Exploring the Cost, Coverage and Rollout Implications of 5G in Britain

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Executive Summary

This report has been provided for the National Infrastructure Commission (NIC) to help inform the UK's 5G strategy. The NIC specifically requested that this research explore the costs of rolling out ubiquitous high-speed mobile data access across Britain for a per user speed of 50 Mbps – approximately three times higher than the current average. It contains research carried out under the EPSRC-funded Multi-scale Infrastructure Systems Analytics (MISTRAL) programme that aims to inform the long-term planning and delivery of national infrastructure.

The UK has committed to becoming a world leader in 5G communications deployment by 2020. In Spring 2016, the incumbent Chancellor instructed the NIC to assess and recommend steps that the UK could take to achieve this via a 5G strategy, due to be launched in Spring 2017. As the 5G standardisation process is still ongoing, there is currently great uncertainty associated with the rollout of the next generation of mobile telecommunications. Regardless, evidence needs to be produced to guide the UK's 5G strategy.

In light of this, the research in this report set out to understand the Total Cost of Ownership (TCO) for a 5G network with a high technical specification, including how the costs of deployment for this network could be reduced. It provides direction for necessary future analysis to support the UK's 5G strategy. There are four key aims to explore under a variety of scenarios:

1. Quantify the potential cumulative cost of rolling out 5G to different proportions of the population.
2. Estimate the total regional investment cost for rolling out a high coverage probability 5G network, in relation to urban-rural settlement patterns.
3. Provide insight into the spatial rollout of 5G, in order to illustrate the locations that are likely to receive new infrastructure first.
4. Consider the degree to which targeted investments may be required to provide a higher probability of 5G coverage on underserved transport infrastructure.

There are a wide range of use cases that have been identified for 5G which broadly fall within ultrafast mobile broadband, massive machine communications, and ultra-reliable and low latency applications. Specific uses of 5G communications within these broad categories include accessing media everywhere, Connected and Autonomous Vehicles (CAVs), increased industrial automation, the Internet of Things, smart cities and e-health.

The analysis presented focuses purely on providing an estimate of the total cost of a non-virtualised 5G network for ultrafast mobile broadband.

Methodology

Considerable technical, economic and behavioural uncertainty is present as 5G is yet to be standardised, there are no market available 5G equipment costs, and we do not yet know the rollout strategies of Mobile Network Operators (MNOs).

In this analysis we consider the incremental delivery of the required capacity as it relates to future demand. The expected traffic demand is calculated based on the required user throughput and population density, assuming a broadband penetration of 100%.

The capacity expansion principles used in this analysis focus on firstly integrating new spectrum (at 700 MHz and at 3.4-3.6 GHz) into existing brownfield sites to meet traffic demand. If additional infrastructure capacity is required, remaining traffic is met by network densification enabled by small cell deployments operating initially at sub-6 GHz but which over the long-term may be utilising millimetre wave spectrum (~26 GHz).

The modelling methodology employed utilises a top-down approach whereby 9000 postcode sectors are segmented into seven geotypes based on population density, as this relates to expected demand. We then dimension a network for these seven geotypes using site density and extrapolate existing 4G LTE and LTE-Advanced characteristics to 5G. The costings presented in the report are based on hypothetical network operators that may share traffic demand, spectrum, site locations and network infrastructure, depending on the scenario.

The total cost is also calculated for shared small cell deployments on transport infrastructure, with the results being reported nationally as well as being visualised at the local authority level.

Scenarios

Nine scenarios are considered in detail where per user speed is considered a proxy for network capacity. The baseline scenario (S1) (50 Mbps) focuses on the development of two networks shared by four operators using current equipment costs. We then explore the impact of a maximum infrastructure sharing scenario (S2) (50 Mbps) whereby a single network (consisting of macro and small cells) is shared by four operators. Due to uncertainty around the potential costs of equipment, we then analyse, in scenarios S3 (50 Mbps) and S4 (50 Mbps), the consequences when the cost of the Radio Access Network (RAN) is 20% lower (with no sharing) and 20% higher (with maximum infrastructure sharing), respectively. In scenario 5 (S5) (50 Mbps), we explore the cost impact of having infrastructure competition in urban and suburban areas, while having infrastructure sharing in only rural areas. In the sixth scenario (S6) the same parameters as the S1 baseline are utilised but for a speed of 30 Mbps per user. Similarly, in the seventh scenario (S7) the same market conditions as S1 are explored but with an end-user speed of 10 Mbps. In the eighth scenario (S8), we test 50 Mbps in all urban and suburban areas, but with only 10 Mbps in rural areas. Finally, we explore in S9 the implications of S1 market conditions but with infrastructure sharing only on the small cell layer.

Results

In every exploratory scenario, ubiquitous 50 Mbps per user coverage is expensive and unviable based on current revenues. However, the results are extremely useful to show how the costs aggregate. On average across the scenarios, the cost of delivering 50 Mbps to the urban population of Britain represented only 2% of the overall capex cost, therefore urban rollout is realistic. Delivery of 50 Mbps to the suburban population of Britain represented 19% of the overall capex cost and is also viable. The most expensive settlement type to deliver 50 Mbps to was rural areas, which on average represented 79% of capex. The very high costs of rolling out a ubiquitous 5G network capable of 50 Mbps result from the need to add a very dense ubiquitous layer of small cells. The density of required small cells is 37 per km^2 in the most populated urban locations. It is interesting to note that given the high capacity required for both the 50 Mbps and 30 Mbps per user speeds, upgrading existing macrocell sites to integrate new spectrum fails to meet traffic demand, requiring small cell deployment. Alternatively, newly integrated spectrum is enough to meet demand in some areas when targeting a 10 Mbps end-user speed.

Based on the cost model in this report, the total capex for delivering shared small cell deployments on A and B road infrastructure is £2.5 billion, with a ten year opex of £1.7 billion. As motorways comprise a much smaller proportion of the transport network, the total capex for deployment on this type of infrastructure is £150 million with a ten year opex of £103 million. Finally, the total capex potentially required for covering rail infrastructure is £547 million, with a ten year opex of £375 million.

One caveat to the cost estimates presented in this report is that technical innovation, including using Software Defined Networks (SDN) and Network Function Virtualisation (NFV) techniques, may deliver significant cost savings in 5G deployment, although the substantive details of how this may happen are less well understood at this time due to ongoing R&D.

Conclusion

The most notable finding in this research is the quantification of the required investment to reach different settlement patterns. Dense small cell deployments delivering 50 Mbps per user in all urban areas is potentially feasible as it represented only 2% of the capex cost of rollout in the baseline scenario. Coverage of this level in suburban locations is also potentially possible. Alternatively, achieving a 50 Mbps speed in rural areas is economically unviable under current conditions. In the baseline scenario rural areas constitute over two thirds of the capex cost for reaching less than a third of the population, therefore significantly lower per user speeds need to be explored for deployment in these areas.

The cost of infrastructure deployment is most sensitive to the degree of infrastructure sharing that takes place rather than the unit costs of RAN equipment. In many ways this is beneficial because the UK has less control over the global manufacturing costs of network equipment but government is able to make regulatory changes to encourage innovative business models that have improved economic viability.

Introduction

The UK has taken the decision to implement a 5G strategy to ensure the expedient delivery of new infrastructure by 2020. Since the emergence of 3G networks in the early 2000s, wireless broadband technologies have enabled a virtuous cycle between investments in mobile networks and fast growth in data service demand and traffic (Holma and Toskala, 2012; Ghosh and Ratasuk, 2011).

Currently, UK MNOs are investing approximately £2 billion per year to upgrade and expand cellular networks in order to meet demand by domestic and commercial customers (Real Wireless, 2015). Over the last decade, several factors have contributed to a cost-effective deployment of mobile broadband services, including new technologies with enhanced spectral efficiency, a more flexible architecture (LTE and beyond), and the allocation of additional spectrum. LTE coverage (provided by at least one operator) was around 90% of UK premises as of 2015, with 46% of premises having access to LTE from all operators (Ofcom, 2015). The deployment of dense heterogeneous mobile networks is ultimately an interplay of traffic demand, deployment costs, network capacity, population and geographical coverage, and power consumption (Ahmed et al. 2014; Lee and Huang, 2012; Zhang et al. 2015). Cost pressures are forcing innovation throughout the digital infrastructure industry; as a result, 5G networks are likely to be both multiservice and multitenant (Droste et al. 2016).

Different industrial, governmental and academic stakeholders are currently working together globally to develop the next generation of mobile networks. These networks will provide new types of mobile services, the delivery of which will require innovative business models to achieve economic viability given that operators are challenged simultaneously with increasing demand and costs, and falling revenues. The successful implementation of 5G will not only entail achieving much larger headline speeds for consumers. Overcoming coverage issues in urban, rural and remote locations will also be important in providing truly mobile data services required for CAVs. To achieve this and make all mobile end-use cases fully functional, we need to be able to provide a high probability of a consistent uninterrupted data connection on every road in the UK.

Infrastructure upgrades will first be rolled out to brownfield sites in the most densely populated areas, followed by the greenfield deployment of new cell sites. Areas with the highest demand will receive preferential deployment as they also offer the best return on investment. As these areas contain the most users, this is also the most efficient way of reaching the largest number of people. The pace at which 5G networks will cover the UK will depend on rollout costs for different geographical areas (mainly characterised through their population density). This rollout will be influenced by the capital intensity that mobile providers can devote to 5G investments and how cost effective different deployment strategies may be.

Research aims

This report assesses the rollout of 5G networks in a spatially disaggregated manner in order to identify those areas that have a high probability of receiving 5G infrastructure before others. The scheduled rollout of 5G will be influenced by the key population and geographic characteristics of local areas affecting data throughput. The pace of this rollout will depend on equipment costs, the business model employed (including the degree of infrastructure sharing) and the amount of newly available spectrum. The research will provide insight into the geographical heterogeneity of rollout across settlement patterns over time within British regions.

The four questions we seek to answer under a variety of rollout scenarios are:

1. What is the cumulative cost of rolling out 5G to different proportions of the population?
2. How much investment is required per region for total coverage, across all urban and rural areas?
3. How may 5G rollout be implemented spatially across Britain according to capital availability?
4. What is the estimated cost of targeted 5G investments for underserved transport infrastructure?

The deployment of 5G is likely at first to be part of an ongoing evolution of wireless networks, as backwards service compatibility to 4G is a key design principle (Hu, 2016). Given that cellular mobile systems are subject to a generation upgrade once every decade, 5G began as a dialogue within the research community regarding the successor to 4G. In reality it will be a number of years until we have a thorough understanding of what the 5G standard truly is, and how much network components may cost. In this report we do not attempt to quantify revenue and, instead, focus purely on estimating TCO, capex and opex for a non-virtualised 5G infrastructure. A set of exploratory scenarios is used to assess the potential investment costs required to rollout 5G infrastructure and provide a high coverage probability. Therefore, with regard to technology, this report is predicated on extrapolating 4G LTE and LTE-Advanced characteristics to the progressive deployment of 5G technologies.

In the following sections of this report, we undertake a literature review and present a methodology to understand the rollout of 5G infrastructure across Britain. The results are then reported and discussed, and appropriate conclusions drawn.

Literature review

This review explores how 5G is currently being defined, the potential economic impact and likely key use cases. We also review the state-of-the-art in mobile cost modelling methodologies along with spectrum choice as a driver for 5G.

A number of different visions for 5G have been outlined by different research groups and these have ranged from 5G as a new form of radio access technology (for example, utilising millimetre wave spectrum), to a more holistic ecosystem that includes everything from the Internet of Things (IoT) to multi-Gbps hot spots. It is not yet clear whether 5G may simply be an incremental development of 4G. It is likely to integrate any new air interface and spectrum with pre-existing LTE and Wi-Fi to provide universal high-rate coverage with a seamless user experience (Galinina et al. 2015). A considerable number of papers have hypothesised the key characteristics of 5G networks and their potential capabilities (e.g. Rost et al. 2016, Akyildiz et al. 2016), as discussed in depth later in relation to 5G use cases. Chih-Lin et al. (2016) outline key performance indicators (KPIs) that encompass peak data rates, through to latency and mobility capabilities (see Table 1).

Table 1 KPIs for 5G networks (Chih-Lin et al. 2016)

KPI items	**KPI for 5G networks**	**Definitions**
Peak data rate	≥10 Gbps	Maximum achievable data rate by user
Minimum guaranteed user data rate	≥100 Mbps	Minimum experience data rate by user
Connection density	1 million connections km^{-2}	Number of connected devices per unit area
Traffic density	≥10 Tbps km^{-2}	Total network throughput per unit area
Radio latency	≥1 ms	Duration between a packet being available at the IP layer in a basestation and the availability of this packet at the IP layer in a terminal
End-to-end latency	Millisecond level	Duration between transmitting a data packet from source node and successfully receiving it at the destination node
Mobility	Up to 500 km h^{-1}	Relative velocity between the receiver and transmitter

As a consequence of this holistic view, the digital communications industry is moving to an even more heterogeneous technology environment (Rong et al. 2016), consisting of a complex adaptive, multi-layered network of overlapping macrocells, remote radio heads (RRHs) and low powered small cells and relays that supply digital connectivity for all devices (smartphones, cars, drones, buildings, infrastructure and all IoT applications) (López-Pérez et al. 2011; Hossain and Hasan, 2015). 5G is therefore not necessarily a single technology but a collection of technology types that incorporate all previous generations of cellular mobile systems along with Wi-Fi, while utilising existing fixed networks for wireless access and backhaul. A key concept of this future is the principle of Anything as a Service (Xaas), where everything, from spectrum to infrastructure to high-performance computing, will be available as a service (Soldani et al. 2015; Taleb et al. 2016).

Network densification and millimetre wave (mmW)

Network densification is the dominant theme of wireless evolution towards 5G (Bhushan et al. 2014; Zhu et al. 2016), especially as high 5G frequency bands with poorer propagation characteristics become more integrated (Thurfjell et al. 2015). Hence, this densification is a consequence of the choice of frequency band enabling a tremendous increase in capacity over the covered area. The drastic reduction in interference to signal power leads to increased spectral efficiency due to the high gain beamforming (Baldemair et al. 2015). Ultimately, interference is a key issue, as identified in Andrews et al. (2014) whereby Larew et al. (2013) show that, in a plausible grid-based urban deployment, the basestation count could be increased in a given area from 36 to 96, decreasing the inter-basestation distance from 170 meters to 85. This increased the cell-edge rate to 1.3 Gbps from 25 Mbps.

As more basestations are delivered and the network becomes increasingly dense in order to meet demand, in practice, the placement of basestations becomes a geographical constraint. This scenario was explored by Gruber (2016) who evaluated this scalability issue by simulating how user distribution, street width and the beam width of the antenna affect maximum average user throughput.

Access points cannot be placed easily in very densely populated pedestrian streets, and must therefore be positioned on walls abutting these areas.

Fund et al. (2016) undertook an economic analysis of spectrum and infrastructure sharing in millimetre wave cellular networks, concluding that 'open' deployments of neutral small cells serving subscribers of any service provider encourage market entry by making it easier for networks to get closer to critical mass.

Moreover, the costs of deployment may be shared. Domestic and commercial customers may install small cells in their own premises, leaving operators responsible for only locating deployments in outdoor hotspots (Kamel et al. 2016). Many of these small cells may utilise existing DSL or cable infrastructure for backhauling, reducing the need for additional expense.

