

Cambridge Judge Business School

Working Paper No. 04/2017 (revised)

TOWARDS 5G: SCENARIO-BASED ASSESSMENT OF THE FUTURE DEMAND FOR MOBILE TELECOMMUNICATIONS INFRASTRUCTURE

Edward Oughton, Zoraida Frias, Tom Russell,
Douglas Sicker, David D Clevely



UNIVERSITY OF
CAMBRIDGE
Judge Business School

Cambridge Judge Business School Working Papers

These papers are produced by Cambridge Judge Business School, University of Cambridge. They are circulated for discussion purposes only. Their contents should be considered preliminary and are not to be reproduced without the authors' permission.

Cambridge Judge Business School author contact details are as follows:

Dr Edward Oughton
Cambridge Judge Business School
University of Cambridge
Trumpington Street, Cambridge CB2 1AG

Email: e.oughton@jbs.cam.ac.uk

Please address enquiries about the series to:

Research Manager
Cambridge Judge Business School
University of Cambridge
Trumpington Street, Cambridge CB2 1AG

Email: research-support@jbs.cam.ac.uk

Tel: 01223 760546

Towards 5G: Scenario-based Assessment of the Future Supply and Demand for Mobile Telecommunications Infrastructure

Edward Oughton^{1*}, Zoraida Frias², Tom Russell³, Douglas Sicker⁴, David D. Cleevly⁵

¹Cambridge Judge Business School, University of Cambridge, Cambridge, UK, ²Information Processing and Telecommunications Center, Universidad Politécnica de Madrid, Madrid, Spain, ³Environmental Change Institute, University of Oxford, Oxford, UK, ⁴ School of Computer Science, Carnegie Mellon University, Pittsburgh, USA, ⁵Raspberry Pi Foundation, Cambridge, UK.

* Corresponding author: e.oughton@jbs.cam.ac.uk at Cambridge Judge Business School, University of Cambridge, Trumpington Street, Cambridge, UK, CB2 1AG



Acknowledgements

Edward Oughton, Zoraida Frias, Tom Russell and David Cleevly would like to express their gratitude to the UK Engineering and Physical Science Research Council for funding via grant EP/N017064/1: Multi-scale InfraSTRucture systems AnaLytics (Mistral). Zoraida Frias would like to thank the Universidad Politécnica de Madrid for their support through the mobility program scholarship. Additionally, we would like to recognise the contribution of all participants at the EPSRC Mistral workshop on *The Future of Digital Communications* at St. Catharine's College, Cambridge, on 1st February 2017. The authors have no competing interests.

Abstract

Moving from 4G LTE to 5G is an archetypal example of technological change. Mobile Network Operators (MNOs) who fail to adapt will likely lose market share. Hitherto, qualitative frameworks have been put forward to aid with business model adaptation for MNOs facing on the one hand increasing traffic growth, while on the other declining revenues. In this analysis, we provide a complementary scenario-based assessment of 5G infrastructure strategies in relation to mobile traffic growth. Developing and applying an open-source modelling framework, we quantify the uncertainty associated with future demand and supply for a hypothetical MNO, using Britain as a case study example. We find that over 90% of baseline data growth between 2016 and 2030 is driven by technological change, rather than demographics. To meet this demand, spectrum strategies require the least amount of capital expenditure and can meet baseline growth until approximately 2025, after which new spectrum bands will be required. Alternatively, small cell deployments provide significant capacity but at considerable cost, and hence are likely only in the densest locations, unless MNOs can boost revenues by capturing value from the Internet of Things (IoT), Smart Cities or other technological developments dependent on digital connectivity.

Key words

5G; Mobile telecommunication; Scenario; Decision support; Rollout; Cost modelling; Strategic management

1 Introduction

The mobile telecommunications industry has a dynamic competitive environment due to widespread and sustained technological change (Curwen and Whalley, 2004; Han and Sohn, 2016). We experience generational upgrades on at least a decadal basis, requiring Mobile Network Operators (MNOs) and other market actors to have an understanding of future digital evolution. Even market leaders with significant advantages in the telecommunications industry can fall behind if they are unable to keep abreast of new developments and actively adapt existing market strategies for new conditions (Asimakopoulos and Whalley, 2017). Indeed, the digital ecosystem is experiencing significant disruption from new digital platforms and services (Ruutu et al. 2017; Wang et al. 2016), with substantial ramifications for MNOs as revenues have been either static or declining (Chen and Cheng, 2010), and these conditions exist alongside the increasing operational costs of serving ever increasing mobile data traffic. Hence, in wireless telecoms, MNOs must be aware of both opportunities and threats arising from technological change, particularly when moving from one generation to the next (du Preez and Pistorius, 2002; Salmenkaita and Salo, 2004).

Telecommunications are essential for modern economic activities, as well as for a fully functioning society. These technologies can enable economic growth through new content, services and applications (Hong, 2017; Krafft, 2010), while also enabling productivity improvements throughout the economy by lowering costs. The ability of Information Communication Technologies (ICT) to interchange data via telecommunications networks is essential for the economic development of the digital economy (Wymbs, 2004; Cheng et al. 2005; Kim, 2006), and the range of industrial sectors it comprises. New cross-sectoral advances have also emerged, such as the Internet of Things (IoT) and Smart Cities (Yang et al. 2013; Hong et al. 2016; Bresciani et al. 2017; Almobaideen et al. 2017), which rely on the availability of digital connectivity for smartphones, sensors and other communications devices. Hence the signal quality of mobile telecommunications infrastructure is an ever more important factor, requiring operators to focus on both network reliability and capacity expansion techniques to meet consumer and industrial requirements (Shieh et al. 2014). This is challenging however, given the weak revenue growth currently experienced, leaving only a modest appetite for infrastructure investment.

Scenario planning is a foresight tool that can be applied to understand how changes in the external environment may affect current or potential market strategies (Ramirez et al. 2015). On the one hand, this approach can be used to foster learning and the adaptive skills of an organisation (Favato and Vecchiato, 2016), while on the other, it supports high-level strategic decision-making (O'Brien and Meadows, 2013; Parker et al. 2015). Quantified approaches allow one to measure the impact of external drivers using systems modelling. Importantly, the choice of how much infrastructure is required, when, and where, is seen to be a problem of decision-making under uncertainty (Otto et al. 2016).

The aim of this paper is to quantify the uncertainty associated with the future demand for mobile telecommunications infrastructure, to test how different strategies perform over the long term. We focus specifically on capacity expansion via 5G mobile telecommunications infrastructure. In undertaking this task, the research questions which we endeavour to answer are as follows:

1. How will the combination of growing data usage and demographic change affect the demand for mobile telecommunications infrastructure?
2. How do different supply-side infrastructure options perform when tested against future demand scenarios?
3. What are the ramifications of the results, and how do they relate to the wider technological change literature, particularly in mobile telecommunications?

As the '5G' standard is still to be determined, the approach taken in this paper is to extrapolate LTE and LTE-Advanced characteristics, and to include those identified frequency bands that may be used for 5G rollout over the next decade, in relation to changing demand. Hence, a spectrum-based strategy

includes integrating 700 and 3500 MHz on existing brownfield macrocellular sites, as these will be the newly available frequency bands to MNOs in Europe. Importantly, we also test the impact of increasing network densification using a small cell deployment strategy, as this is a key technological enabler for delivering expected 5G performance.

In the next section, a literature review will be undertaken in relation to the future demand for telecommunications services, as well as the current state-of-the-art of telecommunications infrastructure assessment. In Section 3 the methodology will be outlined, and the results reported in Section 4. The findings will be discussed in Section 5, and finally conclusions will be stated in Section 6.

2 Literature Review

Although the full specification of '5G' is yet to be determined, it is likely that the technical requirements will include delivering peak rates of 20 Gbps per user in low mobility scenarios, user experienced data rates of 100 Mbps, radio latency of less than 1 ms, significantly higher area traffic capacity (1000 times LTE), and a massive number of devices (ITU, 2015; Shafi et al. 2017). This will provide enhanced mobile broadband, massive machine type communications, and ultra-reliable low latency communications. While new generations of mobile technology can be dominated by marketing spin (Shin et al. 2011), there is consensus that network densification via smaller cells will be a key technique for 5G networks (Andrews et al. 2014). As the research questions outlined in this paper require a focus on technological forecasting, the relevant literature will now be reviewed, before the techno-economic literature on next generation mobile networks is evaluated.

Technological Forecasting in Telecommunications

Modelling and simulation methods are frequently combined with scenario planning approaches to test potential telecommunication strategies. As well as for strategic purposes, MNOs also often rely on demand forecasts methods to justify internally and externally the considerable investments required to move into new markets (see Fildes, 2002; 2003). This is often related to generational upgrades of technologies, where forecasts can help to understand, for example, how different factors affect the demand for future mobile wireless communications services (Frank, 2004). Commonly used methods include time-series econometric approaches (Lee, 1988), innovation diffusion modelling (Jun et al. 2002; Venkatesan and Kumar, 2002; Meade and Islam, 2006; Michalakelis et al. 2008; Chu and Pan, 2008) and technological forecasting (Meade and Islam, 2015). Systems dynamics approaches have also been applied to model the underlying dynamics of mobile telecommunications diffusion (Mir and Dangerfield, 2013).

Generational changes in mobile wireless technology also provide opportunities for new market niches (Nam et al. 2008), but this can often lead to failure (Park et al. 2015). Shin et al. (2011) focus on the socio-technical dynamics of moving from 3G to 4G LTE telecommunications, and study how 4G strategies have been formed, shaped and enhanced. Importantly, the transition between different generations of mobile technologies requires executives to adapt to a dynamically evolving industrial landscape as technology and regulation both change.

Ghezzi et al. (2015) highlight the rapid transformation taking place in the telecommunications industry due to technological change and develop a framework to support MNOs operating in highly competitive markets. Using structured interviews with top- and middle-managers from four Italian MNOs, the authors identify the key drivers of disruptive change and the implications for their current business models. Increasing data traffic and decreasing voice revenues are the key drivers of disruptive change. Indeed, the emergence of Voice-over-IP (VoIP) services is one key driver of decreasing voice-related revenues, as users substitute paid voice services via an MNO for free VoIP access over the Internet (e.g. via Skype), leading the infrastructure owner to lose revenue (Kwak and Lee, 2011). MNOs have addressed this by bundling voice and SMS with data (Stork et al. 2017).

