benefits of spectrum sharing therefore account for potential losses to interference and/or efforts mitigate the overlap between mobile and Wi-Fi – specific details of which are contained in the WP2 report.
2) The economic analysis presented is based on economic models overlaid onto the WP2 network modelling. By their nature, all models involve significant simplification of the real world, using assumptions and simplified relationships by necessity. This is the case for both the network and the economic modelling. Nevertheless, we think that the outputs of the models developed for this research can provide useful results for policy making as long as those results are understood in the context of the limitations of the underlying models. In order to assist this understanding, we have aimed to be as transparent as possible about the structure of the economic models and the assumptions and data sources used in the modelling and we have tested the sensitivity of our results to a number of key assumptions.
3) The timelines and scope for this sandbox have always meant that the scope of the research has been limited in a number of dimensions, as noted in the discussion above on Scope. In particular, only a limited number of use-cases and archetypes can be explored. This naturally presents caveats to the breath and precision of the results, particularly for the scaling up to national level estimates. Incorporating additional use-cases and archetype areas in the future would provide additional data points that would provide specific results for additional use-

cases not currently captured and enable refinement of the scaling by providing additional data points.

4) The aggregate analysis of archetype results is limited to the highest level for which we have data on the working population at a reasonable level of granularity – the geographic extent of Great Britain (England, Scotland, and Wales). Data constraints mean that aggregation is not extended to Northern Ireland.

Abbreviations

5G NR	5th generation New Radio
AI	Artificial Intelligence
AR	Augmented Reality
ARPU	Average Revenue Per User
BEL	Building Entry Loss
BTS	Base Transceiver System
CAV	Connected and Autonomous Vehicle
CAPEX	Capital Expenditure or Capital Expense
CBRS	Citizens Broadband Radio Service
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications Administrations
CIB	Cell Information Block
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CUS	Collective Use of Spectrum
DSRC	Dedicated Short Range Communications
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FPGA	Floating Point Gate Array
GSMA	Global System for Mobile Communications
GVA	Gross Value Added
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISP	Internet Service Provider
ITU	International Telecommunication Union
JSON	Javascript Object Notation
LAL	Local Access Licences
LORAWAN	LOng RAnge Wide Area Network
LPWAN	Low Power Wide Area
LSA	Licensed Shared Access

LTE	Long Term Evolution
M2M	Machine to Machine
MIB	Master Information Block
ML	Machine Learning
mmWave	Millimeter Wave
MNO	Mobile Network Operator
PU	Primary User
RAN	Radio Access Network
RLAN	Radio Local Area Network
ROI	Return On Investment
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
SAL	Shared Access Licenses
SAS	Spectrum Access System
SIB	System Information Block
S/N	Signal to Noise Ratio
SU	Spectrum Users
TDMA	Time Division Multiple Access
TDM	Time Division Multiplexing
USRB	Universal Software Radio Peripheral
UWB	Ultra-Wide Band
V2C	Vehicle to Customer
V2I	Vehicle to Infrastructure
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
VR	Virtual Reality
WAS	Wireless Access System
WLAN	Wireless Local Area Network
WRC	World Radiocommunication Conference
XML	eXtensible Markup Language

PART I: INTRODUCTION AND CONTEXT

This section of the report provides background and context for the study, including an outline of the project objectives, study rationale, study scope, and key caveats and limitations that should be noted when interpreting the study results.

Introduction

This report focuses on the economic analysis of spectrum sharing in the Upper 6 GHz between mobile and Wi-Fi to deliver capacity to address peak demand in high density areas and in lower frequency bands (e.g. Band III and n77) to address poor network coverage in lower density areas.

This report is part of a broader 'Spectrum Sandbox' research project funded by the Department for Science, Innovation, and Technology (DSIT) to investigate the possibilities and implications of increased spectrum sharing between different users and service types within these bands. The aim is to provide an evidence base to the UK Government and Ofcom to determine whether more intensive spectrum sharing approaches should be adopted and under what scenarios.

This sandbox involved four integrated work packages:

1. WP0: Cross cutting activities to characterise the testbed environment, identify and prioritise use cases, define the spectrum sharing mechanism, and identify parameters for measurement to define the parameters for the other three work packages.
2. WP1: Practical field trials to test the feasibility of sharing spectrum between different pairs of users in real world environments, including approaches to mitigate and manage interference between different pairs of users in the same frequency band.
3. WP2: Simulations using three-dimensional (3D) propagation models to broaden the scope of parameters and scenarios being tested for each pair of spectrum users.
4. WP3: Economic modelling to assess the benefits and costs from sharing spectrum between the proposed user pairs for specific use case environments (use cases within a defined geographic area) and (indicatively) for the UK more broadly. The wider policy implications and practical regulatory considerations of spectrum sharing are also assessed qualitatively in this work package.

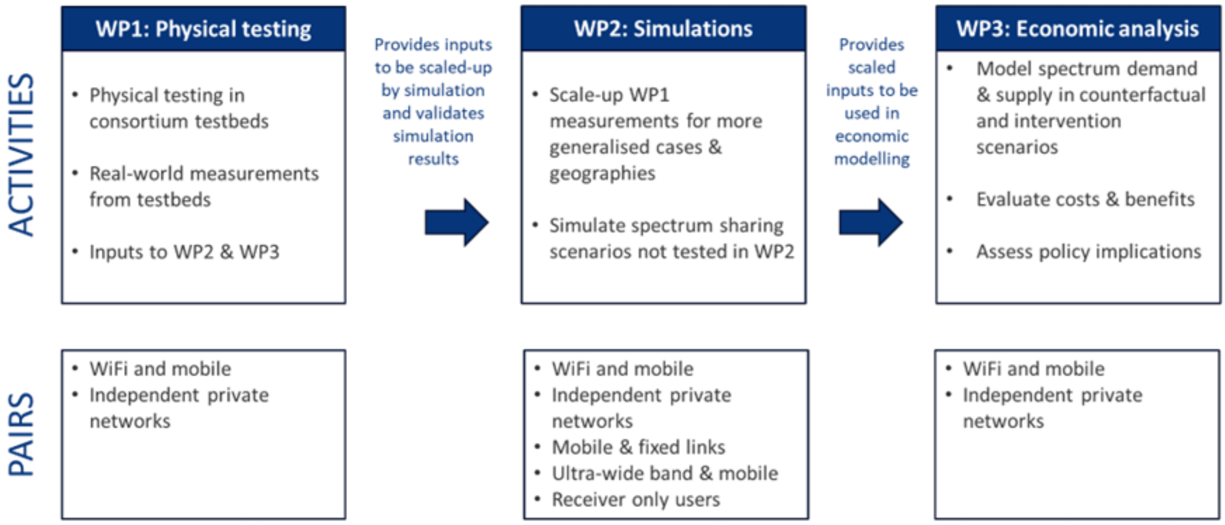
The three work packages are also linked, as detailed in the figure below. In the case of WP3, which is the focus of this report, WP1 and WP2 provide outputs which inform the WP3 analysis. For example, the simulation outputs are used to define the network characteristics and costs required to address target demand parameters for specific use cases in specified geographies and under specific spectrum sharing scenarios. Comparison of the results of different spectrum sharing scenarios (current provision vs no access to new spectrum vs exclusive assignment of spectrum to one user vs spectrum sharing between users) makes it possible to understand the incremental value of different spectrum allocation decisions, relative to the 'do nothing' counterfactual scenario. This means that costs and benefits can be assessed as 'additional'. Likewise, WP3 informed the choice of parameters for WP1 and WP2. For example, WP3 identified policy relevant use cases for spectrum sharing and provided target demand parameters for these use cases within distinct geographic contexts and under specific supply scenarios which informed the WP2 simulations.

This document reports on Work Package 3 (WP3), the economic analysis of the producer and consumer benefits associated with spectrum sharing in five defined use cases:

- Upper 6 GHz: High density urban, Dense Urban, low density urban;
- Lower frequency bands suitable for wide area low density provision: underserved lower density communities.

The use cases chosen for the assessment of costs and benefits are associated with a set of assumptions and parameters, including on geography, period of analysis, and involved user groups.

Figure: Overview of Durham Sandbox activities by Work Package



About the study

Context

Ubiquitous connectivity describes a state where users and their devices are always connected and in all environments without interruption. In theory this can be achieved with a single wireless technology with full indoor and outdoor coverage across the UK. Unfortunately, this does not exist in practice – the huge variance in the connectivity requirements of different users and in the user densities and propagation characteristics of the environments that they reside in mean that a multitude of wireless technologies with different propagation characteristics are needed, and those that do exist do not extend to addressing the requirements of all users in all environments. For example, users in Dense Urban environments face network congestion and weak coverage and rural communities continue to suffer from poor network coverage.

To achieve 'ubiquity' in these environments, spectrum policy must ensure the provision of a wide range of service providers and commercially viable wireless communications technologies across all environments. The mismatch between user demand and the supply of these services indicates a market failure. Greater accessibility of some spectrum bands – on a shared rather than exclusive basis – may enable new operators to enter the market and/or the delivery of new innovate solutions.

It is in this context that this study explores the potential economic benefits of spectrum sharing to address the connectivity gap in these high density and lower density use cases.

This section presents an overview of spectrum management and spectrum sharing, including an introduction to the approaches, benefits, challenges, and rationale for spectrum sharing.

UK spectrum management and policy

The radio spectrum ("spectrum") is indispensable in enabling wireless communication and other services based on wireless information transfers. There are many competing uses and users of the spectrum that also rely on different technologies to communicate using the spectrum. However, the spectrum is a public resource that is only available in a limited amount. Unrestricted usage can cause interference and hamper communications all together. There is a need to regulate spectrum access and usage to minimise harmful interference and optimise the economic and social benefits that can be derived from the services enabled by spectrum access.

As such, the use of the spectrum is regulated at the national and international level. The International Telecommunications Union (ITU) sets out the framework for global coordination and management of spectrum use, including specifications on the allocation of different services to specific frequency bands. Ofcom is the regulatory body responsible for managing spectrum to optimise use and implementing this ITU framework in the UK.

The UK's Department for Science, Innovation, and Technology (DSIT) is the lead UK government department for spectrum policy and strategy. DSIT's 2023 Spectrum Statement sets out the UK's latest strategic principles and ambitions for spectrum policy[2] which focuses on innovation in spectrum management and usage to drive increased spectrum access and greater opportunities for economic and social benefits.

[2] DSIT (2023). Spectrum statement. Available at: https://www.gov.uk/government/publications/spectrum-statement/spectrum-statement#managing-spectrum-use-1

This statement sets out a clear ambition to enhance spectrum sharing arrangements in the UK to improve spectrum availability and address inefficiencies with current spectrum allocation and usage.

About spectrum sharing

What is spectrum sharing?

A solution to increased spectrum access and efficiencies lies in greater spectrum sharing. Much of the spectrum bands in use today have been allocated to specific uses or users on a dedicated basis. An alternative approach involves sharing spectrum bands between different users.[3] Technological advances have made spectrum sharing an increasingly viable solution[4] whilst mitigation potential risks like interference. There are various ways to achieve spectrum sharing as illustrated in Figure 1.

Firstly, there are the technical mechanisms for sharing spectrum in frequency, location, time or signal: Spatial separation involves users sharing the same spectrum band at the same time but in different geographical locations. Temporal separation involves users sharing the same spectrum band in the same geographical location but at different times. Frequency and orthogonal signal separation methods allow for the same spectrum band to be shared by multiple users at the same time and geographical location. Secondly, there is the regulatory dimension that governs the management of the sharing mechanism and mitigation of interference: 1) collective Use of Spectrum (CUS): allowing spectrum to be used by more than one user simultaneously without a licence (i.e. under licence-exempt or a general authorisation model); 2) Licensed Shared Access (LSA) model: where different users are granted individual rights to access a shared frequency band; and 3. combining CUS and LSA.

Benefits and challenges of spectrum sharing

Spectrum sharing if implemented properly can in theory deliver significant benefits to the quality of wireless communication services. These benefits include: 1) increased spectrum efficiency and capacity by supporting multiple users of services within the same spectrum ban; 2) reduced interference from the use of database assignments and cognitive sensing technologies to dynamically allocate the best available frequencies to different tiers of users and minimise signal interference; 3) flexibility and adaptability from the dynamic allocation of spectrum bands to different users based on real-time demand and usage patterns and thus avoiding network congestion; 4) reduced costs associated with acquiring and managing licensed spectrum bands; and 5) facilitation of a greater range of operators to provide services, increasing competition and supporting innovation.

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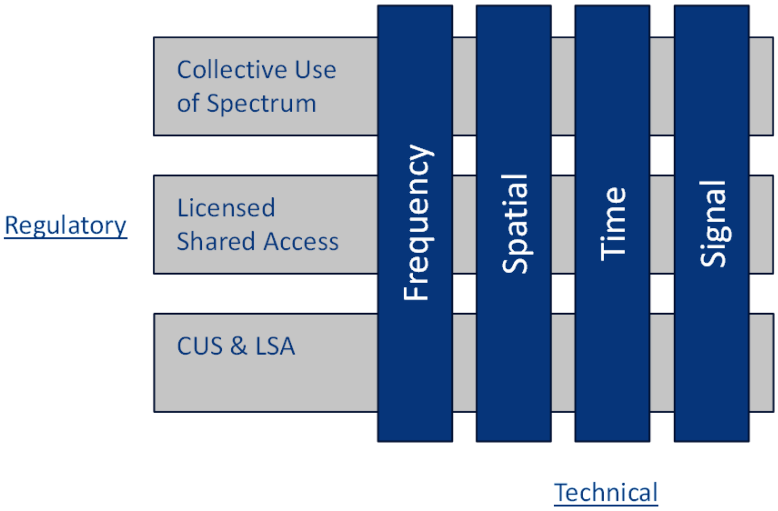
[3] Radio Spectrum Policy Group (2021). Report on Spectrum Sharing. Available at: https://radio-spectrum-policy-group.ec.europa.eu/document/download/aee201a0-06e3-494f-b7f7-36ec3b723291_en?filename=RSPG21-016final_RSPG_Report_on_Spectrum_Sharing.pdf

[4] See: https://digital-strategy.ec.europa.eu/en/policies/shared-use-spectrum

Figure Spectrum sharing approaches



Spectrum sharing also poses challenges that need to be carefully addressed at the government and regulator levels.

Some of the key technical challenges involve managing interference between different users as well as maintaining security and privacy. Spectrum sharing needs to be protected from different types of attacks, including spectrum sensing and information database attacks as well as the more classic jamming and eavesdropping attacks[5]. The use of advanced technologies coupled with robust monitoring and detection processes (e.g. ML-based detection framework[6]) can help mitigate these security and privacy risks.

Some key challenges are of a more economic nature. Spectrum sharing needs to create the right incentives for incumbent and new operators to participate in spectrum sharing and continue to provide widespread high-quality services. Incumbent licensed Mobile Network Operators (MNOs) have concerns that replacing exclusive licenses for increased spectrum sharing could erode the profitability and certainty needed for long-term heavy network investment and high-quality service[7].

Spectrum sharing access decisions therefore need to be non-discriminatory and consider competition and commercial viability concerns[8]. Spectrum sharing should also avoid imposing excessive costs to new and existing users to maintain the right incentives for market entry.

Rationale for spectrum sharing

The need for enhanced spectrum sharing in the UK is driven by a recognition of the mismatch between the demand for spectrum and its fixed supply. The result is underutilisation of spectrum in many locations and across time in the UK[9].

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[5] Qingyang Hu, R. (2012). Seminar: AI/ML in 5G Spectrum Sharing Security. Available at: https://cn.committees.comsoc.org/files/2021/03/cogsec_seminar_jan21.pdf

[6] Ibid.

[7] GSMA. (2021). Spectrum Sharing. Available at: https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2021/06/Spectrum-Sharing-Positions.pdf

[8] Ofcom (2016). A framework for spectrum sharing. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0028/68239/statement.pdf

[9] DSIT (2023). Spectrum statement.

For example:

- Users in Dense Urban environments, such as transport hubs, tourist hotspots, and high-rise downtown areas face poor and unreliable connections, especially at peak times, because of urban canyons and higher user densities that cannot all be supported by the network simultaneously. This problem could be alleviated by adopting more spectrum sharing and allowing new and/or existing operators to intensify the urban network and access unlicenced spectrum bands, such as those used by Wi-Fi, in peak times[10].
- Rural and lower density communities continue to suffer from poor mobile network coverage as low user densities and high deployment costs undermine the case for traditional MNOs network extension[11]. The relevant spectrum bands are left unused or underutilised in these areas, even though there may be other smaller operators or services willing to use them, resulting in a clear inefficiency[12]. Enhanced spectrum sharing could support new service providers to enter the market and address these connectivity 'not-spots'.
- UK's road and rail networks suffer from patchy coverage and low data rates, undermining existing commuter use cases and emerging use cases such as connected and autonomous vehicles (CAVs), logistics, and communications-based train control (CBTC).

This gap between demand and supply will widen as the use of wireless technologies with connectivity needs is expected to grow exponentially in the future[13]. For example, Ofcom modelled the UK demand for mobile data in 2030 to be in ranges of 7.5 times to 52 times 2021 levels, and as high as 19 to 540 times by 2035[14]. Overall global traffic is expected to increase to approximately 5,000 Exabytes[15] (EB)/month in the year 2030, i.e. over 675 times the 2010 levels[16]. This increase in demand is driven by growth at both the intensive (growing data use among existing users) and extensive (new and more numerous users and use cases) margin. The advent of next-generation technologies and applications (e.g. Artificial Intelligence, Augmented Reality, Virtual Reality) is expected to push up data demand at the device/application level, and at the extensive margin, there are expectations of significant growth in the number of users and diversity of applications and devices making use of wireless communication (e.g. Internet of Things, Autonomous Vehicles, and other autonomous systems in general).

While the supply of spectrum is relatively fixed, some factors (other than spectrum sharing) could free up additional spectrum capacity. The first is spectrum clearing, by which regulators reallocate spectrum bands previously used for one application to another (such as the US Federal Communications Commission's (FCC) redistribution of a portion of the C-band spectrum previously from satellite

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[10] Ofcom (2013). The future role of spectrum sharing for mobile and wireless data services Licensed sharing, Wi-Fi, and dynamic spectrum access. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0026/62738/spectrum_sharing.pdf

[11] Ofcom (2023). Connected Nations. Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023

[12] Ofcom (2022). Ofcom's future approach to mobile markets and spectrum. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf

[13] It is difficult to predict demand well beyond 2030. See: Ofcom (2022). Meeting future demand for mobile data. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

[14] Ibid.

[15] One EB is equal to one billion gigabytes (GB).

[16] Iyer, S., Patil, A., Bhairanatti, S., Halagatti, S., and Jashvantbhai Pandya, R. (2022). A Survey on Technological Trends to Enhance Spectrum Efficiency in 6G Communications.

operators to LTE and 5G networks)[17]. Spectrum capacity can also be improved by densifying the networks, e.g. by deploying a large number of small cells to fully leverage on the capacity made available by the mmWave spectrum[18]. Technology upgrades could also improve the efficiency of spectrum usage at the device level, relieving some of the future spectrum demand pressure[19].

These spectrum intensification techniques could help alleviate the spectrum demand pressure in the short term, but more extensive deployment of existing spectrum and licensing of new higher frequencies is the only way of extending the supply of spectrum to meet future demand growth.

While exclusive licencing is suitable for operators requiring the investment certainty for large scale and capital intensive network deployment, spectrum sharing allows new or existing service providers to flexibly deliver new services for underserved users.