Comparative analysis by Nguyen and Sun (2015) showed that small-cell densification is favourable in crowded areas with moderate to high user density, whereas MIMO performs better in low user density areas. When energy efficiency is the key performance metric, small-cell systems outperform M-MIMO.

Over 90% of the allocated radio spectrum falls in the millimetre wave band between 30-300 GHz (Rangan et al. 2014). Hence, millimetre wave transmissions are expected to overlay the incumbent microwave (μW) architecture in the forthcoming 5G cellular network.

Although mmW signals experience orders-of-magnitude more pathloss than the microwave signals currently used in most wireless systems (El Ayach, 2014), it has the potential to offer multi-gigabit-per-second data rates at a lower cost than previous technologies (Murdock et al. 2012).

Real-world measurements at 28 GHz and 73 GHz in New York City, USA, have found that even in non-line of sight positions, strong signals can still be detected 100-200m from potential cell sites (Akdeniz et al. 2014). Reflections and scattering make mmW potentially viable at this distance, even in non-line of sight (NLOS) settings (Rangan et al. 2014).

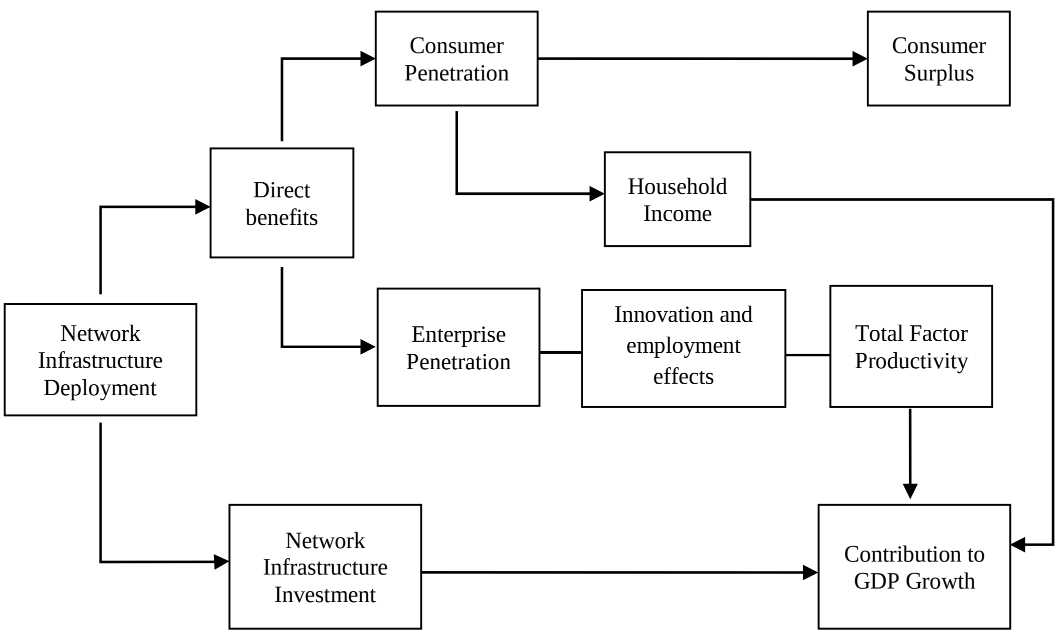
The economic impact of digital communication infrastructure

ICT and digital communications have played a key role in global economic growth in recent decades, especially in advanced nations (Jorgenson and Vu, 2016; Jorgenson et al. 2016). Recent evidence suggests that firms with higher mobile internet access have improved labour productivity, something of particular concern for the UK economy, given the so-called ‘productivity paradox’ of rising employment meeting falling output (Howard-Jones and Hassani, 2015). Across OECD countries, the rollout of fixed broadband infrastructure has been found to have a positive economic impact (Koutroumpis, 2011; Kolko, 2012; Fornefeld et al. 2008), much like the wave of fixed voice telephony that preceded it (Röller and Waverman, 2001). Policy makers have to make tough decisions regarding the degree of coverage and capacity of new digital communications infrastructure, given certain investment constraints. Economic benefits in digital communications are not necessarily gained directly from giving huge capacity to only a proportion of the population. In fact, the network externality benefits that can accrue often arise from instead providing a moderate but ubiquitous service, which provides reliability for new digital content, applications and services. Indeed, some industry commentators have consequently questioned the multi-billion dollar subsidies given to rolling out increasingly high capacity digital infrastructure around the world (Kenny and Kenny, 2011).

Although causality is a perennial problem in attempting to assess the economic impact of infrastructure, empirical time-series analysis of OECD countries by Égert et al. (2009) generally shows positive effects, particularly from investment in digital communications. Importantly however, the returns from infrastructure are highly non-linear and in some cases over investment in infrastructure does take place. In a European analysis, Gruber et al. (2014) find that the accrued benefits from increased broadband access do indeed outweigh the investment costs, but these benefits are not fully captured by the private enterprise making the initial investment, hence the disparities in provision.

Katz and Berry (2014) state that the economic effects of digital communications take place via a number of major pathways. Firstly, like all infrastructure systems, construction effects arise from investment in planning, designing, and building physical assets. Additional job creation from this network deployment leads to multiplier effects which ripple through the economy. Secondly, there are positive externalities which arise for both businesses and consumers, particularly in terms of time-savings and efficiency, leading to improvements in total factor productivity. Thirdly, augmented use by consumers has been found to increase real household income, as well as produce a consumer surplus. Figure 1 illustrates these four concepts, which focus on investment in network infrastructure, and business and consumer effects.

Figure 1 The economic impact of digital communications (Adapted from Katz and Berry, 2014)



According to Czernich et al. (2011) a 10 percentage point increase in broadband penetration led to annual per capita growth of 0.9-1.5 percentage points for a panel of OECD countries between 1996 and 2007. Moreover, a meta-review of the ICT and productivity literature, Cardona et al. (2013) concluded that the majority of studies indicate that the productivity effect of ICT on firms is indeed positive and significant. Previous work finds that a 10% increase in ICT investment leads to a 0.6%

increase in growth on average (Ibid.). The North American case seems more positive than the European experience, however, where aggregate and sectoral accounting methods are used to analyse this phenomenon, although this difference disappears when firm-level data are examined (Ibid.).

Colombo et al. (2013) found that SMEs adopting broadband services needed to undertake complementary strategic and organisational change to achieve productivity benefits, and the gains were dependent on the economic sector and relevance of the new services to their activities. Some researchers have found that mobile broadband has a significantly larger economic impact than fixed broadband (Thompson and Garbacz, 2011). With these results in mind, however, it is worth reminding ourselves that digital communications are a *necessary but not sufficient* factor in economic growth and development. The provision and adoption of digital communications must be combined with adequate human capital (including key technological and economic competencies). Only when this human knowledge leads to actual routine change in firms, motivating investment in more efficient digital services, is it sufficiently aggregated to create a positive and measured economic effect (Colombo et al. 2013).

An overview of potential 5G use cases

There has been a flurry of recent publications attempting to outline and, in some cases, quantify the key use cases of 5G as a starting point upon which to develop key technical specifications (see 5G NORMA, 2015; Tullberg et al. 2016; Mavromoustakis et al. 2016; Hu, 2016). Through the ongoing standardisation of 5G, there have been three key areas of use that have been identified that include providing (i) enhanced mobile broadband, (ii) massive machine-type communications (MMTC), and (iii) ultra-reliable and low latency communications. Whereas the first two key use cases are further developments of technologies that have already achieved success at market, reliability and latency characteristics could arguably be *properties* of a type of 5G network. The need for each of these areas will now be discussed in turn.

Providing ubiquitous 50 Mbps coverage of broadband has been identified as one important target. Current consumer mobile broadband services enabled by 3G and 4G still struggle to meet demand, particularly in very densely populated areas such as city centres, transport hubs, stadia and business districts. Demand for these services is not constant as it reflects commuting patterns, working hours or specific events that may be taking place. During ‘spikes’ in demand, data throughput constraints lead to contention over the access network, lowering the functionality and satisfaction of the end-user experience. A primary use for 5G will be to enable the smoother operation of existing online content, applications and services during these demand ‘spikes’. Moreover, the provision of this additional capacity will enable the delivery of completely new types of innovative content, applications and services that can provide opportunity for employment and value-added output to the economy.

When considering consumer mobile broadband services and how they may change with the delivery of 5G, we must consider in detail the proliferation of high-quality video content and its consumption across a variety of devices within the digital ecosystem. Particularly as High Definition (HD) video becomes the standard, there is an expectation that users can download, record and share video of HD quality across all mobile device platforms, driving demand for bandwidth and further traffic flow across the network. The current cost profile for delivering the needed capacity via existing 3G/4G technologies is also unviable in some low density locations. One potential impact resulting from the introduction of 5G, however, is that new technologies may be more conducive to providing greater coverage and capacity in hard-to-reach locations in the UK at lower cost, even if additional initial investment for deployment is required. Table 2 outlines the key technical requirements for a summary of 5G use cases.

Table 2 Summary of main technical requirements for 5G use cases (Tullberg et al. 2016)

Use case	Requirements	Desired value
Autonomous vehicle control	Latency	5 ms
	Availability	99.999%
	Reliability	99.999%
Emergency communication	Availability	99.9% victim discovery rate
	Energy efficiency	1 week battery life
Factory cell automation	Latency	<1 ms
	Reliability	Packet loss < 10^{-9}
High-speed train	Traffic volume density	100 Gbps/km^2 in DL, 50 Gbps/km2 in UL
	Experienced user throughput	50 Mbps DL, 25 Mbps UL
	Mobility	500 km/h
	Latency	10 ms
Large outdoor event	Experienced user throughput	30 Mbps
	Traffic volume density	900 Gbps/km^2
	Connection density	4 subscribers per m^2
	Reliability	Outage probability < 1%
Massive amount of geographically spread devices	Connection density	1,000,000 devices per km^2
	Availability	99.9% coverage
	Energy efficiency	10 year battery life
Media on demand	Experienced user throughput	15 Mbps
	Latency	5 s (start application), 200 ms (after possible link interruptions)
	Connection density	4000 devices per km^2
	Traffic volume density	60 Gbps/km^2
	Availability	95% coverage
Remote surgery and examination	Latency	Down to below 1 ms
	Reliability	99.999%
Shopping mall	Experienced user throughput	300 Mbps in DL, 60 Mbps in UL
	Availability	At least 95% for all applications and 99% for safety-related applications
	Reliability	At least 95% for all applications and 99% for safety-related applications
Smart city	Experienced user throughput	300 Mbps DL, 60 Mbps UL
	Traffic volume density	700 Gbps/km^2
	Connection density	200 00 users per km^2
Stadium	Experienced user throughput	0.3-20 Mbps
	Traffic volume density	0.1-10 Mbps/m^2
Teleprotection in smart grid network	Latency	8 ms
	Reliability	100.00%
Traffic jam	Traffic volume density	480 Gbps/km^2
	Experienced user throughput	100 Mbps in DL, 20 Mbps in UL
	Availability	95%
Virtual and augmented reality	Experienced user throughput	4-28 Gbps
	Latency	10 ms RTT

In terms of massive machine communications, this area is less about servicing the demand for information access and more about the consolidation of Machine to Machine (M2M), Device to

Device (D2D) or Vehicle to Vehicle (V2V) communication via a single enabling infrastructure such as 5G. This use case captures the rapid increase in the number of connected devices that we will see on an unprecedented scale in the coming years via the IoT (Mavromoustakis et al. 2016; Palattelea et al. 2016). Many of these devices will be low-cost, highly-specialised sensors transmitting relatively small data volumes. Some of these sensors may not be in constant use and may, therefore, be dormant between intermittently transmitting information, requiring them to be highly energy efficient with very long battery life. For example, in smart cities we will see an increasing number of infrastructure assets being embedded with digital sensors allowing data collection across transportation, energy, water and waste management. More data-intensive applications may also include those appliances within smart buildings and smart homes that will be fully Internet-enabled, providing remotely programmable access and control. Cost efficient ICT infrastructures will be critical for enabling smart grid infrastructure (Dorsh et al. 2015). The use of 5G when travelling on high-speed trains will be a particularly challenging task as reliability is impeded by speed of travel, load and cell distance (Erman and Yiu, 2016).

The final area concerns those uses that require the ultra-reliable and low latency communications required, for example, for the operation of CAVs or the management and control of mission-critical assets in the utilities industry. These 5G communications services need to have very high levels of coverage (99.999% availability), and very low latency, enabling their use in the control of critical infrastructure. The delivery of these services to market to enable CAVs is of critical importance for the automotive industry, as it will encourage deployment and uptake, which has an estimated value of £51 billion per year to the UK economy by 2030 (KPMG, 2015).

Cost modelling of digital communications infrastructure

Cost modelling is an approach that allows one to compare the difference between data traffic demands and network deployment costs for different future deployment scenarios (Katsigiannis and Smura, 2015; Nikolikj and Janevski, 2014).

Bouras et al. (2016) found that the cost of dense infrastructure deployments of 5G depend heavily on the throughput density, periodic interest rate, and basestation cost. The reduction of these costs is, thus, necessary for effective, ultra-dense small cell deployments. Interestingly, additional equipment, power and backhauling have a minimal impact on cost despite being fundamental for network functionality.

Small cell deployments have been found to be the most cost efficient way to meet large demand for data rates when the alternative option is building more macrocells (Markendahl and Mäkitalo, 2010).

Infrastructure sharing is one way in which the costs of deploying network upgrades can be reduced. Analysis by Ovando et al. (2015) of LTE rollout in rural areas shows that passive infrastructure sharing does not necessarily constitute a single-cost solution for meeting required coverage obligations in low population density areas, but sharing a single network does begin to make deployment more feasible for operators.

Recent cost modelling of 5G has examined the implications of SDNs with NFV. While still at a nascent stage of development, Bouras et al. (2016) calculate the implications of an evolved core and RAN for a 5G network concluding that the results verify and even exceed the ambitious predictions for cost savings. In particular, significant infrastructure cost reduction was found in the implementation of virtualisation where opex was reduced by 63% and capex by 68% in comparison to traditional scenarios.

Nikolikj and Janevski (2014) made one of the first implementations of a cost modelled heterogeneous network with 28 GHz integration, whereby small cell solutions such as pico cells with mmW systems were deployed in areas of high demand. Firstly, the aggregation of 700 MHz and 2.6 GHz, having been integrated on existing sites, proved the most cost efficient in moderate demand levels. Small cell deployments indoors were the most cost efficient in high demand due to the ability to deliver significant capacity.

Considering improved spectral efficiency for 5G technologies, Nikolikj and Janevski (2015) determine cost efficient capacity expansion strategies for MNOs by specifically relating production cost by transferred data to revenues. They conclude that one solution to ensure the sustainability of outdoor connectivity is the use of mmW small cells, along with IEEE 802.11ac. The cost of infrastructure is most sensitive to the unit cost per macro and micro basestation, and necessary capacity and coverage of the 5G network.

Spectrum choice as a driver for the type of 5G infrastructure

The Radio Spectrum Policy Group (RSPG) that advises the EU on spectrum matters has issued a draft opinion that identifies three 5G pioneer bands: 700 MHz, 3.4-3.6 GHz and 26 GHz. Which of these three bands is employed in a 5G network has a profound implication on the characteristics of the resulting infrastructure. Each of the spectrum choices has been chosen to be ideal for a different direction of providing a leap in performance over today's mobile network infrastructure. Data speeds are a proxy for access capacity:

1. 700 MHz is outstanding for extending coverage, reach (inside/around buildings) and reliability. But its capacity is constrained by the bandwidth available. It is the only band of the three capable of delivering national coverage.
2. 3.4-3.8 GHz is outstanding for delivering Gbps data speeds to mobile users and needs a Radio Frequency (RF) channel widths of at least 100 MHz. This wide RF channel bandwidth differentiates 5G in this spectrum range from a 4G world. Contiguous coverage will be provided by dense clusters of small cells moving to large cells towards the edge of coverage. Millions of indoor cells may also be feasible given means of controlling interference to outside cells. However, the expectation is that it will not be economically feasible to deliver Gbps data speeds to mobile users beyond urban areas.

