Telecommunications Policy 42 (2018) 636–652

Contents lists available at ScienceDirect

Telecommunications Policy

journal homepage: www.elsevier.com/locate/telpol

The cost, coverage and rollout implications of 5G infrastructure in Britain

Edward J. Oughton[a,*], Zoraida Frias[b]

[a] Centre for Risk Studies, Cambridge Judge Business School, University of Cambridge, England, UK
[b] Group of Information Technologies and Communications, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, Madrid, Spain

ARTICLE INFO

Keywords:
5G
Spatial rollout
Cost modelling
Infrastructure sharing

ABSTRACT

Despite 5G still being embryonic in its development, there is already a quest for evidence to support decision-making in government and industry. Although there is still considerable technological, economic and behavioural uncertainty, exploration of how the potential rollout may take place both *spatially* and *temporally* is required for effective policy formulation. Consequently, the cost, coverage and rollout implications of 5G networks across Britain are explored by extrapolating 4G LTE and LTE-Advanced characteristics for the period 2020–2030. We focus on ubiquitous ultrafast broadband of 50 Mbps and test the impact of annual capital intensity, infrastructure sharing and reducing the end-user speed in rural areas to either 10 or 30 Mbps. For the business-*as*-usual scenario we find that 90% of the population is covered with 5G by 2027, but coverage is unlikely to reach the final 10% due to exponentially increasing costs. Moreover, varying annual capital intensity or deploying a shared small cell network can greatly influence the time taken to reach the 90% threshold, with these changes mostly benefiting rural areas. Importantly, simply by integrating new and existing spectrum, a network capable of achieving 10 Mbps per rural user is possible, which is comparable to the UK's current fixed broadband Universal Service Obligation. We contribute to the literature by quantifying the effectiveness of the *spatial* and *temporal* rollout of 5G under different policy options.

1. Introduction

Over the last decade, several factors have contributed to the cost-effective rollout of high-speed mobile broadband services, including the standardisation of LTE networks, enhanced spectral efficiency and the allocation of additional spectrum (Ghosh & Ratasuk, 2011; Holma & Toskala, 2012). While 4G is still reaching maturity different industrial, governmental and academic stakeholders are currently working together globally to develop the next generation of mobile networks known as ‘5G’ (5GPPP, 2016).

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). There is an expectation in the engineering literature that 5G systems will provide peak data rates of 1 Gbps to mobile users and 10 Gbps to stationary users (Chih-Lin, Han, Xu, Sun, & Pan, 2016). The various use cases of 5G include enhanced mobile broadband, massive machine-type communications, and ultra-reliable and low-latency communications (see 5G NORMA, 2016; Tullberg, Fallgren, Kusume, & Hoglund, 2016; Mavromoustakis, Mastorakis, & Batalla, 2016; Hu, 2016). The current hype around 5G is pervasive in the telecommunications industry, with almost daily announcements being made by operators advertising

---

* Corresponding author. Cambridge Judge Business School, Centre for Risk Studies, Trumpington Street, Cambridge, CB2 1AG, UK.
E-mail address: e.oughton@jbs.cam.ac.uk (E.J. Oughton).

http://dx.doi.org/10.1016/j.telpol.2017.07.009
Received 22 December 2016; Received in revised form 5 July 2017; Accepted 20 July 2017

either new test-bed commitments or advocating the potential benefits for vertical industries. Many operators are facing challenging times with static or declining revenues. While some see these technologies as being able to drive revenue, others are concerned about the economics of site densification. Indeed, adding new sites is a key strategy to increase wireless capacity, but the current deployment model is prohibitively expensive. Hence, for effective 5G rollout to take place, there needs to be major cost model changes.

In the UK, 5G has also caught the interest of politicians with the Chancellor of the Exchequer tasking the National Infrastructure Commission (NIC) with developing a strategy that will make the UK a world leader in 5G communications deployment by 2020. Currently this activity is forming a key part of UK industrial strategy, with over £1 billion being allocated to digital infrastructure via the National Productivity Investment Fund (for both fixed fibre and 5G). This also relates to the national infrastructure assessment currently being undertaken by the NIC.

It has been widely acknowledged that ICT and digital communications have played a key role in global economic development in recent decades, in both advanced nations (Jorgenson & Vu, 2016; Jorgenson, Ho, & Samuels, 2016) and less developed contexts (Jensen, 2007; Muto & Yamano, 2009). The rollout of fixed broadband infrastructure has generally been found to have positive economic impacts (Fornefeld, Delauney, & Elixmann, 2008; Kolko, 2012; Koutroumpis, 2009), much like the wave of fixed voice telephony that preceded it (Röller & Waverman, 2001). However, positive externality benefits from previous generations of communication technologies have been most profound when achieving near-ubiquitous coverage (Ibid.), making this an important objective for future rollout.

Poor connectivity in certain locations has implications for both business (affecting productivity) and society (reinforce socioeconomic divides) (Koutroumpis & Leiponen, 2016). Achieving near-ubiquitous coverage is therefore fundamental for economic development regardless of whether governments pursue this as an industrial policy or to solve inequality issues. Indeed, a common argument focuses on the need for greater coverage and consistent connectivity, rather than increasingly large per user speeds (see Webb, 2016 or; Curwen, 2017, pp. 295–296). At this stage, it is not clear how the spatial and temporal rollout of 5G may take place, motivating the research presented in this paper.

Currently within the UK, approximate indoor LTE coverage by all operators reaches 72% of premises and outdoor coverage reaches 86% of premises, however 4% are not covered by any operator (Ofcom, 2016a). Crowdsourced measurements show users struggle to connect to 4G approximately half of the time after accounting for coverage, congestion and indoor effects, ranking the UK 55th out of 80 countries (OpenSignal, 2016). Mobile consumers are often unhappy with current levels of coverage, leading to both widespread media attention and political interest. One example is the creation of the cross-party British Infrastructure Group, comprising over 250 Members of Parliament, which has repeatedly pushed for better telecommunications infrastructure. In contrast, operators state that they struggle to get new sites through planning, while simultaneously losing existing sites as older building stock is demolished. Coverage and capacity can be compared to fixed broadband access where 95% of premises can achieve a fixed broadband speed of $\geq$10 Mbps, leaving the final 5% to be the aspiration of the newly introduced Universal Broadband Obligation (USO). Superfast broadband speeds $\geq$30 Mbps are achievable by most premises (89%), although only a small fraction (2%) can achieve Ultrafast broadband ($\geq$300 Mbps) (Ofcom, 2016a).

The contents of this paper build on an initial report first published in December 2016 that was used as supporting evidence for the UK's 5G strategy (see Oughton & Frias, 2016). After the experience of 4G networks, it is evident that policy-makers can greatly affect the rollout of digital networks, regarding the timely allocation of additional spectrum resources, investment incentives and a favourable regulatory framework. Hence, the purpose here is to explore the spatio-temporal dynamics of the rollout of 5G networks based on a cost framework, with the intention of exploring the following research questions:

1. How may 5G rollout take place for different investment capital intensities?
2. What is the impact of infrastructure sharing?
3. Can targeting different end-user speeds in rural areas achieve increased coverage?
4. What options are available for governments, regulators and policy-makers to speed up 5G rollout?

To answer these research questions, we have developed a cost model that captures the dynamics of the rollout for different capacity expansion strategies that MNOs may implement when transitioning to 5G. A literature review is presented in Section 2 and Section 3 then describes the methodology. We then report the results in Section 4 and discuss their implications for policy in Section 5. Finally, Section 6 concludes the paper by highlighting key findings.

2. Literature review

Although standardisation is still ongoing, in this review we consider the technical aspects of 5G, recent cost modelling studies, and research focusing on the spatial and temporal dimensions of digital networks.

2.1. 5G technical aspects

The digital communications industry is moving to an even more heterogeneous technology environment (Rong, Qiu, Kadoch, Sun, & Li, 2016), consisting of a complex adaptive, multi-layered network of overlapping macrocells, remote radio heads and low powered small cells and relays that supply digital connectivity for all devices (smartphones, cars, drones, buildings, infrastructure and all IoT applications) (Lopez-Perez et al., 2011; Hossain & 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, while utilising existing fixed networks for wireless access and backhaul. A key concept of this future is the principle of ‘Anything as a Service’, where everything, from spectrum to infrastructure to high-performance computing, will be available as a service (Soldani, Barani, Tafazolli, Manzalini, & Chih-Lin, 2015; Taleb, Ksentini, & Jäntti, 2016).

Network densification is the dominant theme of wireless evolution towards 5G (Bhushan et al., 2014; Zhu, She, & Chen, 2016), especially as high frequency bands with poorer propagation characteristics become widespread (Thurfjell, Ericsson, & de Bruin, 2015). Densifying networks, while avoiding increasing inter-cell interference, is a key issue (Andrews et al., 2014). Another key technical aspect of 5G networks will be the use of high-frequency spectrum, above 6 GHz, and particularly the use of millimetre wave (mmW) spectrum. Although mmW signals experience orders-of-magnitude more pathloss than the microwave signals currently used in most wireless systems (Ayach, Rajagopal, Abu-Surra, Pi, & Heath, 2014), it has the potential to offer multi-Gbps data rates at a lower marginal cost than previous technologies (Murdock, Ben-Dor, Qiao, Tamir, & Rappaport, 2012) due to the potential allocation of much more bandwidth at these frequencies. However, real-world measurements of mmW spectrum (28 GHz and 73 GHz) indicate cell sites using these frequencies will have small radii of 100–200 m (Akdeniz et al., 2014). Hence, these bands will not be used for wide area coverage but rather local hotspots, leading to changes in the economic costs of deployment compared to previous generations.

2.2. 5G networks costs

Cost modelling is an approach that allows one to compare the difference between data traffic demand and network costs for different deployment scenarios (Katsigiannis & Smura, 2015; Nikolikj & Janevski, 2014). The costs of 5G infrastructure densification depend heavily on the required throughput density, periodic interest rate, and basestation price (Bouras, Kollia, & Papazois, 2016a). The reduction of these costs is, thus, necessary for effective, ultra-dense small cell deployments. Some have begun to integrate mmW bands spectrum (28 GHz) into cost modelling heterogeneous networks whereby small cell solutions such as pico cells with mmW systems are deployed in areas of high demand (Nikolikj & Janevski, 2014).