The analysis of digital adoption and the diffusion forecasting of mobile telephony has received significant attention in the technological change literature (Islam et al. 2002; Vicente and Gil-de-Bernabé, 2010; Kim et al. 2010; James, 2012; Kyriakidou et al. 2013; Mayer et al. 2015; Pick and Nishida, 2015; Park et al. 2015; Islam and Meade, 2015; Sultanov et al. 2016; Sadowski, 2017), but relatively little focus has been placed on how this may affect mobile traffic growth, operator cost and competitiveness. However, in the rapidly growing ICT market, the forecasting of new technologies is a difficult yet necessary endeavour for operators and not something that should be purely left for the engineering domain as it has important commercial strategy ramifications.

In one such study, Lee et al. (2016) forecast mobile broadband traffic demand in Korea, using a device-based approach and a three-round Delphi expert elicitation process. Scenario analysis was applied to reflect uncertainty in the future dynamics of the sector, with 'optimistic', 'neutral' and 'pessimistic' scenarios being developed. Unsurprisingly, the conclusion was that mobile traffic will continue to increase, but the authors quantify by how much, and Korea is expected to see an increase to approximately 286 Petabytes per month by 2020, which is six times greater than 2012. This is approximately 6 GB of monthly mobile traffic per user.

Velickovic et al. (2016) develop and apply a forecasting model for the deployment of fixed Fibre-To-The-Home (FTTH) telecommunication infrastructure, where demand forecasting is used to enable the dimensioning of necessary network resources. This is essential for operators to understand which investments are required, spatially and temporarily, to meet evolving demand. The network economics of telecommunications networks make it extremely challenging to service low demand areas, as there are inevitably large fixed capital costs in deployment which need to be shared across many users. Hence, demand stimulation is an activity that needs to take place simultaneously when there is poor take-up, to encourage more favourable scale economies (Yoo and Moon, 2006).

There has been relatively little emphasis on how infrastructure, a key mediator in the global economy, affects firm strategy. Often those studies that have addressed this important topic have focused on expert elicitation, Delphi approaches to scenario development or case studies (Schuckmann et al. 2012; Raven, 2014; Bolton and Foxon, 2015; Roelich et al. 2015; Labaka et al. 2016), which are valuable in generating understanding, but can be complemented by modelling, simulation and the testing of 'what if' scenarios (Huétink et al. 2010; Zani et al. 2017).

Techno-economic assessments of next generation mobile networks

Undertaking analysis for the UK telecommunication regulator Ofcom, Real Wireless (2012) examine the impact of the 700 MHz band in meeting growing demand for wireless broadband capacity. Different traffic demand scenarios were developed and tested, focusing on variations in mobile traffic by device penetration and type. Demographic change over time was not included in this analysis for the period 2012-2030 (such as fertility, mortality and migration), despite it potentially having a multiplier effect, as large increases in the population will affect device growth and traffic demand. Ultimately, the cost of 5G systems will be determined by the large number of new components required to operate enhanced network infrastructure, including basestation units and backhaul transmission, as well as the associated cost of site installation, site operation, network optimisation and maintenance, and edge cache placement (Yan et al. 2017).

With the rapid growth of data and additional required network capacity, the solution to this is not merely an engineering domain issue, but also increasingly a techno-economic problem (Zander, 2017). While some of the underlying difficulties are highly technical, including dealing with interference and noise, escalating energy consumption, and using available bandwidth more efficiently, many of them are economic, including the cost of a dense small cell layer. Hence, there is a growing need for disruptive business model innovation to provide technically scalable solutions for enhanced wide-area capacity, while remaining within certain energy consumption and cost constraints.

Breuer et al. (2016) undertook a techno-economic analysis of 5G fronthaul and backhaul, focusing on the convergence benefits with fixed access (ranging from FTTH to Fibre-To-The-Cabinet). Different 'massive 5G' small cell deployments are explored as a broadband data layer coexisting with a macro basestation network. Moreover, economic analysis of '5G superfluid networks' by Chiaraviglio et al. (2017) assessed capex, opex, Net Present Value (NPV) and Internal Rate of Return (IRR) for two case study areas, where operators were migrating from legacy 4G networks, in Bologna, Italy and San Francisco, USA. The analysis found that the cost of deploying dedicated hardware was higher than the cost of deploying commodity hardware running virtual resources. In a profit analysis, the authors also found that the monthly subscription fee could be kept sufficiently low, while still generating profit overall.

An engineering-economic analysis of China's Shanghai region by Smail and Weijia (2017) used cost-benefit modelling to assess the deployment of 5G technologies in relation to legacy 4G mobile networks. Comparison analysis was performed of price, cost, coverage and capacity for different scenarios using heterogeneous basestation types. This included the development of a pricing model. Key findings include the most cost-effective solution being macro cells with improved carrier aggregation, and the use of existing sites being critical to keep down costs. Having reviewed the literature on the modelling of mobile wireless infrastructure, we will now focus on Britain as a case study.

Britain as a Case Study Example

In 2016, the then Chancellor George Osborne tasked the National Infrastructure Commission with advising 'the Government on what it needs to do to become a world leader in 5G infrastructure deployment, and to ensure that the UK can take early advantage of the potential applications of 5G services' (Osborne, 2016:1). Consequently, the UK's 5G strategy was released in 2017, entitled 'Next Generation Mobile Technologies: A 5G Strategy for the UK' (DCMS and HM Treasury, 2017), containing content on the economic case, regulation, governance, coverage and capacity, security, spectrum and technology. The UK is also embarking on its first comprehensive National Infrastructure Assessment, which will include the supply and demand of mobile telecommunications (National Infrastructure Commission, 2017).

Both the 5G Strategy and National Infrastructure Assessment are important market drivers reflecting that some consumers are unhappy with the current state of telecommunications in the UK. For example, the British Infrastructure Group (2016), consisting of over 90 cross-party Members of Parliament, have supported calls for reform to the sector in a recent mobile coverage campaign, based on the elimination of areas of no coverage (known as 'not-spots'). In terms of existing provision, recent analysis by the regulator Ofcom (2016) found that 4G coverage by all four operators now reaches 72% of premises indoors and only 4% of the premises are not covered by 4G signal from any operator. However, only 40% of the geographic area is covered by every operator. Indeed, some feel the experience differs from the reported voice and data coverage statistics leading to disgruntled users, with this therefore becoming a hot topic in the media. OpenSignal's (2017) State of LTE report shows that the UK ranks 43rd globally in terms of 4G availability and 39th in terms of speed (subject to the usual speed test caveats).

The concern is that not enough digital access infrastructure is being deployed, potentially leading to businesses and consumers being dissatisfied. In some cases, demand could exceed supply, which may have potential economic impacts as telecommunications underpin economic activities with bottlenecks leading to productivity issues. Both the National Infrastructure Assessment and the UK's 5G Strategy aim to eliminate or reduce connectivity problems, but there are still a limited range of metrics to help support future decision making in both industry and government, which we aim to address in this analysis.

3 Methodology

There is a lack of *open-source* modelling frameworks for assessing the supply and demand of telecommunications. In this paper, we apply the Cambridge Communications Assessment Model testing it annually up to 2030, based on the methodology illustrated in Figure 1. The approach allows us to assess mobile against future demand scenarios, including (i) required per user traffic and (ii) fertility, mortality and migration. We utilise Object Oriented Programming (OOP) principles to deliver the flexibility required for the multi-level modelling of assets, networks and whole systems. The OOP approach has previously been utilised for technological forecasting by applying it to the UK mobile telecommunications industry to support management decisions (Christodoulou et al. 1999). Transparency and reproducibility are central tenets of the research and therefore we have provided open-source access to the model code (https://github.com/nismod/digital_comms).