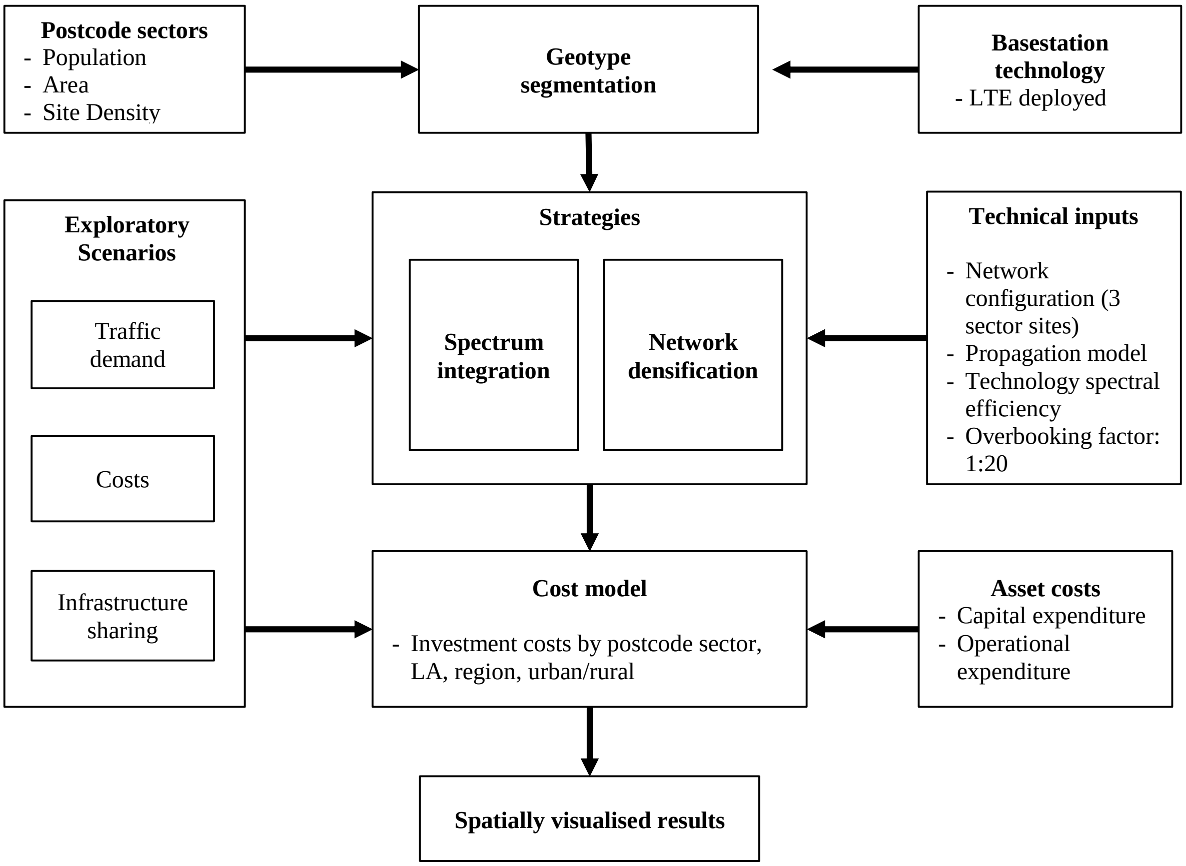
3. 26 GHz is outstanding for delivering 10 Gbps or more to fixed locations of very high footfall such as railways stations and stadia. It will serve nomadic rather than mobile users through tens of thousands of “hot spots”.

5G infrastructure is likely to be a "layered cake" of three new networks on top of the existing infrastructure - the three new networks providing an advance in fixed wireless capacity, mobile wireless capacity and mobile wireless coverage.

Methodology

We take an incremental deployment approach for 5G networks during the 2020-2030 period into examination. Prospective cost analysis on new generation technologies present inherent sources of uncertainty. This uncertainty can be (i) technological, due to the fact that standardisation is ongoing and future spectrum availability of specific bands is not guaranteed, (ii) economic, due to the costs of new equipment, and (iii) behavioural, as both MNO rollout strategies and consumer demand for 5G services are unknown. Despite this, costs assessments are required as technology development and standardisation take place, as they can provide valuable feedback on the viability of 5G R&D. Although high-level design principles are usually well known at that point, it is challenging to assess network performance and study detailed deployment needs for all business cases. Although equipment costs are unknown, future generations of network equipment with enhanced performance tend to be similar in price to those of previous systems (Johansson and Zander, 2007). Figure 2 outlines the sequence of the methodology.

Figure 2 Sequential methodology



In order to assess deployment costs across Britain, the approach used in this study groups areas that have similar cost characteristics together into specific geotypes. The key cost characteristics include population density and existing site density. Once these geotypes have been defined, network dimensioning is undertaken using the key parameters for each geotype segment.

Exploratory scenarios

A set of exploratory scenarios are used to demonstrate the potential costs of deployment, and how the rollout may take place under various potential futures. The uncertainty associated with key economic and regulatory changes are captured within the exploratory scenarios which focus on three areas assumed to be totally exogenous to the analysis: (i) *infrastructure sharing*, which takes place across all macro and small cell infrastructure, (ii) *RAN costs*, which represent an important proportion of the

TCO for rolling out 5G infrastructure, and (iii) *traffic demand* which reflects the expected required end-user speed. We select scenarios that provide the most useful insight into the key policy dimensions affecting 5G national infrastructure strategies, as outlined in Table 3.

Table 3 Scenario overview

	S1 (baseline)	S2	S3	S4	S5	S6	S7	S8	S9
Scenario summary	Baseline – 50 Mbps	Baseline with sharing	Higher costs with sharing	Lower costs, no sharing	S1 with sharing only in rural areas	30 Mbps target	10 Mbps target	S1 with 10 Mbps in rural areas	Shared small cell layer
Existing spectrum (MHz)	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*
New spectrum (MHz)	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600
Densification	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz
Infrastructure sharing	No	Yes	Yes	No	Only in rural areas	No	No	No	Shared small cells
Costs	Current costs	Current costs	Higher RAN costs (+20%)	Lower RAN costs (-20%)	Current costs	Current costs	Current costs	Current costs	Current costs

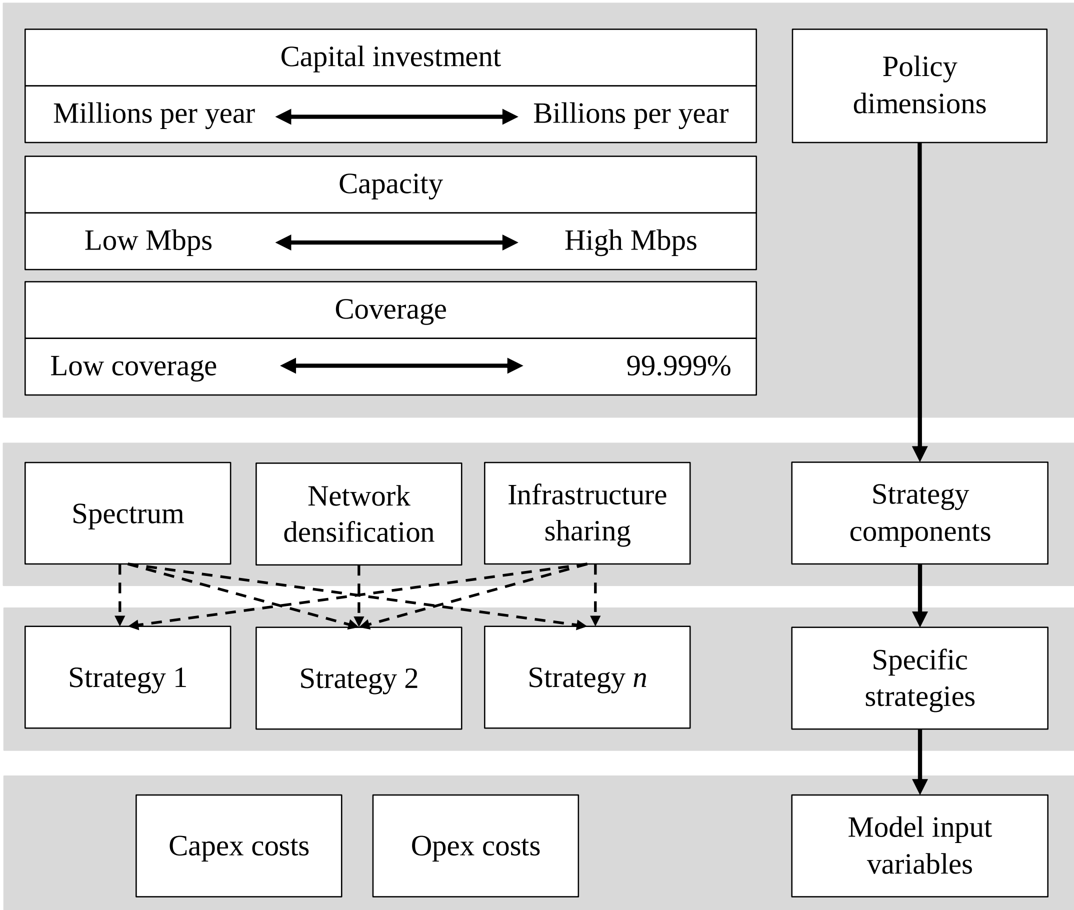
** 800 MHz and 2600 MHz bands are considered in use only in areas where there is 4G coverage.*

The degree to which operators may share 5G infrastructure is considered in this research and is assumed to function in a similar way to current network sharing agreements. Currently, there are partnerships between UK operators whereby O2/Telefonica and Vodafone share infrastructure assets via Cornerstone Telecommunications Infrastructure Limited and, equally, Three has a network sharing agreement on a proportion of EE's sites. This allows operators to increase coverage while decreasing deployment costs in areas of high demand. As the four MNOs are currently in network sharing arrangements, we assume the business-as-usual case where two operators share two networks (2x2), as well as a maximum infrastructure sharing scenario where all operators share one network (4x1). In the business-as-usual (2x2) scenario, each network takes an equal market share and thus half of traffic demand. In the maximum sharing scenarios (4x1), the single network serves 100% of traffic demand. To address costs, we test what happens when the RAN is 20% lower and 20% higher than current prices. Traffic demand is explored at 50 Mbps across the majority of scenarios, although we do explore the implications of a 30 Mbps (S6) and 10 Mbps (S7) traffic demand. As ubiquitous coverage of a single headline speed is unlikely, in scenario 8 (S8) 50 Mbps is delivered to urban and suburban areas, while only 10 Mbps is targeted in rural areas. Finally, we test a headline speed of 50 Mbps but with infrastructure sharing taking place only on the small cell layer, and not over macrosites (S9).

Strategies

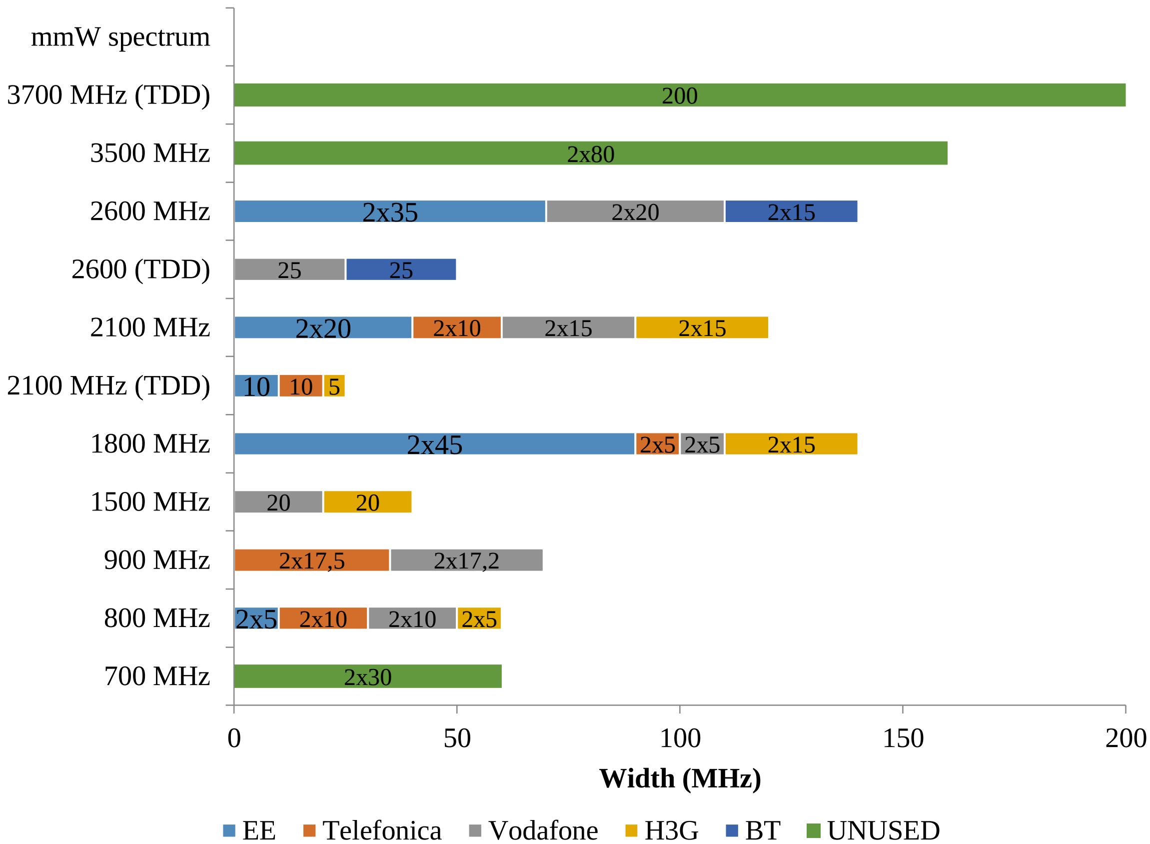
Different strategies are developed to meet the capacity required in the exploratory scenarios, as outlined in Figure 3. The deployment principles employed consider a brownfield-first approach to meet future demand as operators would preference existing assets and sites (especially passive infrastructure) to minimise costs. We assume that operators acquire new spectrum and upgrade their existing assets to provide new capacity where required. This upgrade may include only a new RF module and a software update in an LTE-A network, or a completely new small cell deployment in the event that the demand cannot be otherwise met.

Figure 3 Policy dimensions and consequential strategies employed



We consider three spectrum strategies for capacity expansion of current 4G networks to next generation 5G networks using (i) 700 MHz, (ii) 3400-3600 MHz, and (iii) 3600-3800 MHz. The justification for focusing on this spectrum is that these bands have been allocated to mobile communications systems and thus they are currently not being used by any other legacy system (i.e. 2G, 3G o 4G) (Ofcom, 2016). In addition, 700 MHz is the band with the best propagation characteristics among those currently allocated to mobile communication services. Thus, it has the potential to increase current geographical coverage of mobile broadband to rural and remote areas of the UK, particularly for mobility across national road and rail infrastructure, particularly if 800 MHz is not currently being utilised. This will be important for enabling total continuous coverage in 5G. Although 3.4-3.8 GHz has poorer propagation characteristics, it provides more spectrum allowing for additional capacity, particularly if coupled with new small cell deployments in areas of very high demand. In areas where 4G networks are currently unavailable, we integrate the existing underused 800 MHz and 2600 MHz spectrum first. Figure 4 outlines the current used and unused bands of spectrum held by MNOs.