However, 5G may not just include the integration of mmW. Although challenging, there *may* be improved spectral efficiency of the air interface. Hence, cost efficient capacity expansion strategies for MNOs were explored by Nikolikj and Janevski (2015) by specifically relating the production cost of transferred data to revenues. Consequently, the largest sensitivity found was the individual unit price of the basestation required to deliver a 5G network of a specific coverage or capacity.

Recent cost modelling of 5G has also explored Software Defined Networks (SDN) with Network Function Virtualisation (NFV). Analysis by Bouras, Ntarzanos, and Papazois (2016b) concludes that while still at a nascent stage of development, the implications of an evolved core and Radio Access Network (RAN) for a 5G network verifies and even exceeds the ambitious predictions for cost savings. Significant infrastructure cost reductions were found in the implementation of virtualisation where opex was reduced by 63% and capex by 68% in comparison to traditional scenarios.

Network infrastructure has very high fixed costs of delivery, therefore is greatly affected by scale economies and population density (Katz and Berry, 2014). Fund, Shahsavari, Panwar, Erkip, and Rangan (2016) identify that one way to overcome this is to have ‘open’ deployments of neutral small cells serving subscribers of any service provider. This shared infrastructure approach would encourage market entry by making it easier for networks to get closer to a critical mass.

2.3. Spatial network rollout

There is a significant lack of literature that considers the spatial rollout of telecommunications technologies over time. Often researchers focus on just one key aspect, such as modelling spatial viability, as evident in the fixed broadband literature. For example, the work carried out by Grubesic (2010, 2008), and Mack and Grubesic (2009) analyses the spatial rollout of broadband networks in the USA, along with Oughton, Tyler, and Alderson (2015) undertaking similar analysis for the UK. However, there is no explicit temporal dimension. Indeed, although with the deployment of fibre-based NGA networks there was a significant attempt to quantify the investments needs in Europe, rollout was not explicitly modelled spatially over time (see Analysys Mason, 2008; Elixmann, Ilic, Neumann, & Plückebaum, 2008; Point Topic, 2016). The focus has instead been on assessing cumulative households passed, which is valuable, but only provides partial information to support decision-making.

In mobile and wireless, there has also been limited explicitly spatial modelling of the potential rollout of new technologies. With the aim of closing the digital divide, temporal assessments have ranged from deploying 800 MHz (Ovando, Pérez, & Moral, 2015), to fixed-wireless LTE (Frías, González-Valderrama, Martínez, & others, 2015), to satellite technologies (Analysys Mason, 2010), but these usually focus on snapshots of different temporal periods, rather than producing spatial time-series.

One of the best attempts to introduce temporal aspects for the rollout of next generation technologies is the analysis of 2020 targets for the Digital Agenda for Europe (DAE). Analysis Mason (2012) present a detailed study on the likelihood that market trends and policies would deliver DAE targets by 2020 through different technologies for each European Member State. The study considers both demand-side and supply-side constrains. For the demand-side, varying service take-up rates are forecasted by 2020, while for the supply-side, legacy networks are analysed to estimate the likelihood that they can provide a certain speed by 2020. We conclude from this review that little focus has been placed on technology rollout.

2.4. Summary

Network densification and additional spectrum will play a key role in delivering 5G, but this will have a significant impact on the economics of delivery. Although there has been rather limited analysis of this subject, basestation unit costs are critical and will have a significant impact in network densification strategies. We also identify that there has been rather limited modelling of both the spatial *and* temporal dynamics of the rollout for telecommunication technologies. While the literature on 5G networks provides insight into the technical specifications of various technologies, little emphasis has been placed on the rollout implications for different national infrastructure strategies.

3. Methodology

Focusing on network densification and additional spectrum, we take an incremental approach for 5G network delivery during the 2020–2030 period. To assess deployment costs across Britain, we segment areas that have similar cost characteristics together into specific 'geotypes' (see (1) in Fig. 1). The geotype segmentation includes the key cost characteristics such as population density and existing site density, as well as the basestation technology currently deployed. For each geotype, the costs are assessed considering two strategies to meet traffic demand which include integrating more spectrum and deploying green-field small cells (see (2) in Fig. 1). The costs of each are calculated through network dimensioning to meet the specified traffic demand (see (3) in Fig. 1).

We take a supply-side approach where investments are driven by annual available capital intensity and delivered to areas of highest demand first. This allows us to capture the temporal dimension of the rollout, as it occurs. We dimension networks capable of delivering an end-user speed of 50 Mbps to provide ultrafast mobile broadband which is a key 5G use case (Tullberg et al., 2016), while also accounting for scenarios with 10 Mbps and 30 Mbps in rural areas. Competition, pricing and take-up may well influence these parameters but are not directly considered here. The 30 Mbps capacity target is justified because achieving superfast broadband is a key aim of the DAE. The 10 Mbps capacity target is justified because it is the UK's current USO and has been selected because it provides enough bandwidth to enable basic provision of almost all applications and services. For example, Skouby, Falch, Henten, and Tadayoni (2014) provide download capacity requirements for a wide range of services which can be supported by 10 Mbps. Moreover, adapting Ofcom's analysis (2014:49), total speed requirement for a peak-time household with three users is 9 Mbps. This is comprised of User 1 having a video call (1 Mbps), User 2 watching catch-up TV (2 Mbps), and finally User 3 watching High Definition (HD) video-on-demand and undertaking a video call simultaneously (6 Mbps). Basic provision considers minimal functional requirements, but does not consider user experience.

Prospective cost analysis of new technologies present inherent sources of uncertainty. This uncertainty can be technological because standardisation is ongoing, and future spectrum availability of specific bands is not guaranteed, or economic due to the unknown costs of new equipment. Additionally, there is behavioural uncertainty as both MNO rollout strategies and consumer demand for 5G services are

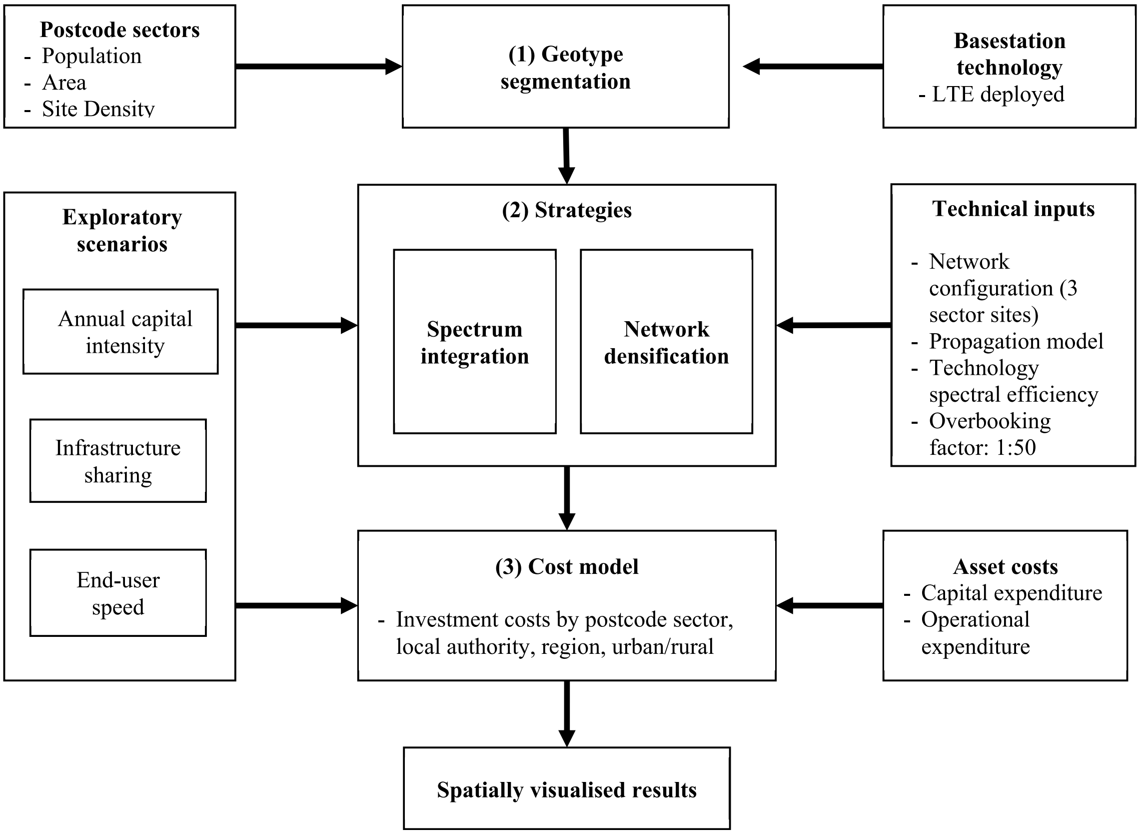

Fig. 1. Sequential methodology.

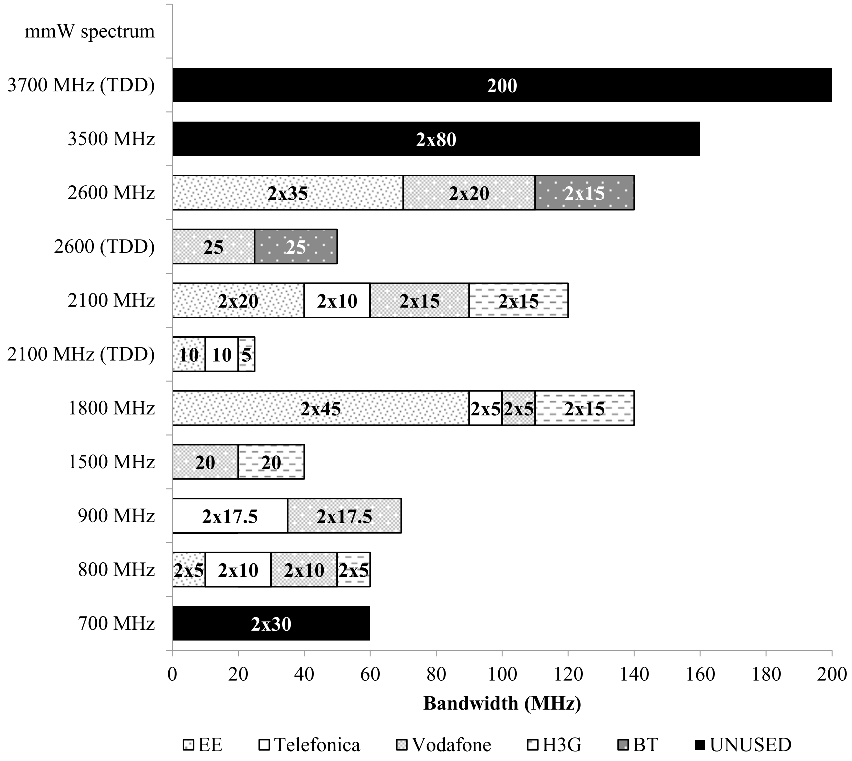

Fig. 2. Spectrum bands by operator.

unknown. Although high-level design principles are known, it is challenging to assess network performance and study detailed deployment needs for all business cases. In the following sections, each part of the methodology is further described and we provide details on how we deal with the sources of uncertainty by taking an exploratory scenario-driven approach to illustrate cost variability.