Scope

This study assesses the economic benefits, costs, and regulatory and policy implications associated with spectrum sharing in two key spectrum bands:

- **Sharing between mobile and Wi-Fi in the Upper 6 GHz band:** exploring how we can facilitate coexistence between mobile and Wi-Fi applications in the Upper 6 GHz to provide additional capacity in environments with a high density of simultaneous users at peak times, such as Dense Urban environments, transport hubs, and high-density sporting or entertainment events.
- **Sharing of other bands with propagation characteristics suitable for wide area provision in lower density areas (e.g. Band III or the n77 band):** exploring how we can facilitate more accessible spectrum for existing MNOs or private network providers to address total and partial connectivity not-spots for mobile users in lower density and rural areas where current network extension is too expensive to deliver. Specifically, this study explores the permissive licensing of Band III and the n77 band to fill connectivity gaps for mobile users. These bands are modelled to provide an indicative assessment of the potential feasibility of service provision under a spectrum sharing scenario. It is acknowledged that other bands may be more suitable for low density areas.

The scope of research and analysis in this report is limited by the following:

- **Scope of analysis**: the analysis assesses the costs and benefits of three intervention scenarios (e.g. Upper 6 GHz band allocated to (i) mobile only, (ii) Wi-Fi only, and (iii) shared between mobile and Wi-Fi) and compares them with each other and with two counterfactual scenarios without allocation of the Upper 6 GHz band (i) current network provision today, and (ii) enhanced network provision without Upper 6 GHz. The assessment of costs and benefits is based on an approach consistent with the HM Treasury Green Book.
- **Scope of benefits**: the benefits to consumers of improvement to throughput based on Willingness to pay estimates are the key measure of benefits. The analysis also assesses how these benefits are allocated between consumers and producers based on assumptions about the price paid for higher levels of throughput. Other potential benefits, such as to business users and wider benefits from greater innovation and new services, are not assessed.

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[17] See: https://www.fcc.gov/document/fcc-expands-flexible-use-c-band-5g-0

[18] Ofcom (2022). Meeting future demand for mobile data. Available at : https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf

[19] Ibid.

- **Scope of costs**: the capital expenditure and operating costs of network development are modelled but any wider costs potentially linked to the policy options, such as the costs of any changes to the regulatory regime, are not assessed.
- **Geographic scope**: the analysis models networks in five small geographical archetype areas in the UK. Whilst we also provide an assessment of aggregate economic impacts at the level of England and Wales[20], this is based on the results from the small number of areas analysed. Extension of the number of geographic areas modelled is a potential area for further research beyond this Sandbox.

Caveats and limitations

The research has been conducted by a team of independent professional economists with specialist knowledge of economic modelling, technology, and telecommunications, using best practice and best judgment. The methodology used, and assumptions made, are described in this report in a transparent manner, with caveats noted as required. Nonetheless, the reader should bear in mind the following high-level limitations and caveats of this study throughout:

1) The economic modelling presented in this report is heavily dependent on the network simulation modelling undertaken as a part of WP2 of this Sandbox. We provide an overview of some relevant elements of the WP2 modelling in this report, but more detail is available from the relevant WP2 report. Specifically:
    - The network modelling is limited by the need to assume that technologies (Wi-Fi, mobile) only have access to one spectrum band per simulation. This is addressed in the modelling through assumptions about offloading to other bands, but with newly available spectrum bands evidence for offloading assumptions is not available. For example, the modelling assumes that indoor Wi-Fi uses the 5GHz band only. Recently the Lower 6GHz band has also been allocated to Wi-Fi and, while low at present, take up of this band by Wi-Fi is likely to increase over the next ten years. This affects interpretation of the modelling results.
    - Ofcom is currently consulting on proposals to enable satellite Direct to Device (D2D) services which could in future improve connectivity for consumers in areas currently underserved by terrestrial networks and provide back-up services. Our analysis of the potential of spectrum sharing in underserved areas does not address the potential interaction between improved services from spectrum sharing and improved services from D2D services, though this is an area for potential future research.
    - The spectrum sharing mechanism assumed by Ranplan Wireless in WP2 is a combination of an indoor/outdoor split which uses building entry losses to isolate mobile and Wi-Fi networks, and adjustments to the power of mobile base stations to reduce the overlap between mobile and Wi-Fi networks further. Estimates of the net benefits of spectrum sharing therefore account for potential losses to interference and/or efforts mitigate the overlap between mobile and Wi-Fi – specific details of which are contained in the WP2 report.
2) The economic analysis presented is based on economic models overlaid onto the WP2 network modelling. By their nature, all models involve significant simplification of the real world, using assumptions and simplified relationships by necessity. This is the case for both the network and the economic modelling. Nevertheless, we think that the outputs of the models developed for

[20] Aggregation of economic impact is only possible to the level of England and Wales because it is based on data for the working population which is not available at a sufficient layer of disaggregation required for the analysis for Scotland and Northern Ireland. The source for the working age population is the ONS Business Register Survey 2023.

this research can provide useful results for policy making as long as those results are understood in the context of the limitations of the underlying models. In order to assist this understanding, we have aimed to be as transparent as possible about the structure of the economic models and the assumptions and data sources used in the modelling and we have tested the sensitivity of our results to a number of key assumptions.

3) The timelines and scope for this sandbox have always meant that the scope of the research has been limited in a number of dimensions, as noted in the discussion above on Scope. In particular, only a limited number of use-cases and archetypes can be explored. This naturally presents caveats to the breath and precision of the results, particularly for the scaling up to national level estimates. Incorporating additional use-cases and archetype areas in the future would provide additional data points that would provide specific results for additional use-cases not currently captured and enable refinement of the scaling by providing additional data points.
4) The aggregate analysis of archetype results is limited to the highest level for which we have data on the working population at a reasonable level of granularity – the geographic extent of Great Britain (England, Scotland, and Wales). Data constraints mean that aggregation is not extended to Northern Ireland.

PART II: ECONOMIC ANALYSIS APPROACH

This section of the report provides a detailed description of the study's methodology. It includes an outline of the economic framework for assessing costs and benefits, a description of the use cases and archetype areas that are modelled, the different spectrum sharing scenarios that are considered, and the approach for aggregating archetype area level results to the highest level for which we have data – i.e. Great Britain (England, Scotland, and Wales).

Specific methodologies are presented for the economic analysis of spectrum sharing in the two spectrum bands of interest: in the Upper 6 GHz between mobile and Wi-Fi to deliver capacity to address peak demand in high density areas and in lower frequency bands (e.g. Band III and n77) to address poor network coverage in lower density areas. The approach for aggregating up the results of the Upper 6 GHz analysis from the individual archetype areas of Great Britain as a whole is also presented in this section of the report.

Overall approach

Overview of economic analysis

The value of spectrum sharing comes from the additional network capacity that is available to service new and existing users. In this study we consider spectrum sharing between mobile and Wi-Fi users, with a broad assumption that the different propagation characteristics of Wi-Fi and mobile mean that they occupy specific niches, with Wi-Fi servicing indoor users and mobile servicing outdoors users. The idea is that spectrum sharing allows users of both networks to access the same band of spectrum which they can then use to do one of two things:

- Deliver services to a larger set of users and/or improve the user experience of existing users for a given quantum of network investment (performance enhancement), or
- Reduce the quantum of network investment required to deliver a given user experience for a given set of users (cost optimisation).

Some portion of the spectrum band may be lost to minimise interference between mobile and Wi-Fi users, but the hypothesis is that there is an overall net gain. The aim of this study is to test this hypothesis.

To do this, the following methodology is adopted, as summarised in the Figure below:[21]

- **Definition of use case area:** the boundary, geographic characteristics, population density, and propagation characteristics of the use case under investigation is defined.
- **Estimation of users:** the number of active users within the use case area is estimated. For the urban use cases characterised by network congestion at peak times, users are estimated at peak, and for the rural use cases characterised by poor availability, users are assessed at average levels. The number of active users accounts for several key variables including total population (residential or working population depending on archetype), the 'activity factor' which represents the proportion of the population actively generating traffic at a given time within a defined geography, and offload factors that define the proportion of users exclusively using the relevant frequency bands of interest.

21 Further details on our methodology are provided in the Annex to this report.

- **Assessment of counterfactual:**
    - The architecture of the existing network is defined so that associated costs (CAPEX and OPEX) and user performance can be estimated.
    - The performance of the existing network is assessed so that a distribution of currently achieved user experience (signal availability and achieved data rates) is generated. For the urban use cases, performance is assessed at peak times, and for the rural use cases, performance is assessed as average.
- **Definition of target demand parameters:** desired user experience parameters (signal availability and achieved data rates for a revised distribution of users) are defined.
- **Simulation of network characteristics for target user experience parameters:** for a given spectrum sharing scenario (exclusive allocation vs shared allocation), a new network architecture is defined to achieve the revised user experience parameters. This new network architecture is defined in WP2 by Ranplan Wireless. A key output from this step are estimates of the costs (CAPEX and OPEX) from this new architecture. The spectrum sharing mechanism assumed by Ranplan Wireless in WP2 is a combination of an indoor/outdoor split which uses building entry losses to isolate mobile and Wi-Fi networks, and adjustments to the power of mobile base stations to reduce the overlap between mobile and Wi-Fi networks further. Estimates of the net benefits of spectrum sharing therefore account for potential losses to interference and/or efforts mitigate the overlap between mobile and Wi-Fi – specific details of which are contained in the WP2 report.

The next stage is to monetise the benefits and costs for the counterfactual and target demand scenarios. Costs and benefits are estimated for 'producers' (i.e. those immediately using spectrum to supply services) and 'consumers' (end users who purchase data services from producers for personal consumption). The difference in costs and benefits for each is defined as the 'producer surplus' and 'consumer surplus.

The producer surplus is defined as the difference between the (market) price that the firm receives and the lowest price at which the producer would be willing to sell, which we assume to equal to the cost of provision (i.e. the break-even point). For this analysis, this is equivalent to the total revenues that accrue to the network provider, which we estimate as the price for the data rates delivered to customers, minus the costs to deliver this additional capacity – or more specifically, the costs of the simulated network architecture – considering CAPEX and OPEX.

The consumer surplus is the difference between what the consumer is willing to pay and what the consumer actually pays. For this analysis, the consumer's willingness to pay is the monetary value that customers place on the data rates that they are given, minus the costs of accessing this service (which is equivalent to the revenues earned by the producer).

The overall value of spectrum sharing is estimated as the difference between the sum of the producer and consumer surplus under the exclusive spectrum allocation (mobile only or Wi-Fi only) and the shared spectrum allocation (mobile and Wi-Fi) scenarios.

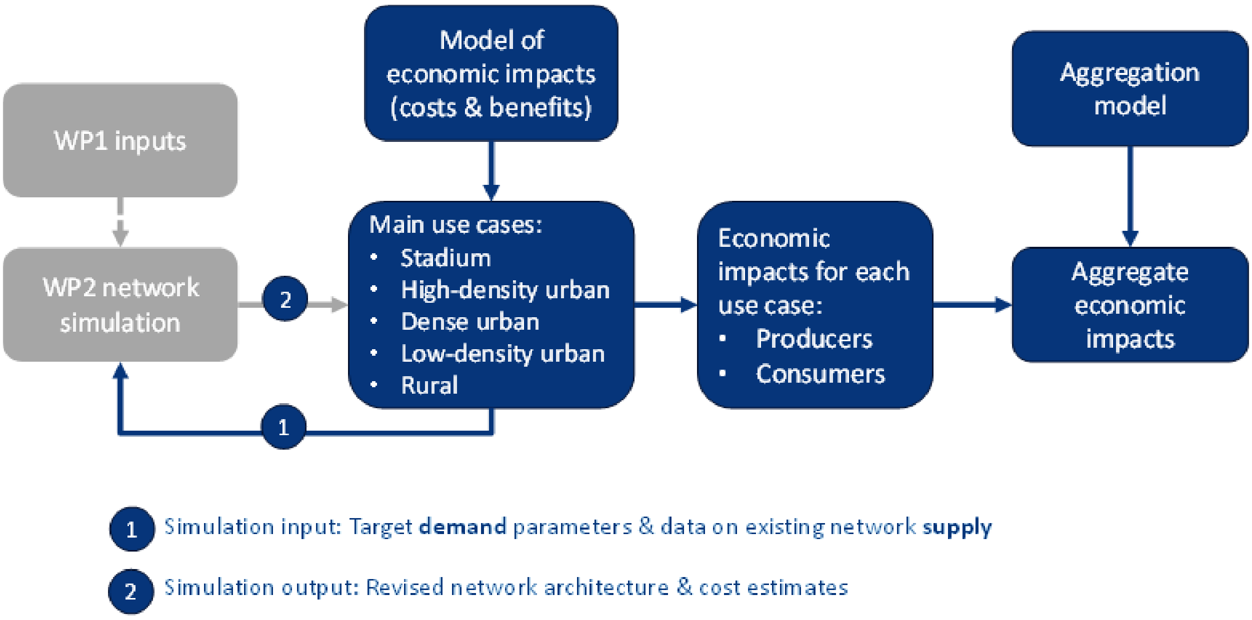
In summary, the key costs and benefits that are quantified in our analysis are the capital and operating costs of the networks simulated in the WP2 work and the benefits to consumers of the higher throughput enabled by the allocation of spectrum in the Upper 6GHz band. The capital and operating costs are estimated in the WP2 analysis by combining the modelled network elements with estimates of unit costs. The unit costs are based on expert judgements and other evidence of market prices for each network element and hence represent opportunity costs. The monetised benefits to consumers of higher throughput are estimated using estimates of willingness to pay for higher throughput from the literature. Further details of these calculations are provided in the Annex to this report.

In addition to the costs of network rollout and the benefits of higher throughput to consumers, there are also likely to be wider costs and benefits that we have not included in our modelling. These may include:

- Benefits from achieving higher throughput more quickly with the use of the Upper 6GHz band for mobile and Wi-Fi services;
- Increased flexibility for network operators, enabling them to adjust more quickly to changes in supply and demand and making more efficient use of spectrum;
- The opportunity cost of staff and other resources at all relevant stages of the supply chain – including Ofcom – that are required to initiate and operate the sharing intervention;
- Whilst our modelling accounts for interference between mobile and Wi-Fi (by simulating networks that avoid interference between them in an acceptable way) there may be interference with existing uses of the Upper 6GHz band or further measures may need to be taken in order to avoid such interference;
- Direct benefits to business users and services from having higher throughput, as well as follow on innovation and productivity gains from the availability of new services;
- Changes in environmental impacts arising from changes in power usage by networks.

In considering all these potential impacts care needs to be taken to consider them in the context of a relevant counterfactual. For example, any indirect impacts of spectrum sharing in the Upper 6GHz band on innovation and productivity may differ substantially when the counterfactual changes from no allocation of the Upper 6GHz band to mobile or Wi-Fi to allocation of the band to mobile only.

Figure: Overview of economic analysis methodology



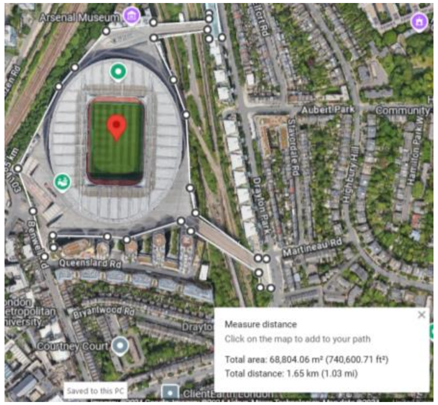
Use cases & archetype areas

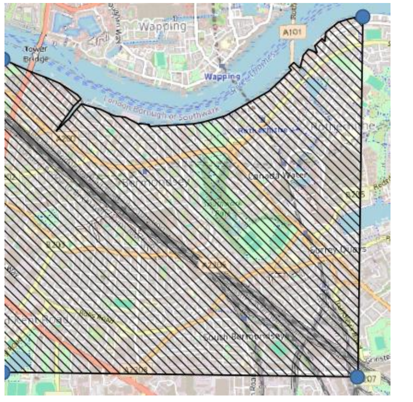
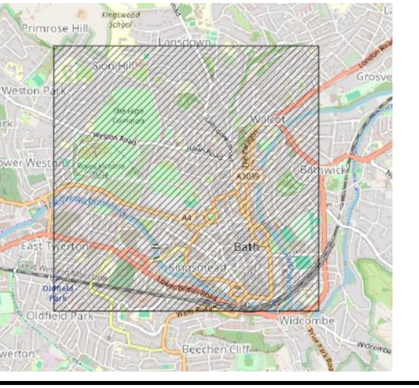
The economic analysis is based on four use cases: a High-Density Urban area, a Dense Urban area, a lower-density urban area, a rural area, and a high-density event.

For each use case a specific example was chosen to serve as an archetype area for which network simulation modelling was undertaken in WP2. Each archetype is a specific geographical location in the UK.

The use cases and chosen archetypes are summarised in the table below and are further elaborated in the discussion that follows.

Table: Summary of use cases

Policy question	Area type	Archetype	Characteristics	
Sharing of Upper 6 GHz band between Wi-Fi and mobile to provide additional capacity	Stadium / events	Emirates Stadium in London	• Very large number of connected devices in a small area • Supply bottlenecks may last for a few hours (e.g. football matches) to a few days (e.g. festivals)	
	High-Density Urban area	City of London	• Numerous connected devices in a small area. • Urban canyons block line of sight • High user densities • Peak demand potentially greater than network capacity	

	Dense Urban area	South London (Bermondsey)	• High user densities • Peak demand potentially greater than network capacity	
	Lower-density urban area	Bath	• Medium user densities	
Permissive licensing of lower spectrum bands to provide capacity in underserved areas / not-spots	Rural and lower-density areas	Northumberland	• Lower user densities • Undersupply and not-spots	

Rationale for use-cases exploring sharing of the Upper 6 GHz band between Wi-Fi and mobile to provide additional capacity

Dense and less Dense Urban areas

Dynamic urban environments (e.g., transport hubs, tourist hotspots high-rise downtown areas) present a challenge to spectrum management because of two issues: urban canyons which may block line of sight, and high user densities. Both factors can be accounted for in the initial planning and deployment of urban networks. However, the evolution of cities means that networks have to be optimised continuously, for example, to account for changes in urban geometries and user densities as buildings and urban use change and as cities with housing shortages (e.g. London) trend towards densification. The problem will also accelerate as user applications become more data intensive and as the number of possible applications increase (e.g. as cities become 'smarter' and as autonomous and connected vehicles become road users).

Dense Urban areas like London tend to use mobile and Wi-Fi spectrum intensely. Additional spectrum capacity is needed by both networks, potentially in the Upper 6 GHz range. This could be achieved by giving Wi-Fi priority indoors and mobile networks priority outdoors. To manage this, spectrum sharing techniques will be needed to manage overlap, take account of simultaneous use of this band among different users, and potentially segment spectrum by indoor/outdoor parameters accordingly[22]. In other words, spectrum sharing techniques may help alleviate the problem by providing access to a higher concentration of spectrum in areas that are underserved.

High-density events

As with high density urban areas, the current set-up of mobile networks results in network congestion in areas of high traffic, especially in cases where demand is event driven and tends to peak for relatively short periods of time such as festivals, sport events, national events. These events are often scheduled in advance, so use is predictable, and time is limited. This means that supply bottlenecks may last for a few hours (football matches or broadcasting of national events) to a few days (festivals or ongoing sporting events) at most. Live streaming and social media create a need for broadband-level connectivity for a very large number of devices, especially as video and images increase in data intensity and as mobile applications become more sophisticated. This demand for data will further increase as events incorporate Virtual Reality.

This use case tests whether it is possible to alleviate network congestion by enabling licensed mobile use in high traffic areas while making use of Wi-Fi elsewhere or vice-versa, by making use of Wi-Fi in high traffic areas while allowing for licensed mobile use elsewhere.

Rationale for use-cases exploring permissive licensing of other bands (e.g. n77 or Band III) to provide capacity in underserved areas / not-spots

Underserved Rural areas

As a scarce national resource, the current approach of awarding national, multi-year licences to the highest bidder has resulted in a restricted deployment environment where licence holders effectively deploy services in areas that are profitable, but then exclude others from using that spectrum in less profitable areas by way of "squatters rights", i.e. those with low user densities in harder to access areas – two characteristics that characterise rural areas.