Figure 4 Spectrum bands by operator



In addition, 900 MHz and 2100 MHz are excluded from the current analysis as 2G and 3G networks operate on that spectrum. Although a 'refarming' process might be expected in the long-term, at this point we do not have any evidence to suggest that these bands will be available for future rollout during the period examined in this study.

The bandwidth considered for each of the scenarios described above is shown in Table 4. To calculate the increased capacity each strategy can provide, we take into account all available spectrum in each frequency band. To calculate this for individual networks where we have no network sharing, we take into account the bandwidth available for each provider.

Table 4 Spectrum use by scenario

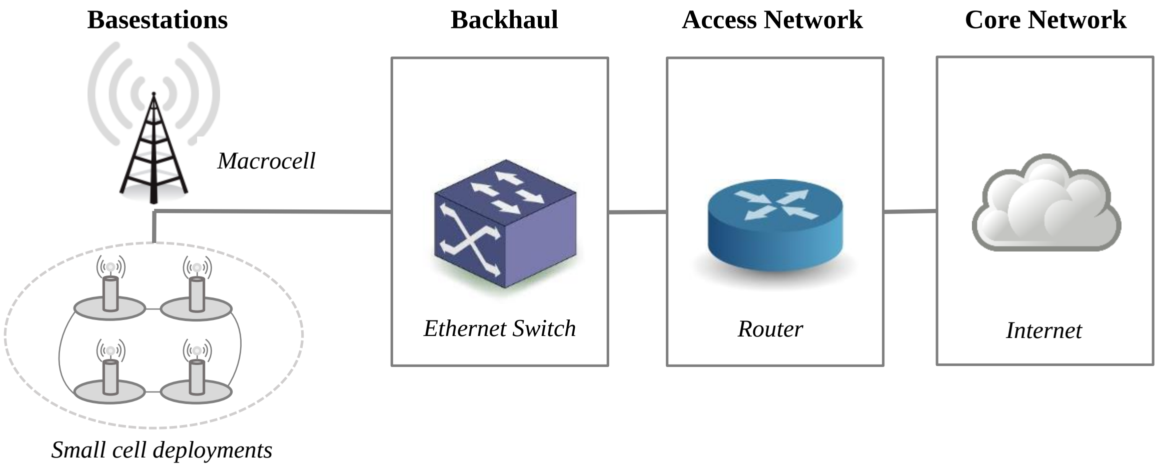
Scenario	Bandwidth for network dimensioning @ 700 MHz	Bandwidth for network dimensioning @ 3500 MHz (3400-3600 MHz)	Bandwidth for small cells @ 3700 MHz (3600-3800 MHz)	Bandwidth for macros where there is no 4G coverage
S2, S3, S5*,	2 x 30 MHz	2 x 80 MHz	200 MHz	2x 30 MHz @ 800 MHz 2 x 70 MHz @ 2600 MHz
S1, S4, S5*, S6, S7, S8	2 x 15 MHz	2x 40 MHz	100 MHz	2x 15 MHz @ 800 MHz 2 x 35 MHz @ 2600 MHz
S9	2x15 MHz	1x40 MHz	200 MHz	2x 15 MHz @ 800 MHz 2 x 35 MHz @ 2600 MHz

** Scenario 5 considers the spectrum configuration of scenario 1 (baseline, no sharing) for urban and suburban areas, while scenario 2 (maximum sharing) for rural areas*

Network architecture

We consider a standard network architecture with a RAN comprised of macro and small cells. Much like 4G, the 5G network architecture will be fully IP-based. The current 4G backhaul network will be reused whenever available and possible, but it is likely that backhaul capacity will need to be upgraded where the RAN delivers far more traffic than before. There is relatively limited information on the average length of backhaul, therefore we make assumptions about this length for different geotypes. We illustrate the network architecture in Figure 5.

Figure 5 Network architecture



The key differences in the network architecture are the degree to which brownfield and greenfield sites are utilised.

Geotypes

Postcode sectors have been selected as the unit of analysis as they reflect the costs of rolling out coverage in a spatially disaggregated way. Approximately 9000 postcode sectors are used in this analysis, covering England, Scotland and Wales. This geography has been used in other work for Ofcom, based on Long Run Incremental Costing (LRIC), such as the wholesale Mobile Call Termination (MCT) review model. Table 5 outlines the data sources used here.

Table 5 Data used in the model

Data Type	Source	Year
Postcode Sector Population - England and Wales	ONS Census Data	2011
Postcode Population - Scotland	ONS Census Data	2011
Area (km^2)	Ordinance Survey Codepoint Polygon Data	January 2015
Site locations	Sitefinder	2012

Population data was taken from the 2011 Census. The data was aggregated from the postcode to the postcode sector. England and Wales have more recent population estimates, but Scotland has not produced similar data for postcodes or postcode sectors in recent years, limiting the use of more current data. The area of each postcode sector was calculated by first removing all vertical postcodes, and then dissolving all polygons at the postcode sector level.

Sitefinder data was used as it is the only publicly available locational data on site positions. A form of ‘Big Data’ from OpenCellID was first analysed to try to obtain a more up-to-date picture of site locations and LTE coverage, however it was not deemed reliable or consistent enough for use here. To estimate the number of actual sites, basestations belonging only to the four major MNOs (EE, Vodafone, O2 and Three; EE’s data was obtained by combining T-Mobile and Orange) were imported into an open-source geographical information system. Sectored macrocells were selected and a buffer zone of 25 meters was added to all points. Intersecting buffer zones were dissolved to create one point for each site. This left 42,136 sites. As Sitefinder contains non-recent coverage information for sites where operators currently have equipment, we are unable to accurately model the rollout based on providing 5G coverage within a site-constrained environment. Consequently, we assume that any site is potentially able to be accessed and shared among all operators.

The seven geotypes used here are categorised based on a minimum population density according to the division presented in a report for the Broadband Stakeholder Group by Analysys Mason (2010), as detailed in Table 6.

Table 6 Geotype data characteristics

Geotype	Area (km^2)	Percentage of total area (%)	Population	Percentage of total population (%)	4G population coverage assumption (%)	Minimum population density (persons per km^2)	Site count	Average site density (sites per km^2)
1	460	0.2	5,127,859	8.3	100	7,959	2,880	6.26
2	4,051	1.7	18,171,212	29.5	100	3,119	8,348	2.06
3	12,371	5.3	20,165,440	32.7	100	782	11,657	0.94
4	46,463	20.0	12,358,847	20.0	100	112	10,212	0.22
5	52,039	22.4	3,830,419	6.2	90.3	47	4,566	0.09
6	33,271	14.3	1,196,409	1.9	80	25	1,873	0.06
7	83,460	36.0	794,688	1.3	80	0	2,197	0.03

The estimated population coverage for 4G is derived from assumptions made in the MCT 2015 model (Ofcom, 2015). Where 100% coverage exists, we expect that all sites have 4G. Where a proportion of the population is not covered by 4G, we expect that the same percentage of sites within that geotype require additional upgrading.

Cost model

In this section we provide an overview of the cost model considered in this report for a non-virtualised 5G infrastructure, whereby:

$$TCO_{5GNet_i} = Capex_{5GNet_i} + PV(Opex_{5GNet_i}) \quad 1$$

The Total Cost of Ownership for a 5G network deployment in area i (TCO_{5GNet_i}) in 2020 is defined as the summation of capital expenditure ($Capex_{5GNet_i}$) and the present value (PV) of operational expenditure ($Opex_{5GNet_i}$) within that area over a ten year period considering a Weighted Average Cost of Capital (WACC) of 5%. The capex component of the TCO is defined as:

$$Capex_{5GNet_i} = C_{Macro_i} + C_{Small\ cells_i} + C_{Backhaul_i} + C_{Core_i} \quad 2$$

where $Capex_{5GNet_i}$ consists of the sum of capex costs for all assets including brownfield macrocell upgrades (C_{Macro_i}), greenfield small cell deployments ($C_{Small\ Cells_i}$), fibre backhaul ($C_{Backhaul_i}$) and core upgrade costs (C_{Core_i}). The opex component of the TCO of the 5G network is defined as:

$$Opex_{5GNet_i} = O_{Macro_i} + O_{Small\ cells_i} + O_{Backhaul_i} \quad 3$$

where $Opex_{5GNet_i}$ consists of the sum of opex costs for all assets including macrocells (O_{Macro_i}), small cell deployments ($O_{Small\ Cells_i}$) and fibre backhaul ($O_{Backhaul_i}$).

The current capex and opex costs for key assets have been sourced predominantly from Ofcom's (2015) MCT model. These costs are broadly accurate and have been agreed upon by industry. We also use costs from 5G NORMA. Table 7 outlines the key cost assumptions.

Table 7 Capex and opex infrastructure costs

Strategy	LTE availability	Cost type	Capex (GBP)	Capex time trend	Opex (GBP)	Opex time trend	Source
Integrating spectrum into the macrocelluar network	Site with 4G LTE	Additional carrier on current BS	15,000	-3%	1,800	0	MTC 2015
	Site with no 4G LTE	Deploying a multicarrier BS	40,900	-3%	3,898	-5%	MTC 2015
		Site lease	-	0	5,000	3%	MTC 2015
		Civil works	18,000	0	-	3%	5G NORMA (2016)
		Fibre backhaul Urban: 1 km	20,000 per km	0	-	0	Provisional assumption
		Fibre backhaul Suburban 1: 2km, Suburban 2: 4km	20,000 per km	0	-	0	Provisional assumption
		Fibre backhaul Rural 1: 8km Rural 2: 10km, Rural 3: 20km, Rural 4: 30km	20,000 per km	0	-	0	Provisional assumption
Network densification through small cells		Small cell equipment	2500	-3%	350	-5%	5G NORMA (2016)
		Small cell civil works	13300	0	0	0	5G NORMA (2016)
		Small cell site rental	-	0	5,000	0	Provisional assumption
		Small cell backhaul	-	0	1,000	3%	5G NORMA (2016)
Core upgrade cost on all strategies			10% mark-up on RAN deployment cost	0	-	0	Provisional assumption

The cost modelling for the backhaul took inspiration from Mahloo et al. (2014). As shown elsewhere, the backhaul is an emerging new bottleneck for 5G networks with no single methodology providing the solution (Jaber et al. 2016). This problem does not only exist in terms of data capacity, as even the power consumption of backhaul has amounted to half of power consumption in a wireless access network (Tombaz et al, 2014). Initially, straight line measurements were taken from every postcode sector polygon centroid to the nearest telephone exchange, but this provided a lower than expected average backhaul length between 1-3km. In reality, the backhaul length would be longer because fixed fibre ends up following existing ducting routes via the road network. Hence, we made provisional assumptions about backhaul length. Moreover, within this analysis backhaul is only upgraded when 4G LTE is not present. Finally, a core upgrade cost is assumed to be an additional 10% of the RAN and backhaul capex.

Network dimensioning and related inputs

To identify the most cost-effective strategy for improving network performance according to the proposed cost model methodology, we need first to assess the extent to which each strategy can enhance that performance.

We consider a brownfield deployment and, therefore, we assume that new basestations will be allocated at existing sites whenever possible. Even if a site does not have available space for more equipment on the existing structure, it will be more efficient to erect a second tower and take advantage of existing power supply and backhaul than to build a new site from scratch.

For this reason, we assume that any strategy based on deploying new macrocells (either upgrading existing 4G equipment to multi-carrier capabilities or deploying a completely new 4G base station) will be carried out on existing sites to minimise cost. Thus, to calculate the network capacity performance of each strategy, we need to assess a number of key issues:

- Current Inter-Site Distance (ISD) as new macrocells are deployed on existing sties (obtained from spatially clustering co-located equipment using Sitefinder data)
- Recently allocated spectrum to mobile services, being currently unused, along with available bandwidth in each of the frequency bands considered (see Table 4)
- Spectral efficiency (Mbps/Hz) of the technology being deployed (LTE-A like)
- Key input parameters as stated in Table 8

Table 8 Network dimensioning parameters

Parameter	Value
Overbooking factor	1:50
Macrocell RAN architecture	Three-sector cells
Frequency reuse factor	1
Shadow fading log-normal distribution	(μ, σ) = (0 dB, σ)
Building penetration loss log-normal distribution	(μ, σ) = (12 dB, 6.5 dB)
Propagation model	SEAMCAT (2010)
% indoor users	50% urban and suburban 0% rural
Bandwidth	Depending on frequency band and sharing (see Table 4)

Spectral efficiency, or, the amount of information that can be transferred per Hz, depends on the Signal to Noise and Interference Ratio (SINR). To calculate the spectral efficiency, we first calculate the SINR distribution for a three-sector cell network according to typical network configuration. Network parameters related to transmitted power, antenna height and propagation are used following the 3GPP technical recommendations (3GPP, 2010). The propagation model used was developed in the SEAMCAT (2010) project and is ‘Hata Extended’, providing continuous modelling of signal path loss propagation in the range of 30 MHz – 3 GHz, helping to understand propagation performance of recently allocated high frequency spectrum. In addition, signals are considered to suffer losses because of two phenomena: slow fading or shadow fading (due to large obstacles), and building penetration losses. Both are modelled through log-normal distributions. Once the probability distribution of SINR for each carrier frequency has been obtained we convert this into a spectral efficiency distribution considering the results of Mogensen (2007).

Network capacity is calculated according to the bandwidth available at each carrier frequency (MHz) and the average spectral efficiency calculated in the former step. All three steps can be summarised as in equation 4:

$$\eta_{sector} = \int \eta\ (SINR) f(SINR)\ dSINR \qquad 4$$

For each carrier frequency (700 MHz, 800 MHz, 2600 MHz, 3500 MHz and 3700 MHz), the average network capacity is calculated based on the average spectral efficiency (Mbps/Hz) that the technology can provide according to the SINR probability distribution. The average sector throughput is easily calculated upon the bandwidth (Hz) available at the carrier frequency:

$$Throughput_{sector}{}^{f} = \eta_{sector}\ BW^{f} \qquad 5$$

Where $Throughput_{sector}{}^{f}$ is the throughput (Mbps) of one sector at frequency f, η_{sector} is the average spectral efficiency calculated as in equation 4, and BW^{f} is the bandwidth available at frequency f.

Considering three-sector cells:

$$Throughput_{cell}{}^{f} = 3\ Throughput_{sector}{}^{f} \qquad 6$$

The unserved demand not met via three-sector macrocells (Mbps/km^2) is routed through the small cell layer. To estimate the required number of small cells required, we consider LTE-like spectral efficiency, the bandwidth in Table 4 (100 MHz for non-sharing scenarios and 200 MHz for sharing scenarios), a DL/UL ratio of 75% over the TDD spectrum at 3700 MHz, and a maximum coverage of 200m.

Traffic demand

We consider the incremental delivery of the required capacity (Mbps/km^2) as it relates to future demand. We calculate traffic demand (Mbps/km^2) according to the:

- Increase in the required throughput per user (Mbps)
- Mobile broadband penetration (% nationally)
- Population density (users/km^2)

We firstly define key values of Mbps/km^2. This is therefore different in the sixth and seventh scenarios considered. When infrastructure sharing scenarios are undertaken, all providers have an equal market share and consequently take an equal share of the traffic demand.