3.1. Exploratory scenarios

A set of exploratory scenarios are used to demonstrate the potential costs of deployment and the spatio-temporal dynamics of the rollout in the future. 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 including annual capital intensity, infrastructure sharing, and end-user speed.

Currently, UK MNOs are investing approximately £2 billion per year across the industry to upgrade and expand cellular networks to meet demand by domestic and commercial customers (Real Wireless, 2015). We assume this is purely spent on network capex and does not include spectrum costs, to explore the sensitivity of five levels of annual capital intensity ranging from £1.5–2.5 billion per year. When reflecting on the 4G licence coverage obligation from 2012, requiring 98% population coverage of 2 Mbps by 2017 (obtained by O2 Telefónica) (Ofcom, 2012a), the headline speeds explored here are significantly more challenging. Thus, these targets will take a longer time to achieve.

The degree to which operators may share 5G infrastructure is examined and assumed to function in a similar way to current network sharing agreements, as much of the existing passive infrastructure will need to be reused. Currently, there are two partnerships between firstly O2/Telefonica and Vodafone, and secondly EE and Hutchinson Three. As the four MNOs currently utilise a network sharing agreement, we assume the business-*as*-usual case would consist of two operators sharing each macrocell network (2 × 2).

We assume that MNOs will continue to share the macrocell layer (2 × 2) and that they will on one hand integrate new spectrum into brownfield macrocell sites and on the other undertake greenfield deployment of 5G small cells. The small cell layer could either be deployed in a similar way to the existing macrocell network (2 × 2, business-*as*-usual), or only a single deployment could be shared by all operators (1 × 4).

Finally, we consider that very high end-user speeds will probably be unviable in rural areas. Thus, we test three different cases with varying end-user speed for rural areas. The first one considers ultrafast broadband of 50 Mbps per user everywhere, while the other two target the provision of 10 Mbps and 30 Mbps in rural areas.

3.2. Strategies

Two main strategies are considered for network dimensioning and meeting the end-user speeds required in the exploratory scenarios.

The deployment principles employed consider a macrocell brownfield-first approach to meet future demand as operators would preference existing assets and sites (especially passive infrastructure) to minimise delivery costs. Hence, we assume that operators would 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 LTE-A basestation with different RF modules where there is no previous LTE network. If upgrading a macrocell basestation and integrating additional spectrum does not meet the required network performance, the network would be densified by deploying completely new small cells.

For the first option (spectrum integration into existing macrocells) we consider two frequency bands for capacity expansion of current 4G networks to next generation 5G networks including (i) 700 MHz and (ii) 3400–3600 MHz. The justification for focusing on these bands is that this spectrum has been allocated to mobile communications systems, therefore they are currently not being used by any other legacy system (i.e. 2G, 3G or 4G) (Ofcom, 2016b). 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 achieving total geographic coverage in 5G. Although 3400–3600 MHz has poorer propagation characteristics, it provides more bandwidth allowing for additional capacity, particularly if coupled with new small cell deployments in areas of very high demand. Where 4G networks are currently unavailable, we integrate the existing underused 800 MHz and 2600 MHz spectrum first.

For the second option consisting of greenfield 5G small cell rollout, we consider these assets will be deployed using 3400–3600 MHz spectrum, as it is currently being refarmed (Ofcom, 2016b). Fig. 2 outlines the current used and unused bands of spectrum held by MNOs.

It is worth noting that 900 MHz, 1800 MHz and 2100 MHz are excluded from the current analysis as legacy 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 or indeed 5G networks during the period examined in this study.

3.3. Geotypes

To undertake a granular analysis of the spatial rollout across Britain, seven geotypes have been created which represent the key supply-side variables that affect rollout costs. Approximately 9000 postcode sectors are utilised in this analysis, covering England, Scotland and Wales. This geography has been applied in other work for Ofcom, based on Long Run Incremental Costing, such as the wholesale Mobile Call Termination (MCT) review model (Ofcom, 2015). We exclude Northern Ireland because demographic data is not released at the postcode level.

Population data is taken from the 2011 Census (ONS, 2016) and is aggregated from the postcode to the postcode sector. Scotland has not produced postcode population data since this period, limiting the use of more current data for England and Wales. The area of each postcode sector was calculated by first taking Ordinance Survey Codepoint (2016) polygon data and eliminating all vertical postcodes, before dissolving at the postcode sector level.

Sitefinder (Ofcom, 2012b) data is then obtained to estimate the number of actual sites, considering the basestations belonging to the four major MNOs (EE, Vodafone, O2 and Three; EE's data was obtained by combining T-Mobile and Orange). Approximately 144,000 basestation points were imported into an open-source geographical information system and sectored macrocells were selected. A buffer zone of 25 m was then added to all points, with any intersecting buffer zones being dissolved to create one point for each site, leaving a total of 42,136. As we do not have access to current coverage information for sites, we assume that any site is potentially able to be accessed and shared by all operators.

The seven geotypes are categorised based on a minimum population density as per the division presented in a report for the UK's Broadband Stakeholder Group by Analysys Mason (2010), as detailed in Table 1.

The estimated population coverage for 4G is derived from assumptions made in the MCT 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. Once the cumulative cost curve has been derived based on each geotype, a spline is used to interpolate the population coverage for a specific annual capital intensity.

Table 1
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)
Urban	460	0.2	5,127,859	8.3	100	7959	2880	6.26
Suburban 1	4051	1.7	18,171,212	29.5	100	3119	8348	2.06
Suburban 2	12,371	5.3	20,165,440	32.7	100	782	11,657	0.94
Rural 1	46,463	20.0	12,358,847	20.0	100	112	10,212	0.22
Rural 2	52,039	22.4	3,830,419	6.2	90.3	47	4566	0.09
Rural 3	33,271	14.3	1,196,409	1.9	80	25	1873	0.06
Rural 4	83,460	36.0	794,688	1.3	80	0	2197	0.03

3.4. Cost model

In this section, we provide an overview of the cost model considered in this paper for a non-virtualised 5G infrastructure. Though the typical metric of the Total Cost of Ownership could be desirable for understanding all the costs that would be involved in a 5G-based business case, we have only considered capital expenditure in this analysis as we are assessing annual capital intensity in relation to the pace of 5G rollout.

For that purpose, we calculate the capex of the rollout for each geotype and for each year *i* of the study period (2020–2030) considering these may vary over time, as indicated in Table 2. The capex is defined in equation (1).

$$Capex_{5GNet_i} = C_{Macro\ cell_i} + C_{Small\ cell_i} + C_{Backhaul_i} + C_{Core_i} \tag{1}$$

where $Capex_{5GNet_i}$ consists of the sum of capex costs for all assets including brownfield macrocell upgrades $(C_{Macro\ cell_i})$, greenfield small cell deployments $(C_{Small\ cell_i})$, fibre backhaul $(C_{Backhaul_i})$ and core upgrade costs (C_{Core_i}). This value would exclude the costs of assets classed under operational expenditure. Maintenance costs of investment assets including the backhaul of small cells are excluded, as they are assumed to be a recurrent operational expenditure. It is likely that many 5G small cells will rely on wireless backhaul on mmW spectrum, since they will be located on street furniture not easily accessible with a wired connection.

The cost modelling for the backhaul took inspiration from Mahloo, Monti, Chen, and Wosinska (2014). As shown elsewhere, the backhaul is an emerging new cost bottleneck for 5G networks with no single solution (Jaber, Imran, Tafazolli, & Tukmanov, 2016; Tombaz et al., 2014). Hence, we use provisional assumptions about backhaul length for costing. 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.

5G equipment costs are obviously unknown at this point. However, future generations of network equipment with enhanced performance tend to be similar in price to those of previous systems (Johansson, Zander, & Furuskar, 2007). The current capex and opex costs for key assets have been sourced predominantly from Ofcom's MCT model (2015). These costs are broadly accurate and importantly have been agreed upon by industry. We also use costs from the European research project 5G NORMA (2016). Assumed costs are derived from discussions with industry stakeholders. We do not consider spectrum costs, as the spectrum we consider is yet to be allocated. In addition, spectrum costs cannot be accurately broken down and attributed to different geographical regions, since it is auctioned at the national level. Table 2 outlines the key cost assumptions.

3.5. Network dimensioning and related inputs

We extrapolate existing 4G LTE and LTE-Advanced characteristics to 5G, to assess network performance to meet required end-user demand. Networks are dimension for each exploratory scenario using a model to calculate the minimum number of basestations required. As stated in the subsections above, this is compared to the number of basestations that could be delivered using existing sites represented by the Inter-Site Distance (ISD). If the number of basestation needed is higher than the existing sites can provide, we assess whether integrating additional spectrum or densifying the network will meet the desired end-user throughput.

To calculate the number of basestations needed we have used the same methodology as (Frias, González-Valderrama, and Pérez, 2017; Oughton & Frias, 2016), whereby network performance curves are generated for ISD system-level simulations. To assess the network performance, we use two metrics: the average user throughput and the cell-edge user throughput (defined as the 10th

Table 2
Capex and opex infrastructure costs.

Strategy	LTE availability	Cost type	Capex (GBP)	Capex time trend	Opex (GBP)	Opex time trend	Source
Spectrum integration on the macrocelluar network	Site with 4G LTE	Additional carrier on current BS	15,000	−3%	1800	0	Ofcom (2015)
	Site with no 4G LTE	Deploying a multicarrier BS	40,900	−3%	3898	−5%	Ofcom (2015)
		Site lease	–	0	5000	3%	Ofcom (2015)
		Civil works	18,000	0	–	3%	5G NORMA (2016)
		Fibre backhaul Urban: 1 km	20,000 per km	0	–	0	Assumption
		Fibre backhaul Suburban 1: 2 km, Suburban 2: 4 km	20,000 per km	0	–	0	Assumption
		Fibre backhaul Rural 1: 8 km Rural 2: 10 km, Rural 3: 20 km, Rural 4: 30 km	20,000 per km	0	–	0	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	5000	0	Assumption
		Small cell backhaul	–	0	1000	3%	5G NORMA (2016)
Core upgrade cost on all strategies			10% mark-up on RAN deployment cost	0	–	0	Assumption

percentile of the cumulative distribution function of user throughput). This approach allows us to identify the maximum ISD that meets the target value for each scenario metric.