22 Ofcom (2024). Mobile and Wi-Fi in Upper 6 GHz. Why hybrid sharing matters. Available here: Mobile and Wi-Fi in Upper 6 GHz - Why hybrid sharing matters (ofcom.org.uk)

Several UK MNOS are now on record as having said that they cannot afford to deploy nationwide 5G-NR services. If more cellular spectrum was available to a wider pool of participants on a low-cost "first come first served" basis, then we could see greater deployment of private cellular solutions and wider coverage in the areas that citizens require it - as can be seen in the USA, with 100x more deployments in CBRS than the UK has in its "Shared Spectrum" regime. Equally, it is acknowledged that to roll out national networks, the licence holder does need long term certainty of available spectrum to secure a return on their investments and to procure relevant equipment. A permissive spectrum sharing regime which allows independently operated private networks to deploy services in these rural communities using underutilised spectrum could help alleviate this issue.

Scenarios

To understand the socioeconomic benefits and costs of i) sharing between mobile and Wi-Fi in the Upper 6 GHz band and ii) flexible sharing of lower spectrum bands (Band 3 / n77) under a permissive licensing regime, the economic analysis considers a range of scenarios for each sharing context. These scenarios are designed to deliver key insights into the additional benefits that spectrum sharing can provide in the respective context relative to existing spectrum availability, as well as insights into the associated differentials in the costs of network delivery.

Scenarios are simulated for each of the relevant archetype areas by Ranplan Wireless (WP2) and validated through insights from physical testing undertaking in WP1. For each scenario, target demand parameters and user numbers were specified by London Economics. Target parameters were chosen to align with potential future demand projections in each of the use cases. Further discussion on the target demand parameters can be found in the annex.

The spectrum sharing mechanism assumed by Ranplan Wireless in WP2 is a combination of an indoor/outdoor split which uses building entry losses to isolate mobile and Wi-Fi networks, and adjustments to the power of mobile base stations to reduce the overlap between mobile and Wi-Fi networks further. Estimates of the net benefits of spectrum sharing therefore account for potential losses to interference and/or efforts mitigate the overlap between mobile and Wi-Fi – specific details of which are contained in the WP2 report.

Scenarios for sharing between mobile and Wi-Fi in the Upper 6 GHz band

To enable understanding of the additional benefits enabled by spectrum sharing in the Upper 6 GHz band, a range of scenarios were simulated by Ranplan Wireless. Each scenario simulated deployment of a mobile and a Wi-Fi network to serve the estimated number of active mobile and Wi-Fi users at peak times who could benefit from 6 GHz deployment and their throughput requirements in each archetype area selected for our use-cases. Further details on the estimation of Wi-Fi/mobile users in scope for each simulation are provided in the annex.

First, Ranplan Wireless simulated a scenario that mimics a deployment providing mobile and Wi-Fi service provision in-line with current service levels for each archetype area. This enables understanding of the baseline costs (CAPEX and OPEX) and existing consumer and producer benefits of delivering a base-level of provision equivalent to current service for the users in scope of the economic analysis. This baseline scenario is called **Scenario 0**. To facilitate these simulations, M2Catalyst, a global telecom data service provider, kindly provided us with granular (800x800m) data on signal strength/quality and coverage across the UK, as well as data on existing mobile network infrastructure in the archetype areas. This was used to help us understand existing provision.

Ranplan Wireless then simulated four forward-looking supply scenarios for each archetype area. Under these scenarios, supply would be expanded to meet demand target parameters for both mobile and Wi-Fi in each use case. This helps understand the infrastructure and associated costs (CAPEX and OPEX) needed to deliver an expanded service that can meet future demand given the spectrum available to mobile and Wi-Fi operators.

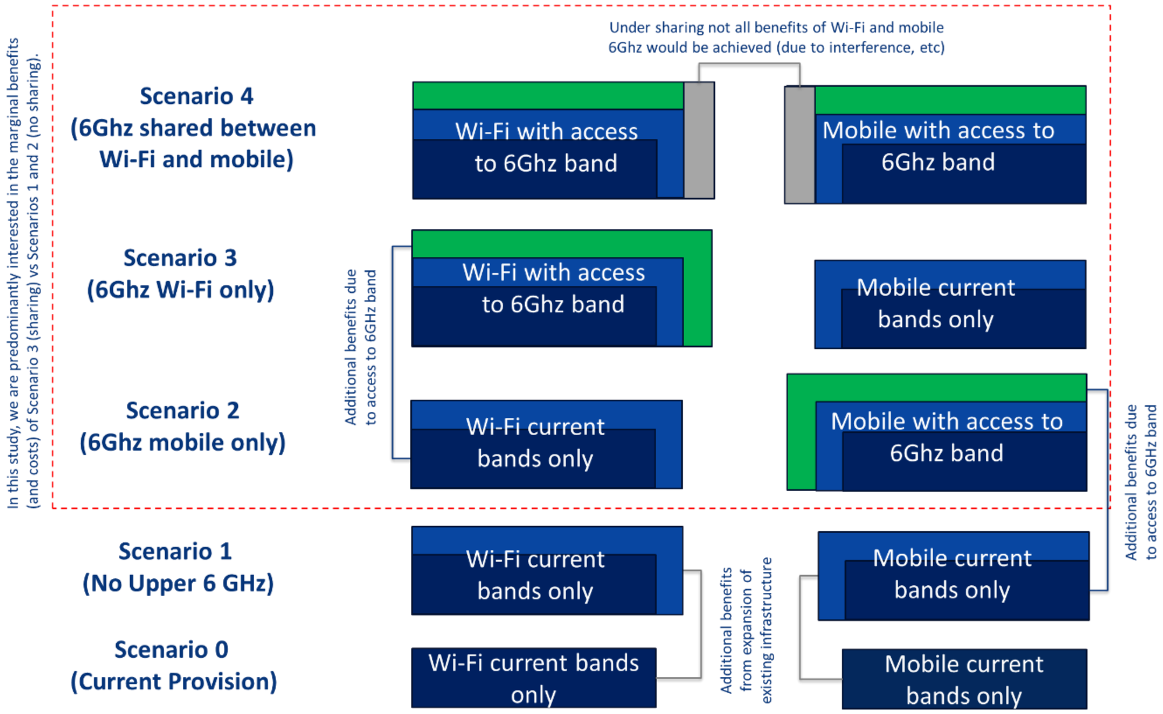
- **Scenario 1 (No Upper 6 GHz):** Mobile and Wi-Fi networks do not have access to the Upper 6 GHz band (they only use current spectrum allocation) to meet the respective demand target parameters. The rationale for this scenario is to provide insights into the additional infrastructure needed and associated additional costs of delivering enhanced service given current spectrum constraints. Where current spectrum is unable to deliver sufficient capacity to meet target parameters, this scenario further provides insights into the practical limitations of service delivery given current spectrum allocation.
- **Scenario 2 (Upper 6 GHz given to mobile Only):** Mobile has access to the full allocation of the Upper 6 GHz band to meet the respective demand target parameters. Wi-Fi does not have access to the 6 GHz band and uses its current spectrum allocation to meet the target demand parameters, in so far as this is possible. This scenario enables us to understand the additional benefits (and associated costs) of delivering an expanded network that can meet future demand. For Wi-Fi, this scenario also provides insights into the limitations of service provision that can be achieved given current spectrum constraints. Note: as mobile has sole allocation of the Upper 6 GHz band, mobile deployment in this scenario can happen both outdoors as well as indoors (through small cell in-building mobile deployment). For consistency with the Wi-Fi scenario, the central scenario does not assume any indoor mobile deployment, though various degrees of indoor deployment are explored in the sensitivity analysis.
- **Scenario 3 (Upper 6 GHz given to Wi-Fi Only):** Wi-Fi has access to the full allocation of the Upper 6 GHz band to meet the demand target parameters. Mobile does not have access to the 6 GHz band and uses its current spectrum allocation to meet the demand target parameters, in so far as this is possible. This scenario enables us to understand the additional benefits (and associated costs) of delivering an expanded network that can meet future demand. For mobile, this scenario also provides insights into the limitations of service provision that can be achieved given current spectrum constraints. Note: 6 GHz Wi-Fi networks in this scenario could in principle also be deployed outdoors. However, for simplicity we assume that users would only access Wi-Fi indoors (see Section X). Therefore, no outdoor 6 GHz Wi-Fi deployment is simulated under this scenario.
- **Scenario 4 (Spectrum Sharing of Upper 6 GHz):** Both mobile and Wi-Fi have access to the Upper 6 GHz band to meet the demand target parameters and share the available 6 GHz spectrum. This scenario provides insights the additional benefits of spectrum sharing over and above allocating the Upper 6 GHz band to either Wi-Fi only or mobile only. The scenario also helps understand any reductions in benefits relative to the scenarios 1 and 2, i.e., possible mobile or Wi-Fi benefits that cannot be realised in a sharing scenario, for example, due to interference levels between Wi-Fi and mobile and a lack of indoor 6 GHz small-cell mobile deployment under an indoor/outdoor sharing mechanism.

The figure below provides a graphical representation of the various scenarios and their links between each other. The size of the boxes represents the benefits that could be realised under each scenario., separately for Wi-Fi and mobile. The colour of the boxes indicates the source of benefits:

- The dark blue boxes represent existing benefits under provision equivalent to current service.

- The light blue boxes represent additional benefits that could be materialised through expansion of the network within current spectrum constraints.
- The green boxes represent the additional benefits enabled by access to the Upper 6 GHz band.
- Finally, the grey boxes represent the potentially unrealised benefits due to limitations from sharing the Upper 6 GHz spectrum (e.g., due to interference and/or interference management).

Figure: Scenarios for dense/urban use-cases



Scenarios for sharing of other bands with propagation characteristics suitable for wide area provision in lower density areas

The Upper 6 GHz scenarios focused on the additional benefits of sharing between mobile and Wi-Fi of the Upper 6 GHz band. Due to due its propagation characteristics and associated higher costs, the 6 GHz band is not a viable option for addressing gaps in provision in underserved areas and not-spots. Therefore, our analysis of lower density areas explores the benefits enabled in underserved lower-density areas through a simplified and expedited permissive licensing process that enables sharing in lower frequency bands.

To understand the costs and benefits of sharing under a permissive licensing process, two scenarios are explored:

- **Scenario 1 – Band 3:** Explores the costs and benefits of deploying small cell Band 3 base-stations providing throughput of 2 Mbps, providing basic mobile services such as texting, audio and basic browsing. This scenario is based on insights on costs to provide coverage to rural areas from our sandbox partners Telet through the MoNeH Rural Connected Communities Test Bed & Trials Programme.[23] Due its propagation characteristics and lower costs, small cell Band 3 may be more appropriate for addressing not-spots in rural areas.

[23] Telet, blue sky, CH4LKE (2022). *MONeH Rural Connected Communities – 5G Test Bed & Trials Programme. Final Report v1.34*. Available at: https://uktin.net/sites/default/files/2023-05/MONeH%20RCC%20-%20Final%20Report.pdf

- **Scenario 2 – n77:** Explores the costs and benefits of deploying small cell n77 base-stations providing throughput of 9 Mbps, enabling use of services demanding higher speeds such as video capabilities. This scenario is based on simulations undertaken by Ranplan Wireless of deploying small-cell mobile network infrastructure in the n77 band in our archetype area (Northumberland). Due to its propagation characteristics and higher throughput, the n77 band may be more appropriate for addressing under provision in denser rural areas or urban environments as well as to provide coverage for denser commercial sites (e.g., caravan parks) or events in rural locations (outside the scope of this analysis).

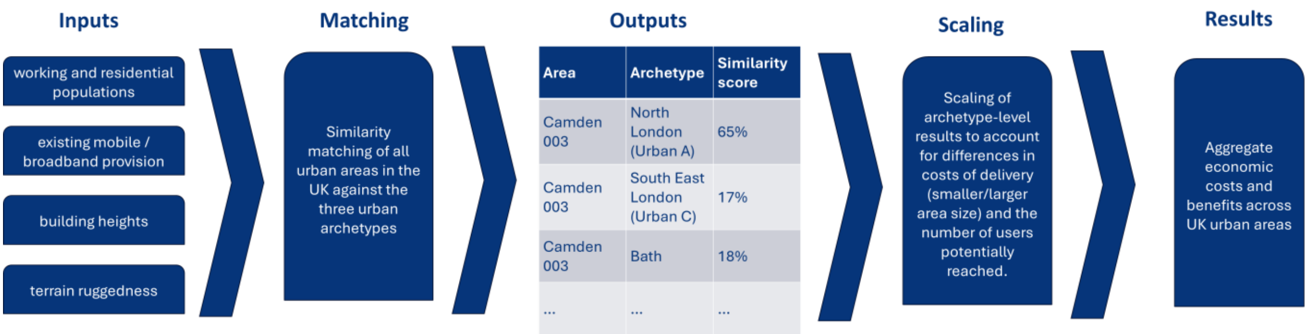
Scaling up economic results of spectrum sharing of the Upper 6 GHz band in urban settings:

To provide an indicative understanding of the magnitude of potential benefits and costs of spectrum sharing in the Upper 6 GHz band more widely, results for the three urban archetype areas are scaled up for urban settings across the UK.

To do this, we first undertook a similarity matching exercise where urban areas across the UK were matched to our three urban archetypes. Each urban area in the UK was compared to each of our three urban archetypes across a number of geospatial characteristics and an overall similarity score to each archetype calculated. Geospatial characteristics include: working and residential populations, population density, existing mobile/broadband provision, mean building height, and terrain ruggedness index.

Economic results for our archetype areas where then scaled by area size and population to account for differences in costs of delivery (smaller/larger area size) and the number of users potentially reached. Where an area matched to several of our archetypes a weighted average, in line with the similarity weights, was taken.

Figure: Illustration of process of scaling up economic results of spectrum sharing of the Upper 6 GHz band in urban settings



Caveat: The scaling exercise is a relatively basic analysis intended to provide a Rough Order of Magnitude (ROM) and indicative understanding of potential benefits. While it tries to capture key geospatial differences affecting delivery costs (e.g., building heights), these aspects are only captured in so far as the areas are similar enough to the three archetype areas analysed. To gain a more robust understanding of the size of potential benefits across the UK further, more detailed, analysis would be needed. This could be achieved by simulating additional archetypes to capture additional heterogeneity across urban centres or through a national-level simulation study.

Analysis of economic benefits of addressing not-spots and underserved areas:

Given the higher deployment costs and propagation characteristics (lower range), sharing in the 6 GHz band is unlikely to address connectivity gaps in underserved areas and not-spots. Nevertheless, these areas could benefit from flexible sharing regimes such as faster and more streamlined licensing process in lower bandwidths (e.g., Band 3 or n77), which may enable smaller providers to deploy infrastructure at lower costs (e.g., using small cells). Competitive effects in turn may incentivise MNOs to increase deployment in underserved areas where they are currently squatting on spectrum.

Therefore, in addition to exploring the benefits of sharing in the Upper 6 GHz band, two further analyses were undertaken: i) one examining the potential economic benefits of providing coverage to not-spots/underserved areas, and ii) another examining the costs and benefits of improving speeds by 10 Mbps in areas where the current speeds offered by MNOs are poor.

In order to identify these areas, M2Catalyst, a global telecom data service provider, provided us with granular (800x800m) data on speeds and coverage across the UK. This was used to help us understand existing provision across the UK and identify underserved areas. The data consists of throughput speeds (in buckets) for 800x800m grids across the UK. Each grid has speed measurements for some or all of the MNOs across 5 buckets of speed.[24]

In this interim report, we have defined not-spots/underserved areas in our first analysis as those where the M2Catalyst data indicates that throughput speed from the second best provider in an area is below 1 Mbps. This means that in identified underserved areas, at most one provider is supplying speeds in excess of 1 Mbps, and in some cases there is no coverage from any supplier at all.

When modelling the costs and benefits of increasing speeds by 10 Mbps in areas where current throughput rates are low, the areas where the throughput provided by at least two MNOs is below 9 Mbps are identified. This means that the areas included in this analysis include the not-spots/underserved areas modelled above.

So as to capture areas where there is a lack of provision but there is demand, both analyses focus on areas where the Global Human Settlement Layer[25], a project by the EU to map population density worldwide, indicates that more than 25 people live in an area.

Costs and benefits are modelled for two scenarios i) raising speeds in not-spots/underserved areas to 2 Mbps through deployment of small-cell Band 3 base-stations based on insights on costs to provide coverage to rural areas from our sandbox partners Telet through the MoNeH Rural Connected Communities Test Bed & Trials Programme[26] and ii) raising existing speeds offered by MNOs by 10 Mbps through deploying small cell n77 base-stations based on simulations by Ranplan Wireless.

As in the analysis of spectrum sharing above, benefits are derived from the willingness to pay estimates in Rabbani et al. (2023). Further details on the assumptions underlying the estimation are provided in the annex.

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[24] The speed buckets are: No signal (0 Mbps), 0-1 Mbps, 1-4 Mbps, 4-9 Mbps, and >9 Mbps.

[25] This data is at the 100x100m level. It can be downloaded here: https://human-settlement.emergency.copernicus.eu/dataToolsOverview.php

[26] Telet, blue sky, CH4LKE (2022). *MONeH Rural Connected Communities – 5G Test Bed & Trials Programme. Final Report v1.34*. Available at: https://uktin.net/sites/default/files/2023-05/MONeH%20RCC%20-%20Final%20Report.pdf

PART III: RESULTS, CONCLUSIONS AND NEXT STEPS

This section of the report presents the findings of the study, including results, conclusions, suggested recommendations, and suggested areas for further research. Findings from an industry-wide consultation on the benefits, costs, concerns, and required actions for enabling spectrum sharing are also integrated into this section of the report.

The results of the study are organised into the two spectrum bands of interest: in the Upper 6 GHz between mobile and Wi-Fi and in lower frequency bands (e.g. Band III and n77). Use case specific results are presented for the Upper 6 GHz analysis first, with the results of the aggregation exercise to scale these results to Great Britain as a whole presented subsequently, along with the results of a sensitivity analysis to assess the impact of changes in key model parameters. The results of the economic analysis of spectrum sharing in lower frequency bands is presented at the aggregate level for two different scenarios.

Upper 6 GHz sharing results

Use-case specific results

The baseline use-case specific results demonstrate that spectrum sharing is the most economically beneficial deployment of the Upper 6 GHz band when compared with exclusive allocation to mobile or Wi-Fi in almost all cases. The exceptions are the Stadium use case where the Wi-Fi only allocation is preferred, and the Low-Density Urban area, where the mobile only allocation is preferred.

Here, ‘baseline’ means that there is 0% indoor deployment for Upper 6 GHz mobile in scenario 2, where the Upper 6 GHz is allocated exclusively to mobile operators. Additionally, in scenario 4 (spectrum sharing), none (0%) of the indoor mobile users utilising the Upper 6 GHz band are offloaded to Wi-Fi. A more detailed explanation of these two assumptions is available in the ‘Aggregate results’ section. [27] To account for variations in indoor deployment in scenario 2 and indoor Wi-Fi offloading in scenario 4, a range of results is presented for each use case in the Annex.

Spectrum sharing generates the highest net present surplus per peak active user compared to the Wi-Fi-only scenario in the Dense Urban use case, reaching £820 per peak active user. Meanwhile, compared to the mobile-only allocation, spectrum sharing provides the greatest net present surplus in Stadiums, at £750 per peak active user.

[27] Please note that these assumptions apply to the Urban use cases only and are not relevant for the Stadium.