Transport infrastructure analysis

An analysis of the cost of small cell rollout on transport infrastructure in Britain is undertaken. Ordinance Survey Open Road data is used to obtain the geographical structure of the road network. This is broken down into two types of road: (i) motorways, and (ii) A and B roads. All roads were intersected with the geography used by Ofcom which broadly covers 27 counties, 146 local authorities and the London city-region, giving 174 statistical units. Ordinance Survey Strategi is used to obtain the geographical structure of the rail network and the same analysis is carried out by intersecting the network with Ofcom's statistical geography.

The length of transport infrastructure in kilometres is obtained from each statistical unit and we then assume a similar network architecture and cost structure as in the nationwide analysis, with a few key exceptions. As small cells are deployed on a linear transport network we assume that rather than a 200m range, they operate in a directional way at a range of 500m, as higher antenna gains are possible in this case. Hence, two small cells are deployed every kilometre of infrastructure, each of them pointing in in opposite directions along the infrastructure asset. In terms of the cost structure, we assume that there would be no site rental for this deployment and that small cells could be deployed at the side of the road, motorway or rail track on existing structures. We still assume an operational cost for radio equipment along with a backhaul lease cost.

All newly deployed infrastructure is assumed to be shared by all operators. Based on the assumed technical dimensions of small cells we utilise the following:

$$Infrastructure\ Capex_{type} = Cell\ coverage \cdot Small\ cell_{Capex} \qquad 7$$

whereby $Infrastructure\ Capex_{type}$ represents the total capex for a specific type of infrastructure fully deployed in a single year based on current costs. Moreover, $Cell\ coverage$ represents the coverage of a single small cell, multiplied by the $Small\ cell_{Capex}$, representing the cost of the radio equipment and installation. Numbers are rounded to obtain the total number of individual small cell units.

Similarly, this is calculated for the total opex of this new deployment as follows:

$$Infrastructure\ Opex_{type} = Cell\ coverage \cdot Small\ cell_{Opex} \qquad 8$$

whereby $Infrastructure\ Opex_{type}$ represents the total present value (PV) of operational expenditure over a ten year period considering a Weighted Average Cost of Capital (WACC) of 5% for a specific type of infrastructure. $Cell\ coverage$ represents the coverage of a single small cell, and finally this is multiplied by the $Small\ cell_{Opex}$, representing the cost of operating the radio equipment and backhaul. Numbers are rounded to obtain the total number of individual small cell units.

Results

In this section, we report the results of this analysis, starting with the TCO for deployment of a high coverage probability 5G network in 2020. We will then present by scenario variant the cumulative investment costs, the total regional investment costs, the spatial rollout of 5G infrastructure, and, finally, the transport infrastructure analysis.

Table 10 recaps the potential future scenarios explored for the rollout of 5G and reports the aggregate costs broken down by capex, opex and TCO. In every exploratory scenario, ubiquitous 50 Mbps per user coverage is extremely expensive and unviable based on revenues. However, the results are extremely useful to show how the costs aggregate. On average across the scenarios, the cost of delivering 50 Mbps to the urban population of Britain (8.3% of the total population) represented only 2% of the total cost, therefore urban rollout is realistic. Delivery of 50 Mbps to the suburban population of Britain (62.2% of the total population) represented 19% of the total cost. The most expensive proportion of the population to deliver 50 Mbps to were rural areas (29.5% of the population), which on average represented 79% of the cost. The very high costs of rolling out a ubiquitous 5G network capable of 50 Mbps result from the need to add a very dense ubiquitous layer of small cells, as this capacity cannot be met purely via spectrum integration on macrocells.

The baseline scenario (S1), even with the integration of the 700 MHz, 3400-3600 MHz, and 3600-3800 MHz frequency bands, was still estimated to have a £42 billion capex based on 2020 costs. The ten year Net Present Value (NPV) opex cost for a ubiquitous network built in 2020 and operated for a decade was estimated to be £29 billion. These costs are high because two networks need to be built. Moreover, integrating new spectrum does not meet demand, requiring new small cell network deployments at densities up to 37 per km^2 in the most populated urban locations (e.g. central London). Like all infrastructure investments, these deployments require large fixed capital expenditure even if the assets are relatively underused once deployed.

In order to explore potential cost savings, the second scenario (S2) includes infrastructure sharing of all available macro sites and small cell deployments. With a capex of £22 billion, this provides a 48% cost saving by building a single network. A similar saving of 45% is made in opex as approximately half the number of assets are required for operating a ubiquitous 50 Mbps service. However, the exact business model for how this scenario could be realised in reality is still unknown.

Both scenario 3 and 4 explore the implications of cost differences in the RAN and how that would feed through to the degree of infrastructure sharing that takes place. In S3, the implications of RAN costs being 20% higher in 2020 is combined with infrastructure sharing, and there would be an increased probability of this scenario occurring in the face of even higher capex requirements. S3 was estimated to have a capex of £24 billion, with an accompanying ten year opex of £16 billion.

Table 10 Scenario overview with capex, opex and total costs

	S1	S2	S3	S4	S5	S6	S7	S8	S9
Scenario summary	Baseline – 50 Mbps	S1 with sharing	Higher costs with sharing	Lower costs, no sharing	S1 with sharing only in rural areas	30 Mbps target	10 Mbps target	S1 with 10 Mbps in rural areas	Shared small cell layer
Existing spectrum (MHz)	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*	800*, 900, 1500, 1800, 2100, 2600*
New spectrum (MHz)	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600	700, 3400-3600
Densification	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz	Small cell deployments at 3600-3800 MHz
Infrastructure sharing	No	Yes	Yes	No	Only in rural areas	No	No	No	Shared small cells
Costs	Current costs	Current costs	Higher RAN costs (+20%)	Lower RAN costs (-20%)	Current costs	Current costs	Current costs	Current costs	Current costs

Capex (£billion)	£42	£22	£24	£39	£24	£37	£12	£15	£27
Opex (£billion)	£29	£16	£16	£29	£17	£13	£8	£10	£20
TCO (£billion)	£71	£38	£40	£68	£41	£50	£20	£25	£47
Capex saving on S1	-	48%	43%	7%	43%	12%	71%	64%	36%
Opex saving on S1	-	45%	45%	0%	41%	55%	72%	66%	31%
TCO saving on S1	-	46%	44%	4%	42%	30%	72%	65%	34%

Capex - Urban (£billion)	£0.7	£0.4	£0.4	£0.7	£0.7	£0.4	£0.2	£0.7	£0.5
Capex - Suburban (£billion)	£5.6	£3.4	£3.7	£5.2	£5.6	£3.8	£3.3	£5.6	£3.8
Capex - Rural (£billion)	£35.6	£18.2	£19.8	£33.5	£17.8	£33.0	£8.6	£8.6	£23.1

If RAN costs decrease by 20% by 2020, operators may be more inclined to share less infrastructure with other competitors. S4 reflects this outcome. The capex of building two separate networks in S4 was estimated to be £39 billion, £3 billion less than the baseline S1, while the opex remained the same. The TCO is £68 billion.

As there are a number of benefits that competitive markets can provide, S5 reflects maintaining network competition in urban and suburban areas, but having a shared infrastructure only in rural areas. The capex for S5 is £24 billion, providing a significant cost saving of approximately 43% on the baseline scenario. The opex is estimated to be £17 billion along with an aggregate TCO of £41 billion.

The sixth scenario, S6, represents the same parameterisation as the S1 baseline but instead the target end-user speed is 30 Mbps. With a capex of £37 billion, this relates to a saving of approximately 12% on the S1 baseline. This scenario produced a large opex saving of £17 billion (55%) and had a TCO that was 30% less than S1 at £50 billion. The seventh scenario, S7, also explored the same baseline market conditions as S1 but with an end-user speed of 10 Mbps. This was a significantly cheaper option, with a TCO of only £20 billion, consisting of £12 billion capex and £8 billion opex. This is a saving on the TCO of 72%, but would provide significantly different end-user performance.

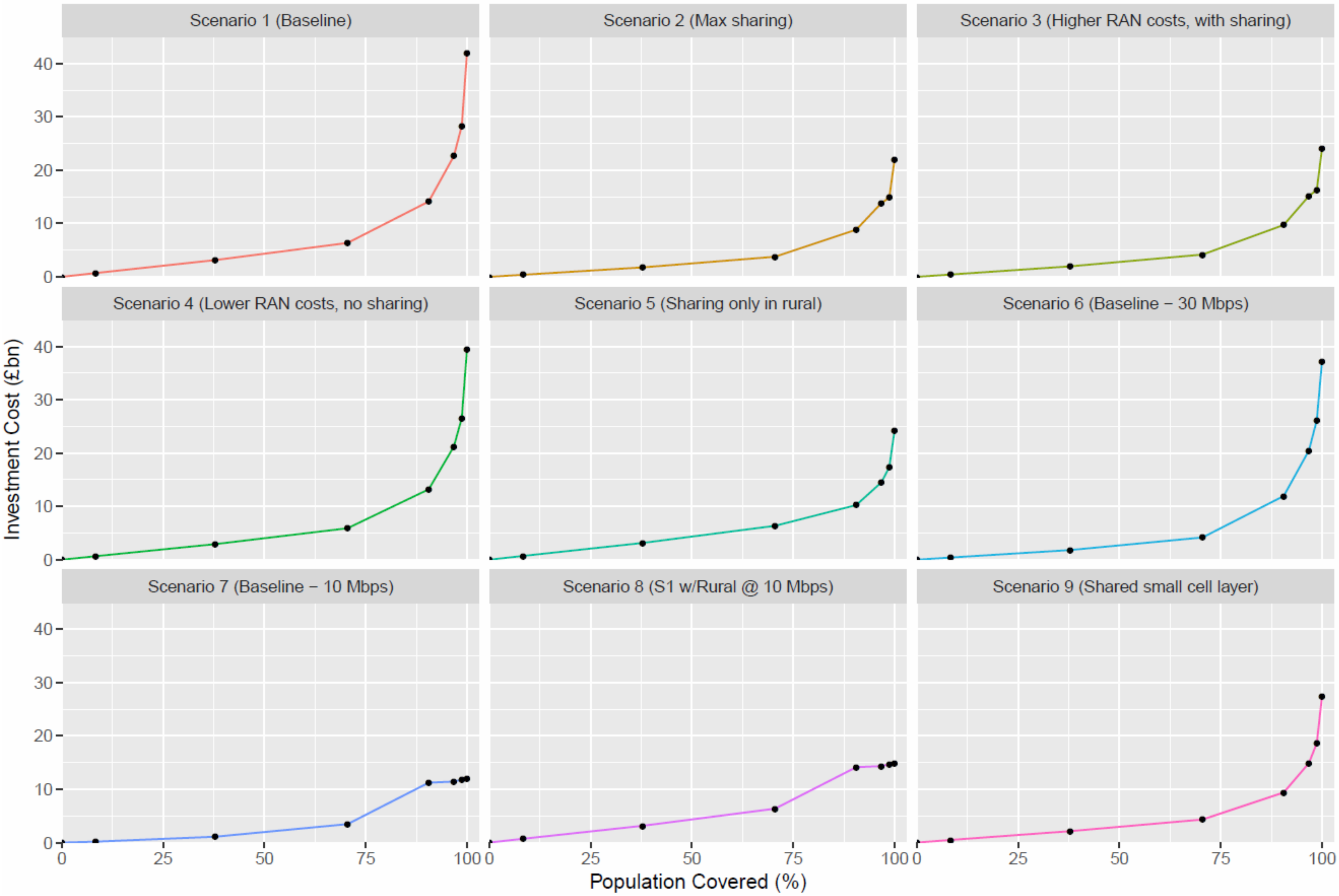
It may be more appropriate to compromise on capacity in rural areas where greater coverage is a higher priority. Therefore, the eighth scenario (S8) combines 50 Mbps in urban and suburban areas, while only delivering 10 Mbps in rural areas. The capex for this scenario is £15 billion, with a ten year opex for the network of £10 billion. The TCO is £25 billion overall, with a saving on S1 of 65%.

In the final scenario we consider two separate macrocell networks, but with a shared small cell layer. This produces a capex of £27 billion and a ten year opex of £20 billion. A TCO of £47 billion is obtained, providing a 34% saving on the S1 scenario.

Cumulative investment

The cumulative capex cost has been illustrated against the population covered in Figure 6. Aside from showing the differences in the aggregate total capex required to implement different end-user speeds ubiquitously, Figure 6 provides insight into the size of the required capex in order to meet different proportions of the population. Each section of the curve represents one of the seven geotypes explored. In S1, the first third of the population can be reached by approximately £3 billion and the second third of the population can be reached by another £3 billion of capex. The cost of the final third is considerable at roughly £35 billion.

Figure 6 Cumulative capex cost for each scenario by population covered



While S3 and S4 merely show the cost differences in the RAN equipment against the degree of sharing, S2 and S5 show some of the most interesting variations on the S1 baseline. The S2 scenario shows that with infrastructure sharing, the first two thirds of the population can be reached with approximately £4 billion – roughly two years of annual capex for the UK mobile communications industry. As S5 is a combination of building multiple networks in urban and suburban areas, and a single network in rural areas, the cumulative cost curve is a hybrid of S1 and S2. The most significant finding of S5 is that by sharing in rural areas the costs stay significantly lower compared to other scenarios, as the first 90% of the population can be reached with £9 billion of capex. This scenario should be explored further as a way of simultaneously managing required investment with the desire for increasing coverage.

In the sixth scenario (S6) the baseline is explored under the variant of delivering 30 Mbps ubiquitously. This scenario is approximately £2 billion cheaper than the S1 baseline for reaching the first 90% of the population. The last 10% is highly expensive, as even serving this proportion of the population with 30 Mbps is estimated to cost £25 billion. Delivering fixed superfast broadband (>30 Mbps) in these remote areas is considerably challenging and encounters similar exponentially increasing costs when reaching lower population densities.

Both the seventh and eighth scenarios (S7 and S8) produce different cost curves and do not exhibit exponentially increasing costs in reaching the final 10%. This is because the integration of new spectrum on existing macrocells is sufficient to meet end-user demand of 10 Mbps in rural areas where there is low population density. As spectrum costs are not included here, the costs of meeting this demand are minimal. In S7, the costs are negligible in urban and suburban areas as spectrum integration and existing network density is sufficient in meeting 10 Mbps per end-user. In S8, additional small cell deployment is required in urban and suburban areas to meet 50 Mbps, thus leading to higher cost.