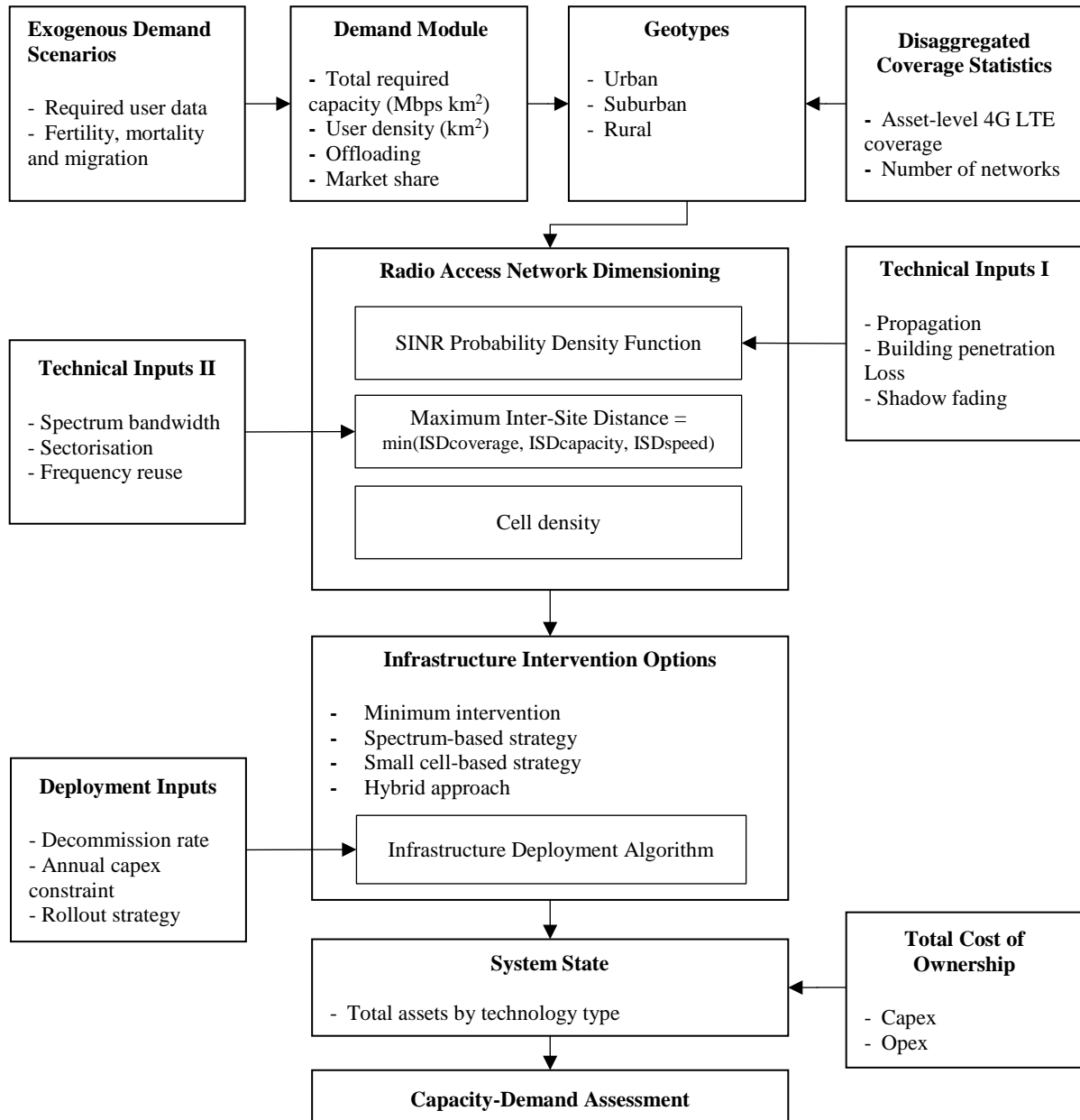


Figure 1 Methodological sequence

The process of producing the exogenous demographic scenarios is articulated in Thoung et al. (2016) with the projections considering fertility, mortality and migration. A baseline was developed by calibrating the microsimulation model with UK population data between 2001 and 2011. The data are

very high resolution using the Local Authority District as the statistical unit of projection. We then disaggregate these projections annually between 2016 and 2030 to approximately 9000 postcode sectors, using a population weighting from the last UK census (ONS, 2013).

Although there has been exponential traffic growth over the last decade, future data demand is unknown. In the UK, according to the data reported by Ofcom (2012c; 2013; 2014; 2015a; 2016), the average data consumption was 110 MB per month in March 2011. This demand more than doubled in one year, to 240 MB in 2012. In 2016, average monthly data consumption per user reached 1.3 GB. Figure 2 shows the historical series for the UK in light blue. The reasons behind this large increase in data demand are mainly related to the rollout of 4G LTE, allowing for higher mobile broadband speeds, driving data consumption, particularly from video and ‘data-hungry’ applications.

Latest data from Cisco (2017) report that video accounts for 63% of all mobile traffic in the UK and that it will grow seven-fold by 2021, meaning that by then video would be 81% of the UK mobile data traffic. The same report forecasts a Compound Annual Growth Rate (CAGR) of 38% for mobile traffic in the UK over the next five years, as shown in orange in Figure 2.

As the proportion of video in mobile traffic reaches saturation levels, CAGRs for per-user data demand tend to slow (Cisco, 2011; 2012; 2013; 2014; 2015; 2016, 2017). As 4G reaches maturity, future data demand growth is more uncertain, as this will depend on potential 5G use cases and services. Hence, in this paper we explore three different scenarios regarding data demand for connectivity services once 5G technologies start to be commercially deployed from 2020:

1. High demand, with sustained exponential growth at 25% CAGR over 2021-2030.
2. Baseline demand, where data demand follows a linear increase over the long-term.
3. Low demand, modelled by a logistic curve (as stated in equation 1), which represents the ‘worst’ scenario for 5G adoption, where there is no new ‘killer app’, causing demand to plateau.

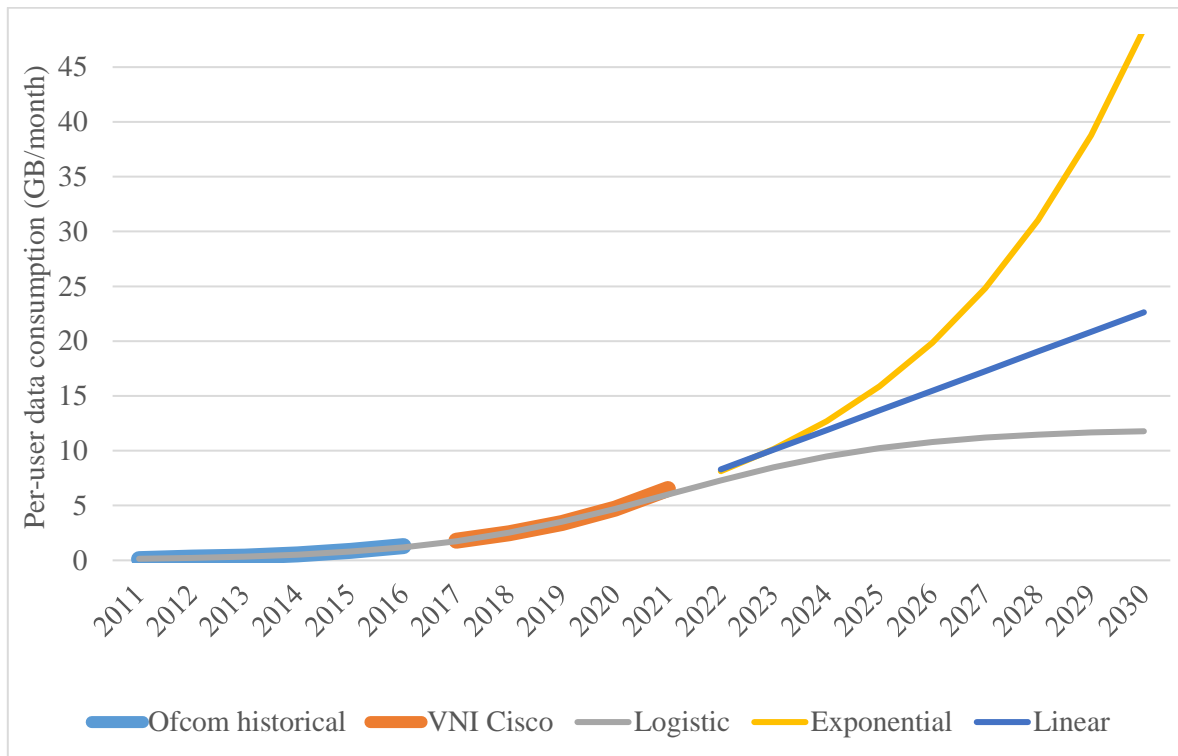


Figure 2 Data growth per user by scenario

Equation (1) represents the logistic curve to model the low demand scenario, where k is 1.764 and D 12 GB. Within the Demand Module, the monthly data demand in a specific year (D_t) is then converted to the number of Mbps required per user (R_t) in time t .

$$f(t) = \frac{D}{1 + e^{-k(t-t_0)}} \quad (1)$$

We dimension the network across 30 user activity days per month (n_d), based on 15% of traffic taking place in the busiest hour (f_{dh}) (Holma & Toskala, 2009). We illustrate this in equation (2):

$$R_t = D_t \times 1024 \times 8 \times \frac{1}{n_d} \times \frac{f_{dh}}{100} \times \frac{1}{3600} \quad (\text{Mbps/user}) \quad (2)$$

where D_t is the data demand at any given time over the study period, as illustrated in Figure 2.

The user density (U) of area i at time t is calculated annually based on the local population (P_{it}), a smartphone take-up rate of 80% ($T = 0.8$) based on the Ofcom (2017) technology tracker, a market share parameter for a hypothetical operator assumed to be 30% ($M_s = 0.3$), and the geographical area (A_i) of the postcode sector, as outlined in equation (3):

$$U_{it} = \frac{(P_{it} \times T \times M_s)}{A_i} \quad (\text{users/km}^2) \quad (3)$$

The Total Demand per km² (TD) of area i at time t is calculated in equation (3) using the bit rate required per user (R_t) in time t and the user density (U_{it}).

$$TD_{it} = (R_t \times U_{it}) \quad (\text{Mbps/km}^2) \quad (4)$$

As high-resolution, purely bottom-up modelling is a challenging task, we instead adopt a geotyping approach that groups areas based on similar characteristics, such as population density, to define the type of clutter environment. This is undertaken for England, Scotland and Wales (with Northern Ireland being excluded due to data discrepancies), using polygon data from Ordnance Survey Codepoint (2015). We use the annual Ofcom (2016) Connected Nations data of 4G geographic coverage by Local Authority District to disaggregate coverage to postcode sectors. This disaggregation is carried out by taking the aggregate percentage of area covered by 4G LTE, and allocating it to the most densely populated postcode sectors first. All sites within areas with LTE coverage are considered to have LTE assets. This is a method for taking the site information from Sitefinder (Ofcom, 2012d), and updating the technologies present, considering the basestations belonging to the four major operators (EE, Vodafone, O2 and Three; EE's data were obtained by combining T-Mobile and Orange). Currently, there are two macrocellular networks with sites shared between firstly O2/Telefonica and Vodafone, and secondly EE and Hutchinson Three. Hence, to obtain a single network, we split the total number of sites in two in each local area.

We reuse the geotypes outlined in a report for the Broadband Stakeholder Group by Analysys Mason (2010), which have been applied elsewhere in the literature as they align with the 90th percentile of population coverage (see Oughton and Frias, 2016; Oughton and Frias, 2017). Seven geotype segmentations are used based on the minimum number of persons per km², which include Urban (>7,959 persons per km²), Suburban 1 (>3,119 persons per km²), Suburban 2 (>782 persons per km²), Rural 1 (>112 persons per km²), Rural 2 (>47 persons per km²), Rural 3 (>25 persons per km²) and

Rural 4 (>0 persons per km²). The population density bands are held static, while postcode sectors can transition between bands based on demographic change over the study period. The population density is hence a proxy for building density and is used in the network dimensioning based on three clutter types (urban, suburban and rural). In the dimensioning of the Radio Access Network (RAN), LTE and LTE-Advanced characteristics are extrapolated. For each geotype, networks are dimensioned using a model to calculate the minimum number of basestations required to meet different levels of demand, allowing a set of network performance curves to be generated for Inter-Site Distance (ISD) system-level simulations (Frias et al. 2017). The performance of the network is evaluated based on the average per user throughput for different spectrum bands, guaranteeing desired Quality of Experience, 90% of the time. Using the performance curves, a set of lookup tables are developed for reference when simulating the performance of different capacity expansion strategies.