Table: Baseline net present surplus of Upper 6 GHz spectrum sharing over exclusive mobile or Wi-Fi access by use case

Use case	10-year present value	
	Total net present surplus of spectrum sharing compared with Wi-Fi only allocation	Total net present surplus of spectrum sharing compared with mobile only allocation
Stadium	-£0.6m (-£40 per peak active user)	£11m (£750 per peak active user)
High-Density Urban area	£51m (£390 per peak active user)	£4m (£28 per peak active user)
Dense Urban area	£11m (£820 per peak active user)	£7m (£565 per peak active user)
Low-Density Urban area	£1m (£175 per peak active user)	-£3m (-£465 per peak active user)

Note: These results assume 0% indoor Upper 6 GHz mobile deployment in scenario 2 and 0% indoor users offloaded to Wi-Fi in scenario 4. These are the baseline results for each use case.

The difference in net present surplus across use cases is driven by variations in producer costs. Consumer surplus remains constant across scenarios 1-4 because both consumer benefits and costs are unchanged – consumers have the same willingness to pay for speed and incur the same expenses for those speeds. Since consumer surplus and producer revenues are identical across scenarios, the only factor influencing net benefits is producer cost. This variation arises from differences in spectrum allocation, which impact the infrastructure costs for both mobile and Wi-Fi providers.

The baseline results are broken down into more detail in the subsections below for each use case.

Stadium

The table below summarises total present value of surpluses for each of the scenarios where Upper 6 GHz is deployed for the Stadium. Spectrum sharing of the Upper 6 GHz provides a total present surplus of £76.8m (£5,100 per peak active user) over a 10-year period. While this is slightly lower than the surplus from exclusive Wi-Fi allocation (£77.4m, £5,140 per peak active user), it is higher than exclusive mobile allocation (£65m, £4,350 per peak active user). Therefore, spectrum sharing is beneficial over a mobile-only allocation, but not over a Wi-Fi-only allocation in the Stadium.

Table: Total and net present surplus of Upper 6 GHz spectrum sharing over exclusive mobile or Wi-Fi access for the Stadium

Scenario	Spectrum allocation	10-year present value	
		Total (net) surplus	Total (net) surplus per peak active user
Scenario 2	Exclusive allocation of Upper 6 GHz to mobile	£65m	£4,350
Scenario 3	Exclusive allocation of Upper 6 GHz to Wi-Fi	£77.4m	£5,140
Scenario 4	Spectrum sharing of Upper 6 GHz between mobile & Wi-Fi	£76.8m	£5,100
Scenario 4 – Scenario 2	Comparison of Upper 6 GHz spectrum sharing with exclusive mobile allocation	£11m	£750
Scenario 4 – Scenario 3	Comparison of Upper 6 GHz spectrum sharing with exclusive Wi-Fi allocation	-£0.6m	-£40

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

High-Density Urban area

In the High-Density Urban area, spectrum sharing of the Upper 6 GHz band provides a total present surplus of £2,347m (£17,840 per peak active user) for mobile and Wi-Fi producers and consumers. This is higher than both exclusive mobile allocation (£2,343m, £17,810 per peak active user) and exclusive Wi-Fi allocation (£2,294m, £17,450 per peak active user). Therefore, in this case the analysis suggests that spectrum sharing is the preferred policy option. It generates an additional net present surplus of £51m (£390 per peak active user) compared to a Wi-Fi exclusive approach and an additional net present surplus of £4m (£28 per peak active user) compared to exclusive mobile allocation.

Table: Baseline total and net present surpluses of Upper 6 GHz spectrum sharing over exclusive mobile or Wi-Fi access for the High-Density Urban area

Scenario	Spectrum allocation	10 year present value	
		Total (net) surplus	Total (net) surplus per peak active user
Scenario 2	Exclusive allocation of Upper 6 GHz to mobile	£2,343m	£17,810
Scenario 3	Exclusive allocation of Upper 6 GHz to Wi-Fi	£2,294m	£17,450
Scenario 4	Spectrum sharing of Upper 6 GHz between mobile & Wi-Fi	£2,347m	£17,840
Scenario 4 – Scenario 2	Comparison of Upper 6 GHz spectrum sharing with exclusive mobile allocation	£4m	£28
Scenario 4 – Scenario 3	Comparison of Upper 6 GHz spectrum sharing with exclusive Wi-Fi allocation	£51m	£390

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Dense Urban area

In the Dense Urban area, spectrum sharing of the Upper 6 GHz band results in a total present surplus of £240m (£18,400 per peak active user) for mobile and Wi-Fi producers and consumers. This is higher than the exclusive mobile allocation (£233m, £17,830 per peak active user) and better than exclusive Wi-Fi allocation (£229m, £17,580 per peak active user). Therefore, in this case the analysis suggests that spectrum sharing is the preferred policy option. Compared to exclusive mobile allocation, spectrum sharing provides a net present surplus increase of £7m (£570 per peak active user). Meanwhile, compared to exclusive Wi-Fi allocation, it provides a net present surplus increase of £11m (£820 per peak active user).

Table: Baseline total and net present surpluses of Upper 6 GHz spectrum sharing over exclusive mobile or Wi-Fi access for the Dense Urban area

Scenario	Spectrum allocation	10 year present value	
		Total (net) surplus	Total (net) surplus per peak active user
Scenario 2	Exclusive allocation of Upper 6 GHz to mobile	£233m	£17,830
Scenario 3	Exclusive allocation of Upper 6 GHz to Wi-Fi	£229m	£17,580
Scenario 4	Spectrum sharing of Upper 6 GHz between mobile & Wi-Fi	£240m	£18,400
Scenario 4 – Scenario 2	Comparison of Upper 6 GHz spectrum sharing with exclusive mobile allocation	£7m	£570
Scenario 4 – Scenario 3	Comparison of Upper 6 GHz spectrum sharing with exclusive Wi-Fi allocation	£11m	£820

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Low-Density Urban area

For the Low-Density Urban area use case, spectrum sharing of the Upper 6 GHz band results in a total present surplus of £99m (£17,640 per peak active user) over a 10-year period. This is slightly lower than exclusive mobile allocation (£102m, £18,100 per peak active user), but higher than exclusive Wi-Fi allocation (£98m, £17,465 per peak active user). Therefore, in this case the analysis suggests that allocation of the upper 6 GHz band to mobile is the preferred policy option. Compared to a mobile-only approach, sharing generates a slight net loss of -£3m (-£465 per user), whilst compared to a Wi-Fi-only approach, it adds £1m (£175 per user).

Table: Baseline total and net present surpluses of Upper 6 GHz spectrum sharing over exclusive mobile or Wi-Fi access for the Low-Density Urban area

Scenario	Spectrum allocation	10 year present value	
		Total (net) surplus	Total (net) surplus per peak active user
Scenario 2	Exclusive allocation of Upper 6 GHz to mobile	£102m	£18,100
Scenario 3	Exclusive allocation of Upper 6 GHz to Wi-Fi	£98m	£17,465
Scenario 4	Spectrum sharing of Upper 6 GHz between mobile & Wi-Fi	£99m	£17,640
Scenario 4 – Scenario 2	Comparison of Upper 6 GHz spectrum sharing with exclusive mobile allocation	-£3m	-£465
Scenario 4 – Scenario 3	Comparison of Upper 6 GHz spectrum sharing with exclusive Wi-Fi allocation	£1m	£175

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Aggregate results

The table below provides the estimated aggregate net present surpluses across Great Britain of spectrum sharing in the Upper 6 GHz band over i) exclusive allocation of the 6 GHz band to Wi-Fi and ii) exclusive allocation of the 6 GHz band to mobile. This shows that in this baseline assessment the greatest benefits are from spectrum sharing. These benefits are £0.2bn higher than the benefits from mobile only allocation, whereas the benefits of spectrum sharing are £3.3bn higher than the benefits of Wi-Fi only allocation of the band. This indicates that Wi-Fi only allocation of the band would be the least beneficial option of the three.

Table: Baseline net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive Wi-Fi allocation or exclusive mobile allocation for Great Britain

10-year present value	
Additional benefits of spectrum sharing compared to Exclusive Wi-Fi allocation	**Additional benefits of spectrum sharing compared to Exclusive mobile allocation**
+ £3.3bn	+ £0.2bn

Note: The baseline results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Accounting for difference in indoor mobile deployment and additional Wi-Fi offloading

In-line with the use-case specific results, the baseline aggregate estimates presented above assume no indoor mobile (or outdoor Wi-Fi) deployment. In practice, allocating the 6 GHz band exclusively to mobile (as opposed to sharing of the band), would allow mobile operators to also deploy mobile base-stations indoors (e.g., through indoor small-cells) to better serve indoor users. In a sharing scenario using an indoor/outdoor split between Wi-Fi and mobile this is not possible. Therefore, the magnitude of benefits realised under indoor/outdoor sharing over mobile-only allocation of the 6 GHz band varies with the degree of indoor mobile deployment that takes place in practice.

Similarly, while offloading of indoor mobile users to Wi-Fi is assumed in-line with present offloading factors indicated by the literature, no additional offloading of indoor mobile users to 6 GHz Wi-Fi is assumed in the baseline results provided above. However, in a sharing scenario, deployment of fast indoor 6 GHz Wi-Fi may incentivise additional indoor mobile users to switch to Wi-Fi when indoors.

To explore the impact of these assumptions on benefit estimates of sharing vs. exclusive allocation, the table below explores how net present surplus estimates of spectrum sharing over exclusive mobile allocation and exclusive Wi-Fi allocation vary for different degrees of indoor Upper 6 GHz mobile deployment in scenario 2 (when Upper 6 GHz is given exclusively to mobile) and for different degrees of additional offloading of indoor mobile users to 6 GHz Wi-Fi in scenario 4 (when Upper 6 GHz is shared between mobile and Wi-Fi).

The results show that higher levels of indoor mobile offloading to Wi-Fi in scenario 4 consistently increase the net present surplus of spectrum sharing. Conversely, greater indoor Upper 6 GHz mobile deployment reduces the net surplus, with negative values appearing as deployment increases beyond 25% in the scenario when no indoor mobile users are offloaded to Wi-Fi in scenario 4. This highlights that spectrum sharing is most beneficial when Wi-Fi offloading is maximised in scenario 4 and indoor mobile deployment in scenario 2 is minimised.

However, these figures are indicative of the potential benefits that could be achieved under different indoor mobile deployment and additional Wi-Fi offloading scenarios only. In practice, the actual degree of additional offloading will be dependent on a range of factors, including the degree of adoption of indoor 6 GHz Wi-Fi that takes place (and in turn the roll-out of fibre connections across the UK enabling ultrafast 6 GHz Wi-Fi speeds). Similarly, the degree of indoor mobile deployment in practice will depend on a range of factors such as coordination with and agreement from building owners and private network operators. This means that the benefits indicated by the higher end of the scenarios explored are unlikely to materialise in practice.

Importantly, however, the results show high additional net surpluses of sharing over mobile-only allocation, including for high degrees of indoor mobile deployment, even at the lower end (25%) of the additional offloading range explored. This is reflective of the higher cost of deploying indoor small-cell mobile solutions to provide coverage for indoor mobile users compared to the much lower cost of Wi-Fi access points.

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive mobile allocation for Great Britain dependent on sensitivities in scenarios 2 and 4.

Degree of indoor Upper 6 GHz mobile deployment in scenario 2 (%)	Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
	0% (No additional 6 GHz Wi-Fi offloading)	25%	50%	75%	100% (All indoor mobile users offloaded to 6 GHz Wi-Fi)
0% (No indoor 6 GHz mobile deployment)	£0.2bn	£5.7bn	£10.0bn	£14.6bn	£19.5bn
25%	-£1.0bn	£4.5bn	£8.9bn	£13.4bn	£18.4bn
50%	-£1.7bn	£3.8bn	£8.1bn	£12.7bn	£17.6bn
75%	-£2.1bn	£3.3bn	£7.7bn	£12.2bn	£17.2bn
100% (Full indoor 6 GHz mobile deployment)	-£2.5bn	£3.0bn	£7.4bn	£11.9bn	£16.8bn

Note: The calculation of baseline peak active Wi-Fi and indoor mobile users accounts for baseline offloading of indoor mobile users to Wi-Fi in line with historical trends indicated in the literature. Under indoor/outdoor sharing of the 6 GHz band there may be additional offloading of indoor mobile users to indoor 6 GHz Wi-Fi. The actual degree of additional offloading will be dependent on a range of factors, including the degree of adoption of indoor 6 GHz Wi-Fi that happens in practice. Similarly, the baseline mobile only 6 GHz scenario assumes no deployment of indoor mobile small cells. Additional deployment of mobile cells indoors may yield additional benefits by providing better signal to indoor mobile users. The degree of indoor mobile deployment in practice will depend on a range of factors such as coordination with and agreement from building owners.

The table below explores how the benefits of spectrum sharing over exclusive Wi-Fi allocation vary depending on the additional proportion of indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4. As with the previous table, the higher the additional proportion of indoor mobile users offloaded to Wi-Fi when there is spectrum sharing, the higher the net present surplus of spectrum sharing, ranging from £3.3bn when offloading is at 0% (i.e., there is no additional offloading) and £22.7bn when there is a full level of offloading at 100% (i.e., all indoor mobile users are offloaded to 6 GHz Wi-Fi).

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz over exclusive Wi-Fi allocation for Great Britain

Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
0% (No additional 6 GHz Wi-Fi offloading)	**25%**	**50%**	**75%**	**100%** (All indoor mobile users offloaded to 6 GHz Wi-Fi)
£3.3bn	£8.8bn	£13.2bn	£17.7bn	£22.7bn

Note: The calculation of baseline peak active Wi-Fi and indoor mobile users accounts for baseline offloading of indoor mobile users to Wi-Fi in line with historical trends indicated in the literature. Under indoor/outdoor sharing of the 6 GHz band there may be additional offloading of indoor mobile users to indoor 6 GHz Wi-Fi. The actual degree of additional offloading will be dependent on a range of factors, including the degree of adoption of indoor 6 GHz Wi-Fi that happens in practice.

The network modelling which underlies the economic analysis presented above assumes that indoor Wi-Fi uses the 5GHz band only. Recently the Lower 6GHz band has also been allocated to Wi-Fi and, while limited at present, take up of this band by Wi-Fi is likely to increase considerably over the next ten years. It has not been possible to model the impacts of this development, but it is likely that the gains from allocating the Upper 6GHz band to Wi-Fi only would be reduced since Wi-Fi would already have access to the Lower 6GHz band. It would also reduce the marginal benefits of the indoor/outdoor sharing scenario since in that scenario too, Wi-Fi would already have access to the Lower 6GHz band and so the gains from allocation of the Upper 6GHz band to Wi-Fi indoors would be reduced. This means that it is likely that the additional benefits of the sharing mechanism relative to mobile only allocation of the band would be reduced. The extent to which they are reduced will depend on a number of factors including the speed at which Lower 6GHz band is taken up by Wi-Fi services; the extent to which the availability of the Upper 6Ghz band for Wi-Fi provides additional capacity benefits; the appropriate mix of Wi-Fi spectrum bands for consumers based on propagation characteristics as well as throughput; and equipment and other network costs.

Sensitivity analysis

This section evaluates the net present surplus of spectrum sharing in the Upper 6 GHz band over exclusive allocation to mobile or Wi-Fi by applying different sensitivities to the modelling assumptions. Sensitivities to the following key parameters are assessed: the discount rate, throughput pricing, producer costs (CAPEX and OPEX associated with network deployment), and consumer willingness to pay for higher throughput speeds.

Discount rates

The table below shows how the net present surplus of spectrum sharing in the Upper 6 GHz band changes based on the discount rate used over the 10-year time horizon.

The Green Book discount rate [28] of 3.5% is used as the baseline assumption, whilst an estimate of the UK Telecoms Weighted Average Cost of Capital (WACC)[29] of 8% is used as a sensitivity assumption. WACC represents a company's average cost of funding its operation and investments, considering both equity and debt financing, reflecting the minimum return a company needs to generate on its investments to satisfy investors and lenders. By using the UK Telecoms WACC, it accounts for the riskiness of cash flows in the UK Telecoms market [30], ensuring that the net present value calculations align with the telecom-specific market conditions in the UK.

As expected, by using a higher discount rate, all else equal, the net present surplus of spectrum sharing over exclusive Wi-Fi or mobile allocation declines from £3,338m to £2,599m and from £184m to £139m over the 10-year period. However, this does not change the overall conclusion that spectrum sharing is more economically beneficial than exclusive allocation to either Wi-Fi or mobile.

Table: Net present surplus of spectrum sharing in the Upper 6 GHz over exclusive mobile or Wi-Fi allocation with discount rate sensitivities for Great Britain

Discount rate	Spectrum sharing vs. Exclusive Wi-Fi allocation	Spectrum sharing vs. Exclusive mobile allocation
Green Book (3.5%)	£3,338m	£184m
UK Telecoms WACC (8%)	£2,599m	£139m

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Pricing

The table below illustrates the net present surplus of spectrum sharing over exclusive Wi-Fi or mobile allocation under different pricing assumptions for throughput (network speeds that users experience). The baseline pricing assumptions are based on the weighted average monthly prices of standalone fixed broadband services in the UK [31] , where pricing is based on the throughput that users can expect to experience. A full breakdown of this pricing is given in the Annex.

The key finding is that as consumer prices for higher throughput increase, the net present surplus of spectrum sharing increases over exclusive allocation to Wi-Fi or mobile, all else equal. This occurs because the increase in producer surplus outweighs the loss in consumer surplus. Under initial pricing assumptions, spectrum sharing generates £3,338m more than exclusive Wi-Fi allocation and £184m more than exclusive mobile allocation. When prices increase by 50%, these figures rise to £6,010m and £202m, respectively, while a 200% increase results in £7,145m and £255m. This trend reflects the fact that higher consumer costs (and therefore higher producer revenues) lead to a greater total surplus, as the additional revenue captures by operators exceeds the reduction in consumer surplus.

[28] HM Treasury. (2022). *The Green Book.* Available at: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government/the-green-book-2020

[29] Enterprise Telecom Consultants. (2019). *How to determine the regulated WACC in European Telecoms?* Available at: https://eu-etc.com/2019/01/28/how-to-determine-the-regulated-wacc-in-european-telecoms/

[30] Wall Street Prep. (2024). *WACC.* Available at: https://www.wallstreetprep.com/knowledge/wacc/

[31] Ofcom. (2024). *Pricing trends for communications services in the UK.*

Table: Net present surplus of spectrum sharing over exclusive Wi-Fi or mobile allocation with price sensitivities for Great Britain

Sensitivity	Spectrum sharing vs. Exclusive Wi-Fi allocation	Spectrum sharing vs. Exclusive mobile allocation
Initial pricing assumptions	£3,338m	£184m
50% increase	£6,010m	£202m
200% increase	£7,145m	£255m

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Producer costs

The table below represents how the net present surplus of spectrum sharing over exclusive Wi-Fi or mobile allocation changes with producer costs, reflecting the Green Book guidance for optimism bias for Equipment/Development projects.[32] Based on this, one scenario is modelled where producer costs (both CAPEX and OPEX) increase by 50% and another where they increase by 200%. [33]

Under initial cost assumptions, spectrum sharing generates a £3,338m surplus over exclusive Wi-Fi allocation and £184m over exclusive mobile allocation. However, when producer costs increase by 50%, the net surplus compared to Wi-Fi allocation drops to £1,344m, while the surplus over mobile allocation slightly increases to £267m. In the 200% cost increase scenario, the surplus over exclusive allocation falls significantly to £164m, whereas the surplus over mobile allocation rises to £2,596m. Therefore, as producer costs rise proportionately for both mobile and Wi-Fi producers, the economic advantage of sharing over Wi-Fi diminishes, whereas the economic advantage of sharing over mobile increases. This occurs because Wi-Fi infrastructure is less expensive to deploy than mobile, meaning that as costs increase, the savings from spectrum sharing in a Wi-Fi context become smaller, whilst the savings become larger for mobile.