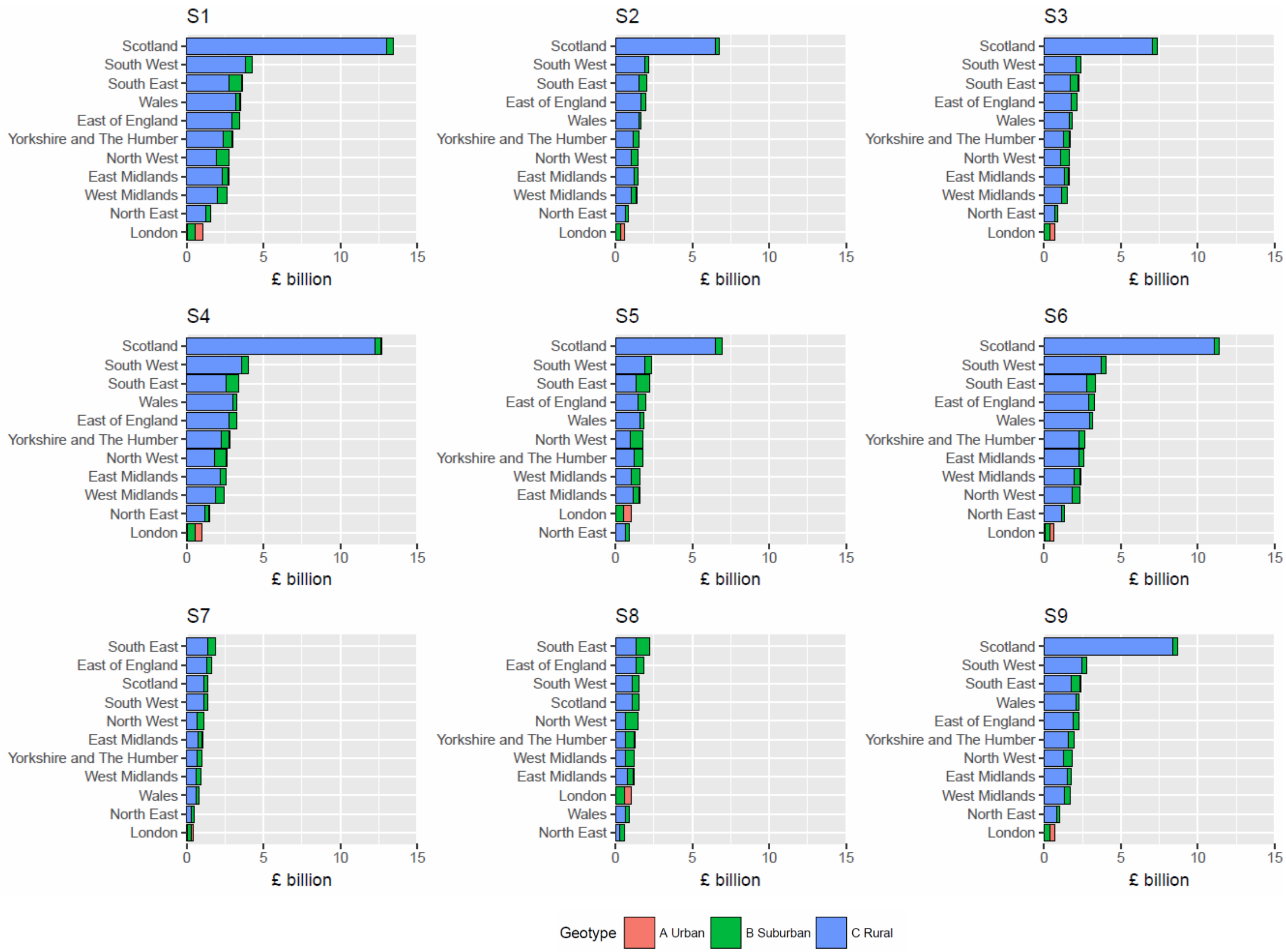
In the final scenario, S9, sharing only takes place on the new small cell layer that is added, which enables the first 90% of the population to be reached for only £9 billion. This scenario proves slightly more expensive that S2 (maximum sharing), but it is more probable as it allows operators to retain existing macro sites and only share small cell deployments.

Total regional investment

The total regional investment is a function of both population and geography. We illustrate these costs by scenario in Figure 7 for each urban, suburban and rural geotype.

Scotland is by far the most expensive region to cover with ultrafast broadband due to its large and remote landscape. Due to low population densities much of rural Scotland has very little existing 4G LTE coverage, having a major consequential impact on required 5G upgrade costs in scenarios targeting either 50 Mbps or 30 Mbps per user in rural areas. Total coverage of Scotland under S1 baseline conditions amounts to more than 60% of the capex we could expect the whole telecoms industry to invest in the Britain over the entire 2020-2030 period.

Figure 7 Total regional investment by scenario for urban rural geotypes



The South West and South East were the next most expensive regions. Whereas the South West is considerably rural, the South East is the most populated region in Britain, with much of this population spread across urban, suburban and rural settlement patterns. Although visible in the cumulative cost curves, viewing the breakdown of costs in this way for each geotype category emphasises how modest the investment would need to be to serve urban areas, thanks to the economies of scale of user density, and proximity to existing backhaul and core infrastructure.

The North East has the smallest population and therefore it is one of the cheapest regions to cover ubiquitously. In many scenarios, London is the cheapest region to cover as it has near-ubiquitous 4G LTE coverage and the existing network is considerably denser than other regions. In reality, London is a city-region and not a region in its own right as it has a very small amount of rural area within it, therefore benefiting from a high population density.

Spatial infrastructure rollout

Under each scenario explored we analysed the hypothetical spatial rollout across Britain. Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12 illustrate this and show that based on annual investment of £2 billion (i) infrastructure sharing, (ii) unit cost and (iii) the technical specification of the user throughput (e.g. speed) have a very large impact on the pace of rollout in terms of population coverage. In the S1 baseline (50 Mbps) rollout is slow and in the first year only predominantly urban areas receive 5G. By 2030 all urban and suburban populations receive access to 5G infrastructure, but only a proportion of the rural population is reached. This can be contrasted with S2, whereby urban and suburban populations have been covered within the first two years by 2022. By 2025 over 95% of the population is likely to be reached, which means that by 2030 approximately 99% of the population has been covered by 5G.