As defined in equation (5), the probability density function of the Signal-to-Noise-plus-Interference Ratio (SINR) is developed for each cell size, allowing the calculation of an *average* spectral efficiency based on the technology, following Mogensen (2007). The average spectral efficiency of a cell (in bps/Hz) for a particular spectrum band f and Inter-Site-Distance is defined by η_{ISD}^f .

$$\eta_{ISD}^f = \int \eta^f(SINR) f(SINR) dSINR \quad (5)$$

Based on the available bandwidth in the defined carrier frequency for a three-sector cell, the average throughput (Mbps) is calculated, as defined in equation (6).

$$Throughput_{ISD}^{cell} = 3 \sum_f \eta_{ISD}^f BW^f \quad (6)$$

Options involving small cells focus on deploying them at 3700 MHz using Time Division Duplexing (TDD). Here, LTE-like spectral efficiency is assumed (1.5 bps/Hz) for estimating the number required, along with 100 MHz available bandwidth, a maximum coverage of 200m and a 75% download-to-upload ratio. Parameter values are outlined in Table 1.

Parameter	Value
Macrocell RAN architecture	Three-sector cells
Frequency reuse factor	1
Shadow fading log-normal distribution	$\sigma = \begin{cases} 4.2 + 1.3 \log_{10}(f(\text{MHz})) \text{dB}; & \text{urban} \\ 3.5 + 1.3 \log_{10}(f(\text{MHz})) \text{dB}; & \text{other} \end{cases}$
Building penetration loss log-normal distribution	$(\mu, \sigma) = (12 \text{ dB}, 6.5 \text{ dB})$
Propagation model	SEAMCAT (2010)
% indoor users	50% urban and suburban, 0% rural
Bandwidth	Dependent on frequency band

Table 1 Key network dimensioning parameters

We follow the 3GPP technical recommendations for defining transmitted power, antenna height and propagation (3GPP, 2010). Using the SEAMCAT (2010) ‘Hata Extended’ propagation model, log-normal distributions are utilised for signal loss due to (i) slow fading or shadow fading (due to clutter), and (ii) building penetration loss.

We test a set of strategy options (Table 2) that include minimum intervention, spectrum integration, small cell deployment and a hybrid approach of spectrum and small cells. Capital expenditure is constrained across the telecommunications industry to £2 billion per year as this is approximately in line with historical capex rates (Real Wireless, 2015). The hypothetical operator takes a proportion of this spending based on its market share.

Strategy Type	Strategy Name	Description
Minimum intervention	Minimum Intervention	Operate and maintain existing network
Capacity expansion	Spectrum Integration Strategy	Upgrade to LTE if not available (800 and 2600 MHz). Integrate all other spectrum on the brownfield macrocellular network (700, 3500 MHz)
Capacity expansion	Small Cell Strategy	Upgrade to LTE if not available (800 and 2600 MHz). Deploy a greenfield small cell layer operating in TDD at 3700MHz
Capacity expansion	Hybrid Strategy	Upgrade to LTE if not available (800 and 2600 MHz). Integrate all other spectrum on the brownfield macrocellular network (700, 3500 MHz). Deploy a greenfield small cell layer operating in TDD at 3700MHz

Table 2 Strategy descriptions

We program the model to reflect that MNOs must meet specific coverage obligations. Recent variations to the UK's 3G licences (for 900 and 1800 MHz bands) require holders to deliver 768 Kbps to 90% of the population (Ofcom, 2012a). For 4G LTE (800 and 2600 MHz bands), licence holders are required to deliver 2 Mbps coverage to 98% of the population by 2017 (with no less than 95% in each of England, Wales, Scotland and Northern Ireland) (Ofcom, 2012b). Hence, we assume 5G is likely to require a 5 Mbps coverage obligation and that the operator must meet this level of service.

Infrastructure is deployed to postcode sectors by the hypothetical operator based on different investment decisions. We assume operators would first deploy LTE if this technology was not already present (integrating 800 and 2600 MHz) on a site. Then, sites with LTE in operation may have 700 MHz and 3500 MHz integrated. Finally, a small cell layer is deployed (to increasing densities of small cell sites) within each postcode sector operating in TDD at 3700 MHz.

At each modelled time-step, postcode sectors are considered in order of high to low population density. Each area's capacity and demand are compared using a capacity margin metric, and upgrades are applied based on the options available until either the demand is met or the annual budget is exhausted. The capacity margin ($CapacityMargin_{it}$) for area i at time t is calculated by subtracting $Capacity_{it}$ from $Demand_{it}$ as illustrated in equation (7):

$$CapacityMargin_{it} = Capacity_{it} - Demand_{it} \quad (7)$$

Within the Cost Module we calculate the costs of infrastructure upgrades over the course of the study period, according to the Total Cost of Ownership (TCO) of new assets. We exclude the costs of operating legacy network assets. We use costs sourced from the Ofcom Mobile Call Termination (MCT) Model (2015b), as well as from 5G NORMA (2016). Costs are calculated by finding the NPV of the TCO for each infrastructure asset over a 20-year period, based on the methodology dictated by Ofcom for the cost of extending coverage for the 4G LTE auction (Real Wireless, 2012). This includes a 20-year NPV calculation with no account for price trends, and a 3.5% social discount rate. We assume a 10-year equipment lifetime for macrosites and 5-year equipment lifetime for small cells, with civil works not being repeated. There is no residual value at the end of the period.

The cost structure of assets is affected by the fact that we take a brownfield approach for spectrum integration using the existing macrocellular network and a greenfield approach for small cell deployment. Small cells are deployed on local authority owned street furniture for no cost. Detailed asset costs are outlined in Table 3, including references to their sources. We assume a 10% mark-up on all costs for upgrades in the core network. The results will now be reported in Section 4.

Strategy	LTE availability	Cost type	Capex (GBP)	Opex (GBP)	Source
Spectrum integration on the macrocellular network	Site with 4G LTE	Additional carrier on current BS	15,000	1,800	Ofcom (2015a)
	Site with no 4G LTE	Deploying a multicarrier BS	40,900	3,898	Ofcom (2015a)
		Civil works	18,000	-	5G NORMA (2016)
		Fibre backhaul	20,000	-	Assumption
Network densification through small cells		Small cell equipment	2,500	350	5G NORMA (2016)
		Small cell civil works	13,300	0	5G NORMA (2016)
		Small cell backhaul	-	1,000	5G NORMA (2016)
Core upgrade cost on all strategies			10% mark-up	-	Assumption

Table 3 Infrastructure deployment costs

4 Results

We start by reporting the results by scenario for long-term demand, before progressing to the performance of different supply-side infrastructure strategies. A discussion is then undertaken on the ramifications of these findings in Section 5.

4.1 Demand results

In the demographic scenarios tested, the baseline population grew by 5.3 million, to 68.6 million. This contrasts with the high growth scenario where there was an additional 7.8 million people (reaching 72.8 million in 2030), and the low growth scenario which saw much smaller growth of 2.7 million people (reaching 64.4 million in 2030). The baseline population density grew from 274 persons per km², and finished at 297 persons per km² (an increase of 23 persons per km²). Figure 3 illustrates population growth graphically by scenario. Population forecasts have minor differences in starting points as the most recently available data are from 2015.