Table: Net present surplus of spectrum sharing over exclusive Wi-Fi or mobile allocation with producer cost sensitivities for Great Britain

Sensitivity	Spectrum sharing vs. Exclusive Wi-Fi allocation	Spectrum sharing vs. Exclusive mobile allocation
Initial cost assumptions	£3,338m	£184m
50% increase	£1,344m	£267m
200% increase	£164m	£2,596m

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

[32] HM Treasury. (2013). *Green Book supplementary guidance: optimism bias*. Available at: https://www.gov.uk/government/publications/green-book-supplementary-guidance-optimism-bias

[33] Due to a lack of other available estimates, we assumed the same optimism bias estimates for OPEX and CAPEX.

Willingness to pay

The table below shows now the net present surplus of spectrum sharing changes under different willingness to pay (WTP) sensitivities for the throughput that users experience. The results indicate increasing WTP does not significantly alter the overall net present surpluses, with only minor reductions observed as WTP increases.

This stability occurs because the net present surplus is calculated as the difference between two scenarios, meaning that changes in WTP affect both spectrum sharing and exclusive Wi-Fi or mobile allocations similarly. Since user throughput is the same for mobile and Wi-Fi users in the different Upper 6 GHz scenarios, and WTP influences both consumer WTP for mobile and Wi-Fi services, any increase in WTP impacts both sides of comparison, effectively cancelling out much of the impact of the net difference.

Table: Net present surplus of spectrum sharing over exclusive mobile or Wi-Fi allocation with WTP sensitivities for Great Britain

Sensitivity	Spectrum sharing vs. exclusive Wi-Fi allocation	Spectrum sharing vs. exclusive mobile allocation
Initial WTP assumptions	£3,338m	£184m
50% increase	£3,329m	£175m
200% increase	£3,302m	£148m

Note: These results assume 0% indoor mobile deployment in scenario 2 (mobile only) and 0% of indoor mobile users are offloaded to Wi-Fi in scenario 4 (spectrum sharing).

Addressing not-spots/underserved areas and those with poor connectivity

Given the higher deployment costs and propagation characteristics (lower range), sharing in the 6 GHz band is unlikely to address connectivity gaps in underserved areas and not-spots. Nevertheless, these areas could benefit from flexible sharing regimes such as faster and more streamlined licensing processes in lower bandwidths (e.g., Band 3 or n77), which may enable smaller providers to deploy infrastructure at lower costs (e.g., using small cells). Competitive effects in turn may incentivise MNOs to increase deployment in underserved areas where they currently hold underutilised on spectrum.

Therefore, in addition to exploring the benefits of sharing in the Upper 6 GHz band, two analyses were undertaken to understand the potential economic benefits of improving provision in poorly served areas.

- In the first analysis, the costs and benefits associated with raising speeds to 2 Mbps through deployment of small-cell Band 3 base-stations are modelled. Cost estimates are based on insights into providing coverage to rural areas from Telet through the MoNeH Rural Connected Communities Test Bed & Trials Programme.[34]
- In the second analysis, costs and benefits are estimated for raising speeds by an additional 10 Mbps compared with current provision through a network of small-cell N77 base stations. This is based on simulations conducted by Ranplan.

[34] Telet, blue sky, CH4LKE (2022). *MONeH Rural Connected Communities – 5G Test Bed & Trials Programme. Final Report v1.34*. Available at: https://uktin.net/sites/default/files/2023-05/MONeH%20RCC%20-%20Final%20Report.pdf

Ofcom is currently consulting on proposals to enable satellite Direct to Device (D2D) services which could in future improve connectivity for consumers in areas currently underserved by terrestrial networks and provide back-up services. Our analysis of the potential of spectrum sharing in underserved areas does not address the potential interaction between improved services from spectrum sharing and improved services from D2D services, though this is an area for potential future research.

Total surplus – not-spots/underserved areas using Band 3 spectrum

The not-spots analysis includes three sensitivities of the costs and benefits of addressing not-spots/underserved areas in the UK using small-cells operating on Band 3 and find that total surplus ranges from £30m to £300m net present value over 10 years[35]. These three sensitivities are based on: i) a baseline cost central willingness to pay scenario; ii) a 50% increase in costs reduced willingness to pay scenario, and iii) a 200% increase in cost and low willingness to pay scenario. The 200% increase in cost sensitivity is in line with the green book recommendations regarding optimism bias for equipment/development projects.

Sensitivity	Willingness to pay	Producer Costs (CAPEX + OPEX)	Total surplus	Percent of not spots addressed
Baseline	**£406m**	**£104m**	**£302m**	**94%**
Sensitivity I	£196m	£82m	£115m	73%
Sensitivity II	£69m	£38m	£30m	31%

Note: Sensitivity I assumes 50% increase in costs and reduced willingness to pay; Sensitivity II assumes 200% increase in cost and a lower willingness to pay still. The percentage of not-spots addressed is calculated at the M2 800x800m grid level.

As areas are only included in the analysis where consumer willingness to pay exceeds deployment and operational costs (i.e., total surplus is positive), the percentage of not-spots that could feasibly be addressed decreases as cost increases and willingness to pay decreases. This is because with higher costs and lower willingness to pay, the cost of building and operating a network exceeds the total price consumers would be willing to pay for the service in more areas. With a negative total surplus, there is no rationale to build a network and additional government intervention would be needed to serve these areas.

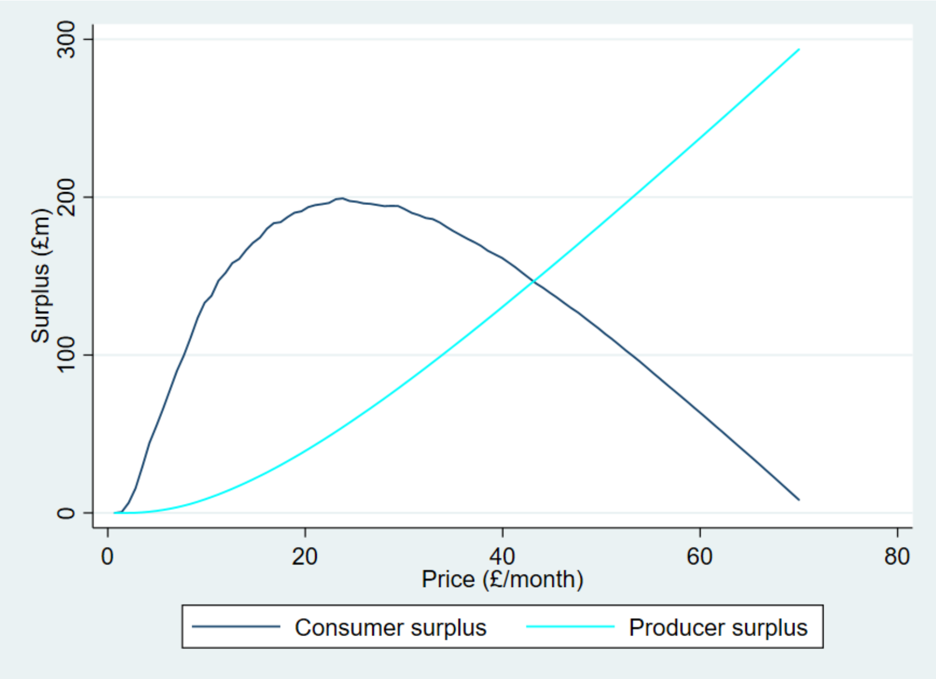
For this analysis, only total surplus is reported, with no distinction between consumer or producer surplus. This is because the allocation of surplus between producers and consumers is driven by the price of throughput. For example, where there is positive producer surplus, but negative consumer surplus, a higher price would allow 'sharing' of some consumer surplus for producer surplus as a higher price provides incentives to deploy networks where it means that producer surplus is greater than zero. This analysis is therefore agnostic about the final price that would be reached in these areas. These areas are generally harder to reach with higher costs and a provider would not face competition (at least upon building a network), so it is likely that the price will differ from other areas of the UK.

[35] Net present value is calculated using a 3.5% discount rate in line with the green book. The first year is considered a "build year" where there are only capex costs, and no opex or willingness to pay benefits.

Consumer and producer surplus – addressing not-spots/underserved areas using Band 3

While estimates of consumer and producer surplus are not modelled in the above analysis, an indicative illustration of consumer and producer surplus in underserved areas is provided below based on different equilibrium prices [36], and assuming baseline cost and willingness to pay estimates.

Figure: Consumer and producer surplus of addressing UK not-spots, as a function of price (NPV over 10 years)



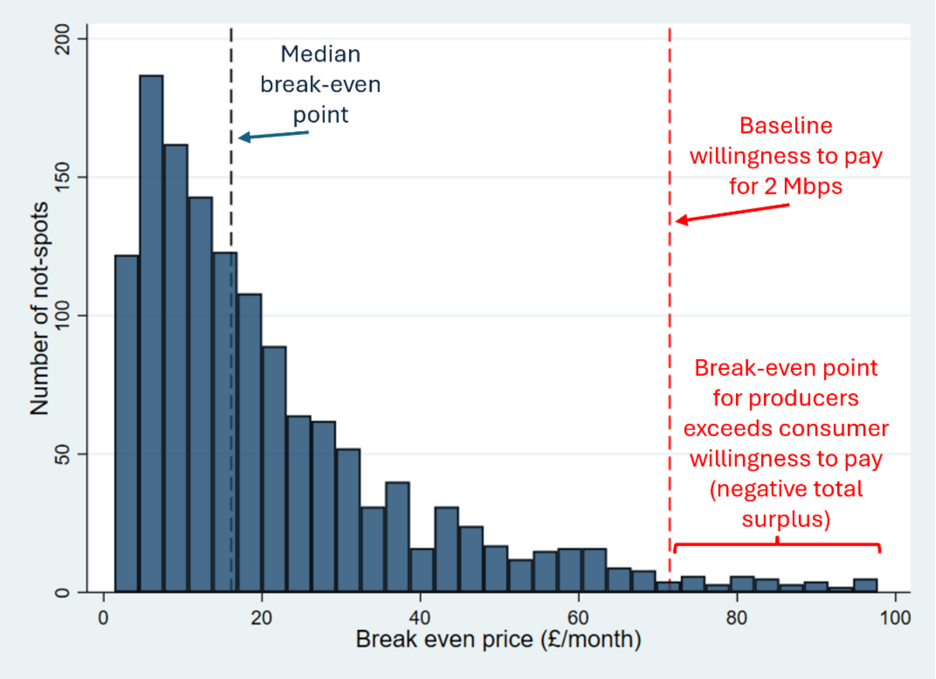
In the above, only areas which would be profitable at a given price are included. As such, consumer surplus is initially increasing as more not-spots can be profitably addressed and more consumers can benefit. Consumer surplus is then decreasing with price as the number of areas which can be addressed does not offset the decreasing consumer surplus in areas which are already addressed. Producer surplus is increasing in the range of 0 – £70 per month as higher price means higher revenues for producers (but would reach 0 if it exceeded the maximum willingness to pay of customers as no customers would purchase).

[36] The net present value over 10 years of consumer and producer surplus is presented.

The break-even price required for underserved areas to be addressed by Band 3 in not-spots/underserved areas

Additional analysis is undertaken to demonstrate the price required for a producer to break-even based on baseline cost assumptions – i.e. the break-even point price. This analysis demonstrates that the median break-even price (i.e., the price point at which producers could break-even or profitably address 50% of not-spots) is£16/month. The 75th percentile (i.e., the price point at which producers could break-even or profitably address 75% of not-spots) is estimated at £30/month, while the 90th percentile is estimated at £55/month.

Figure: Distribution of break-even price across different UK not-spots[37]



This is not meant to reflect the final price that might be charged by providers in underserved areas, but merely to illustrate (using our assumptions on cost) the number of areas that could be addressed without loss at a given price. Further, the analyses' assumptions around deployment cost, while based on existing literature, are likely simplifications. They assume that cost per UPRN is uniform when in reality it is likely to vary between areas based on geospatial characteristics. This may mean the break-even price is different to that presented above.

Analysis of addressing areas with speeds below 9 Mbps using N77

In addition to the above, additional analysis is undertaken to model the costs and benefits of building infrastructure which would provide an additional 10 Mbps average speed in areas where at least two MNOs had average speed below 9 Mbps. This was based on simulations conducted by Ranplan Wireless who model the cost of providing an additional 10 Mbps in rural Northumberland.

[37] Both costs and willingness to pay are based on our mid-level assumptions with CAPEX cost per UPRN at £1156 and annual OPEX at £525, and willingness to pay per user per month at £43.

A cost comparison was undertaken between building such a network using traditional infrastructure, such as base stations, and small cells. In line with the findings in Telet's (2022) report[38], the analysis demonstrates that providing throughput to underserved areas using small cells is more cost effective than using traditional infrastructure. The CAPEX costs per user of providing coverage using small cells is £353, whereas the CAPEX costs using base stations is £597 per user. As such, this analysis demonstrates that improving speeds using small cells is 41% more cost effective than using base stations in the rural archetype.

In order to model the benefits of increasing speeds, willingness to pay for an additional 10 Mbps was estimated for users in an area, based on the current provision in that area. To calculate the total benefits in an area, the number of users on each network was estimated based on MNO market shares[39], and total population in the area. This was multiplied by per user willingness to pay estimates. An area was only included in the analysis if there were at least two MNOs with below 9 Mbps current speeds to capture areas where a potential commercial opportunity exists. Benefits were only estimated for estimated users of networks with poor coverage in that area.

Based on this approach, we estimate that the total surplus of improving throughput in areas where current speeds are poor ranges from ~£30m to ~£500m net present value over ten years.[40]

Table: Costs and benefits of addressing areas with poor current speeds

Sensitivity	Number of poor connectivity spots addressed	Willingness to pay	Producer Costs (CAPEX, OPEX, Overheads)	Total surplus
Baseline	**1,972**	**£687m**	**£164m**	**£523m**
Sensitivity I	1,289	£289m	£112m	£177m
Sensitivity II	692	£132m	£98m	£35m

Note: Sensitivity I assumes 50% increase in costs and reduced willingness to pay; Sensitivity II assumes 200% increase in cost and a lower willingness to pay still. The number of spots with poor connectivity which are addressed are calculated at the M2 800x800m grid level.

These findings suggest that permissive licensing schemes could not only help to address total connectivity not-spots, but also improve speeds in areas where connectivity is already provided by MNOs, but where user experienced throughput is currently poor.

Conclusions & policy implications

Study conclusions

Ofcom and the UK Government have been actively development policies on proposals to facilitate spectrum sharing across various frequency bands, including the Upper 6 GHz and n77 band.

[38] See MONeH Rural Connected Communities here.

[39] See 2024 shares here.

[40] Net present value is calculated using a 3.5% discount rate in line with the green book. The first year is considered a "build year" where there are only capex costs, and no OPEX or willingness to pay benefits.

Ofcom is currently consulting (Ofcom, 2025[41]) on sharing the Upper 6 GHz band between commercial mobile and Wi-Fi services. They propose to authorise low power indoor Wi-Fi across the whole band on a licence exempt basis as soon as possible, potentially by end 2025 (Phase 1) and then, in Phase 2, to allow sharing of the band between mobile and Wi-Fi. Phase 2 is dependent on future proposals for a European harmonised approach to shared use of the Upper 6 GHz band by mobile and Wi-Fi.

Ofcom are reviewing two potential sharing mechanisms:

- **Prioritised spectrum split**: Wi-Fi is given priority in the lower portion of the Upper 6 GHz band and mobile is given priority in the upper portion of the band. Each set of users would be able to access the other portion where it would not cause interference.
- **Indoor/outdoor split**: Wi-Fi is used for coverage indoors and mobile is used for coverage outdoors.

Ofcom currently favour the prioritised spectrum split approach as they believe it would support higher power mobile than the indoor/outdoor split approach, which would be more consistent with current macro cell mobile architectures. They recognise, however, that in the longer term changes in the ways in which mobile networks are deployed, alongside poorer coverage in buildings as they become more energy efficient, may mean that an indoor-outdoor split could become a more attractive option in future.

Ofcom's Shared Access Licence (SAL) framework is intended to promote local spectrum sharing. This framework allows various users, including private network operators, to access lower frequency spectrum on a shared basis to encourage new suppliers to deploy localised 5G services and new services. Two types of licences are available under this framework: 1) Low Power Licences for deployments with limited coverage and lower transmission power, and 2) Medium Power Licences for deployments with wider coverage and higher transmission power.

In this Sandbox, the economic analysis in this report is focused on understanding the economic impact of spectrum sharing in two cases: spectrum sharing of the Upper 6 GHz between mobile and Wi-Fi on an indoor/outdoor basis to address under provision during peak periods in high density areas, and lower frequency spectrum sharing to address under provision in lower density areas too uneconomic for traditional network deployments.

Our analysis has demonstrated that there are net benefits from the adoption of shared spectrum for the Upper 6 GHz band between mobile and Wi-Fi users within several defined geographic contexts. Net benefits are achieved for both 'producers' of communications services and 'consumers' who use such services. We see positive and significant surplus for both groups, suggesting that there is both an incentive to provide these services and incentive to purchase them. This implies a new revenue earning opportunity for both existing suppliers and new operators.

We also see positive surplus across many of the lower density areas analysed, indicating that opportunities for network expansion through easier access to spectrum also exist in these use-cases e.g. through a permissive licensing scheme enabling use of appropriate lower bandwidth spectrum.

In the case of producers, these benefits reflect the value of supplying bandwidth to address minimum user requirements for the average user at market prices, and for consumers, these reflect the willingness to pay for additional coverage and faster data rates. We assume that the additional

[41] Ofcom (2025). Expanding access to the 6 GHz band for mobile and Wi-Fi services. Proposals for AFC in Lower 6 GHz and mobile / Wi-Fi sharing in Upper 6 GHz. Consultation. Available here: Consultation: Expanding access to the 6 GHz band for commercial mobile and Wi-Fi services

spectrum from the Upper 6 GHz band is used to optimise network architecture, in effect to lower CAPEX and OPEX, to address defined user requirements, in excess of what is delivered today. The main value of spectrum sharing therefore comes from the ability of producers to lower costs. These benefits exist even after accounting for the potential reservation of spectrum to mitigate interference between mobile and Wi-Fi users.

Furthermore, our results are driven by assumptions regarding indoor handover of mobile traffic to Wi-Fi and the level of indoor deployment expected in various scenarios. Spectrum sharing is most beneficial when the offloading of mobile traffic to Wi-Fi is maximised, and indoor mobile deployment is minimised. This result arises because mobile small cell solutions are less inefficient than comparatively lower cost Wi-Fi access points at serving indoor traffic. In practice, the degree of indoor uptake of Upper 6 GHz-enabled Wi-Fi and the Wi-Fi offloading will depend on several factors, including: the incentives of private building owners and private network operators to deploy indoor solutions, the cost of Wi-Fi equipment, and ultimately the capacity of the 'last mile' connection to buildings (i.e. roll out of 'full fibre' connections).

The benefits of spectrum sharing are evident even under various sensitivities to key assumptions, including variation to the discount rate, throughput pricing, producer network costs, and consumer willingness to pay for improved throughput. Notably, increases in producer costs erode the economic advantage of spectrum sharing over Wi-Fi only allocations, whereas the economic advantage of spectrum sharing over mobile-only allocations is improved. This is because Wi-Fi infrastructure is less expensive to deploy than mobile, meaning that as costs increase, the savings from spectrum sharing in a Wi-Fi context become smaller, while the savings are larger for mobile.

In certain cases, the existence of positive consumer surplus (and total overall surplus) and negative producer surplus indicates a potential market failure – there are clear overall benefits and benefits to consumers but no producer incentive to supply. In such cases, there is an argument for sharing the surplus, suggesting that higher prices can be accommodated in markets that would otherwise be unserved.

We also identified areas where benefits are possible, though costs exceed total surplus. In these cases, additional government intervention, or a further reduction in costs of service provision - would be needed to address under-provision. Such costs reductions may be achieved if spectrum sharing is adopted at scale, whereby market signals to equipment suppliers and economies of scale can help achieve lower unit costs of network equipment.