To calculate network performance, we calculate the probability distribution of the Signal to Noise and Interference Ratio (SINR) within each cell size. Once obtained, we convert it into an *average* spectral efficiency for the cell based off the *potential* spectral efficiency for each possible SINR value, assuming the results of Mogensen et al. (2007).

$$\eta_{ISD} = \int \eta \; (SINR) f(SINR) \; dSINR \tag{2}$$

Where η_{ISD} is the averaged spectral efficiency (bps/Hz) in the cell for a certain spectrum configuration. The average cell throughput (in Mbps) is calculated according to the bandwidth available in each carrier frequency, as in equation (3), where the factor 3 accounts for three-sector cells.

$$Throughput_{ISD}^{cell} = 3 \sum_{f} \eta_{ISD}^{f} \; BW^{f} \tag{3}$$

Having integrated all possible spectrum within each scenario, the unserved demand not met via three-sector macrocells is routed through the small cell layer operating over Time Division Duplexing (TDD) spectrum at 3500 MHz. To estimate the number of small cells required, we consider LTE-like spectral efficiency (1.5 bps/Hz), the bandwidth available (100 MHz for non-sharing scenarios and 200 MHz for sharing scenarios), a DL/UL ratio of 75%, and a maximum coverage of 200 m. The following configuration parameters listed in Table 3 are applied.

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'. 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.

4. Results

In reporting the results, we first illustrate the rollout of a national 5G network under business-*as*-usual conditions. We then explore the spatio-temporal dynamics under three exploratory variables including annual capital intensity, degree of infrastructure sharing in greenfield deployments, and required end-user speed. This is executed by using the cumulative population covered to represent the spatial dimension, and the years of the study period for the temporal dimension.

4.1. Baseline scenario

Fig. 3 illustrates how 5G networks would rollout across Britain both spatially and temporally. We assume rollout takes place from the most densely populated postcode sectors first. Rural areas will only receive 5G after all urban and suburban areas, hence London receives the most 5G coverage first, while Scotland is generally last. Based on an annual capital intensity for all years of £2 billion, the proportion of the population covered annually decreases over time, as the costs of delivery rise for less populated areas.

London accounts for over 6 million of the 16 million users covered in the first year, whereas Wales only accounts for less than 200,000 users. Fig. 4 shows the annual spatial rollout across Britain using Ofcom's standard statistical geography. Visualised geographically, it emphasises that England (98%) receives near-ubiquitous coverage by 2030, whereas Wales (90%) and Scotland (86%) have areas that are still poorly served by the market at the end of the study period.

Within the first year of rollout, the city centres of all ONS defined Primary Urban Areas receive 5G infrastructure. Most suburban areas then receive coverage between 2022 and 2023. Rural area coverage takes place between 2024 and 2030.

4.2. Annual capital intensity

The cumulative population covered over the study period based on different annual capital intensities ranging from £1.5 billion to £2.5 billion is shown in Fig. 5.

The results are not linear as the costs increase exponentially for the last 20% of the population. Thus, the varying annual capital

Table 3
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

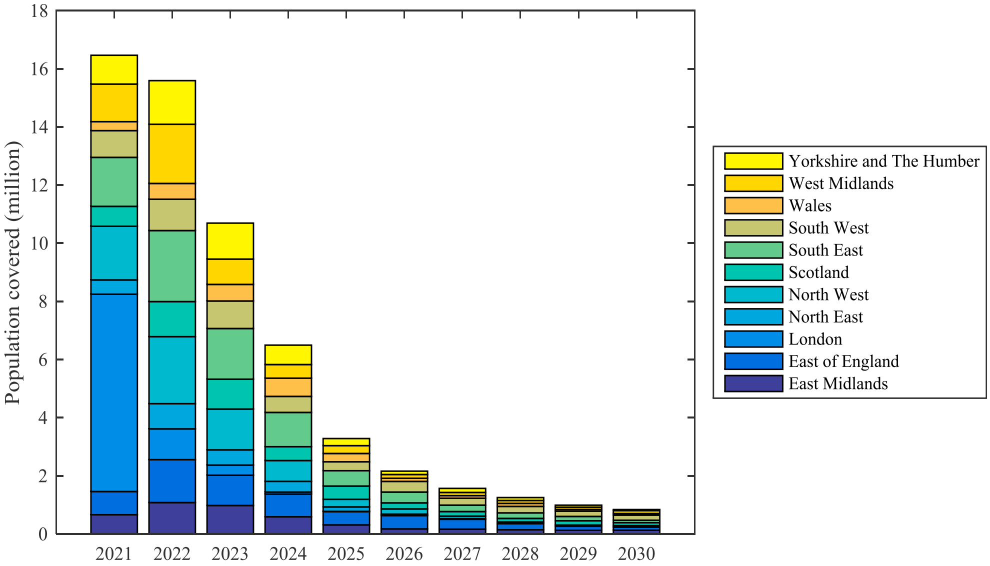

Fig. 3. Baseline regional rollout for 2020–2030.

intensity affects the cumulative population covered in multiple ways. For example, if MNOs collectively invested £1.5 billion in the first year, 17.8% of the population would be covered. Alternatively, if the annual capital commitment was £2.5 billion this would lead to a population coverage of 30%, reaching an additional 12.2% of the population. However, this difference in capital investment only leads to 7% more population coverage by 2030, raising the question as to whether this is worth the additional £10 billion in capex. As Fig. 5 illustrates, the growth rate changes considerably at the 90th percentile where rollout slows. However, the population prior to this point is affected by the speed of delivery due to capital intensity. For instance, by investing £2.5 billion per year it would take five years to reach 90% of the population, while it would take eight years with a capex intensity of £1.5 billion per year. The disparity in the cost of rollout for different settlement patterns is evident in Fig. 6, in relation to the total population covered annually for different capital intensities.

In terms of the spatial dimension of the rollout, Figs. 7 and 8 show the proportion of the population covered annually by region for capital intensities of £1.5 billion and £2.5 billion. These figures illustrate those regions benefiting from an early deployment of 5G services through higher levels of annual capital intensity. For lower capital intensities, it would take longer to cover London and other major urban conurbations, which would account for more than half of the population covered during the first year. For the highest level of annual capital intensity considered (£2.5 billion annually), Scotland would benefit the most, as by 2030, 25% of the population covered that year would be in that region.

4.3. *Infrastructure sharing*

The results above assume a 'business-*as*-usual' approach to infrastructure. This means that the two existing macrocell networks (each shared by two of the four MNOs) would enhance their performance through two different networks of small cells. However, one possible way to reduce costs, and thus potentially increase the pace of rollout, would be to build a single shared layer of small cells routing traffic of any provider. Fig. 9 shows the cumulative population covered over the study period based on these two different approaches.

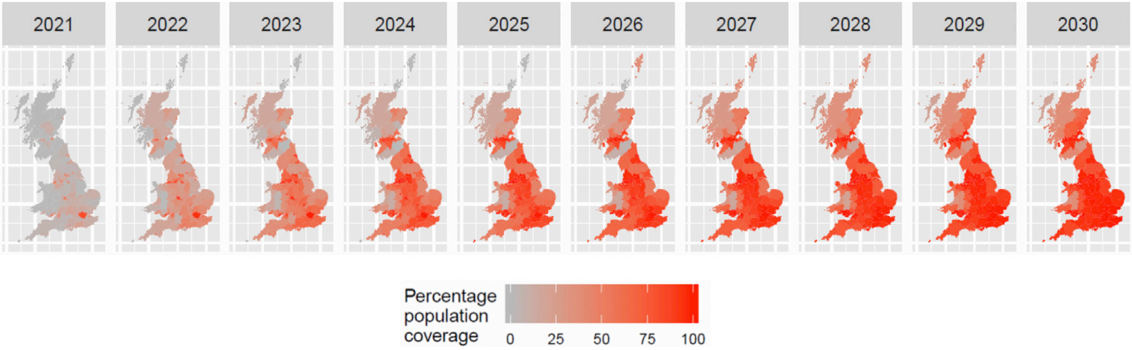

Fig. 4. Baseline spatial rollout for 2020–2030.

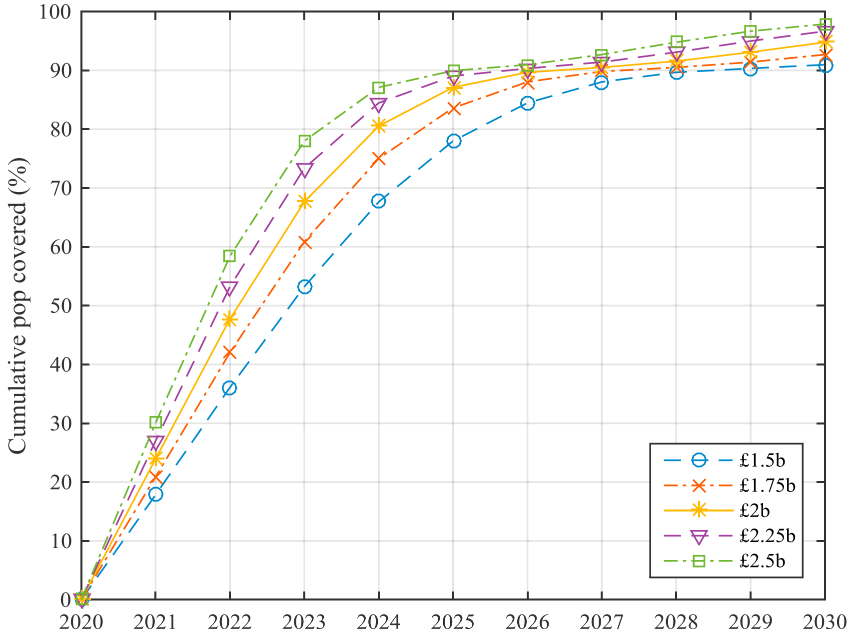

Fig. 5. Cumulative population covered based on different annual capital intensities.