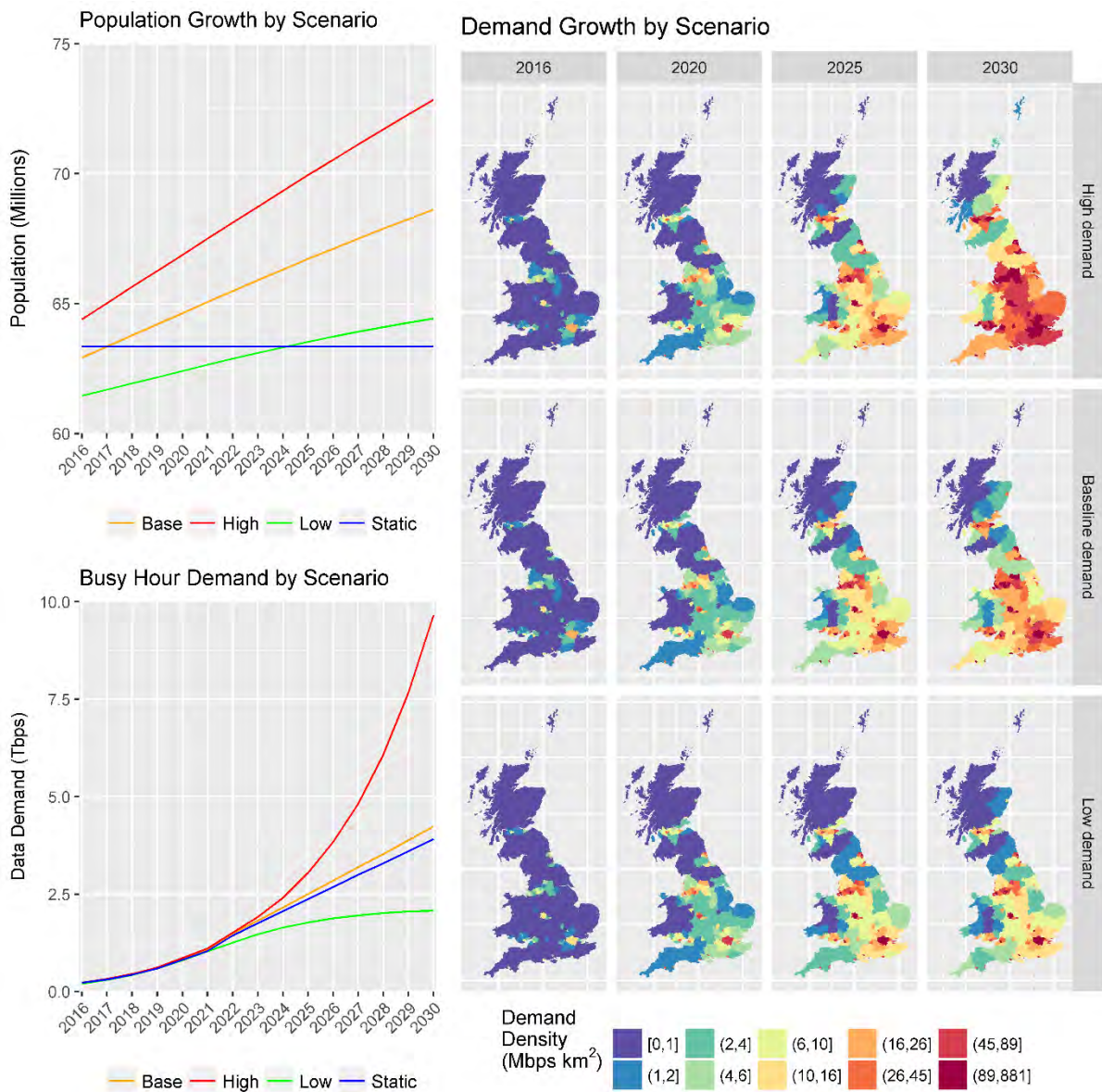


Figure 3 Demand growth metrics by scenario

In terms of the aggregate area demand, there was an increase in the baseline from approximately 0.2 Tbps in 2016 to 4.23 Tbps in 2030. The low growth scenario grew from 0.2 Tbps in 2016 to 2.08 Tbps in 2030, whereas the high growth scenario grew from 0.2 Tbps in 2016 to 9.7 Tbps. As this represents a hypothetical MNO with only 30% market share, the total national demand would be significantly higher. Where this demand takes place spatially, is of vital importance to MNOs. Figure 4 also illustrates the demand evolution across Britain over time, reflecting the underlying demographic characteristics of local areas. Across all scenarios, there is a lower demand in northern and western regions of Britain, particularly in Scotland and Wales, as the population is either static or declining. In the low scenario, demand is mostly concentrated within major cities such as London, Birmingham, Manchester, Newcastle and Glasgow, as one would expect. However, under baseline or high growth there is considerable demand in lower population density suburban and rural areas too, particularly in the South East and Midland areas of England, which would prove a considerable challenge to meet in a cost-efficient way.

The 'Static' scenario specifically considers no demographic change from 2016 onwards, only focusing on baseline data demand growth. This allows the impact of the population and data exogenous drivers to be isolated and compared. The key finding is that in the 'Static' scenario, the aggregate demand was quite similar to the baseline in 2030 at 3.9 Tbps, whereas the baseline reached 4.23 Tbps. This indicates that population growth in the baseline scenario led to an additional required 0.3 Tbps of capacity at the end of the study period. To summarise for the baseline scenario, only 8% of the growth for 2016 to 2030 results from demographic change, whereas 92% is from per user data demand. Therefore, this means technological progress accounts for more than 90% of the growth in total data demand.

4.2 Supply-side strategy results

We tested four different options, including (i) minimum intervention, (ii) spectrum integration, (iii) small cell deployment and (iv) a hybrid approach using both spectrum and small cells. Figure 4 illustrates the performance of all strategy options across each exogenous demand scenario.

In the case of the minimum intervention strategy, we found that the current system is not sufficient in meeting long-term demand. The capacity deficit grew considerably between 2017 and 2030 depending on the scenario, with this metric being smallest under low growth and largest under high growth as one would logically expect. This 'do nothing' scenario provides an important comparison for the effectiveness of other strategies.

The performance of the spectrum strategy had mixed results based on different demand scenarios. For example, there was only a minor capacity deficit in the baseline when compared to the high growth scenario. Fortunately, in the low growth scenario system capacity narrowly managed to meet long-term demand, avoiding a capacity deficit in all areas except the London region. Yet, these results indicate that a purely spectrum-based approach would not be a robust strategy to meet long-term demand. However, it is promising that this strategy could meet demand in many locations outside of the major urban conurbations.

The small cell deployment option performed well across all scenarios, with aggregate system capacity being positive in all cases, avoiding the capacity deficit that often arose in other options. Small cells provide very high capacity in localised areas (due to small coverage radii per cell), but such a large system capacity surplus may lead to overprovisioning, which could be economically inefficient. More cost efficient wide-area coverage solutions are likely to be needed.

In the hybrid strategy, we see a very similar outcome to the previous small cell strategy. This is because the additional spectrum (specifically in urban areas), is not sufficient to meet required demand, therefore the decision layer in the model results to small cell deployment. In certain scenarios, a capacity deficit arose in London and the South East. Moreover, in the high demand scenario there was a capacity deficit in many other English regions, particularly around the main conurbations in the Midlands and North

West. Appendix A contains detailed results for the five areas with the largest capacity margin deficits, broken down by scenario and year, for the baseline scenario.

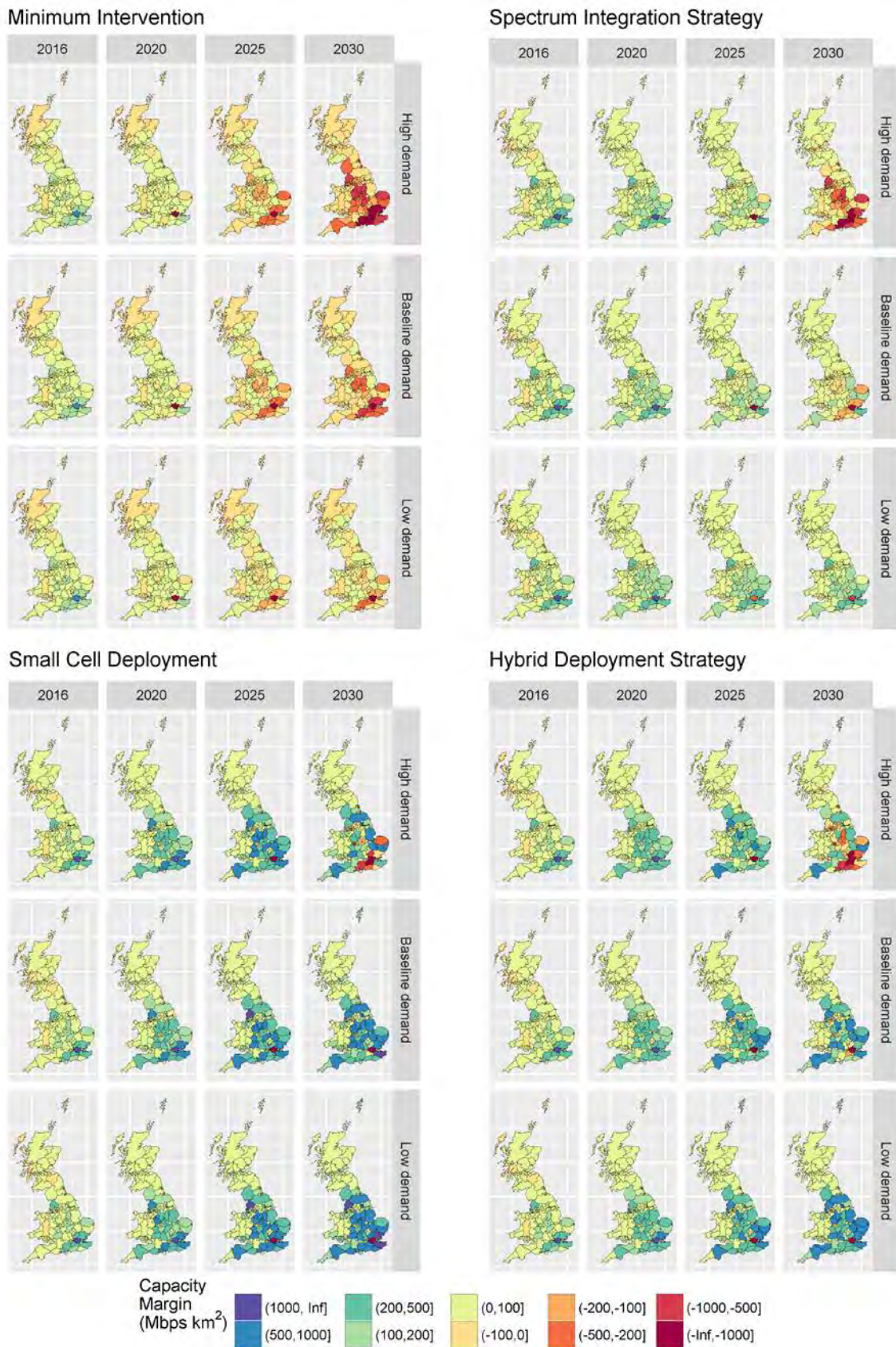


Figure 5 Strategy performance over time

To understand the commercial ramifications of these results, each demand scenario and deployment strategy must be evaluated in relation to cost. Moreover, it is particularly helpful to quantify how capital expenditure takes place across urban, suburban and rural areas. Consequently, Figure 5 visualises the results for the rollout of infrastructure over the study period of 2016-2030.

As the UK has incomplete LTE coverage, in all expansion options, this commonly took place in the early years of the study period, up until 2020 when the 5G spectrum bands became available. Spending on LTE was generally high because it requires a whole new basestation as opposed to simply integrating additional carriers for 700 or 3500 MHz on an existing site. Spending on urban areas made up a small proportion of the overall capital expenditure, with suburban and the densest rural areas absorbing considerable resources particularly later in the study period from 2021 to 2030.

During the LTE upgrade in the first three years of the study period, resources were pushed out to some of the lowest population density areas in remote Britain. In the spectrum strategy, this option runs out of new bands to integrate leading to a decrease in total capex spending annually over the study period. However, the shape of this decline indicates that not all areas have a negative capacity margin when the bands come online, with spending taking place in two phases. Firstly, in 2020 a range of urban, suburban and rural areas with a capacity deficit receive new spectrum, with this spending tailing off in 2021, before rising again by 2023. In the strategies containing small cells, the limited radii of these assets cause spending to ramp up to the maximum annually allowed. Small cells dominate the spending profile from 2020 onwards with a small proportion in early years spent on integrating 700 MHz, and an even smaller proportion spent on 3500 MHz.

Having reported both the demand and infrastructure performance results, we will now discuss what this means for future decision making.