While this analysis suggests value in spectrum sharing, a pre-requisite for truly ubiquitous connectivity – the main objective of future telecommunications policy - is for seamless handover of user devices between network typologies (e.g. between Wi-Fi, mobile, and private networks). This requires investment in device level capabilities and agreement between operators for standards which can be enable this, as well as potential regulatory adjustments too.

Industry views and policy implications of spectrum sharing

Industry perspectives on spectrum sharing in the Upper 6 GHz band vary and reveal a complex interplay of economic, technical, and regulatory factors.

On the one hand, the Upper 6 GHz band's ability to offer 200 MHz contiguous channels makes it particularly attractive for mobile use. Mobile Network Operators are reluctant to share this high-value resource, citing potential concerns over the practical management of interference and perceived impact of spectrum sharing on the quality and efficiency of their mobile networks. MNOs are particularly worried about the possibility incurring additional costs to implement advanced mitigation techniques, which they argue may counterbalance the savings from sharing for other operators. Uncertainty regarding the scale of these costs and who bears it may deter network investment.

At the same time, there is recognition that a regulatory framework that promotes spectrum sharing could liberate spectrum for other innovative services across the broader digital ecosystem. This could encourage new market entrants and address unmet demand across the UK. Independent and private operators are particularly supportive of spectrum sharing in principle.

Likewise, Ofcom believe that greater benefits for consumers may be achieved from a shared spectrum scenario for the Upper 6 GHz spectrum in the long-term. This is based on the premise that enhancements to building insulation for energy efficiency will make it harder for mobile signals to penetrate indoor environments. Ofcom anticipate operators increasingly relying on 'in-building' solutions like Wi-Fi deployments to address indoor requirements.

Perception of the technical challenges of spectrum sharing are the primary concern, particularly regarding interference management. Although Wi-Fi and modern mobile systems are robust when operating independently, their co-existence on shared frequencies could lead to performance degradation if not carefully managed. Ensuring effective separation between these waveforms is critical. This could be achieved through the development of cross-technology signalling protocols, the implementation of power control mechanisms, or by partitioning the spectrum into dedicated segments for each technology. These mitigation strategies are vital to reduce the risk of mutual interference and therefore maintaining the integrity and efficiency of both networks. The results from this Sandbox – comprising the measurements from WP1, the simulations of spectrum sharing and appropriate interference mitigation measures from WP2, and the economic analysis presented in this report (WP3) – suggest that the potential network optimisation benefits offset potential losses from interference.

Regulatory uncertainty further complicates the picture. There is an ongoing debate over the rules for access prioritisation during interference events and how best to coordinate between different technologies. Reforming the regulatory framework to encourage sharing could unlock additional spectrum resources for alternative uses. Such a framework would need to establish clear rules that define when exclusive or shared allocations are appropriate. For example, the economic value of sharing varies by context. In High-Density Urban areas, optimised network design through sharing can generate cost savings and improved performance. In contrast, specific use cases may benefit more from dedicated allocations. This context dependency suggests that any spectrum management strategy must be tailored to the specific needs of different environments rather than adopting a universal approach. Streamlined licensing and coordination processes is also essential for minimising administrative delays and reducing potential costs associated with interference management.

To move forward effectively, several key recommendations have emerged:

1. Robust technical standards must be developed to manage interference between coexisting technologies, including dynamic spectrum access and cross-technology signalling protocols where necessary. Clear rules for access prioritisation during interference events must also be developed to reduce regulatory uncertainty.

2. Industry-wide standardised frameworks should be established to delineate the appropriate circumstances for exclusive versus shared spectrum use.
3. Policymakers should consider introducing incentives—such as reduced licensing costs or expedited licensing procedures—to encourage spectrum sharing from a broader policy perspective. Our analysis shows that operators achieve positive surplus from both 6 GHz network deployment and spectrum sharing over exclusive spectrum allocation scenarios, even assuming discount rates in line with UK telecom industry benchmarks. Incentives to encourage
4. Current spectrum management decisions need to be aligned with future technology roadmaps, particularly for emerging technologies like 6G, ensuring that the integrity of high-capacity channels is maintained for long-term innovation.
5. Policies makers should support policies that incentivise private building owners and private network operators to deploy indoor solutions. These policies can be supported by broader infrastructure development initiatives such as full fibre roll outs to ensure that last mile connectivity is not a bottleneck to Upper 6 GHz enabled Wi-Fi.
6. Policymakers should incentivise development in device-level capabilities, network interworking technologies, and standards to enable seamless handover between network technologies and therefore truly ubiquitous connectivity of mobile devise.
7. Full realisation of the benefits of spectrum sharing implies significant network expansion of both Wi-Fi and mobile. Policymakers should send a clear market signal to equipment manufacturers to undertake investments to lower unit costs and reduce potential bottlenecks in deployment.

In summary, while spectrum sharing of the Upper 6 GHz is discouraged by Mobile Network Operators because of perceived interference management challenges, a reformed regulatory environment that encourages spectrum sharing could offer significant long-term advantages for the broader digital landscape. Achieving a balance between exclusive access for high-performance mobile networks and the potential for broader spectrum availability will require careful technical, regulatory, and economic planning—a challenge that future policy and standardisation efforts must address.

Further research not feasible within the confines of this sandbox

Further research beyond the scope of the sandbox to further enhance the results of the economic analysis could include:

- **Refining breadth and precision of analysis with more use-cases and archetype areas:** The timelines and scope for this sandbox have always meant that only a limited number of use-cases and archetypes can be explored. This naturally presents caveats to the breadth and precision of the results, particularly for the scaling up to national level estimates. Incorporating additional use-cases and archetype areas would provide additional data points that would provide specific results for additional use-cases not currently captured and enable refinement of the scaling by providing additional data points.
- **Extension to non-consumer users and more specific scenarios:** The economic analysis currently only captures end-users in the form of consumers. In addition to consumers, spectrum sharing could bring additional benefits to a wider range of users not captured. This includes benefits to industry such as private deployments, for example, for high-tech industries, smart farming, etc.; commercial activities in rural areas such as caravan parks and events; privately owned dense environments such as education and research campuses or airports; as well as through serving new use-cases not directly analysed such as transport, a rise in IoT devices, and autonomous vehicles. Some of these benefits (in particular a rise in IoT devices)

could at least partially be captured through extending the simulations to higher user (device) numbers and higher demand target parameters such as those specified in our envisaged high scenarios. Others would require specifying new scenarios specific to those use-cases.

- **Refining sensitivities through additional simulations:** Due to the complexity and compute requirements of simulating network deployment, and therefore the time required to run simulations, it was only possible to simulate a limited number of scenarios. Additional simulations would provide further insights and help refine key sensitivities around the central results presented in this study. In particular, the analysis in this report provides results for our central target demand parameters for our archetype areas. In the annex, we have also set-out low and high target demand parameters that could be used to help understand sensitivities of the results presented around the central target demand parameters specified.
- **Modelling the value of spectrum sharing for additional technology pairs, such as Direct to Device:** The benefits of spectrum sharing assessed in this report is limited to spectrum sharing between mobile and Wi-Fi in the Upper 6 GHz for areas of high demand density and in lower frequency bands for areas of underserved provision. This analysis could be extended to consider the value of spectrums sharing between other technology pairs, such as between mobile and satellite services. For example, the value of spectrum sharing between mobile and Direct to Device services to improve connectivity for users in areas underserved by mobile networks is not addressed in this study. Ofcom's current consultation on proposals to enable satellite Direct to Device (D2D) services could be benefit from this additional analysis.

ANNEXES

Methodology: Evaluating the economic benefits of spectrum sharing in the Upper 6 GHz spectrum band

The economic benefits of spectrum sharing in the Upper 6 GHz band are assessed using a welfare approach, measuring the impact on both producers and consumers through their respective consumer and producer surpluses over a ten-year period.

The approach consists of defining three demand scenarios (low, central and high) across five different spectrum and infrastructure supply scenarios (scenarios 0-4) for four different use cases: Stadium, High-Density Urban, Dense Urban and Low-Density Urban. The table below illustrates the relationship between the supply and demand scenarios for the analysis.

Table: Illustration of the interaction between supply and demand scenarios

Supply scenario	Demand scenario		
	Low	Central	High
Scenario 0	Current mobile and Wi-Fi networks are simulated such that they meet currently provided speeds using current spectrum allocations for each use case.		
Scenario 1	Additional mobile and Wi-Fi provision is simulated such that it meets the respective low/central/high target speeds for users using current spectrum allocations.		
Scenario 2	Simulated mobile network meets respective low/central/high target speeds for users using exclusive allocation of Upper 6 GHz, whilst the Wi-Fi network meets respective low/central/high target speeds for users using its current spectrum allocation. Sensitivities were applied to this scenario around the percentage of indoor Upper 6 GHz mobile deployment when mobile has exclusive access to the band (ranging between 0%-100%).		
Scenario 3	Simulated Wi-Fi network meets respective low/central/high target speeds for users using exclusive allocation of Upper 6 GHz, whilst the mobile network meets respective low/central/high target speeds for users using its current spectrum allocation		
Scenario 4	Simulated mobile and Wi-Fi networks meet respective low/central/high target speeds for users given that the Upper 6 GHz is shared between mobile and Wi-Fi operators. Sensitivities were applied to this scenario, changing the percentage of indoor mobile users that are offloaded to Wi-Fi (ranging between 0-100%).		

Note: Due to time constraints, only the central demand scenario was modelled across the five different supply scenarios for each use case.

For each use case, the number of peak active users is determined, and target throughput values are defined for each demand scenario (low, central, high). To evaluate how mobile and Wi-Fi networks can meet this demand under different spectrum allocations, Ranplan Wireless conducted network design and simulations in WP2, assessing the infrastructure costs required for producers.

Using the WP2 outputs, the economic benefits of each scenario are calculated as follows:

1) **Calculate the total present value of consumer surplus**
    - Consumer surplus is calculated based on users' willingness to pay for throughput (benefits) and the prices users pay to access throughput (costs).
    - Since target speeds remain the same across scenarios 1-4, consumer surplus is identical in these scenarios. The costs and benefits of consumers experiencing these speeds is assumed to be the same for all use cases.
    - Only scenario 0 differs, where current speeds are used as a baseline
2) **Calculate the total present value of producer surplus**
    - Producer surplus is calculated based on revenues (benefits) and capital and operating expenditures (costs) for mobile and Wi-Fi operators.
    - Producer revenues remain constant in scenarios 1-4 because consumer pricing is based on fixed target speeds. Producer revenues differ in scenario 0 because currently provided speeds are different to the target speeds.
    - Producer costs vary across all scenarios (0-4), as different spectrum allocations impact capital and operating expenditure, due to differences in infrastructure deployment.
3) **Calculate the total present surplus for each scenario**
    - The total present surplus is determined by summing consumer and producer surplus in each scenario for each use case.
4) **Determine the total net present surplus differences between scenarios. The table below illustrates the description of different scenario comparisons below.**
    - The net difference in surplus is calculated for each scenario within each use case.
    - Since consumer surplus and producer revenues remain unchanged across scenarios 1-4, the only driver of differences in net present surplus is producer costs, which vary due to spectrum allocations.

Table: Description of different scenario comparisons

Scenario comparison	Description
Scenario 1 - Scenario 0	Additional provision with current spectrum bands vs. Current provision with current spectrum bands
Scenario 2 – Scenario 0	Additional Upper 6 GHz allocation for mobile only vs. Current provision with current spectrum bands
Scenario 3 – Scenario 0	Additional Upper 6 GHz allocation for Wi-Fi only vs. Current provision with current spectrum bands
Scenario 4 – Scenario 0	Additional Upper 6 GHz allocation with spectrum sharing vs. Current provision with current spectrum bands
Scenario 2 – Scenario 1	Additional Upper 6 GHz allocation for mobile only vs. Additional provision with current spectrum bands
Scenario 3 – Scenario 1	Additional Upper 6 GHz allocation for Wi-Fi only vs. Additional provision with current spectrum bands
Scenario 4 – Scenario 1	Additional Upper 6 GHz allocation with spectrum sharing vs. Additional provision with current spectrum bands
Scenario 4 – Scenario 2	Spectrum sharing of Upper 6 GHz vs. Exclusive allocation of Upper 6 GHz to mobile
Scenario 4 - Scenario 3	Spectrum sharing of Upper 6 GHz vs. Exclusive allocation of Upper 6 GHz to Wi-Fi

Target demand parameters

The two primary demand parameters that vary across the low, central and high scenarios are target throughput (user speeds) and the number of users.

Target throughput parameters

User throughput is the measure of the average data transmission speed that an end-user device achieves over time. This throughput depends on the network's efficiency, user demand and the specific conditions of the wireless environment.[42] User throughput requirements vary depending on the use case and the type of connectivity, whether mobile or Wi-Fi.

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[42] Marsch, P., Monserrat, J.F., and Osseiran, A. *5G Mobile and Wireless Communications Technology.* Available at: https://digilib.stekom.ac.id/assets/dokumen/ebook/feb_6dc75f6bb1ff6ccaf3c3bc84d5bfb41cd71f701a_1652450470.pdf, p.30

Mobile speeds

The user throughput requirements for mobile broadband vary depending on the use case, with different parameters for low, central and high demand scenarios. In urban and suburban environments, the primary challenge lies in addressing low user-experienced speeds caused by network congestion and bottlenecks. In these scenarios, users may have decent signal strength but still experience poor throughput due to high demand on the network. To overcome this, the focus is on evaluating economic costs and benefits of deploying a network capable of delivering the speeds needed to support advanced future data requirements.

Table: Mobile uplink and downlink requirements by use case and demand scenario

Use case	Target user downlink requirements			Target user uplink requirements		
	Low	Central	High	Low	Central	High
Stadium	10 Mbps	25 Mbps	50 Mbps	1 Mbps	50 Mbps	50 Mbps
High-Density Urban area	10 Mbps	100 Mbps	300 Mbps	1 Mbps	50 Mbps	50 Mbps
Dense Urban area	10 Mbps	50 Mbps	100 Mbps	1 Mbps	25 Mbps	50 Mbps
Low-Density Urban area	10 Mbps	50 Mbps	100 Mbps	1 Mbps	25 Mbps	50 Mbps

The target speeds are based on two primary sources:

- **IMT-2020 requirements.** The IMT-2020 regulations set by the ITU-R form the basis of target user throughput for either the central or high demand scenario, depending on the use case. The fifth generation of mobile network technology (5G) is designed to provide enhanced Mobile Broadband (eMBB) for higher data rates, lower latency and greater connectivity for a wide range of data-intensive applications.[43] To meet these requirements, the ITU-R set target values of 100 Mbps for downlink (DL) and 50 Mbps for uplink (UL).[44] These requirements are set for the High-Density Urban environment in the central demand scenario. Meanwhile, they form the basis of the target requirements in the high demand scenarios of Dense Urban and Low-Density Urban use cases.

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[43] International Telecommunications Union (ITU). (2015). *IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond.* Available at: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

[44] Mohyeldin, E. (2016). *Minimum Technical Performance Requirements for IMT-2020 radio interface(s).* Available at: https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Documents/S01-1_Requirements%20for%20IMT-2020_Rev.pdf

- **DSIT high density-demand (HDD) scenarios.**[45] According to DSIT, for highly crowded environments, like a Stadium, the relevant experienced downlink and uplink rates are 25 Mbps DL and 50 Mbps UL – these form the central target speeds for the Stadium. Meanwhile, for a 'Dense Urban' area, with a user density of ~25,000 users/km^2 the experienced data rates are 300 Mbps and 50 Mbps for DL and UL respectively – in line with the relevant user density, these are the high target speeds for the very Dense Urban area in this study. Finally, the 50 Mbps DL and 25 Mbps UL data rates for an 'urban macro' area form the central scenarios for the Dense Urban and Low-Density Urban areas.
- **Ofcom's 'decent' broadband requirements.** Ofcom defines 'decent' broadband as a connection with a download speed of at least 10 Mbps and an upload speed of at least 1 Mbps. This benchmark is based on the minimum requirements needed for essential online activities such as web browsing, streaming and video calls. While this definition currently only applies to fixed broadband for households, it forms the basis of the low scenarios for mobile broadband to ensure that users can perform the same essential online activities, whether at home or on the go.

Wi-Fi speeds

The user throughput requirements of Wi-Fi are growing significantly due to advancements in video technology and the emergence of Extended Reality (XR) applications.

While current video streaming services use compression to offer HD quality at less than 5 Mbps, higher resolutions like 4K can require up to 50 Mbps, and 8K streams can demand up to 300 Mbps.

XR technologies will amplify this demand, with advanced applications needing speeds of 1-2 Gbps and ultra-low latency of less than 3 ms. Currently, augmented reality (AR) and mixed reality (MR) devices are used in enterprise environments, but consumer-grade devices, such as AR glasses and virtual reality (VR) headsets, are becoming more common, driven by investments from companies like Meta. By 2030, applications such as VR, 4K video and smart home systems will be widely adopted, while cloud gaming, e-health and 8K video will grow rapidly. For these innovations to be accessible to all, broadband networks must evolve to support the high bandwidth and low latency required.

The downlink requirements of future data-intensive applications form the basis of the low, central and high demand scenarios for Wi-Fi as shown in the table below. Uplink requirements are assumed to be 50% of the downlink requirements, which is the same ratio that the IMT-2020 requirements use for mobile broadband.

Table: Wi-Fi throughput requirements by demand scenario

	Low	Central	High
Throughput	300 Mbps DL 150 Mbps UL	1,000 Mbps DL 500 Mbps UL	2,000 Mbps DL 1,000 Mbps UL
Applications	8K Video	High-quality XR	XR free-viewpoint

Source: World Broadband Association. (2024). 'Next-Generation Broadband Roadmap 2023 to 2030.' Available at: https://worldbroadbandassociation.com/wp-content/uploads/2024/06/Next-generation-broadband-roadmap-2023-to-2030.pdf

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45 DSIT. (2022). *Open Ran in High Demand Density Environments Technical Guidance.* Available at: https://www.gov.uk/government/publications/open-ran-in-high-demand-density-environments-technical-guidance/open-ran-in-high-demand-density-environments-technical-guidance#hdd-scenario-analysis

Estimating user numbers

To stress test the scenarios, the number of users during peak times is considered the most critical user parameter for the analysis. This approach ensures that the network is designed to handle the highest levels of demand, which typically occur during busy hours when user activity is at its maximum. By focusing on peak usage, the analysis evaluates the cost of a network to deliver consistent performance, maintain quality of service, and avoid congestion under the most demanding conditions.

The table below shows the starting population of each use case before mobile and Wi-Fi user numbers are calculated.

Table: Total population for each use case

Use case	Population	Type	Source
Stadium	60,700	Stadium capacity	Premier League
High-Density Urban	469,067	Working population	Business Register Employment Survey
Dense Urban	51,073	Working population	Business Register Employment Survey
Low-Density Urban	21,210	Residential population	Global Human Settlement Layer

Mobile users

To calculate the total number of peak active mobile users in the n78 band (scenarios 0 and 1) and the Upper 6 GHz band (scenarios 2,3 and 4) for each specific use case, the total population is taken and multiplied by an activity factor and the complement of the offload factor as shown by the equation below.

$$Peak\ active\ mobile\ users = Population * Activity\ factor * (1 - Offload\ factors)$$

The table below shows the number of peak active mobile users for each use case, split by indoor and outdoor for the low, central and high demand scenarios. According to Ericsson, 70-80% of mobile data traffic is assumed to be indoors. [46] Therefore, in all use cases, except for the Stadium, where all users are assumed to be outdoors, a 70%-30% split is applied, meaning 70% of mobile users are indoors and 30% are outdoors.