Much like in the previous case, the results show that market forces will be unlikely to cover the final 10% with 50 Mbps ultrafast broadband. At low levels of cumulative population coverage, there is less of a disparity between the two cases. For example, to cover the first third of the population it would only take approximately half a year longer if the greenfield small cell layer was not shared. However, this shift increases along with the level of population covered. For reaching 90% of the population, this difference would grow to three years between the two scenarios. This results from small cells being capacity-constrained in urban environments. Thus, the savings obtained from sharing a small cell layer only arise from sharing the costs of delivering passive infrastructure (civil engineering works), as the two networks operate at full capacity. However, in rural areas the potential gain from sharing is much higher, as small cell assets have underused capacity, leading to a more efficient use of capital.

Figs. 10 and 11 show the breakdown by regions for business-*as*-usual and shared small cell scenarios, considering an equal capital intensity of £2 billion annually for both cases. A shared small cell network would most benefit the areas with the lowest population densities (i.e. Scotland), as these areas see the largest cost savings.

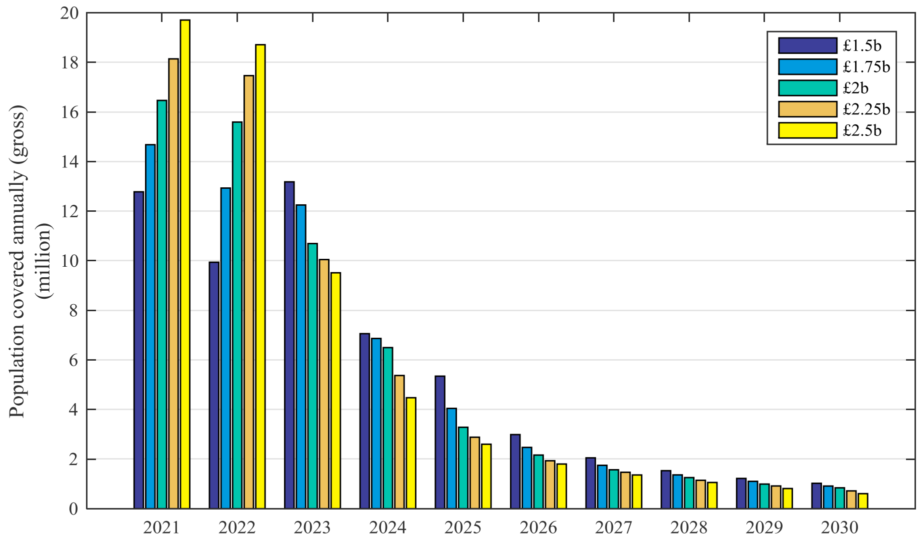

Fig. 6. Population covered based on different annual capital intensities.

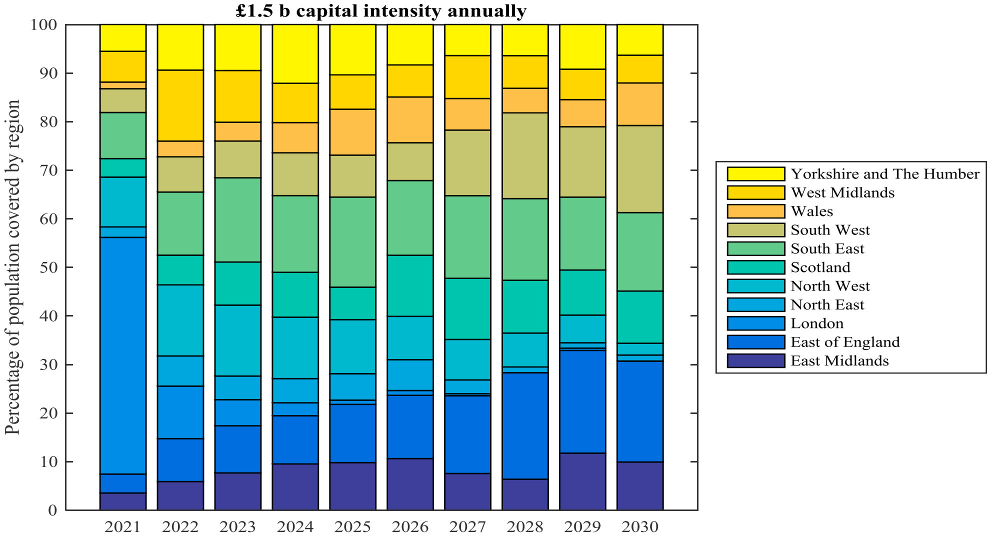

Fig. 7. Regional rollout with £1.5 billion annual capex.

4.4. End-user speed

The economics of the rollout of 5G networks show that for the business-*as*-usual scenario 90% of the population could be covered by 2026. However, 3.7% of the population would be left out of the 5G footprint by 2030, even if the same investment intensity is assumed for the last few years of the study period. Sharing small cell infrastructure would improve the business case pushing towards near-ubiquitous coverage by 2030. This is, however, unlikely to occur as investing an additional £12 billion to cover the final 10%, while the first 90% only required £6 billion, may not be an attractive prospect for industry or government. Thus, it may be more appropriate to compromise on capacity in rural areas to achieve greater coverage of a lower speed target.

Fig. 12 shows the results of the 5G rollout for 2020–2030 based on different end-user speeds for rural settlement patterns.

Firstly, for all end-user speeds the three cases show equal results for approximately 86% of the initial population, as the rural segment only represents the last 14%. Secondly, even for the last 14% there is no difference in the costs of providing either 30 Mbps or 50 Mbps per user in rural areas, because if spectrum integration fails to meet demand leading to small cell deployment, the fixed costs are the same for delivering 30 Mbps or 50 Mbps per user.

Finally, the cumulative curve for the 10 Mbps case does 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 due to low population density. As spectrum costs are not included here, the resources required in meeting this demand are minimal.

5. Policy implications

Based on analysis of previous generations of telecommunications technologies, the largest economic impacts are achieved when reaching near-ubiquitous coverage (Röller & Waverman, 2001). Hence, this is an important objective regardless of whether governments pursue this as an industrial policy or to reduce digital divide issues. We will now discuss the key policy dimensions of this research.

5.1. Market failure, state aid and Brexit

Since the pace of the rollout is increasingly important for government, policy makers' desire ways to accelerate the delivery of next-generation services, and state aid may be one option in areas of market failure. If the UK government is willing, funding could be allocated centrally from Westminster (as in the Mobile Infrastructure Project) or by devolved administrations (such as Wales' Superfast Cymru fixed broadband rollout programme). Some UK regions currently receive European Regional Development Funds for digital infrastructure investment to address market failure. Although the terms of leaving the European Union (EU) are yet to be decided, this funding option may no longer be available post-Brexit, hence would need to be replaced domestically.

Traditionally, standard EU guidelines require geographical areas to be segmented into 'black', 'grey' and 'white' depending on levels of competition, both currently and within the next three years. This therefore acknowledges the temporal dimension of market failure in telecommunication networks and could be a way for government to intervene where market forces may not deliver 5G services before 2024 or later. Whether this is reasonable or not is a political position and must be assessed on a case-by-case basis by governments, with the key caveat being that only passive infrastructure is eligible to receive state aid based on current EU rules.

However, the UK's referendum decision to leave the EU may change the options available for state aid. Indeed, during the

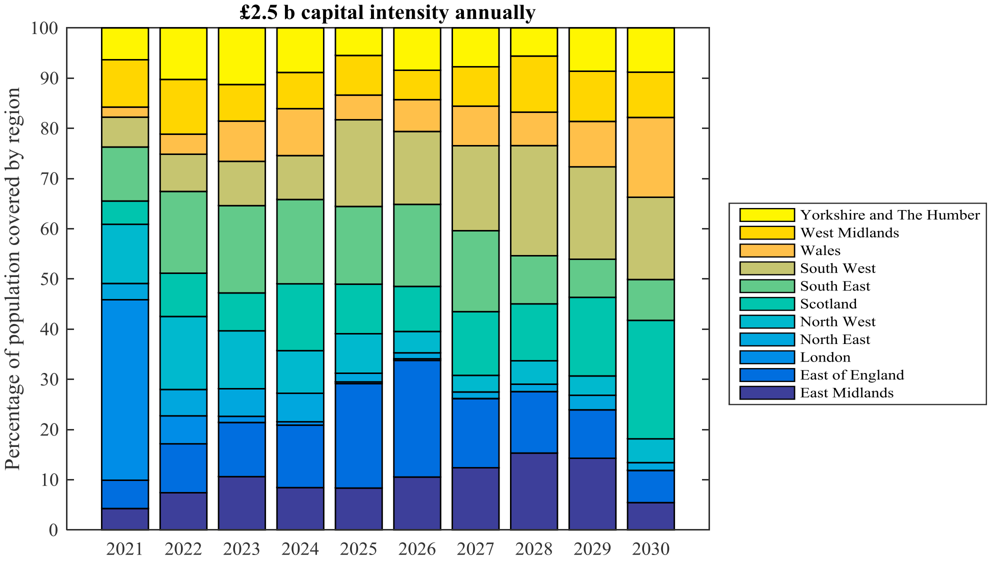

Fig. 8. Regional rollout with £2.5 billion annual capex.

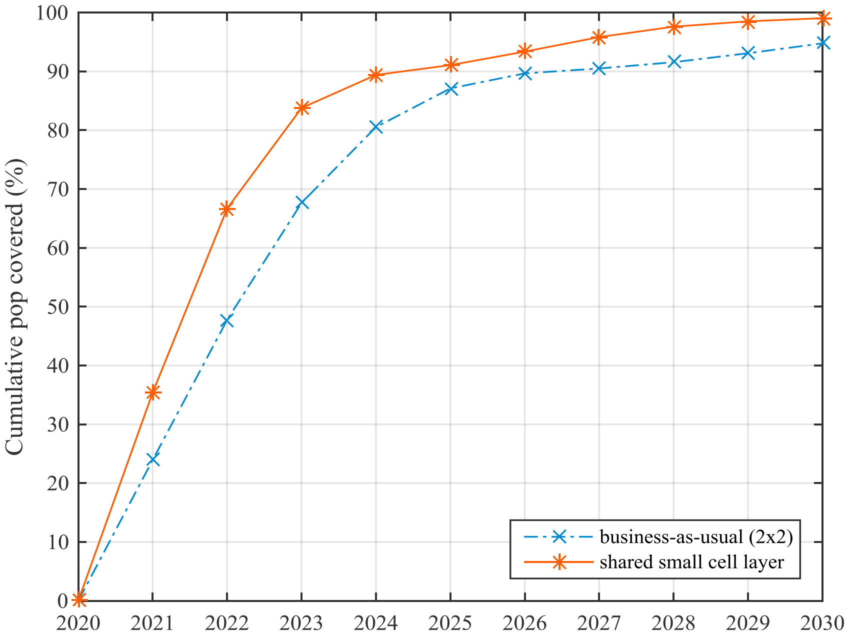

Fig. 9. Rollout for 2020–2030 based on business-*as*-usual vs infrastructure sharing.

referendum campaign EU state aid rules were raised many times because of the limitations they impose on the UK's industrial policy options. Post-Brexit, should the government choose to invest in both passive *and* active telecommunications infrastructure to resolve market failure issues, it would have increased flexibility to do so. However, this is far from a favoured option by the UK's digital communications industry, as articulated by the Broadband Stakeholder Group (2017).