Figure 8 Rollout in S1 and S2 between 2020-2030

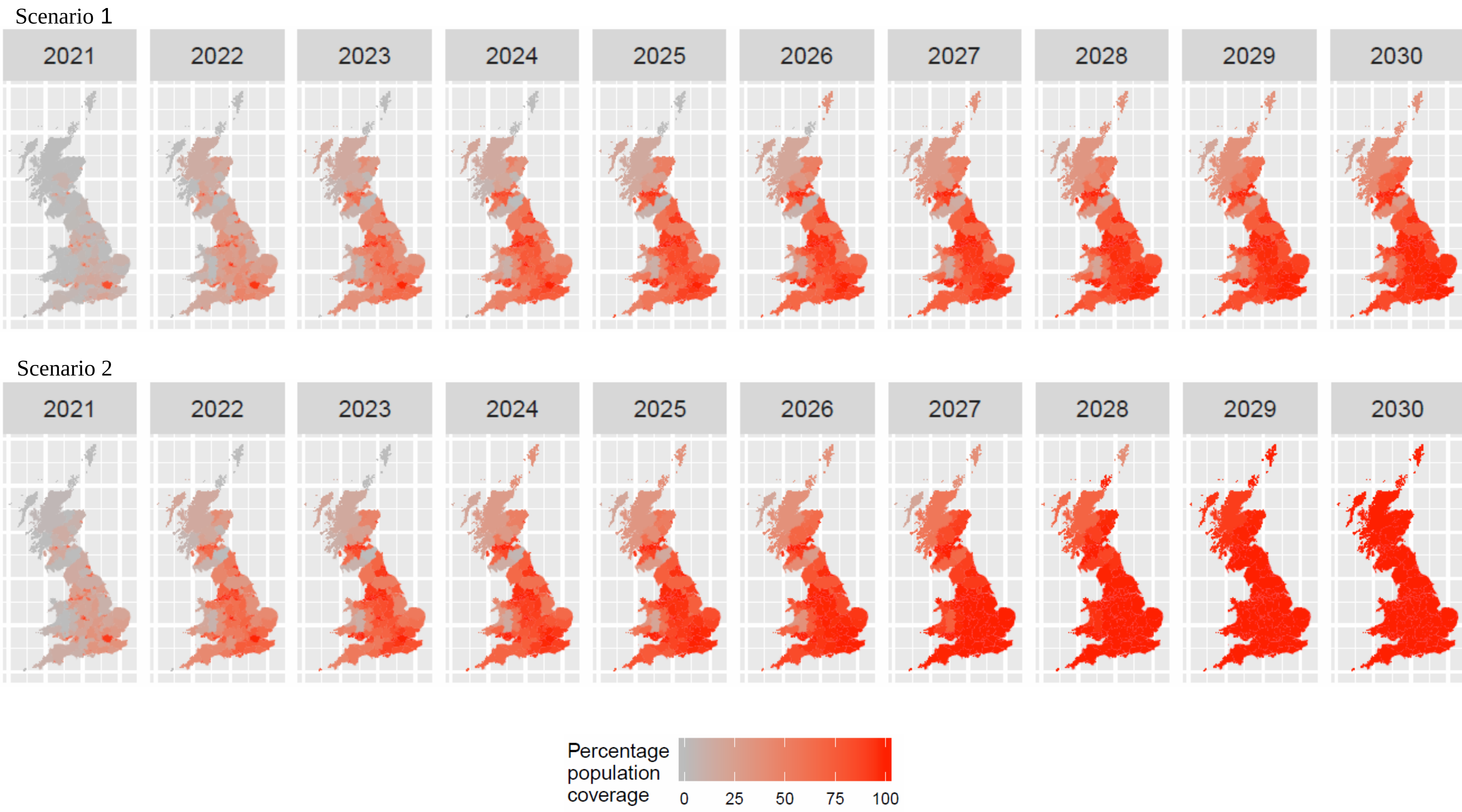


Figure 9 Rollout in S3 and S4 between 2020-2030

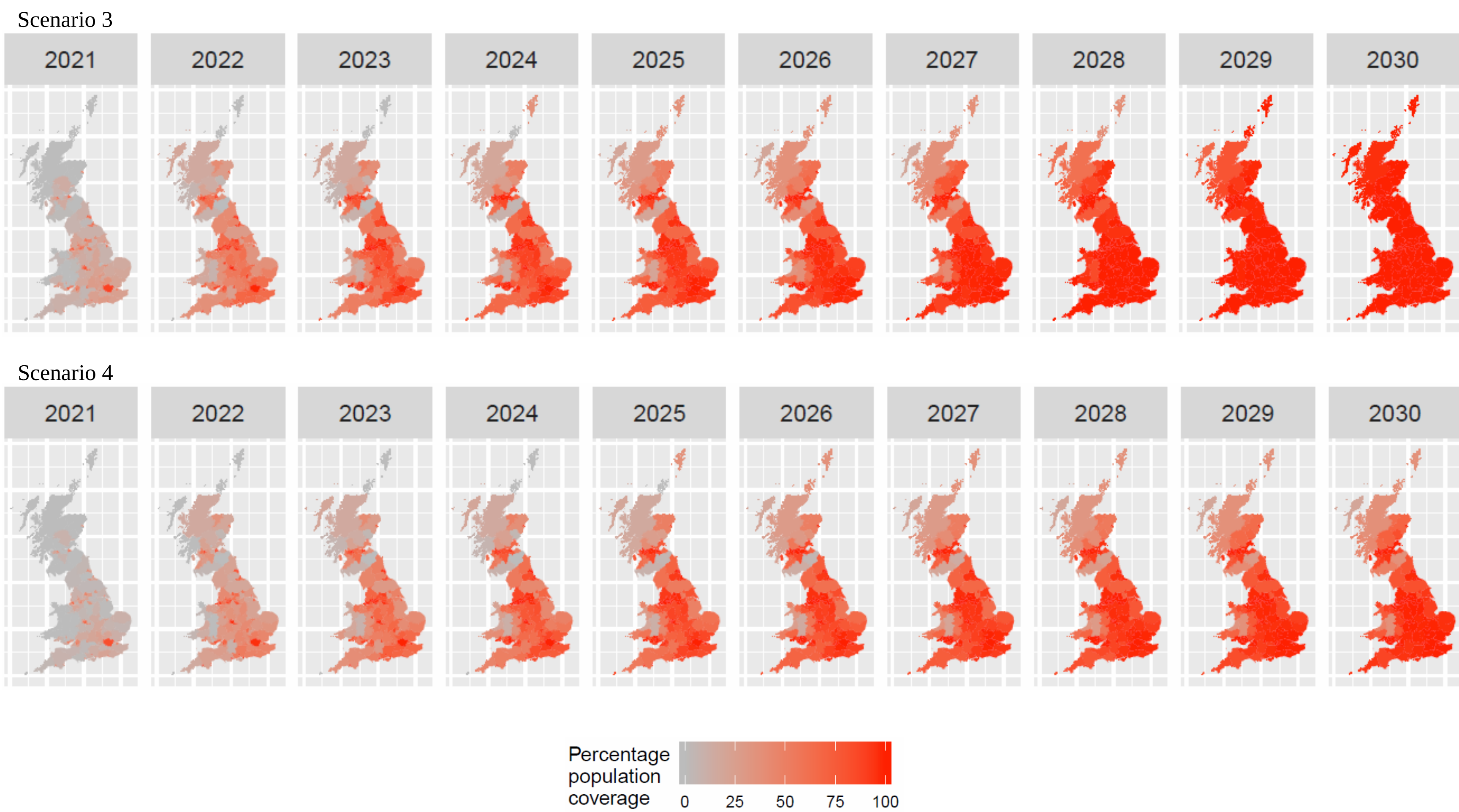


Figure 10 Rollout in S5 and S6 between 2020-2030

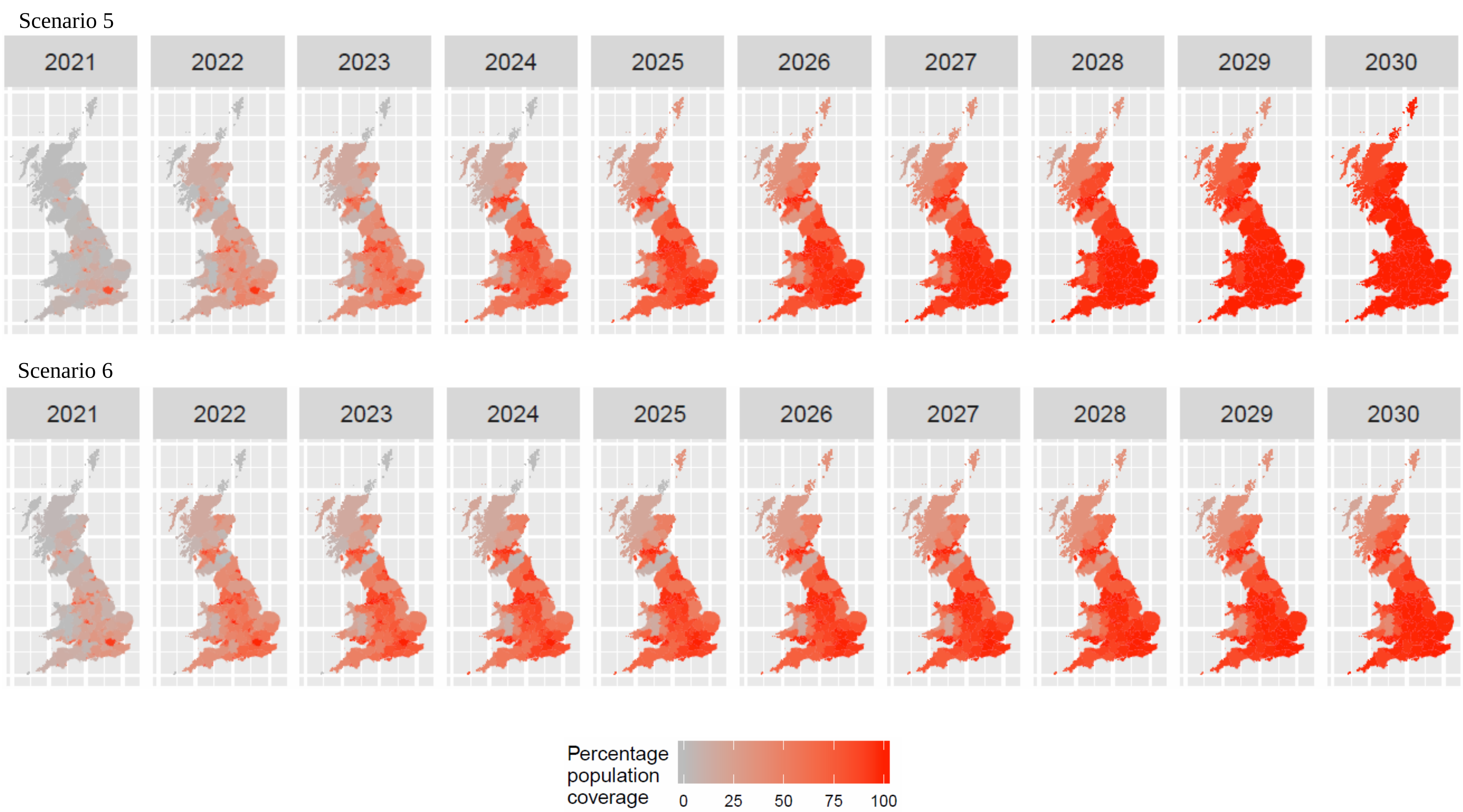


Figure 11 Rollout in S7 and S8 between 2020-2030

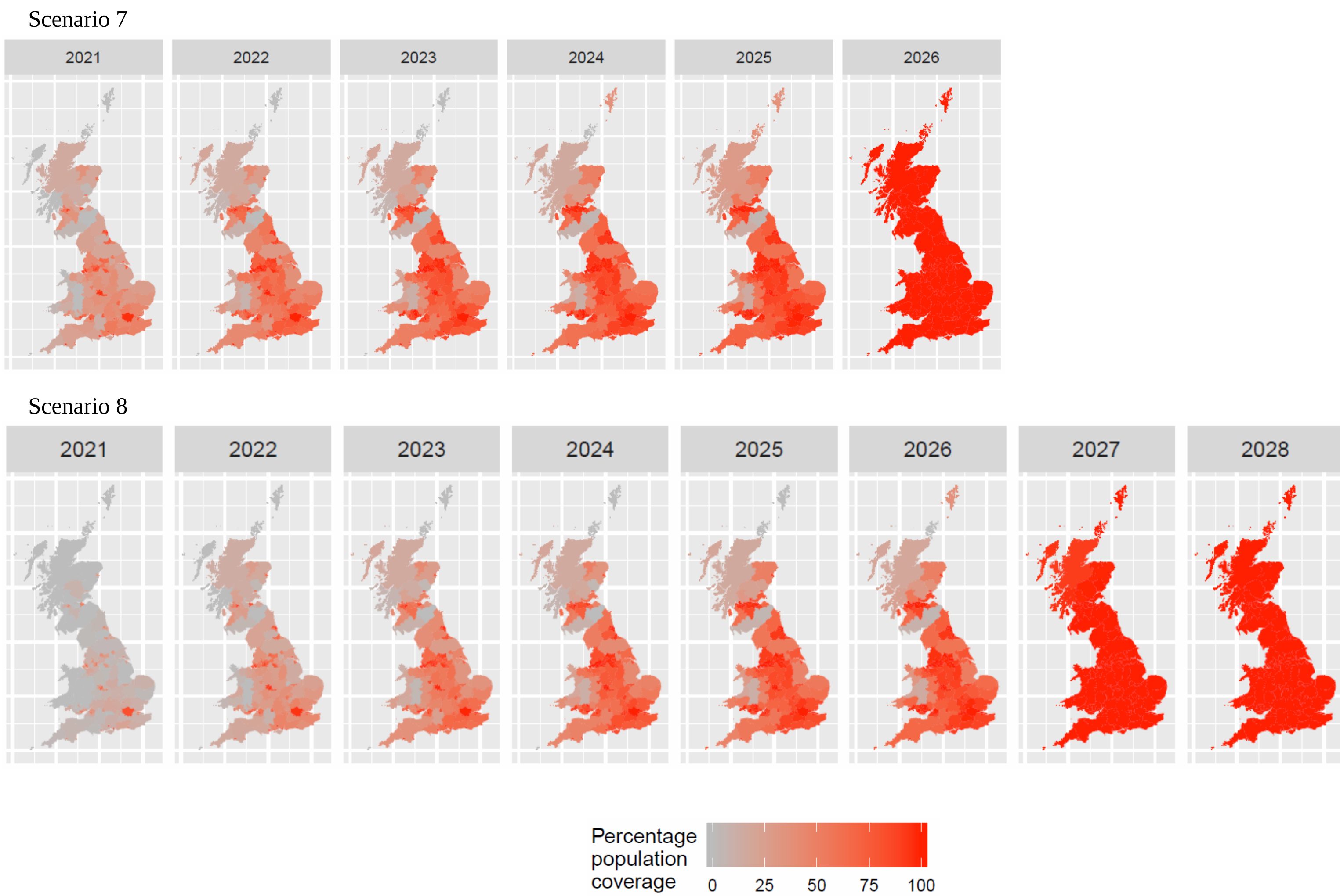
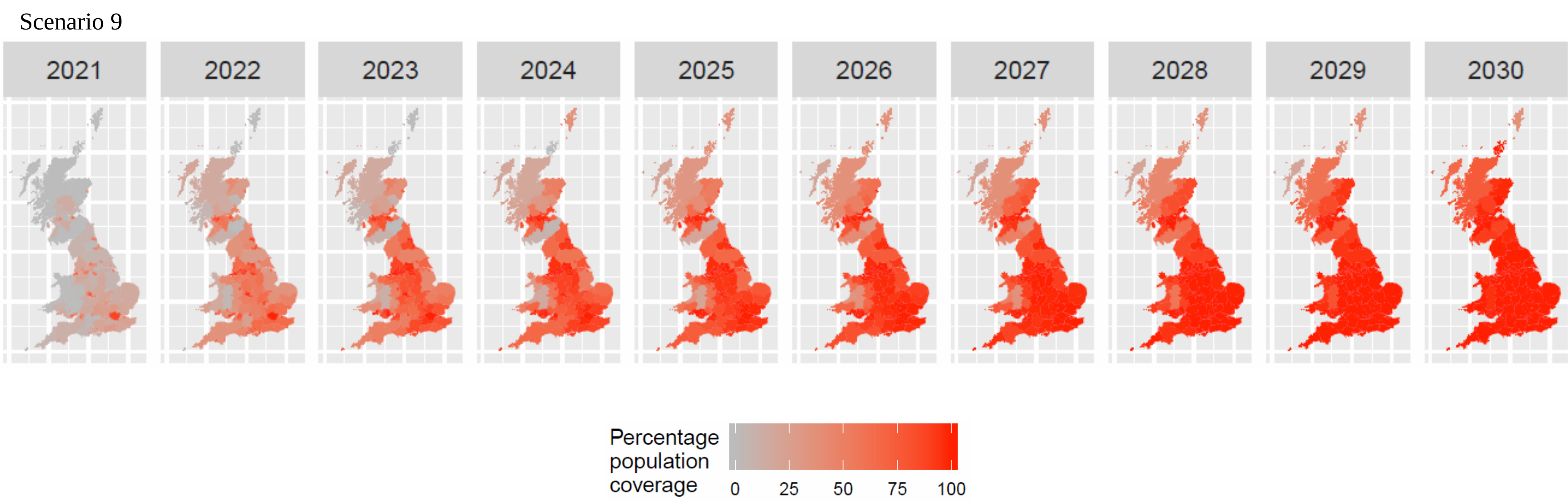


Figure 12 Rollout in S9 between 2020-2030



Sharing has a bigger impact on coverage rollout than lower RAN costs, as S3 has higher rollout despite having more expensive RAN equipment. This is an interesting finding given that, while operators have relatively little influence over equipment costs, other market structures and institutional changes, including business model innovation, could prove the best solution to increasing coverage and capacity across Britain.

It is important to note that in Scenario 7 and Scenario 8, where lower end-user speeds are explored, 100% coverage is achieved by 2026 and 2028 respectively. Decision-makers will have to choose a desirable technical specification for 5G that will have to balance capacity and coverage. Importantly, the technical specification targeted for urban and suburban areas ends up influencing the timing of infrastructure delivery in rural locations. Therefore, high technical specifications (e.g. 50 Mbps) in cities leads to slower rollout of 5G to rural areas. Sacrificing high headline per user speeds in urban areas expedites the delivery of 5G infrastructure to rural areas.

Transport infrastructure analysis

In this section we report the results of the transport analysis, with aggregate coverage costs shown in both Table 11 and Figure 13.

Table 11 Coverage of transport infrastructure

Variable	Road	Motorway	Rail
Total infrastructure length (km)	79,196	4,757	17,301
Number of small cells required	158,393	9,514	34,602
Total capex for small cell deployments (£ million)	2,503	150	547
Total opex for small cell deployments 2020-2030 (£ million)	1,716	103	375
Total Cost of Ownership 2020-2030 (£ million)	4,219	253	922

Figure 13 Cost of small cell rollout

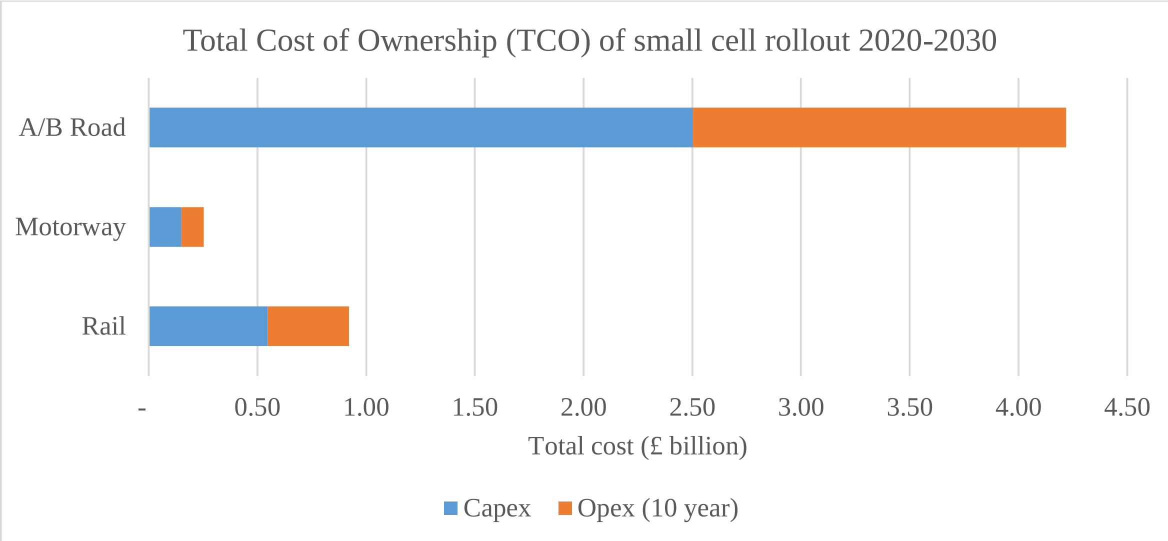


Table 11 shows the total length of each transport infrastructure where A and B roads are by far the longest in terms of length, followed by rail. In comparison there is a relatively short amount of motorway. Approximately 158,393 small cells are required for A and B roads, while only 9,514 are required for motorways. Total coverage of rail requires 34,602 small cells. This results in an approximate total capex for small cell deployment on road infrastructure of £2.5 billion, on motorway infrastructure of £150 million, and on rail infrastructure of £547 million. The opex costs for small cell deployment on road infrastructure between 2020-2030 is £1.7 billion, on motorways £103 million, and on rail £375 million. This results in a TCO for 2020-2030 of £4.2 billion for road, £253 million for motorways, and £922 million for rail, as illustrated in Figure 13.

As this analysis has been undertaken geographically, we are able to show the results graphically in a sequence of figures (Figure 14 and 15) based on the structure of the transport infrastructure network, for each unit within the Ofcom geography.

Figure 14 Capex for total infrastructure coverage (A – road, B – motorway and C – rail)