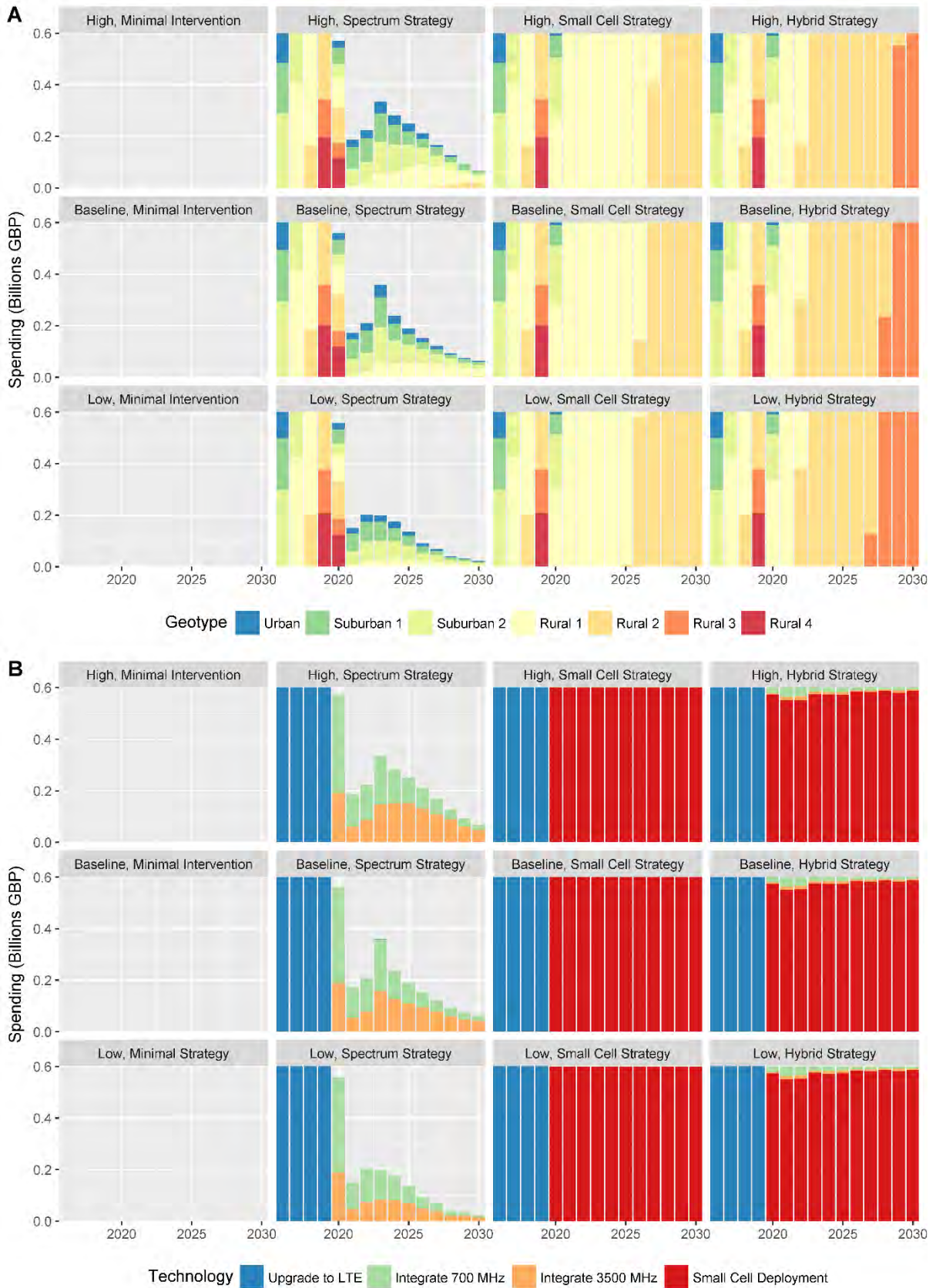


Figure 6 (A) Annual spending by geotype, and (B) Annual spending by technology

5 Discussion

Estimating the future demand for mobile telecommunications infrastructure is a challenging task, as there is a very high degree of uncertainty. The aim here was to quantify the impact of the industry standard forecast by Cisco up until 2021, and then use high (exponential), baseline (linear) and low (logistic) growth scenarios to explore future mobile traffic demand up to 2030. Population projections were also integrated. We find that data demand is by far the largest driver of mobile traffic (constituting 92% of baseline growth), with demographic change including fertility, mortality and migration having only a marginal impact on future demand (8% in the baseline). This is an important finding because it encourages technological forecasters in industry and government to focus on refining future data demand forecasts, rather than population projections, contrasting strongly with energy or transport systems where demographic growth is often the major driver.

The results show within the methodology applied here, that per user monthly mobile traffic demand is estimated to be 4.7 GB in 2020 for the UK. This estimate is comparative to the results of Lee et al. (2016) who developed forecasts of mobile broadband traffic using a combination of scenario analysis and the Delphi method, finding that South Korea would have a monthly user demand of approximately 6 GB by 2020. Although the demand scenarios used here for the UK were lower, the difference in adoption and access capacity between each country provides an explanation. As carried out in Lee et al. (2016), further research should put a larger emphasis on modelling devices and their impact on data demand, and using these scenarios to drive the existing modelling framework.

Additionally, although this paper included annual migratory trends (predominantly towards urban areas), daily commuting and travel patterns were excluded. This is however important, and a further incremental development would be to better reflect mobility in the busy hour estimation, particularly in cities, as this is where the mobile network can easily become overloaded. Indeed, user mobility can make it a challenge to report mobile statistics; hence one approach is to anchor data usage to the population or premises (as used by Ofcom, 2016). Although the method used here is a simplification, the results still provide useful comparative insight across scenarios. The growth of computational power, combined with new crowd-sourced data, may help in overcoming this issue as user mobility can be tracked through time and space.

To evaluate how options performed against future demand scenarios, the second research question focused on assessing interactions between supply and demand during a mobile telecommunications generational upgrade. Different infrastructure strategies could be assessed against the minimum intervention option. The results found that the spectrum strategy performed well in the baseline and low demand scenarios up until 2025, demonstrating that this will play an important role in meeting mid-term demand. However, spectrum-based options were more sensitive to demand uncertainty than small cell deployment, which was more capable of dealing with higher demand growth, although this was at the expense of increased cost. The small cell and hybrid strategies provide huge capacity in some areas, but still fail to meet demand in others. This is due to limited coverage per cell in combination with constrained capital expenditure.

Importantly, if there is a desire for the large per user speeds mooted by 5G, which cannot be achieved by spectrum strategies alone in non-urban areas, new revenue streams consequently need to be found to boost infrastructure investment. Therefore, the obvious prospect is to capture some of the potential value created from the new market opportunities and productivity gains associated with IoT, Smart Cities and other digitally connected systems, as has been identified in the technological change literature (Yang et al. 2013; Sadowski, 2017). Of course, in this analysis we tested a relatively narrow range of supply-side strategies, therefore further research must focus on defining strategies of emerging 5G technologies including higher order MIMO and millimetre wave small cells to enhance supply capacity.

In answering the final research question, we explore the ramifications of the results. Firstly, the quantified future scenarios used in this paper, in combination with the performance of different supply-side options, are a useful tool for understanding the economic costs of increasing mobile demand. Ghezzi et al. (2015) provide a decision framework for MNOs to identify the key drivers of potentially disruptive change to their operations, market strategy and different business models. Importantly, increasing data traffic is treated as one of the key drivers. Hence, the scenario-based analysis produced here provides complementary quantitative information for MNOs to anticipate how changing demand may affect the value proposition, value creation, value delivery and value appropriation of their business model.

Moreover, while this information may be readily available within some organisations, particularly MNOs or telecommunication regulators, the findings can also be valuable elsewhere, perhaps where they are not so readily available. For example, it is vital information for small and medium-sized (SME) digital economy firms, as well as for governmental institutions which sit outside of the telecommunication regulator and hence might not be able to access commercially sensitive data. Indeed, Shin et al. (2011) undertake an analysis of the socio-technical dynamics of moving from 3G to 4G LTE in Korea, determining that moving to a new generation of mobile technology cannot be driven by a single organisation as it requires a tremendous number of partnerships between private and public organisations. Hence, the scenario analysis undertaken here can help in this endeavour by providing transparent assessment of the supply and demand of mobile telecommunications for MNOs, SME digital economy firms and government institutions.

Indeed, plentiful spectrum resources play an important short- to mid-term capacity enhancing option, as illustrated in this analysis. Therefore, the UK Government's timely delivery of the bands outlined in the Public Sector Spectrum Release programme (750 MHz of sub-10 GHz spectrum by 2022, with 500 MHz being available by 2020) will be highly important specifically for rural areas where small cell rollout will be unviable (UK Government Investments, 2016). On the other hand, in urban areas with high data demand, small cell deployments are a cost-efficient strategy for MNOs, therefore government must ensure these assets can be efficiently and cheaply installed. Often, stringent local planning regulations combined with historical protections for older buildings can prevent timely deployment, requiring innovative private and public solutions to overcoming these barriers.

In both the spectrum integration and small cell strategy options, backhaul capacity and its consequential cost is a significant potential issue. Options should be explored that can focus on enhancing fibre access in areas with little backhaul capacity, as this could lower deployment costs. Ultimately in 5G we will see increased convergence within the telecommunications industry, as MNOs who also own a fixed network may allow low-cost access for backhaul to provide a competitive cost advantage.

6 Conclusion

Rapid technological innovation in mobile telecommunications affects our ability to accurately forecast long-term capacity and demand, making it essential that rigorous examination of this uncertainty is both quantified and visualised to support decision-making. The analysis presented here can help MNOs, SME digital economy firms and government institutions understand the implications of increasing demand (particularly the economic implications) resulting from change in both per user traffic and demographics. Additionally, quantified assessment of the performance of different 5G supply-side strategies were presented as ways for MNOs to cope with dynamic mobile traffic growth.

We find that increasing per user traffic resulting from technological change has a major impact on future demand, whereas demographic change (fertility, mortality and migration) has only a minor effect. For example, in the baseline scenario only 8% of the growth in data for 2016 to 2030 resulted from demographic change, whereas 92% was from per user data demand. Hence, technological progress accounts for more than 90% of the growth in total data demand. Consequently, technological forecasters should be encouraged to focus on refining per user data demand, rather than devoting time to developing population projections, contrasting strongly with energy or transport systems.