5.2. *Infrastructure sharing*

A key way to reduce the costs of 5G infrastructure rollout is via infrastructure sharing, as illustrated in Section 4.3, where the cumulative population coverage over the study period increased at a faster rate due to deployment of a single small cell layer. Although infrastructure sharing of small cells may make it easier to achieve a critical mass of infrastructure at a faster rate, this must be balanced with the need to maintain competitive market dynamics, ensure infrastructure resilience and avoid potential collusion among market

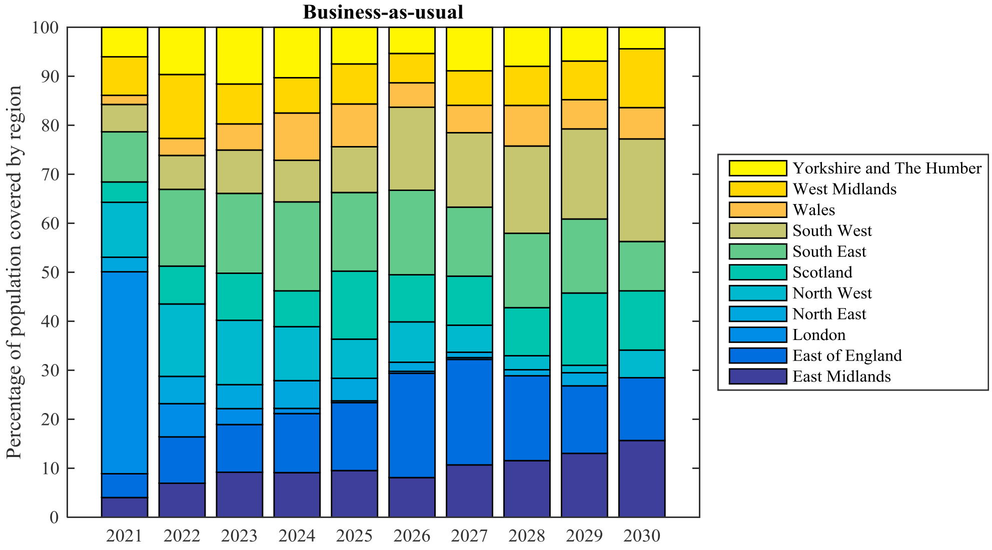

Fig. 10. Regional rollout for 2020–2030 based on business-*as*-usual.

players. Expedient deployment of infrastructure is positively correlated with competitive market environments, as competition encourages MNOs (through necessity) to deliver new services if they wish to maintain market share. Therefore, to retain a market structure that utilises the benefits of both infrastructure sharing and competition, policy makers should explore the use of infrastructure sharing in areas where infrastructure capacity may be underutilised, and market failure is likely to occur (e.g. rural areas). Policy makers should embrace these changes, while being cognisant of the potential impact on reducing competition and resilience within the telecommunications industry.

5.3. Spectrum and coverage obligations

Since we consider frequency bands that are yet to be allocated to MNOs, spectrum costs for 5G are unknown at this point, and therefore not included. However, historical auctions provide useful context and the total cost spent by operators during the UK's 4G auction was £2.3 billion (Ofcom, 2013), indicating a relative magnitude. In this paper, we also avoided testing specific coverage obligations because of the current level of uncertainty around key 5G technical parameters. The results show in Section 4.4 that integrating 700 MHz and 3500 MHz spectrum into existing 4G macrocells fails to meet traffic requirements if the end-user speed is set to either 30 or 50 Mbps. Thus, a layer of greenfield small cells is required. Hence, in rural areas deploying small cells is not necessarily a viable option for wide area coverage, and a much less efficient use of capital if spectrum resources could be utilised to meet demand instead. Our results demonstrate that MNOs can provide cost-effective 10 Mbps coverage to all rural areas through integrating 700, 800, 2600 and 3500 MHz spectrum into existing sites. Therefore, spectrum plays a major role in lowering the costs of a network rollout capable of proving 10 Mbps per user in rural areas, with wireless methods deserving further analysis for meeting the fixed access USO (Ofcom, 2016a).

Coverage obligations have traditionally been used to address these issues and the upcoming auction of 700 MHz spectrum will provide policy makers the option of imposing new coverage obligations in rural areas. Ofcom also has the option to vary existing licences (see Ofcom, 2016c). Based on our findings the rollout costs are proportionate and potentially viable for 10 Mbps per user in rural areas, although more research needs to explore how spectrum and densification will affect coverage and capacity under different population densities. However, 10 Mbps should not be taken as an optimal USO target without further analysis exploring the cost implications below and above this level. Although these are small capacity targets, reliable consistent coverage of these levels with low-latency would enable most mobile applications and services providing they did not make intensive use of video. We will now provide conclusions from this analysis.

6. Conclusion

This article analysed the cost, coverage and rollout implications of 5G ultrafast mobile broadband in Britain. It did this by assessing the rollout implications of different capital intensities, infrastructure sharing and end-user speed. The policy options available to decision makers to expedite the rollout of 5G were then discussed.

In the baseline scenario using existing capital intensity levels, coverage would reach 90% of the population by 2027 with 50 Mbps, although the final 10% would see exponentially increasing costs making this proportion unlikely to be served by the market. Importantly, spectrum plays a major role in lowering the costs of a network rollout capable of providing 10 Mbps per user in rural areas. However, brownfield spectrum integration cannot provide headline end-user speeds equal or higher than 30 Mbps.

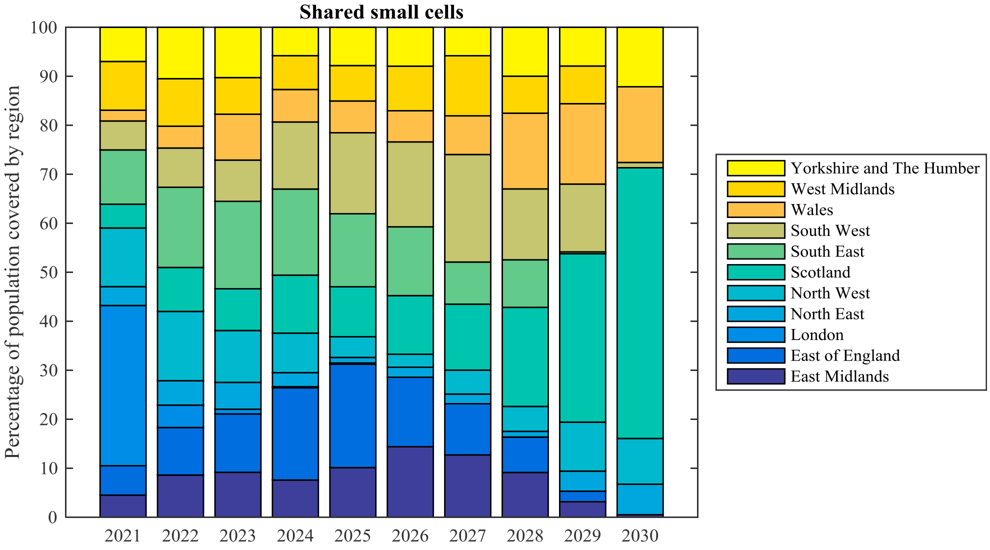

Fig. 11. Regional rollout for 2020–2030 based on infrastructure sharing.

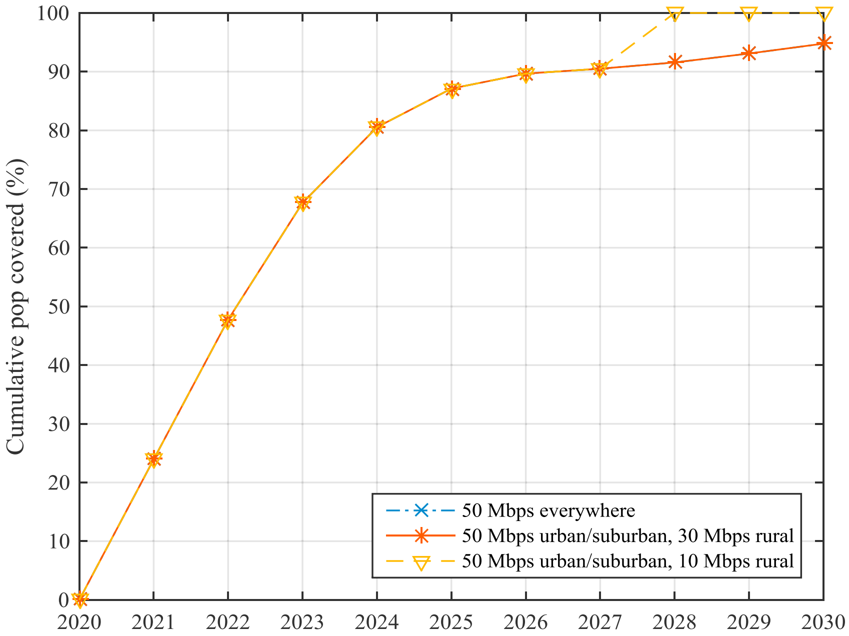

Fig. 12. Rollout based on different end-user speeds for rural areas.

These results suggest that policy makers need to be cautious regarding large headline speeds in rural areas. If these are desired politically, then financial support may be required. However, it may be more appropriate to focus on achieving near-ubiquitous coverage of a moderate level using spectrum resources to support the vertical industries that 5G will purportedly enable. Unless we see a new 'killer-app' for this generation, there is a high probability that market-based 5G ultrafast broadband infrastructure will mainly be the prerogative of urban and suburban areas. At least in the foreseeable future within Britain.