[46] Ericsson. (2021). *Planning in-building coverage for 5G: from rules of thumb to statistics and AI.* https://www.ericsson.com/en/reports-and-papers/mobility-report/articles/indoor-outdoor

Table: Peak active mobile users by use case and demand scenario

Use case	Low		Central		High	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Stadium	-	14,568	-	15,054	-	13,658
High-Density Urban area	39,402	16,886	50,894	21,812	36,939	15,831
Dense Urban area	2,860	1,226	4,648	1,992	3,933	1,685
Low-Density Urban area	1,188	509	2,079	891	1,782	764

The table below summarises the user densities of each use case, illustrating the range of densities across the use cases and low, central and high demand scenarios.

Table: Peak active mobile user densities by use case and demand scenario

Use case	Low	Central	High
Stadium	211,744 users/km^2	281,802 users/km^2	198,510 users/km^2
High-Density Urban area	27,062 users/km^2	34,955 users/km^2	25,370 users/km^2
Dense Urban area	771 users/km^2	1,253 users/km^2	1,060 users/km^2
Low-Density Urban area	424 users/km^2	742 users/km^2	636 users/km^2

Activity factor

The activity factor represents the proportion of mobile users actively generating traffic at a given time within a specific area. For instance, a 20% activity factor means that 20% of users in a given area are using the network at the same time. The activity factor implicitly accounts for offload to Wi-Fi for all use cases, apart from the Stadium. This factor is essential for modelling realistic network demand, as not all users are simultaneously active.

Based on assumptions and sensitivities from Coleago Consulting and the European Telecommunications Standards Institute (ETSI), activity factors range from 10% to 50% to reflect varying levels of user engagement across different environments. A lower activity factor (closer to 10%) might be appropriate for scenarios with sporadic usage, while a higher factor (up to 50%) would suit environments with more consistent user activity.

The activity factor is expected to rise over time with the growth of data intensive applications. It is anticipated that a busy city in a high income and highly industrialised country, like London, would be expected to have an activity factor of 15% in 2025, rising to 25% by 2030, assuming 100% of smartphone users utilise 5G. Therefore, the High-Density Urban use case has an activity of 15% for the low demand scenario, rising to 25% for the central and high scenarios.

The Dense Urban and Low-Density Urban use cases both have central and high activity factors of 20%, based on 5G performance requirements from the ETSI. This activity factor is relevant for environments with user densities between 100 and 10,000 users/km^2, encompassing the relevant user environments for the two aforementioned use case. As a low sensitivity, a 10% activity factor is employed for both as well.

Furthermore, according to ETSI's 5G user requirements, for scenarios where users required 'Broadband access in a crowd', like in a Stadium, where the user density is ~500k users/km^2, the appropriate activity factor is 30%. Stadium attendees frequently engage in data-intensive activities during events, such as live streaming, uploading photos and videos to social media, using event-specific apps, or accessing live statistics and replays. Stadium events, like a football match, are likely to last a few hours, during which users are likely to remain active on their devices for communication, entertainment and real-time updates. Therefore, 30% was chosen as the low parameter with 40% and 50% chosen as the central and high parameters respectively, to stress test a high density of users.

Table: Mobile activity factors by use case

Use Case	Activity Factor (%)		
	Low	Central	High
Stadium	30%	40%	50%
High-Density Urban	15%	25%	25%
Dense Urban	10%	20%	20%
Low-Density Urban	10%	20%	20%

Offload Factors

The model uses offload factors to calculate the number of mobile users that are exclusively using the n78 band (supply scenarios 0 and 1) or the Upper 6 GHz band (supply scenarios 2,3 and 4).

In the future, more high-band sites (mmWave) are anticipated to be deployed in densely populated areas to handle increasing traffic. [47] These frequencies can offer exceptionally high data rates, approaching or exceeding 1 Gbps to cope with the more intensive use cases of 5G that are anticipated

[47] Coleago Consulting. (2021). *Estimating the mid-band spectrum needs in the 2025-2030 time frame.* Available at: https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf

in the future. Whilst these frequencies have shorter wavelengths, resulting in smaller coverage areas and challenges in penetrating walls and windows, operators can mitigate these challenges by using mmWave radios with beamforming technologies to provide coverage for specialised in-building deployments that support line-of-sight connectivity with few obstructions. [48] By 2030, it is anticipated that 10% to 45% of 5G traffic in cities will be offloaded to these high-band sites. The broad range reflects uncertainties in timing and deployment density, influenced by variations in population density, the pace of network development, and other area-specific factors. [49]

Offloading traffic to these high bands becomes increasingly feasible as network activity intensifies. In scenarios with lower activity factors, the demand for high-band spectrum offloading remains limited because existing lower bands can typically hand the traffic. However, with higher activity factors, the capacity constraints on lower bands make high-band offloading more critical. By 2030, it is expected that such areas could offload 30-45% of their data traffic to high-band spectrum, improving network efficiency and alleviating congestion on lower-frequency bands. [50]

Furthermore, to meet the higher throughput requirements of users in the future, it is anticipated that upper mid-band small cells will be deployed indoors to ensure speed coverage. These indoor small cells help reduce the capacity demand on outdoor cell sites. In urban environments, it is assumed that 10% of (5G) mobile traffic will be offloaded to these indoor upper mid-band small cells. [51]

Therefore, the total indoor offload factor for mobile users is the sum of the high-band offload and the upper mid-band offload. Given the 10% indoor upper mid-band and the 10%-45% range for the high band offload, the following offload factors are calculated in the table below.

As it is anticipated that over time, more traffic will be offloaded to high bands, the low demand scenario takes the high-band offload value of 10% for all use cases. For the use cases with the highest user densities (Stadium and High-Density Urban), the high demand scenario takes 45% and the central scenario takes the mid-point of these two values (28%). For the Dense and Low-Density Urban areas, the central scenario has a 25% and 20% high-band offload factor, with 35% and 30% for the high demand scenario respectively. As a consequence, the higher offload factor in the high demand scenarios may mean that there are actually a lower number of Upper 6 GHz users in the high scenarios compared with the central. The total offload factor for each use case and demand scenario is summarised in the table below.

[48] Samsung. (2020). *Key Considerations to Solve the Challenges in Bringing 5G Indoors.* Available at: https://images.samsung.com/is/content/samsung/assets/global/business/networks/insights/white-paper/key-considerations-to-solve-the-challenges-in-bringing-5g-indoors/Solving-Inbuilding-5G-Challenges-Solution-Brief-010720.pdf

[49] Coleago Consulting. (2021). *Estimating the mid-band spectrum needs in the 2025-2030 time frame.* Available at: https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf

[50] Ibid.

[51] Coleago Consulting. (2021). *Estimating the mid-band spectrum needs in the 2025-2030 time frame.* Available at: https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf

Table: Mobile offload factors by use case and demand scenario

Use Case	Total Offload Factor = High Band + Upper Mid Band (%)		
	Low	Central	High
Stadium	20% = (10% + 10%)	38% = (28% + 10%)	55% = (45% + 10%)
High-Density Urban	20% = (10% + 10%)	38% = (28% + 10%)	55% = (45% + 10%)
Dense Urban	20% = (10% + 10%)	35% = (25% + 10%)	45% = (35% + 10%)
Low-Density Urban	20% = (10% + 10%)	30% = (20% + 10%)	40% = (30% + 10%)

Wi-Fi users

The calculation for peak active Wi-Fi users follows a similar approach to mobile users. However, unlike mobile, where the activity factor inherently accounts for Wi-Fi offloading, this adjustment does not directly apply to Wi-Fi. Instead, the estimation of Wi-Fi users in a given use case considers a specific proportion of users along with a busy hour factor, which represents the share of Wi-Fi users active during peak times. No offload factors are assumed.

For supply scenarios 0,1 and 2 the number of users reflects those operating within the 5 GHz Wi-Fi band, which is currently accessible to Wi-Fi providers. In supply scenarios 2, and 4, peak active Wi-Fi users refer to those utilising the Upper 6 GHz spectrum band. All Wi-Fi users are assumed to be indoor.

$$Peak\ active\ WiFi\ users = Population * Prop\ of\ WiFi\ users * Busy\ hour\ factor$$

Table: Peak active Wi-Fi users by use case

Use case	Low	Central	High
Stadium	14,568	15,054	13,658
High-Density Urban	23,453	58,821	88,232
Dense Urban	2,554	6,405	9,607
Low-Density Urban	1,061	2,660	3,990

Note: Stadium has the same number of mobile and Wi-Fi users, following the mobile calculation method.

Table: Proportion of Mobile and Wi-Fi Usage

Connection type	Number of connections (millions)	Proportion of connections
Fixed Line	28.5	20%
Mobile	116.1	80%
Total	144.6	100%

Source: 'UK Ofcom Communications Market Report (2024).' Available at: https://www.ofcom.org.uk/phones-and-broadband/service-quality/communications-market-report-2024-interactive-data/

Based on the above calculations, in each use case, it is assumed that 20% of users are utilising Wi-Fi in the Central demand scenarios. To account for variability, a 10% sensitivity is applied: in the low scenario, only 10% of users are assumed to rely on Wi-Fi, while in the high scenario, this proportion increases to 30%. These parameters are summarised in the table below.

Table: Proportion of Wi-Fi users by demand scenario

Low	Central	High
10%	20%	30%

As with mobile, to account for the simultaneous number of users demanding Wi-Fi at peak times, there is a 'busy hour factor'. For each use case, the busy hour factor is assumed to be 50% in the low demand scenario and 62.7% in the central and high scenarios. These parameters were adopted by the Electronic Communications Committee (ECC) as part of the European Conference of Postal and Telecommunications Administration (CEPT) and are shown formally in the table below. [52]

Table: Busy hour factor by demand scenario

Low	Central	High
50%	62.7%	62.7%

Source: Electronic Communications Committee. (2019). 'ECC Report 302.' Available at:
https://docdb.cept.org/download/cc03c766-35f8/ECC%20Report%20302.pdf

Calculating consumer surplus

Once the number of peak active users has been calculated along with the target parameters for each use case, the total present value of consumer surplus for each scenario in each use case can be calculated. Consumer surplus is estimated as the difference between the monetary value that consumers place on having access to improved internet connectivity [53] and the cost that they incur as a result.

The calculation of consumer surplus is based on the costs and benefits associated with consumers accessing higher throughput speeds (measured in Mbps). The benefits are determined by consumers' willingness to pay for increased data speeds, while the costs reflect the prices paid by consumers to access these speeds.

Consumer benefits: Willingness to pay

In reality, the monetary amount that one is willing to spend to access higher internet speed (e.g. to go from X Mbps to Y Mbps) varies across users due to a multitude of factors including the user's data usage profile and personal characteristics (e.g. age, profession, income level) as well as environmental factors (time and space). However, with any modelling exercise, there is a trade-off between accuracy and

[52] European Conference of Postal and Telecommunications Administrations (CEPT). (2019). *ECC Report 302.* Available at: https://docdb.cept.org/download/cc03c766-35f8/ECC%20Report%20302.pdf, p.23

[53] Mobile broadband or Wi-Fi

feasibility. As such, the willingness to pay (WTP) values used as inputs in the model are taken to be homogeneous across all users, use cases and scenarios.

WTP values used in the model are based on Rabbani's estimates of marginal WTP for improved internet throughput in 2024.[54] Rabbani's values were estimated using a survey-based choice experiment administered to 5,200 respondents across Alaska, Michigan, Texas, or West Virginia between May and June 2022 and extrapolated using curve-fitting. Rabbani provides estimates of the marginal WTP (MWTP) for 1 Mbps higher internet speed at different starting throughput values. For example, consumers with access to 10 Mbps of internet speed were estimated to be willing to pay an additional £3.14 per month [55] on average to access to internet speed that is 1 Mbps faster, i.e. 11 Mbps. The marginal willingness to pay was estimated to be a power law decaying function, undefined at 0 Mbps.[56]

This analysis looks at the total WTP for a given level of throughput. As such, the integral of Rabbani's function, resulting in a natural logarithmic function that is also undefined at 0 Mbps. This means we are unable to calculate total WTP to go from 0 Mbps to a given level of throughput, as it is not possible to difference out 0 (and drop the constant of integration) to calculate total WTP. [57] Therefore, a range of close-to-zero proxies are taken, and results of these sensitivities are presented in the overall report. [58]This gives a final total willingness to pay function of:

$$Total\ WTP = \alpha \ln\left(\frac{Current\ speed}{\delta}\right)$$

where δ is the close-to-zero proxy (in our report taking values 0.2, 0.5, 0.75 depending for the baseline, reduced, and low willingness to pay sensitivities), and α is a constant estimated in the Rabbani report.[59]

A selection of total WTP values for higher throughput speed used as model inputs is shown in the table below.

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[54] Rabbani, M. et al., (2024). *Willingness to pay for internet speed and quality.* Available here: https://www.sciencedirect.com/science/article/pii/S0736585324000777

Rabbani's estimates were identified as the most recent, empirically robust (based on survey of 5,200 respondents across four demographically diverse US states and curve fitting), granular (Marginal WTP values) and publicly available values on consumer WTP for better internet throughput at the time where this analysis was largely undertaken (November 2024 – February 2025). Recency is a key factor in determining the relevance of WTP values for better internet connectivity. Consumer value placed on good quality connection and internet speed has greatly increased over time, as everyday life use cases requiring good connectivity have multiplied as well as grown more data intensive.

[55] Original value in Rabbani's paper is 3.43 USD/month. Converted to GBP using June 2022 average exchange rate of 0.81 GBP per USD and adjusted with UK inflation rate over December 2022–January 2025 of 12.9% based on GDP deflators.

[56] Marginal WTP (MWTP) for 1 Mbps faster internet when starting at throughput S (in USD/month) = $a*S^b$; where S is in Mbps, a = 34.316 and b = -1

[57] Due to the MWTP function specification, MWTP values estimated for values closer to 0 are very high and economically not sensible.

[58] Sensitivities around the close-to-zero proxy are only provided for the not-spots analysis as current provision is always non-zero for the Urban use cases and Stadium.

[59] Estimated to be 34.3 in their report. However, in this analysis it is converted to GBP using June 2022 average exchange rate of 0.81 GBP per USD and adjust by UK inflation rate over December 2022 – January 2025 of 12.9 % giving a final value of 31.0.

Table: Selection of marginal and total WTP values for higher user throughput at different throughput levels, at current value (January 2025) for all use cases apart from the Stadium

Throughput (Mbps)	Total WTP (£/Month) - using 0.2 as 0 proxy	Total WTP (£/Month) - using 0.5 as 0 proxy	Total WTP (£/Month) - using 0.75 as 0 proxy
1	49.95	21.51	8.93
2	71.47	43.03	30.44
5	99.91	71.47	58.88
10	121.42	92.98	80.39
25	149.86	121.42	108.83
50	171.37	142.93	130.35
75	183.96	155.52	142.93
100	192.88	164.45	151.86
300	226.98	198.54	185.96
500	242.84	214.40	201.81
1000	264.35	235.91	223.33

Source: LE analysis of WTP estimates provided in Rabbani et al. (2024).

In the above, total WTP is decreasing as the proxy value for 0 Mbps increases. This is because with a higher proxy, a larger number of small values for current throughput is included where marginal WTP is higher.

For all use cases excluding the Stadium use case, WTP values in the form of £/month, which is then scaled up to £/annum before carrying out the present value calculation of consumer benefits for each use case.

In the case of the Stadium, it is more appropriate to estimate WTP values in terms of £/event because Stadium networks experience high, irregular demand spikes during events rather than continuous monthly usage. Unlike in the other use cases, Stadium visitors are infrequent, making a monthly WTP less meaningful. Since network infrastructure must handle intense, short-duration peaks, event-based WTP better reflects actual user benefits.

The Stadium use case is the Emirates Stadium, the home of Arsenal football club. In recent seasons, Arsenal has played between 50 to 60 matches across all competitions.[60] Assuming half of these are home games, the Emirates Stadium would host approximately 25 to 30 men's matches per season. With an increasing number of Arsenal Women matches also taking place at the Emirates alongside non-football events, such as music events, it is assumed that there are an average of 36 events at the Emirates Stadium each year, averaging three per month, for simplicity. As a result, the £/month estimates can be divided by three to calculate marginal and total WTP.

[60] Worldfootball.net. (n.d.). Arsenal FC – Historical results. Available at: https://www.worldfootball.net/teams/arsenal-fc/21/?utm_source

Table: Selection of total WTP values for higher throughput in the Stadium use case

Throughput (Mbps)	Total WTP (£/Event) - using 0.2 as 0 proxy	Total WTP (£/Event) - using 0.5 as 0 proxy	Total WTP (£/Event) - using 0.75 as 0 proxy
1	16.65	7.17	2.98
2	23.82	14.34	10.15
5	33.30	23.82	19.63
10	40.47	30.99	26.80
25	49.95	40.47	36.28
50	57.12	47.64	43.45
75	61.32	51.84	47.64
100	64.29	54.82	50.62
300	75.66	66.18	61.99
500	80.95	71.47	67.27
1000	88.12	78.64	74.44

Source: LE analysis of WTP estimates provided in Rabbani et al. (2024).

Consumer costs: Throughput pricing

In practice, fixed broadband pricing is based on speed (Mbps), while mobile broadband pricing is determined by data usage (GB). However, for consistency and simplicity, fixed broadband pricing is used as a proxy for the prices consumers pay for both Wi-Fi and mobile speeds. The table below summarises consumer prices by throughput bands, based on Ofcom data.

Table: UK fixed broadband monthly pricing

Throughput (Mbps)	Quality	Price (£/month)	Price (£/event)
< 30	Standard	26.00	8.67
30 – 99	Superfast	34.00	11.33
100 -299	Superfast	35.00	11.67
300 – 999	Ultrafast	42.00	14.00
≥ 1,000	Gigabit	60.00	20.00

Note: Weighted average monthly prices of standalone fixed broadband services in the UK, excluding set-up cost.
Source: Ofcom. (2024). 'Pricing trends for communication services in the UK.' p.19

To calculate the throughput speeds at a granular level within intervals, a diminishing marginal cost formula is used to reflect how prices change within intervals:

$$P_s = (P_{current} - P_{prev}) * \left(\frac{s}{S_{upper}}\right)^a$$

where:

- P_s is the price of the throughput value being calculated

- $P_{current}$ is the price of the current throughput interval
- P_{prev} is the price of the previous throughput interval
- s is the value of throughput that price is being calculated for
- s_{upper} is the upper bound of the current throughput interval
- a is the diminishing marginal cost scaling factor.[61]

This approach ensures a smooth and realistic pricing transition across different throughput levels to reflect economies of scale as network capacity expands: the marginal cost of providing higher speeds decreases.

As with the WTP values, given that three events per month are assumed, the price of £/event is worked out by dividing the £/month value by three.

Calculating producer surplus

The present value of producer surplus over the 10-year horizon is calculated in the following way:

$$PV(Producer\ surplus) = PV(Producer\ benefits) - PV(Producer\ costs)$$

where

$$PV(Producer\ benefits) = PV(Producer\ revenues)$$

and

$$PV(Producer\ costs) = PV(Producer\ CAPEX) + PV(Producer\ OPEX)$$

The methodology for calculating producer benefits and producer costs is broken down in the subsections below.

Producer benefits: Revenues

As consumer costs are simply the prices that consumers pay producers for accessing connectivity, producer benefits are equal to consumer costs. Therefore, it must be the case that

$$PV(Producer\ benefits) = PV(Consumer\ costs)$$

Producer costs: CAPEX and OPEX

Producer costs are categorised into capital expenditure (CAPEX) and operating expenditure (OPEX), representing different aspects of investment and ongoing costs. CAPEX includes upfront investments in infrastructure, such as deployment and construction costs for network equipment, including mobile base stations, antennas, Wi-Fi access points and indoor small cells. OPEX, on the other hand, covers recurring costs such as maintenance, power and other ongoing overhead costs. Some further details on the cost assumptions for the various network elements are provided in the WP2 report.