The modelled results indicate that spectrum strategies could perform well in most scenarios up until 2025, and hence will play an important role in meeting mid-term demand. However, if demand growth was very high, spectrum failed to meet demand. This contrasts with small cell deployment, which provided huge increases in capacity, but at the expense of much higher capital expenditure due to limited coverage per cell. Unless new revenue can be obtained from the value created by IoT, Smart Cities, or other new technological developments, the investment appetite for rolling out small cells anywhere other than urban areas will be low. In any case, telecommunications capacity needs to be balanced with demand, which will mean MNOs avoid overprovisioning. 5G small cell deployments are highly likely in urban and suburban locations, but more cost-efficient wide-area coverage solutions are required to meet lower population density areas.

Qualitative frameworks have been put forward in the technical change literature to aid with business model adaptation for MNOs facing on the one hand increasing traffic growth, while on the other declining revenues. The contribution of this paper is to provide a scenario-based assessment of telecommunications supply and demand as we move towards 5G, to serve as complementary evidence for high-level decision-makers to develop successful market strategies that are robust to different futures.

7 References

- 3GPP, 2010. TR 36.814 - Further advancements for E-UTRA: physical layer aspects [WWW Document]. URL http://www.3gpp.org/ftp/Specs/archive/36_series/36.814/. (accessed 10.31.16).
- 5G NORMA, 2016. Deliverable D2.1: Use cases, scenarios and requirements. 5G PPP.
- Almobaideen, W., Krayshan, R., Allan, M., Saadeh, M., 2017. Internet of Things: Geographical Routing based on healthcare centers vicinity for mobile smart tourism destination. *Technological Forecasting and Social Change* 123, 342–350. doi:10.1016/j.techfore.2017.04.016
- Analysys Mason, 2010. The costs and capabilities of wireless and satellite technologies - 2016 snapshot. Analysys Mason, London.
- Andrews, J.G., Buzzi, S., Choi, W., Hanly, S.V., Lozano, A., Soong, A.C., Zhang, J.C., 2014. What will 5G be? *IEEE Journal on Selected Areas in Communications* 32, 1065–1082.
- Asimakopoulos, G., Whalley, J., 2017. Market leadership, technological progress and relative performance in the mobile telecommunications industry. *Technological Forecasting and Social Change* 123, 57–67. doi:10.1016/j.techfore.2017.06.021
- Bolton, R., Foxon, T.J., 2015. Infrastructure transformation as a socio-technical process — Implications for the governance of energy distribution networks in the UK. *Technological Forecasting and Social Change* 90, 538–550. doi:10.1016/j.techfore.2014.02.017
- Bresciani, S., Ferraris, A., Del Giudice, M., 2017. The management of organizational ambidexterity through alliances in a new context of analysis: Internet of Things (IoT) smart city projects. *Technological Forecasting and Social Change*. doi:10.1016/j.techfore.2017.03.002
- Breuer, D., Weis, E., Grobe, K., Krauss, S., Musumeci, F., Gijon, J.T., Skubic, B., 2016. 5G Transport in Future Access Networks, in: *ECOC 2016; 42nd European Conference on Optical Communication*. Presented at the ECOC 2016; 42nd European Conference on Optical Communication, pp. 1–3.
- British Infrastructure Group, 2016. Mobile Coverage: A good call for Britain? British Infrastructure Group, London.
- Chen, P.-T., Cheng, J.Z., 2010. Unlocking the promise of mobile value-added services by applying new collaborative business models. *Technological Forecasting and Social Change* 77, 678–693. doi:10.1016/j.techfore.2009.11.007
- Cheng, J.Z., Yu, H.-C., Sincoskie, W.D., 2005. Meeting the broadband access infrastructure demands: The promise of Gigabit Ethernet. *Technological Forecasting and Social Change* 72, 1–10. doi:10.1016/j.techfore.2003.11.006
- Chiaraviglio, L., Blefari-Melazzi, N., Chiasserini, C.F., Iatco, B., Malandrino, F., Salsano, S., 2017. An economic analysis of 5G Superfluid networks, in: *2017 IEEE 18th International Conference on High Performance Switching and Routing (HPSR)*. Presented at the 2017 IEEE 18th International Conference on High Performance Switching and Routing (HPSR), pp. 1–7. doi:10.1109/HPSR.2017.7968690
- Christodoulou, K., Jensen, K., Vlahos, K., 1999. Using Object-Oriented Simulation to Explore Substitution Between Technologies: An Application to the UK Mobile Telecommunications Industry. *Technological Forecasting and Social Change* 62, 203–217. doi:10.1016/S0040-1625(99)00044-X
- Chu, C.-P., Pan, J.-G., 2008. The forecasting of the mobile Internet in Taiwan by diffusion model. *Technological Forecasting and Social Change* 75, 1054–1067. doi:10.1016/j.techfore.2007.11.012
- Cisco, 2017. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021. Cisco American Headquarters, San Jose, CA.

- Cisco, 2016. Cisco visual networking index: Global mobile data traffic forecast update, 2015–2020. Cisco American Headquarters, San Jose, CA.
- Cisco, 2015. Cisco visual networking index: Global mobile data traffic forecast update, 2014–2019. Cisco American Headquarters, San Jose, CA.
- Cisco, 2014. Cisco visual networking index: Global mobile data traffic forecast update, 2013–2018. Cisco American Headquarters, San Jose, CA.
- Cisco, 2013. Cisco visual networking index: Forecast and methodology, 2012–2017. Cisco American Headquarters, San Jose, CA.
- Cisco, 2012. Cisco visual networking index: Forecast and methodology, 2011–2016. Cisco American Headquarters, San Jose, CA.
- Cisco, 2011. Cisco visual networking index: Global mobile data traffic forecast update, 2010–2015. Cisco American Headquarters, San Jose, CA.
- Curwen, P., Whalley, J., 2004. *Telecommunications Strategy: Cases, Theory and Applications*. Routledge, Abingdon, Oxfordshire.
- Department for Culture, Media and Sport, HM Treasury, 2017. *Next Generation Mobile Technologies: A 5G Strategy for the UK*. DCMS / HM Treasury, London.
- du Preez, G.T., Pistorius, C.W.I., 2003. Analyzing technological threats and opportunities in wireless data services. *Technological Forecasting and Social Change* 70, 1–20. doi:10.1016/S0040-1625(02)00253-6
- Favato, G., Vecchiato, R., 2016. Embedding real options in scenario planning: A new methodological approach. *Technological Forecasting and Social Change*. doi:10.1016/j.techfore.2016.05.016
- Fildes, R., 2003. Corrigendum to “Telecommunications demand forecasting—a review”: [International Journal of Forecasting 18 (2002) 489–522]☆. *International Journal of Forecasting* 19, 337. doi:10.1016/S0169-2070(03)00039-6
- Fildes, R., 2002. Telecommunications demand forecasting—a review. *International Journal of Forecasting, Telecommunications Forecasting* 18, 489–522. doi:10.1016/S0169-2070(02)00064-X
- Frank, L.D., 2004. An analysis of the effect of the economic situation on modeling and forecasting the diffusion of wireless communications in Finland. *Technological Forecasting and Social Change* 71, 391–403. doi:10.1016/S0040-1625(02)00392-X
- 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, 518–532. doi:10.1016/j.telpol.2016.12.008
- Ghezzi, A., Cortimiglia, M.N., Frank, A.G., 2015. Strategy and business model design in dynamic telecommunications industries: A study on Italian mobile network operators. *Technological Forecasting and Social Change* 90, 346–354. doi:10.1016/j.techfore.2014.09.006
- Han, E.J., Sohn, S.Y., 2016. Technological convergence in standards for information and communication technologies. *Technological Forecasting and Social Change* 106, 1–10. doi:10.1016/j.techfore.2016.02.003
- Holma, H., Toskala, A. (Eds.), 2012. *LTE-Advanced: 3GPP Solution for IMT-Advanced*. John Wiley & Sons, Ltd, Chichester, UK.
- Hong, J., 2017. Causal relationship between ICT R&D investment and economic growth in Korea. *Technological Forecasting and Social Change* 116, 70–75. doi:10.1016/j.techfore.2016.11.005
- Hong, J., Shin, J., Lee, D., 2016. Strategic management of next-generation connected life: Focusing on smart key and car–home connectivity. *Technological Forecasting and Social Change* 103, 11–20. doi:10.1016/j.techfore.2015.10.006

- Huétink, F.J., der Vooren, A. van, Alkemade, F., 2010. Initial infrastructure development strategies for the transition to sustainable mobility. *Technological Forecasting and Social Change*, Issue includes a Special Section on “Infrastructures and Transitions” 77, 1270–1281. doi:10.1016/j.techfore.2010.03.012
- International Telecommunication Union, 2015. IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond. International Telecommunication Union, Geneva, Switzerland.
- Islam, T., Fiebig, D.G., Meade, N., 2002. Modelling multinational telecommunications demand with limited data. *International Journal of Forecasting, Telecommunications Forecasting* 18, 605–624. doi:10.1016/S0169-2070(02)00073-0
- Islam, T., Meade, N., 2015. Firm level innovation diffusion of 3G mobile connections in international context. *International Journal of Forecasting* 31, 1138–1152. doi:10.1016/j.ijforecast.2013.05.002
- James, J., 2012. The ICT Development Index and the digital divide: How are they related? *Technological Forecasting and Social Change* 79, 587–594. doi:10.1016/j.techfore.2011.08.010
- Jun, D.B., Kim, S.K., Park, Y.S., Park, M.H., Wilson, A.R., 2002. Forecasting telecommunication service subscribers in substitutive and competitive environments. *International Journal of Forecasting, Telecommunications Forecasting* 18, 561–581. doi:10.1016/S0169-2070(02)00067-5
- Kim, J., 2006. Infrastructure of the digital economy: Some empirical findings with the case of Korea. *Technological Forecasting and Social Change* 73, 377–389. doi:10.1016/j.techfore.2004.09.003
- Kim, J., Daim, T., Anderson, T., 2010. A look into the future of wireless mobile communication technologies. *Technology Analysis & Strategic Management* 22, 925–943. doi:10.1080/09537325.2010.520472
- Krafft, J., 2010. Profiting in the info-coms industry in the age of broadband: Lessons and new considerations. *Technological Forecasting and Social Change* 77, 265–278. doi:10.1016/j.techfore.2009.07.002
- Kwak, J.H., Lee, B.G., 2011. Estimating demand curve in the Korean VoIP telecommunications market. *Technological Forecasting and Social Change* 78, 713–728. doi:10.1016/j.techfore.2010.09.007
- Kyriakidou, V., Michalakelis, C., Sphicopoulos, T., 2013. Driving factors during the different stages of broadband diffusion: A non-parametric approach. *Technological Forecasting and Social Change* 80, 132–147. doi:10.1016/j.techfore.2012.07.001
- Labaka, L., Hernantes, J., Sarriegi, J.M., 2016. A holistic framework for building critical infrastructure resilience. *Technological Forecasting and Social Change* 103, 21–33. doi:10.1016/j.techfore.2015.11.005
- Lee, J.C., 1988. Nested Rotterdam model: Applications to marketing research with special reference to telecommunications demand. *International Journal of Forecasting* 4, 193–206. doi:10.1016/0169-2070(88)90077-5
- Lee, S., Cho, C., Hong, E., Yoon, B., 2016. Forecasting mobile broadband traffic: Application of scenario analysis and Delphi method. *Expert Systems with Applications* 44, 126–137. doi:10.1016/j.eswa.2015.09.030
- Mayer, W.J., Madden, G., Jin, Z., Tran, T., 2015. Modelling OECD broadband subscriptions in disequilibrium. *Technological Forecasting and Social Change* 90, 476–486. doi:10.1016/j.techfore.2014.03.010
- Meade, N., Islam, T., 2015. Forecasting in telecommunications and ICT—A review. *International Journal of Forecasting* 31, 1105–1126. doi:10.1016/j.ijforecast.2014.09.003