The timely rollout of 5G networks will become increasingly important to achieve the productivity benefits desired by industrial policy, as well as dealing with digital divide issues. The contribution of this research is the quantification of the cost, coverage and rollout implications of 5G based on different policy options. Indeed, as the rollout of telecommunications infrastructure is inherently *spatial* and *temporal*, this is a necessary exploit and one that is becoming increasingly valuable considering the geographical disparities in provision that have arisen in the rollout of previous generations.

Further research needs to focus on refining the costs of both spectrum and infrastructure deployment (including exploring backhaul costs), calibration of investment levels against coverage obligations, and the rollout of 5G in relation to competition, pricing and take-up.

Indeed, greater refinement and exploration of the time lag taken for rollout between different levels of capital expenditure would help decision-making processes involving both operators and government. Moreover, sensitivity analysis is one key tool that can help to identify the cost boundaries which have the largest impact on telecommunications coverage and capacity, and should be explored in future work. While the focus here was on network densification and additional spectrum, the increased spectral efficiency gains of 5G is an area of future uncertainty that requires analysis.

Acknowledgements

This work was supported by the UK Engineering and Physical Science Research Council programme grant entitled Multi-scale InfraSTRucture systems AnaLytics (EP/N017064/1). Modest funding was provided by the National Infrastructure Commission for the production of the original report to cover travel and writing costs. All research was conducted entirely independently. The authors would like to thank Henry Shennan, Joe Butler and James Padden of the HM Treasury's National Infrastructure Commission, as well as Stephen Temple, David Cleevely, Gerry Foster, Graham Louth and Monica Paolini for feedback and direction on the research. No conflicts of interest are present. Zoraida Frias would like to thank the Universidad Politécnica de Madrid for their support through the mobility program scholarship.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.telpol.2017.07.009.

References

3GPP. (2010). *TR 36.814-further advancements for E-UTRA: Physical layer aspects*. Retrieved 31 October 2016, from http://www.3gpp.org/ftp/Specs/archive/36_series/36.814/.

5G NORMA. (2016). *Deliverable D2.1: Use cases, scenarios and requirements. 5G PPP*. Retrieved from https://5gnorma.5g-ppp.eu/wp-content/uploads/2015/11/5G-NORMA_D2.1.pdf.

5GPPP. (2016, December 21). *5G–PPP: The 5G public private partnership*. Retrieved from https://5g-ppp.eu/.

Akdeniz, M. R., Liu, Y., Samimi, M. K., Sun, S., Rangan, S., Rappaport, T. S., et al. (2014). Millimeter wave channel modeling and cellular capacity evaluation. *IEEE Journal on Selected Areas in Communications, 32*(6), 1164–1179.

Akyildiz, I. F., et al. (2016). 5G roadmap: 10 key enabling technologies. *Computer Networks, 106*, 17–48. http://dx.doi.org/10.1016/j.comnet.2016.06.010.

Analysys Mason. (2008). *The costs of deploying fibre-based next-generation broadband infrastructure*. Cambridge: Analysys Mason. Retrieved from http://www.analysysmason.com/PageFiles/5766/Analysys-Mason-final-report-for-BSG-(Sept2008).pdf.

Analysys Mason. (2010). *The costs and capabilities of wireless and satellite technologies - 2016 snapshot*. London: Analysys Mason.

Analysys Mason. (2012). *Digital Agenda for Europe: The green light for fibre?* London: Analysys Mason. Retrieved from http://www.analysysmason.com/About-Us/News/Newsletter/Digital_Agenda_Europe_Insight_Nov2010/.

Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C., et al. (2014). What will 5G be? *IEEE Journal on Selected Areas in Communications, 32*(6), 1065–1082.

Ayach, O. E., Rajagopal, S., Abu-Surra, S., Pi, Z., & Heath, R. W. (2014). Spatially sparse precoding in millimeter wave MIMO systems. *IEEE Transactions on Wireless Communications, 13*(3), 1499–1513. http://dx.doi.org/10.1109/TWC.2014.011714.130846.

Bhushan, N., Li, J., Malladi, D., Gilmore, R., Brenner, D., Damnjanovic, A., et al. (2014). Network densification: The dominant theme for wireless evolution into 5G. *IEEE Communications Magazine, 52*(2), 82–89. http://dx.doi.org/10.1109/MCOM.2014.6736747.

Bouras, C., Kollia, A., & Papazois, A. (2016a). Dense deployments and DAS in 5G: A techno-economic comparison. *Wireless Personal Communications*, 1–21. http://dx.doi.org/10.1007/s11277-016-3711-0.

Bouras, C., Ntarzanos, P., & Papazois, A. (2016b). *Cost modeling for SDN/NFV based mobile 5G networks*. Retrieved from http://ru6.cti.gr/ru6/system/files/publications/PID4422375.pdf.

Broadband Stakeholder Group. (2017). *Implications of Brexit on the digital communications sector*. London: Broadband Stakeholder Group. Available at: http://www.broadbanduk.org/wp-content/uploads/2017/04/Implications-of-Brexit-on-the-digital-communications-sector-FINAL.pdf. (Accessed 16 April 2017).

Chih-Lin, I., Han, S., Xu, Z., Sun, Q., & Pan, Z. (2016). 5G: Rethink mobile communications for 2020+. *Philosophical Transactions of the Royal Society A, 374*(2062), 20140432.

Curwen, P. (2017). *The 5G Myth: And why consistent connectivity is a better future*. Cambridge, UK: William Webb. Webb Search Limited. http://dx.doi.org/10.1016/j.telpol.2017.03.002 (2016)', Telecommunications Policy, 41(4).

Elixmann, D., Ilic, D., Neumann, K.-H., & Plückebaum, T. (2008). *The economics of next generation access-final report*. WIK: Bad Honnef. Retrieved from http://ppp.worldbank.org/public-private-partnership/sites/ppp.worldbank.org/files/documents/The_Economics_of_Next_Generation_Access_Final_Report.pdf.

Fornefeld, M., Delauney, G., & Elixmann, D. (2008). *The impact of broadband on growth and productivity (A Study on Behalf of the European Commission)*.

Frías, Z., González-Valderrama, C., Martínez, J. P., & others. (2015). Keys and challenges to close the rural broadband gap. The role of LTE networks in Spain. In *26th European regional ITS conference, Madrid 2015*. International Telecommunications Society (ITS). Retrieved from https://ideas.repec.org/p/zbw/itse15/127137.html.

Frias, Z., González-Valderrama, C., & Pérez Martínez, J. (2017). Assessment of spectrum value: the case of a second digital dividend in Europe. *Telecommunications Policy. (Optimising Spectrum Use), 41*(5), 518–532. http://dx.doi.org/10.1016/j.telpol.2016.12.008.

Fund, F., Shahsavari, S., Panwar, S. S., Erkip, E., & Rangan, S. (2016). *Spectrum and infrastructure sharing in millimeter wave cellular Networks: An economic perspective*. arXiv Preprint arXiv:1605.04602. Retrieved from http://arxiv.org/abs/1605.04602.

Ghosh, A., & Ratasuk, R. (2011). *Essentials of LTE and LTE-A*. Cambridge: Cambridge University Press. Retrieved from http://ebooks.cambridge.org/ref/id/CBO9780511997082.

Grubesic, T. H. (2008). The spatial distribution of broadband providers in the United States: 1999–2004. *Telecommunications Policy, 32*(3–4), 212–233. http://dx.doi.org/10.1016/j.telpol.2008.01.001.

Grubesic, T. H. (2010). Efficiency in broadband service provision: A spatial analysis. *Telecommunications Policy, 34*(3), 117–131. http://dx.doi.org/10.1016/j.telpol.2009.11.017.

Holma, H., & Toskala, A. (2012). *LTE-advanced: 3GPP solution for IMT-advanced*. Chichester, UK: John Wiley & Sons, Ltd. Retrieved from http://doi.wiley.com/10.1002/9781118399439.

Hossain, E., & Hasan, M. (2015). 5G cellular: Key enabling technologies and research challenges. *IEEE Instrumentation & Measurement Magazine, 18*(3), 11–21.

Hu, F. (2016). *Opportunities in 5G networks: A research and development perspective*. CRC Press. Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=UcL1CwAAQBAJ&oi=fnd&pg=PP1&dq=Opportunities+in+5G+Networks:+A+Research+and+Development+Perspective&ots=9EMNUwww8P&sig=yJ0ewZNGxSt7Nq0OUFYh9inAdIY.

Jaber, M., Imran, M. A., Tafazolli, R., & Tukmanov, A. (2016). 5G backhaul challenges and emerging research directions: A Survey. *IEEE Access, 4*, 1743–1766. http://dx.doi.org/10.1109/ACCESS.2016.2556011.

Jensen, R. (2007). The digital Provide: Information (technology), market performance, and welfare in the South Indian fisheries sector. *The Quarterly Journal of Economics, 122*(3), 879–924. http://dx.doi.org/10.1162/qjec.122.3.879.

Johansson, K., Zander, J., & Furuskar, A. (2007). Modelling the cost of heterogeneous wireless access networks. *International Journal of Mobile Network Design and Innovation, 2*(1), 58–66. http://dx.doi.org/10.1504/IJMNDI.2007.013805.

Jorgenson, D. W., Ho, M. S., & Samuels, J. D. (2016). The impact of information technology on postwar US economic growth. *Telecommunications Policy, 40*(5), 398–411. http://dx.doi.org/10.1016/j.telpol.2015.03.001.

Jorgenson, D. W., & Vu, K. M. (2016). The ICT revolution, world economic growth, and policy issues. *Telecommunications Policy, 40*(5), 383–397. http://dx.doi.org/10.1016/j.telpol.2016.01.002.

Katsigiannis, M., & Smura, T. (2015). A cost model for radio access data networks. *Info, 17*(1), 39–53. http://dx.doi.org/10.1108/info-09-2014-0036.

Katz, R. L., & Berry, T. A. (2014). *Driving demand for broadband networks and services*. Cham: Springer International Publishing (Signals and Communication Technology). Available at: http://link.springer.com/10.1007/978-3-319-07197-8 (Accessed 31 October 2016).

Kolko, J. (2012). Broadband and local growth. *Journal of Urban Economics, 71*(1), 100–113. http://dx.doi.org/10.1016/j.jue.2011.07.004.