CAPEX

CAPEX is assumed to be incurred entirely in the first year and is not discounted since it is a one-time expense. The cost of each piece network equipment is summarised in the table below.

[61] The current value of a is chosen at 0.75, but it could be adjusted for sensitivity analysis.

Table: Mobile and Wi-Fi network equipment costs

Equipment	Unit cost	Construction cost
Antennas	£2,000	£0
Mobile base stations	£10,000	£6,000
Indoor small cells	£5,000	£3,000
Wi-Fi access points	£162	£0

Source: Ranplan Wireless and Telet

OPEX

OPEX, covering recurring costs such as maintenance, power and ongoing overheads begins in the second year after the network is built, continuing throughout the ten-year period. OPEX costs are assumed to remain at current (2025) prices and are discounted at a rate of 3.5% [62] to reflect its present value over the time horizon.

Table: OPEX assumptions

OPEX item	Assumption
Maintenance	40% of CAPEX costs
Overheads	15% of producer revenues
Power unit costs	24.86 pence per kWh

Annual maintenance costs are assumed to be 40% of CAPEX costs, covering expenses related to repairs, backend systems, customer support and general upkeep.[63] Meanwhile, annual overhead costs are assumed to be 15% of producer revenues.

Power costs are determined based on the maximum power usage deployed in simulations by Ranplan Wireless for each use case. The methodology accounts for peak and off-peak usage across mobile base stations, indoor small cells, and Wi-Fi access points. For the Stadium, the event duration is assumed to last three hours, with all data consumption considered peak usage.[64] In all Urban use cases, a 12-hour peak period is assumed, capturing both busy work and leisure usage in each area.

[62] HM Treasury. (2022). Guidance: *The Green Book (2022).* Available at: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government/the-green-book-2020

[63] Estimate from Telet

[64] DSIT. (2023). *Open RAN in High Demand Density Environments Technical Guidance*. Available at: https://www.gov.uk/government/publications/open-ran-in-high-demand-density-environments-technical-guidance/open-ran-in-high-demand-density-environments-technical-guidance#hdd-scenario-analysis

Table: Peak and off-peak duration assumptions for each use case

Use case	Peak duration	Off-peak duration
Stadium	3 hours	0 hours
All Urban use cases	12 hours	12 hours

Based on these durations, total daily power consumption (in kWh) is calculated and then scaled up to annual power consumption. Each mobile base station, Wi-Fi access point, or indoor small cell is set to a maximum power level (W) by Ranplan Wireless. The mean power consumption of the network is also recorded in kilowatt hours (kWh).

Peak power consumption is assumed to be 90% of the maximum power usage in the network:

$$Power_{peak} = 0.9 \times Power_{max}$$

where:

- $Power_{peak}$ is power consumption at peak times
- $Power_{max}$ is the maximum power consumption set by Ranplan Wireless

The mean power consumption is reported for the full mobile or Wi-Fi network, but it is not itemised by base station, access point or small cell. Therefore, for example, if a mobile network consisted of a combination of base stations and small cells, mean power consumption of base stations for a specific mobile network is calculated as:

$$Power_{mean_{BS}} = Power_{mean_{total}} \times \left(\frac{BS_{quantity} \times Power_{BS_{max}}}{\left(BS_{quantity} \times Power_{BS_{max}}\right) + \left(SC_{quantity} \times Power_{SC_{max}}\right)} \right)$$

where:

- $Power_{mean_{Bs}}$ is the mean power consumption of mobile base stations
- $Power_{mean_{total}}$ is the mean power consumption for the entire network
- $BS_{quantiy}$ is the number of base stations deployed in the network
- $Power_{Bs_{max}}$ is the maximum power consumption per base station
- $SC_{quantiy}$ is the number of small cells
- $Power_{SC_{max}}$ is the maximum power consumption per small cell

Hourly off-peak power consumption is derived from peak power and mean power consumption using:

$$Power_{offpeak} = Power_{mean} \times \left(\frac{Duration_{peak} + Duration_{offpeak}}{Duration_{offpeak}} \right) - Power_{peak}$$

where:

- $Power_{offpeak}$ is power consumption during off-peak times
- $Power_{mean}$ is mean power consumption for the network
- $Duration_{peak}$ is peak usage duration (in hours)
- $Duration_{offpeak}$ is off-peak usage duration (in hours)

Once hourly peak and off-peak power are calculated, total daily (or per Stadium event) power consumption is determined using:

$$Power_{daily(per\ event)} = \left(Power_{peak} \times Duration_{peak}\right) + (Power_{offpeak} \times Duration_{offpeak})$$

where:

- $Power_{daily(per\ event)}$ is total power consumed per event or daily
- $Power_{peak} \times Duration_{peak}$ is power consumed during peak hours
- $Power_{offpeak} \times Duration_{offpeak}$ is power consumed during off-peak hours

The daily power consumption is then scaled up to annual power consumption as follows:

$$Power_{annual} = Power_{daily} \times 365$$

For the Stadium, since power usage is event-based, annual power consumption is calculated as

$$Power_{annual} = Power_{per\ event} \times Number\ of\ stadium\ events\ per\ annum$$

Finally, annual power costs are determined by multiplying annual power consumption (in kWh) by Ofgem's power unit cost, which is currently 24.86 pence per kWh: [65]

$$Power_{cost_{annual}} = Power_{annual} * Power_{cost_{unit}}$$

where

- $Power_{cost_{annual}}$ is the total annual power cost (£)
- $Power_{annual}$ is annual power consumption (kWh)
- $Power_{cost_{unit}}$ is unit cost of power (pence per kWh)

Adjusting for variations in scenario 2 and scenario 4

Scenario 2: Adjusting for differences in indoor Upper 6 GHz mobile deployment

An additional variation that is added to scenario 2 – where mobile operators have exclusive access to the Upper 6 GHz spectrum band – is the percentage of buildings in each use case that have indoor Upper 6 GHz mobile deployment (in the form of indoor small cells). The baseline case is to assume that there is 0% indoor deployment, ranging up to full indoor deployment (100%), although the latter is unlikely to materialise in reality.

As this is an assumption made after Ranplan has modelled the network, the percentage of indoor deployment is reflected in the changes in the average throughput that indoor Upper 6 GHz mobile users experience in scenario 2. The average throughput that indoor Upper 6 GHz mobile users experience in different indoor deployment variations in scenario 2 is calculated in the following way:

$$Throughput_{indoor} = Throughput_{target} - ((1 - Deployment_{indoor}) * \left(Throughput_{target} - Throughput_{S1}\right)$$

where

- $Throughput_{indoor}$ is the throughput that indoor Upper 6 GHz mobile users experience in scenario 2 (assuming 100% indoor deployment as Ranplan modelled).
- $Throughput_{target}$ is the target throughput that the average user is expected to experience in scenario 2
- $Deployment_{indoor}$ is the percentage of indoor Upper 6 GHz mobile deployment in scenario 2

[65] Ofgem. (2025). *Energy price cap*. Available at: https://www.ofgem.gov.uk/energy-price-cap

- $Throughput_{S1}$ is the throughput that indoor mobile users experience in scenario 1 with current bands (n78). This is considered the minimum average throughput that indoor mobile users experience.

Scenario 4: Adjusting for indoor Upper 6 GHz mobile users being offloaded to Wi-Fi

Another assumption in scenario 4 - where there is spectrum sharing between mobile and Wi-Fi – accounts for indoor Upper 6 GHz mobile users being offloaded to Wi-Fi. Given that there are extra users being offloaded onto the Wi-Fi network in scenario 4 [66], there is likely to be a decline in the average speed that Wi-Fi users experience in scenario 4, given a specific network design.[67]

The following calculation is carried out to account for degraded average throughput for Wi-Fi users:

$$Average\ WiFi\ user\ throughput = \frac{Aggregate\ WiFi\ network\ throughput\ simulated\ by\ Ranplan}{Number\ of\ WiFi\ users\ after\ offloading}$$

Since average Wi-Fi user throughput is calculated by dividing the total network throughput by the number of users, this concept can be extended to account for additional user offloading onto the Wi-Fi network. By keeping the total Wi-Fi network throughput constant while increasing the number of users, the average throughput per user decreases. As the numerator remains unchanged and the denominator grows, greater offloading leads to a decline in average Wi-Fi user throughput.

This approach helps prevent overestimating consumer benefits by ensuring that the throughput experienced per user (and therefore their willingness to pay) and the revenues producers receive from increased throughput are more accurately reflected. As a result, it provides a more realistic assessment of the net benefit of spectrum sharing compared to the exclusive allocation of the Upper 6 GHz band to either mobile or Wi-Fi.

[66] Note that the overall number of Upper 6 GHz users (mobile and Wi-Fi) stays the same. The only difference is that there are a higher proportion of Wi-Fi users than in the baseline case (0% offloading) as some indoor Upper 6 GHz mobile users are offloaded onto the Wi-Fi network.

[67] Ranplan could also have modelled a network that accounted for these additional Wi-Fi users, so that they are all able to experience the target Wi-Fi speeds. However, due to time constraints, it is assumed that Wi-Fi users experience degraded speeds due to additional offloading onto the network, rather than simulating a new network to cope with these additional Wi-Fi users.

Detailed use-case specific results: Evaluating the economic benefits of spectrum sharing in the Upper 6 GHz

This section breaks down the economic benefits of spectrum sharing in the Upper 6 GHz band based on different variations in scenarios 2 and 4. As explained in the overall report, there are variations in the percentage of indoor Upper 6 GHz mobile deployment in scenario 2 (ranging between 0%-100%), whilst in scenario 4, there are variations in the percentage of indoor Upper 6 GHz mobile users offloaded to Wi-Fi (also ranging between 0%-100%). This section illustrates how the net present surplus of spectrum sharing over exclusive allocation to Wi-Fi changes depending on these variations for each Urban use case.

High-Density Urban

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive mobile allocation for the High-Density Urban use case dependent on sensitivities in scenarios 2 and 4.

Degree of indoor Upper 6 GHz mobile deployment in scenario 2 (%)	Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
	0% (No additional 6 GHz Wi-Fi offloading)	25%	50%	75%	100% (All indoor mobile users offloaded to 6 GHz Wi-Fi)
0% (No indoor 6 GHz mobile deployment)	£4m	£120m	£215m	£304m	£389m
25%	-£86m	£30m	£125m	£215m	£300m
50%	-£137m	-£21m	£74m	£163m	£249m
75%	-£173m	-£57m	£38m	£128m	£213m
100% (Full indoor 6 GHz mobile deployment)	-£196m	-£80m	£15m	£104m	£190m

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive Wi-Fi allocation for the High-Density Urban use case dependent on sensitivities in scenario 4.

Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
0% (No additional 6 GHz Wi-Fi offloading)	**25%**	**50%**	**75%**	**100%** (All indoor mobile users offloaded to 6 GHz Wi-Fi)
£51m	£167m	£262m	£351m	£437m

Dense Urban

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive mobile allocation for the Dense Urban use case dependent on sensitivities in scenarios 2 and 4.

Degree of indoor Upper 6 GHz mobile deployment in scenario 2 (%)	Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
	0% (No additional 6 GHz Wi-Fi offloading)	**25%**	**50%**	**75%**	**100%** (All indoor mobile users offloaded to 6 GHz Wi-Fi)
0% (No indoor 6 GHz mobile deployment)	£7m	£16m	£23m	£30m	£39m
25%	£5m	£14m	£21m	£28m	£36m
50%	£4m	£13m	£20m	£26m	£35m
75%	£3m	£12m	£19m	£25m	£34m
100% (Full indoor 6 GHz mobile deployment)	£2m	£11m	£18m	£25m	£33m

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive Wi-Fi allocation for the Dense Urban use case dependent on sensitivities in scenarios 2 and 4.

Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
0% **(No additional 6 GHz Wi-Fi offloading)**	**25%**	**50%**	**75%**	**100%** **(All indoor mobile users offloaded to 6 GHz Wi-Fi)**
£11m	£20m	£26m	£33m	£42m

Low-Density Urban

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive mobile allocation for the Low-Density Urban use case dependent on sensitivities in scenarios 2 and 4.

Degree of indoor Upper 6 GHz mobile deployment in scenario 2 (%)	**Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)**				
	0% **(No additional 6 GHz Wi-Fi offloading)**	**25%**	**50%**	**75%**	**100%** **(All indoor mobile users offloaded to 6 GHz Wi-Fi)**
0% **(No indoor 6 GHz mobile deployment)**	-£2.62m	£2.13m	£5.97m	£10.18m	£14.43m
25%	-£2.99m	£1.76m	£5.60m	£9.81m	£14.06m
50%	-£3.24m	£1.50m	£5.34m	£9.56m	£13.80m
75%	-£3.28m	£1.47m	£5.31m	£9.52m	£13.77m
100% **(Full indoor 6 GHz mobile deployment)**	-£3.39m	£1.36m	£5.20m	£9.41m	£13.66m

Table: Range of net present surpluses of spectrum sharing in Upper 6 GHz band over exclusive Wi-Fi allocation for the Low-Density Urban use case dependent on sensitivities in scenarios 2 and 4.

Additional indoor mobile users offloaded to 6 GHz Wi-Fi in scenario 4 (% of remaining peak active indoor users that use mobile in simulations)				
0% (No additional 6 GHz Wi-Fi offloading)	25%	50%	75%	100% (All indoor mobile users offloaded to 6 GHz Wi-Fi)
£0.99m	£5.74m	£9.58m	£13.79m	£18.04m

Methodology: Evaluating the economic benefits of addressing not-spots/underserved areas and areas with poor speeds using Band 3 or N77

Given the higher deployment costs and propagation characteristics (lower range), sharing in the 6 GHz band is unlikely to address connectivity gaps in underserved areas and not-spots. Nevertheless, these areas could benefit from flexible sharing regimes such as faster and more streamlined licensing process in lower bandwidths (e.g., Band 3 or n77), which may enable smaller providers to deploy infrastructure at lower costs (e.g., using small cells). Competitive effects in turn may incentivise MNOs to increase deployment in underserved areas where they are currently squatting on spectrum.

Therefore, in addition to exploring the benefits of sharing in the Upper 6 GHz band, analysis was undertaken to understand the potential economic benefits of providing coverage to not-spots and underserved areas.

In order to identify not-spots and underserved areas, M2Catalyst, a global telecom data service provider, provided us with granular (800x800m) data on speeds and coverage across the UK. This was used to help us understand existing provision across the UK and identify underserved areas, or areas of poor speeds below 9 Mbps. The data consists of throughput speeds (in buckets) for 800x800m grids across the UK. Each grid has speed measurements for some or all of the MNOs across 5 buckets of speed.[68]

In our analysis of addressing not-spots/underserved areas using Band 3, we have defined underserved areas as those where the M2Catalyst data indicates that throughput speed from the second best provider in an area is below 1 Mbps. This means that in our underserved areas, at most one provider is supplying speeds in excess of 1 Mbps, and in some cases there is no coverage from any supplier at all. So as to capture areas where there is a lack provision but there is demand, we also focus on areas where the Global Human Settlement Layer[69], a project by the EU to map population density worldwide, indicates that more than 25 people live in an area, and where the ONS UPRN directory indicates dwellings are present.

In our analysis of improving speeds by 10 Mbps using a network N77 small-cells, we have included areas where at least two providers have speeds below 9 Mbps, and there are at least 25 people in an area.

We model the costs and benefits associated with two scenarios:

i) raising speeds to 2 Mbps through deployment of small-cell Band 3 base-stations based on insights on costs to provide coverage to rural areas from our sandbox partners Telet through the MoNeH Rural Connected Communities Test Bed & Trials Programme[70] and

ii) raising speeds by 10 Mbps through deploying small cell n77 base-stations based on simulations by Ranplan Wireless.

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[68] The speed buckets are: No signal (0 Mbps), 0-1 Mbps, 1-4 Mbps, 4-9 Mbps, and >9 Mbps.

[69] This data is at the 100x100m level. It can be downloaded here: https://human-settlement.emergency.copernicus.eu/dataToolsOverview.php

[70] Telet, blue sky, CH4LKE (2022). *MONeH Rural Connected Communities – 5G Test Bed & Trials Programme. Final Report v1.34*. Available at: https://uktin.net/sites/default/files/2023-05/MONeH%20RCC%20-%20Final%20Report.pdf

Estimation of benefits

As in the analysis of spectrum sharing above, benefits are derived from the willingness to pay estimates in Rabbani et al. (2023).

In the case of our analysis of the costs and benefits of building a 2 Mbps network in not-spots/underserved areas, this gives a willingness to pay for 2 Mbps in the range of £30 to £71[71] per user per month when there is no coverage, and an additional willingness to pay when speed is 0.5 Mbps in the range of £30 to £43, depending on what sensitivity we use.[72] To calculate total willingness to pay in an area, we multiply population by willingness to pay per user per month.

In our analysis of improving the current throughput in an area by 10 Mbps, sensitivities around willingness to pay are less relevant. This is because they only affect results when current provision is zero, but in this analysis we include all areas where at least two MNOs have below 9 Mbps current speed, which includes areas where current provision is greater than 0. Nevertheless, we include sensitivities around willingness to pay in our analysis.

Estimation of costs

In our analysis of addressing underserved areas/not-spots using Band 3, we use 3 different sensitivities for CAPEX costs of £811 per UPRN as our baseline which we increase by 50% and 200%. Our baseline is based on a study conducted by our Sandbox partners Telet which found that the average cost per UPRN of building a 2 Mbps network were £811.16.[73] The sensitivities with increased costs reflect Green Book guidance for optimism bias for Equipment/Development projects.

In our analysis of improving speeds by 10 Mbps using N77, we use £354 per user as our baseline which comes from our sandbox partners Ranplan who modelled the cost of increasing throughput using N77 small-cell base stations in rural Northumberland which we also increase by 50%, and 200% in line with Green Book guidance.

In both analyses, for OPEX costs, we take the percentage of OPEX costs from CAPEX costs for small cells as indicated by Telet (40%). In addition, we include the energy costs per small cell, assuming each small cell runs at an average of 200W. This gives OPEX costs at 45% of CAPEX costs. We further estimate overhead costs as 15% of producer revenues. Producer revenues are based on our pricing assumptions used in previous sections where we take the weighted average of monthly prices of standalone fixed broadband services in the UK[74] as a proxy for mobile prices in terms of speeds. A full breakdown of this pricing is given in the "Consumer costs: throughput pricing" section of this Annex.

In order to calculate total costs, for our analysis of providing coverage to underserved areas/not-spots using Band 3, in each of our cost sensitivities we multiply cost per UPRN by the total number of UPRNs

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[71] Whilst this may seem high, we note that the average price for Starlink which in fixed broadband and mobile coverage not-spots is one of the only available options for connectivity, is ~£70 per month. This indicates that willingness to pay when there is no connectivity is in fact high. Customers who purchase Starlink have a willingness to pay in excess of £70.

[72] These ranges are based on the fact that Rabbani's marginal willingness to pay function is undefined at 0 Mbps. To account for this, we take a range of approximations for willingness to pay when there is no coverage (at 0 Mbps): i) 0.2 Mbps, ii) 0.5 Mbps) and iii) 0.75 Mbps. As marginal willingness to pay is decreasing as speed increases, 0.75 Mbps as a proxy for the willingness to pay when there is no coverage gives the lowest willingness to pay estimates.

[73] Telet, blue sky, CH4LKE (2022). *MONeH Rural Connected Communities – 5G Test Bed & Trials Programme. Final Report v1.34*. Available at: https://uktin.net/sites/default/files/2023-05/MONeH%20RCC%20-%20Final%20Report.pdf

[74] Ofcom. (2024). *Pricing trends for communications services in the UK.*

in an area. For our analysis of improving speeds using N77 we multiply cost per user by the total number of users.

Overall, we assume the first year is “a build year” in which no OPEX costs or willingness to pay is counted.