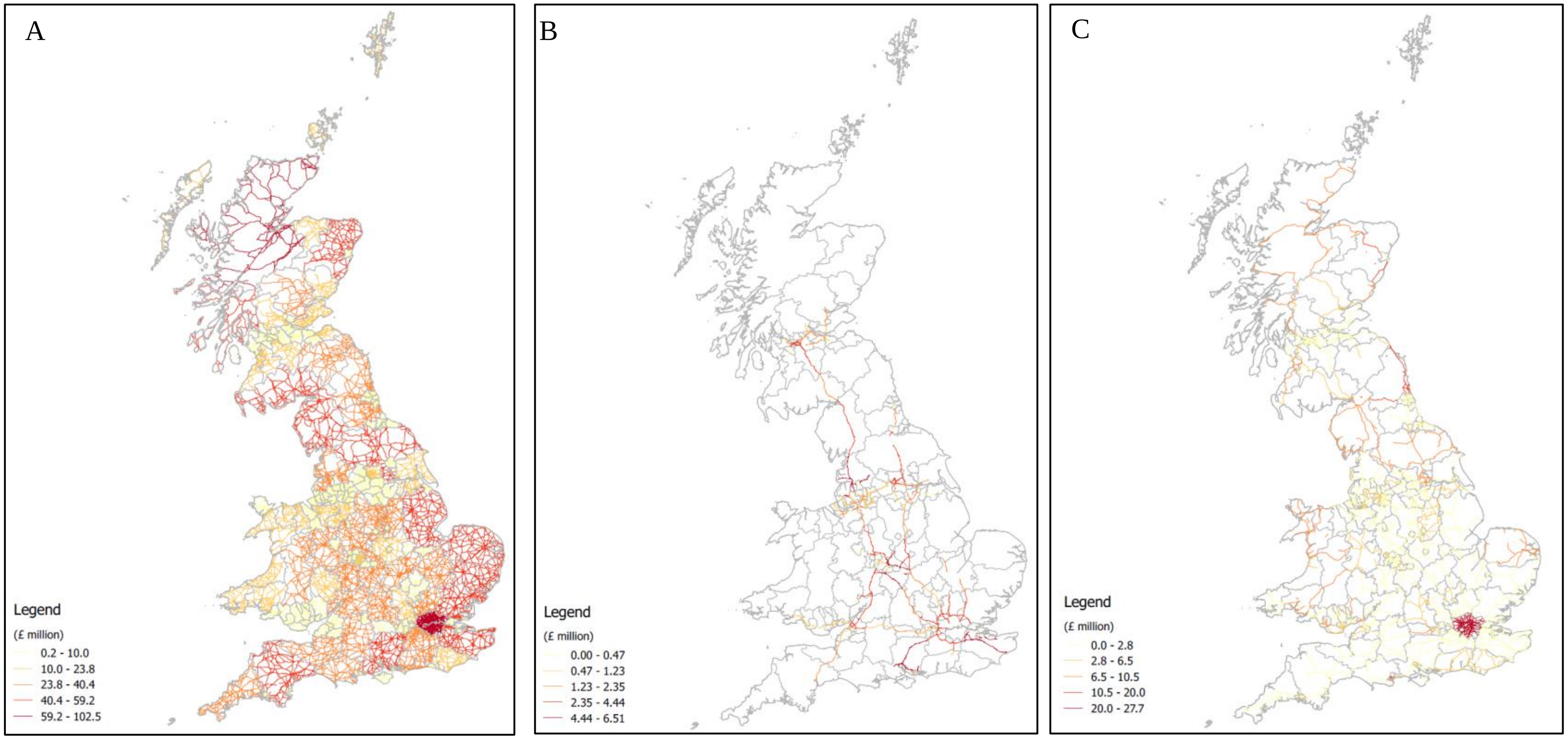
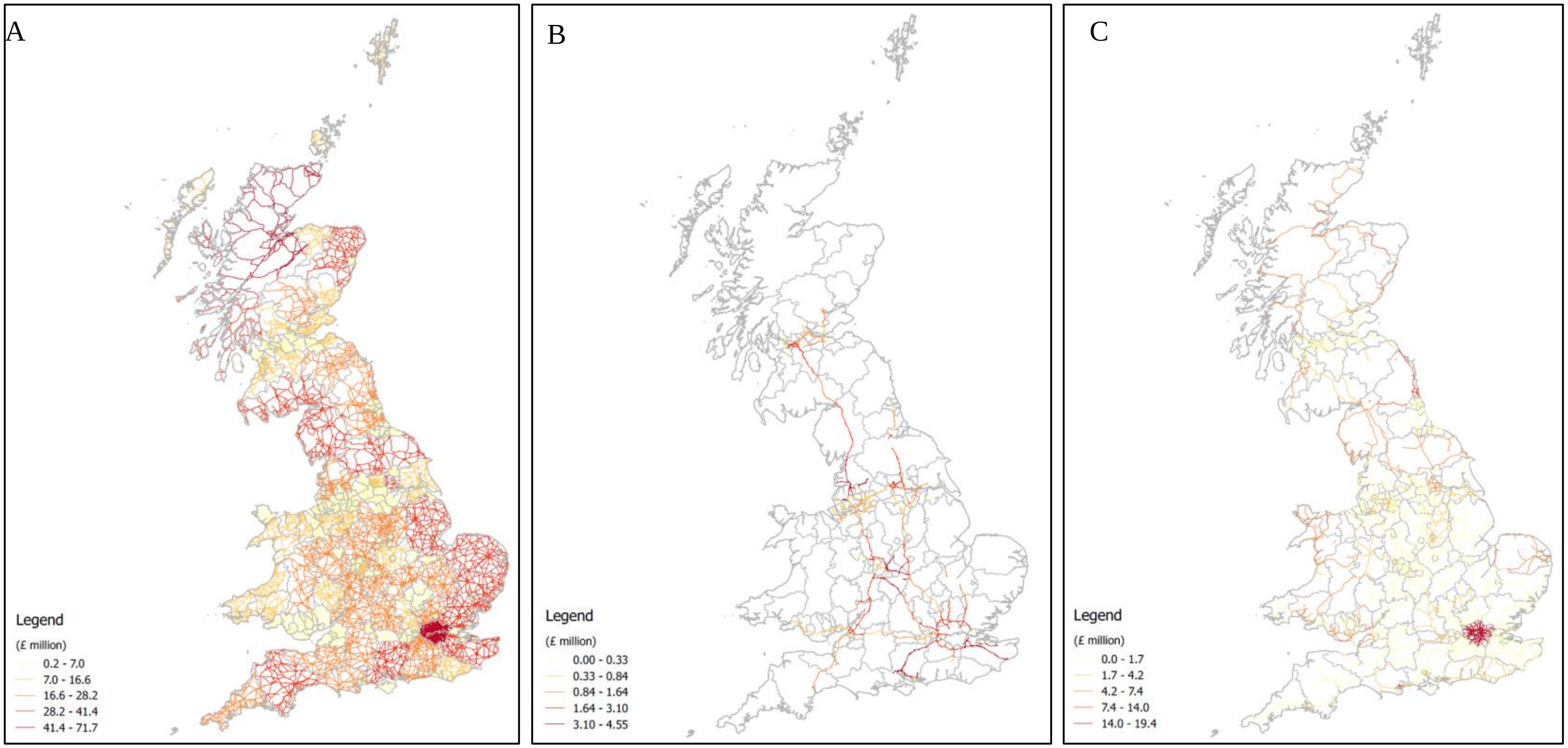


Figure 15 Opex (10 year) for total infrastructure coverage (A – road, B – motorway and C – rail)



Those areas with the longest stretches of transport infrastructure require the highest capex investment levels. In terms of road infrastructure, Highland (3308 km), London (2366 km), and Lincolnshire (1909 km) have the most kilometres of A and B road, leading to capex of £105 million, £75 million and £60 million respectively. Motorway lengths were highest in Kent (1498 km). Lancashire (1191 km) and Warwickshire (946 km), leading to approximate capex requirements of £7 million, £7 million and £6 million respectively. London (894 km), Aberdeenshire (645 km) and Poole (627 km) have the most rail infrastructure leading to approximate capex requirements of £28 million, £20 million and £20 million respectively.

Discussion

Having presented the results of this analysis it is important to revisit the research questions that motivated this work.

There were four key aims to explore under a variety of future scenarios:

1. Quantify the potential cumulative cost of rolling out 5G to different proportions of the population.
2. Estimate the total regional investment cost for rolling out a high coverage probability 5G network, in relation to urban-rural settlement patterns.
3. Provide insight into the spatial rollout of 5G, in order to illustrate the locations that are likely to receive new infrastructure first.
4. Consider the degree to which targeted investments may be required to provide a higher probability of 5G coverage on underserved transport infrastructure.

Each of these questions will now be discussed in turn. It is important to reiterate at this stage that due to the uncertainty around 5G, in terms of technology, economics and MNO rollout, attempting to provide accurate estimates of 5G infrastructure is a challenging task. However, here we have demonstrated a methodology that explores the key cost factors under different scenarios, relates them to important policy objectives, and provides indicative estimates of investment that would provide a high coverage probability by 5G infrastructure.

Due to the deployment principles used in this analysis, we are not able to break down costs by strategy (e.g. spectrum integration versus increased network densification via small cells). However, we are able to broadly explain where the majority of costs accrue via the TCO of 5G network deployment within the spatial framework utilised here. The benefit of this is that it helps us to understand how key technical requirements, costs, and business models may lead to either faster or slower rollout of 5G infrastructure.

It is important to make two key points in relation to the work undertaken. Firstly, although infrastructure sharing has been tested here in a variety of scenarios, it is not known how feasible this is in reality given that operators have historically differentiated themselves from competitors by network coverage. Secondly, in terms of opex we present the ten year Net Present Value of operating a ubiquitous network over the full 2020-2030 period, when in reality this expenditure for new infrastructure would take place incrementally as rollout takes place.

What is the cumulative cost of rolling out 5G to different proportions of the population?

Each scenario was illustrated in terms of cumulative investment, and how this relates to population coverage. Simply stating aggregate costs for strategies is less useful than understanding how different constrained investment scenarios lead to increased or decreased population coverage. Due to the agglomeration benefits of urban areas, which include both economies of scale and access to existing fixed infrastructure, the subsequent costs of serving areas with low population densities are considerably higher. On the whole, the cumulative cost most resembles an exponential curve as a result, where the costs of delivery become increasingly expensive. Hence, the degree to which it is desirable to rollout 5G in terms of coverage and capacity, much like previous generations of mobile technology, is a trade-off. In some scenarios there were significant cost savings in meeting certain important thresholds of the population, such as the first two thirds of consumers within urban and suburban areas. Moreover, the results showed that delivery to the first 90% followed one cost trend, while rollout to the final 10% generally had exponentially increasing costs. Delivery to the final 10% therefore cost more than delivery to the first 90% at high end-user bit rates.

How much investment is required by region for total coverage, across all urban and rural areas?

In answering this question, we showed how the regional cost is very sensitive to three highly interrelated factors including: (i) population density; (ii) existing infrastructure such as site density and access to backhaul; and (iii) the aggregate geographical structure of a region in terms of its urban, suburban and rural composition.

In urban areas, where demand is highest, densifying the RAN through small cell deployments is the only way to deal with the degree of traffic placed on the network for high end-user speeds (e.g. 50 Mbps). Thus, small cells account for a large proportion of all needed investments. Whereas urban areas have a much higher RAN cost per km^2 because the network is capacity constrained and requires additional investment, backhauling costs are considerably lower due to existing available infrastructure. Additionally, urban areas already have near-ubiquitous 4G LTE coverage. Within the segmentation used in this analysis, urban areas (population density >7959 km^2) are a significantly smaller proportion of the UK overall accounting for just 0.2% of Britain.

On the other hand, in the most rural areas, especially those where there is underused spectrum as a result of low 4G coverage, the existing macrocell infrastructure can be upgraded and integrated with new spectrum to meet future traffic demand. Although the cost per km^2 of serving rural areas is considerably cheaper, it forms a much higher proportion of the total area of the UK. For example, rural areas within this analysis (population density <112 km^2) accounted for approximately 92.7% of the total surface area of Britain, leading to it becoming by far the most expensive settlement type.

As a consequence of this, regions with either small populations or predominantly urban settlement patterns, were significantly cheaper. Alternatively, regions with very low population densities and large areas, such as Scotland, were very expensive, amounting almost a quarter of the overall cost while being only a fraction of the total population. It is highly improbable that all regions of the UK will receive near-ubiquitous 5G coverage of 50 Mbps via market methods due to the unviable cost. Hence, alternative wide-area coverage solutions should be explored.

How may 5G rollout spatially across Britain according to capital availability?

The spatial rollout across Britain is affected by factors already discussed, such as the degree of infrastructure sharing, RAN costs, and the technical specification of the desired end-user throughput (e.g. 50, 30 or 10 Mbps). Additionally, the rate of capital investment by the whole telecoms industry has a significant impact on rollout, but it is not immediately clear how this could be increased given

MNOs across the sector have been experiencing static or declining revenues. As investment begins in the areas of highest demand such as the densest urban locations, the degree to which the suburban and rural population gets coverage depends not just on cost savings in less dense locations. If the costs of urban capacity deployment, which depends significantly on small cell unit costs in this case, are decreased then there will be a consequential impact on the rate at which rollout takes place in suburban and rural areas.

What is the estimated cost of targeted 5G investments for transport infrastructure?

Although the scenarios we have already explored would provide a high probability of coverage across the *population*, it does not guarantee the geographic coverage required to meet many end-use cases such as CAVs. One option is to specifically target additional investment at *shared* small cell deployments along transport infrastructure. If this is deemed a potential future option, it needs to be determined how this would work within the existing network coverage by each MNO.

Motorways cost considerably less than other types of transport infrastructure. However, to ensure reliable conditions for the testing and use of CAVs, it may be necessary to increase coverage along A and B roads as well, which would be considerably more expensive. However, this would ensure the testing of new CAVs could take place in the UK which is potentially vital given the importance of the British automotive industry. In terms of rail connectivity, small cell deployments on this type of transport infrastructure would potentially resolve the perennial issue of poor voice and data coverage, although this is partly because historically it has been challenging to deploy new infrastructure along rail lines.

Conclusion

The research within this report was guided by the NIC's request to consider the costs of rolling out ubiquitous high-speed mobile data access across Britain for a per user speed of 50 Mbps – approximately three times higher than the current average. Four key areas were explored under different future scenarios. These included assessing (i) the cumulative investment costs in relation to population coverage, (ii) the total regional costs across urban-rural settlement patterns, (iii) the spatial rollout across Britain, and finally (iv) the costs of targeted 5G investments for transport infrastructure.

Using a model based on publicly available data, reflecting current market conditions, the S1 baseline scenario produced an extremely high TCO of £71 billion. This is for a ubiquitous 5G network delivering 50 Mbps, which is built in 2020 and operated until 2030. When infrastructure sharing was taken into account in the S2 scenario this achieved a TCO of £38 billion and a 46% saving. In this analysis, the S3 and S4 scenarios demonstrate that infrastructure sharing has the largest impact on TCO when compared to either higher or lower RAN costs, within plausible cost changes in RAN equipment.

In the S5 scenario, we tested having RAN competition in urban and suburban areas by building multiple networks, but having a shared infrastructure in rural areas. While still very expensive, with a TCO of £41 billion for ubiquitous coverage (a 42% cost saving on the S1 baseline), it provides increased 5G coverage in the densest rural areas. For example, once population coverage reaches approximately 70% in this scenario (all of the urban and suburban population), a further investment of £4 billion can reach an additional 20% of the population in rural areas via a single network. Within this scenario, 90% of the population can be reached with 50 Mbps by a total capex of £10 billion, which although expensive, is more plausible than other scenarios explored and should be the focus of future analysis. We additionally assess the rollout of 30 Mbps ubiquitously in S6, which produces a £2 billion capex saving on reaching the first 90% of the population when compared with the S1 baseline, and a TCO of £50 billion (saving 30%). The lowest cost achieved across all scenarios was S7, as it only aimed for an end-user speed of 10 Mbps, giving a TCO for the network of £20 billion between 2020-2030. The eighth scenario (S8) produced a TCO of £25 billion for rolling out 50 Mbps in urban and suburban areas, and only 10 Mbps in rural areas. Finally, in the ninth scenario (S9) sharing took place but only on the small cell layer, allowing operators to retain existing macrosites. This produced a TCO of £47 billion, consisting of a capex cost of £27 billion and a ten year opex cost of £20 billion.

The most notable finding in this research is the quantification of the required investment to reach different settlement patterns. Dense small cell deployments delivering 50 Mbps per user in all urban areas is potentially feasible as it represented only 2% of the capex cost of rollout in the baseline scenario (£0.7 billion). Alternatively, achieving a 50 Mbps speed in most rural areas is economically unviable under current conditions. In the baseline scenario rural areas constitute well over two thirds of the capex cost (£35.6 billion) for only 29.5% of the population, therefore significantly lower per user speeds should be expected. Deployment in suburban locations is generally viable across the scenarios explored here.

Future research needs to refine both the network architecture and the cost structure that has been applied. For example, it would be useful to have costs for (i) spectrum, (ii) radio network planning, and (iii) different migration strategies for implementing 5G networks. SDN and NFV are hot topics but it is not yet clear how these techniques can be used within 5G network deployments to drive down costs, due to the additional capex required for migration. As the 5G standardisation process develops it may become easier to implement a cost analysis of a virtualised 5G network infrastructure. Moreover, we require better understanding of how spectrum costs may affect the eventual spatial rollout of 5G. The MNOs could be incentivised to rollout more infrastructure to hard-to-reach areas if there was the prospect of having the costs of spectrum licences returned or reduced.

It is evident that if current costs, market structure and the existing regulatory framework stay static we will see constrained rollout of 5G infrastructure that may not meet our long-term needs nor provide the most widespread economic return from investment in digital communications. One option for decreasing rollout costs, thereby increasing the coverage of 5G, is via business model innovation. This could be made possible through a form of infrastructure sharing, particularly in hard-to-reach locations.

In order to provide insight for decision-makers working on a national 5G infrastructure strategy, a number of assumptions and abstractions had to be made in order to undertake this analysis. The costings presented here should not be taken as definitive, but are estimates based on best available evidence and publicly available data. The aim of this research has been to consider the costs and the rollout of infrastructure as MNOs have national networks, and the economic benefits of 5G will be limited under constrained coverage. Work must continue as the 5G standardisation process takes place in order to provide greater understanding of the cross-cutting themes associated with the economics of infrastructure delivery, the viability of different business models, and how regulatory frameworks can be used to achieve specific coverage and capacity objectives.

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