Koutroumpis, P. (2009). The economic impact of broadband on growth: A simultaneous approach. *Telecommunications Policy, 33*(9), 471–485. http://dx.doi.org/10.1016/j.telpol.2009.07.004.

Koutroumpis, P., & Leiponen, A. (2016). Crowdsourcing mobile coverage. *Telecommunications Policy, 40*(6), 532–544. http://dx.doi.org/10.1016/j.telpol.2016.02.005.

Lopez-Perez, D., Guvenc, I., De la Roche, G., Kountouris, M., Quek, T. Q., & Zhang, J. (2011). Enhanced intercell interference coordination challenges in heterogeneous networks. *IEEE Wireless Communications, 18*(3), 22–30.

Mack, E. A., & Grubesic, T. H. (2009). Broadband provision and firm location in Ohio: An exploratory spatial analysis. *Tijdschrift Voor Economische En Sociale Geografie, 100*(3), 298–315. http://dx.doi.org/10.1111/j.1467-9663.2008.00487.x.

Mahloo, M., Monti, P., Chen, J., & Wosinska, L. (2014). Cost modeling of backhaul for mobile networks. In *2014 IEEE international conference on communications workshops (ICC)* (pp. 397–402). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6881230.

Mavromoustakis, C. X., Mastorakis, G., & Batalla, J. M. (2016). In *Internet of things (IoT) in 5G mobile technologies* (Vol. 8). Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-30913-2.

Mogensen, P., Na, W., Kovacs, I. Z., Frederiksen, F., Pokhariyal, A., Pedersen, K. I., et al. (2007). LTE capacity compared to the shannon bound. In *2007 IEEE 65th vehicular technology conference - VTC2007-Spring* (pp. 1234–1238). http://dx.doi.org/10.1109/VETECS.2007.260.

Murdock, J. N., Ben-Dor, E., Qiao, Y., Tamir, J. I., & Rappaport, T. S. (2012). A 38 GHz cellular outage study for an urban outdoor campus environment. In *2012 IEEE wireless communications and networking conference (WCNC)* (pp. 3085–3090). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6214335.

Muto, M., & Yamano, T. (2009). The impact of mobile phone coverage expansion on market Participation: Panel data evidence from Uganda. *World Development, 37*(12), 1887–1896. http://dx.doi.org/10.1016/j.worlddev.2009.05.004.

Nikolikj, V., & Janevski, T. (2014). A cost modeling of high-capacity LTE-advanced and IEEE 802.11ac based heterogeneous networks, deployed in the 700MHz, 2.6GHz and 5GHz bands. *Procedia Computer Science, 40*, 49–56. http://dx.doi.org/10.1016/j.procs.2014.10.030.

Nikolikj, V., & Janevski, T. (2015). State-of-the-Art business performance evaluation of the advanced wireless heterogeneous networks to be deployed for the 'TERA age'. *Wireless Personal Communications, 84*(3), 2241–2270. http://dx.doi.org/10.1007/s11277-015-2491-2.

Ofcom. (2012a). *4G coverage obligation notice of compliance verification methodology: LTE*. London: Ofcom. Available at: https://www.ofcom.org.uk/_data/assets/pdf_file/0026/58292/4gcov-verification.pdf. (Accessed 14 May 2017).

Ofcom. (2012b). *Sitefinder*. Retrieved 21 December 2016, from https://www.ofcom.org.uk/phones-telecoms-and-internet/coverage/mobile-operational-enquiries.

Ofcom. (2013). *Ofcom announces winners of the 4G mobile auction*. Available at: https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2013/winners-of-the-4g-mobile-auction. (Accessed 4 July 2017).

Ofcom. (2014). *Infrastructure report 2014*. London: Ofcom. Available at: http://stakeholders.ofcom.org.uk/market-data-research/market-data/infrastructure/infrastructure-2014/. (Accessed 25 May 2015).

Ofcom. (2015). *Mobile call termination market review 2015-18*. London: Ofcom. Retrieved from https://www.ofcom.org.uk/consultations-and-statements/category-1/mobile-call-termination-14.

Ofcom. (2016a). *Connected nations 2016*. London: Ofcom. Retrieved from http://stakeholders.ofcom.org.uk/market-data-research/market-data/infrastructure/connected-nations-2015/.

Ofcom. (2016b). *Mobile data strategy: Update on our strategy for mobile spectrum*. London: Ofcom. Retrieved from https://www.ofcom.org.uk/_data/assets/pdf_file/0033/79584/update-strategy-mobile-spectrum.pdf.

Ofcom. (2016c). *Ofcom varies mobile operators' licences to improve coverage*. Ofcom. Available at: https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2015/mno-variations. (Accessed 14 May 2017).

ONS. (2016). *2011 Census: Headcounts and household estimates for postcodes in England and Wales*. Office for National Statistics. Retrieved 21 December 2016, from https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/2011censusheadcountsandhouseholdestimatesforpostcodesinenglandandwales.

OpenSignal. (2016). *The state of LTE*. London: OpenSignal. Available at: https://opensignal.com/reports/2016/11/state-of-lte (Accessed 12 December 2016).

Ordinance Survey. (2016, December 21). *Code-Point 2015: Locates every postcode unit in the UK*. Retrieved 21 December 2016, from https://www.ordnancesurvey.co.uk/business-and-government/products/code-point.html.

Oughton, E. J., & Frias, Z. (2016). *Exploring the cost coverage and rollout implications of 5G in Britain - Oughton and Frias report for the NIC*. London: National Infrastructure Commission. Retrieved from https://www.gov.uk/government/publications/connected-future.

Oughton, E., Tyler, P., & Alderson, D. (2015). Who's superconnected and Who's Not? Investment in the UK's information and communication technologies (ICT) infrastructure. *Infrastructure Complexity, 2*(1), 6. http://dx.doi.org/10.1186/s40551-015-0006-7.

Ovando, C., Pérez, J., & Moral, A. (2015). LTE techno-economic assessment: The case of rural areas in Spain. *Telecommunications Policy, 39*(3–4), 269–283. http://dx.doi.org/10.1016/j.telpol.2014.11.004.

Point Topic. (2016). *Europe's broadband investment needs: Quantifying the investment needed to deliver superfast broadband to Europe*. London: Point Topic. Retrieved from http://point-topic.com/free-analysis/europes-broadband-investment-needs/.

Real Wireless. (2015). *UK spectrum usage & Demand: First edition. Pulborough: Real wireless*. Retrieved from https://www.techuk.org/insights/reports/item/6825-uk-spectrum-usage-demand-second-edition.

Röller, L.-H., & Waverman, L. (2001). Telecommunications infrastructure and economic development: A simultaneous approach. *The American Economic Review, 91*(4), 909–923.

Rong, B., Qiu, X., Kadoch, M., Sun, S., & Li, W. (2016). *5G heterogeneous networks*. Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-39372-8.

Rost, P., Banchs, A., Berberana, I., Breitbach, M., Doll, M., Droste, H., et al. (2016). Mobile network architecture evolution toward 5G. *IEEE Communications Magazine, 54*(5), 84–91.

SEAMCAT. (2010). *Spectrum engineering advantage Monte Carlo analysis tool (SEAMCAT) handbook*. SEAMCAT. Retrieved from http://www.seamcat.org/.

Skouby, K. E., Falch, M., Henten, A., & Tadayoni, R. (2014). Need for broadband infrastructure in a 2020 perspective. *Wireless Personal Communications, 76*(2), 271–289. http://dx.doi.org/10.1007/s11277-014-1688-0.

Soldani, D., Barani, B., Tafazolli, R., Manzalini, A., & Chih-Lin, I. (2015). Software defined 5G networks for anything as a service [Guest Editorial]. *IEEE Communications Magazine, 53*(9), 72–73. http://dx.doi.org/10.1109/MCOM.2015.7263348.

Taleb, T., Ksentini, A., & Jäntti, R. (2016). 'Anything as a service' for 5G mobile systems. *IEEE Network*. http://dx.doi.org/10.1109/MNET.2016.1500244RP.

Thurfjell, M., Ericsson, M., & de Bruin, P. (2015). Network densification impact on system capacity. In *2015 IEEE 81st vehicular technology conference (VTC Spring)* (pp. 1–5). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7145947.

Tombaz, S., Monti, P., Farias, F., Fiorani, M., Wosinska, L., & Zander, J. (2014). Is backhaul becoming a bottleneck for green wireless access networks. In *2014 IEEE international conference on communications (ICC)* (pp. 4029–4035). http://dx.doi.org/10.1109/ICC.2014.6883951.

Tullberg, H., Fallgren, M., Kusume, K., & Hoglund, A. (2016). 5G use cases and system concept. In A. Osseiran, J. F. Monserrat, & P. Marsch (Eds.), *5G mobile and wireless communications technology* (pp. 1–20). Cambridge: Cambridge University Press. Retrieved from http://ebooks.cambridge.org/ref/id/CBO9781316417744A014.

Webb, W. (2016). *The 5G Myth: And why consistent connectivity is a better future*. Cambridge: Webb Search Limited.

Zhu, J., She, X., & Chen, P. (2016). Ultra dense Networks: General introduction and design overview. In F.-L. Luo, & C. Zhang (Eds.), *Signal processing for 5G* (pp. 483–508). Retrieved from: John Wiley & Sons, Ltd. http://onlinelibrary.wiley.com/doi/10.1002/9781119116493.ch20/summary.

Edward Oughton has worked as part of the EPSRC-funded Infrastructure Transitions Research Consortium since 2012, where his research first developed models for understanding the factors driving investment in fixed and mobile broadband markets. Ed currently leads the digital communications modelling work with David Cleevely on the EPSRC-funded project entitled Multi-scale InfraSTRucture systems AnaLytics (Mistral). His recent research was contributed as evidence for the UK's National Needs Assessment. The 5G cost assessment model developed as part of ITRC Mistral was used by HM Treasury's National Infrastructure Commission as evidence for the national 5G strategy.

Zoraida Frias is an assistant professor at the Universidad Politécnica de Madrid, where she has been a fellow of the Group of Information Technologies and Communications (GTIC) since 2010. She has contributed to several research projects related to telecommunications regulation and public policies, among others, for the Spanish State Secretary of Telecommunications through the Red.es Professorship. She holds a PhD in Telecommunication Engineering from the Universidad Politécnica de Madrid. In 2015 she was a visiting researcher at the Center for Technology, Innovation and Competition (CTIC) of the University of Pennsylvania. Her interests revolve around competition policy, especially with regard to next-generation networks deployment and spectrum management.