- Meade, N., Islam, T., 2006. Modelling and forecasting the diffusion of innovation – A 25-year review. *International Journal of Forecasting*, Twenty five years of forecasting 22, 519–545. doi:10.1016/j.ijforecast.2006.01.005
- Meeting the broadband access infrastructure demands: The promise of Gigabit Ethernet, 2005. *Technological Forecasting and Social Change* 72, 1–10. doi:10.1016/j.techfore.2003.11.006
- Michalakelis, C., Varoutas, D., Sphicopoulos, T., 2008. Diffusion models of mobile telephony in Greece. *Telecommunications Policy* 32, 234–245. doi:10.1016/j.telpol.2008.01.004
- Mir, M., Dangerfield, B., 2013. Propagating a digital divide: Diffusion of mobile telecommunication services in Pakistan. *Technological Forecasting and Social Change* 80, 992–1001. doi:10.1016/j.techfore.2012.08.006
- Mogensen, P., Na, W., Kovacs, I.Z., Frederiksen, F., Pokhariyal, A., Pedersen, K.I., Kolding, T., Hugl, K., Kuusela, M., 2007. LTE Capacity Compared to the Shannon Bound, in: 2007 IEEE 65th Vehicular Technology Conference - VTC2007-Spring. Presented at the 2007 IEEE 65th Vehicular Technology Conference - VTC2007-Spring, pp. 1234–1238. doi:10.1109/VETECS.2007.260
- Nam, C., Kim, S., Lee, H., 2008. The role of WiBro: Filling the gaps in mobile broadband technologies. *Technological Forecasting and Social Change* 75, 438–448. doi:10.1016/j.techfore.2007.04.008
- National Infrastructure Commission, 2017. National Infrastructure Assessment [WWW Document]. URL <https://www.nic.org.uk/our-work/national-infrastructure-assessment/> (accessed 8.10.17).
- O'Brien, F.A., Meadows, M., 2013. Scenario orientation and use to support strategy development. *Technological Forecasting and Social Change*, Scenario Method: Current developments in theory and practice 80, 643–656. doi:10.1016/j.techfore.2012.06.006
- Ofcom, 2017. Ofcom Nations and Regions Technology Tracker - H1 2017 [WWW Document]. URL https://www.ofcom.org.uk/__data/assets/pdf_file/0015/101292/technology-tracker-data-tables-h1-2017.pdf (accessed 8.10.17).
- Ofcom, 2016a. Connected Nations 2016. Ofcom, London.
- Ofcom, 2016b. Infrastructure Report 2014. Ofcom, London.
- Ofcom, 2015a. Connected Nations 2015. Ofcom, London.
- Ofcom, 2015b. Mobile call termination market review 2015-18. Ofcom, London.
- Ofcom, 2013. Infrastructure report: 2013 update. Ofcom, London.
- Ofcom, 2012a. 3G Coverage Obligation Verification Methodology. Ofcom, London.
- Ofcom, 2012b. 4G Coverage Obligation Notice of Compliance Verification Methodology: LTE. Ofcom, London.
- Ofcom, 2012c. Infrastructure report: 2012 update. Ofcom, London.
- Ofcom, 2012d. Sitefinder [WWW Document]. URL <https://www.ofcom.org.uk/phones-telecoms-and-internet/coverage/mobile-operational-enquiries> (accessed 12.21.16).
- Office for National Statistics, 2013. 2011 Census: Headcounts and household estimates for postcodes in England and Wales [WWW Document]. URL <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/2011censusheadcountsandhouseholdestimatesforpostcodesinenglandandwales> (accessed 12.21.16).
- OpenSignal, 2017. The State of LTE. OpenSignal, London.
- Ordnance Survey, 2015. Code-Point - locates every postcode unit in the UK [WWW Document]. URL <https://www.ordnancesurvey.co.uk/business-and-government/products/code-point.html> (accessed 10.8.17).

- Osborne, G., 2016. Letter to the National Infrastructure Commission.
- Ott, D., Himayat, N., Talwar, S., 2017. 5G: Transforming the User Wireless Experience. *Towards 5G: Applications, Requirements and Candidate Technologies* 34–51.
- Otto, A., Hall, J.W., Hickford, A.J., Nicholls, R.J., Alderson, D., Barr, S., Tran, M., 2016. A Quantified System-of-Systems Modeling Framework for Robust National Infrastructure Planning. *IEEE Systems Journal* 10, 385–396. doi:10.1109/JSYST.2014.2361157
- Park, J., Kim, S., Nam, C., 2015. Why has a Korean telecommunications technology failed: A case study on WiBro. *Telematics and Informatics* 32, 603–612. doi:10.1016/j.tele.2015.01.002
- Park, S.R., Choi, D.Y., Hong, P., 2015. Club convergence and factors of digital divide across countries. *Technological Forecasting and Social Change* 96, 92–100. doi:10.1016/j.techfore.2015.02.011
- Parker, A.M., Srinivasan, S.V., Lempert, R.J., Berry, S.H., 2015. Evaluating simulation-derived scenarios for effective decision support. *Technological Forecasting and Social Change* 91, 64–77. doi:10.1016/j.techfore.2014.01.010
- Pick, J.B., Nishida, T., 2015. Digital divides in the world and its regions: A spatial and multivariate analysis of technological utilization. *Technological Forecasting and Social Change* 91, 1–17. doi:10.1016/j.techfore.2013.12.026
- Ramirez, R., Mukherjee, M., Vezzoli, S., Kramer, A.M., 2015. Scenarios as a scholarly methodology to produce “interesting research.” *Futures* 71, 70–87. doi:10.1016/j.futures.2015.06.006
- Raven, P.G., 2014. The future’s four quarters: Proposing a quadrant methodology for strategic prototyping in infrastructural contexts. *Technological Forecasting and Social Change* 84, 115–130. doi:10.1016/j.techfore.2013.10.012
- Real Wireless, 2015. *UK Spectrum Usage & Demand: First Edition*. Real Wireless, Pulborough.
- Real Wireless, 2012. *Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030*. Real Wireless, Pulborough.
- Roelich, K., Knoeri, C., Steinberger, J.K., Varga, L., Blythe, P.T., Butler, D., Gupta, R., Harrison, G.P., Martin, C., Purnell, P., 2015. Towards resource-efficient and service-oriented integrated infrastructure operation. *Technological Forecasting and Social Change* 92, 40–52. doi:10.1016/j.techfore.2014.11.008
- Ruutu, S., Casey, T., Kotovirta, V., 2017. Development and competition of digital service platforms: A system dynamics approach. *Technological Forecasting and Social Change* 117, 119–130. doi:10.1016/j.techfore.2016.12.011
- Sadowski, B.M., 2017. Advanced users and the adoption of high speed broadband: Results of a living lab study in the Netherlands. *Technological Forecasting and Social Change* 115, 1–14. doi:10.1016/j.techfore.2016.09.009
- Salmenkaita, J.-P., Salo, A., 2004. Emergent foresight processes: industrial activities in wireless communications. *Technological Forecasting and Social Change* 71, 897–912. doi:10.1016/j.techfore.2003.09.001
- Schuckmann, S.W., Gnatzy, T., Darkow, I.-L., von der Gracht, H.A., 2012. Analysis of factors influencing the development of transport infrastructure until the year 2030 — A Delphi based scenario study. *Technological Forecasting and Social Change* 79, 1373–1387. doi:10.1016/j.techfore.2012.05.008
- SEAMCAT, 2010. *Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT) Handbook*. SEAMCAT.
- Shafi, M., Smith, P.J., Zhu, P., Haustein, T., Molisch, A.F., 2017. Guest Editorial Deployment Issues and Performance Challenges for 5G, Part I. *IEEE Journal on Selected Areas in Communications* 35, 1197–1200. doi:10.1109/JSAC.2017.2690498

- Shieh, L.-F., Chang, T.-H., Fu, H.-P., Lin, S.-W., Chen, Y.-Y., 2014. Analyzing the factors that affect the adoption of mobile services in Taiwan. *Technological Forecasting and Social Change* 87, 80–88. doi:10.1016/j.techfore.2013.11.004
- Shin, D.-H., Choo, H., Beom, K., 2011. Socio-Technical Dynamics in the Development of Next Generation Mobile Network: Translation Beyond 3G. *Technological Forecasting and Social Change* 78, 514–525. doi:10.1016/j.techfore.2010.04.017
- Smail, G., Weijia, J., 2017. Techno-economic analysis and prediction for the deployment of 5G mobile network, in: 2017 20th Conference on Innovations in Clouds, Internet and Networks (ICIN). Presented at the 2017 20th Conference on Innovations in Clouds, Internet and Networks (ICIN), pp. 9–16. doi:10.1109/ICIN.2017.7899243
- Stork, C., Esselaar, S., Chair, C., 2017. OTT - Threat or opportunity for African Telcos? *Telecommunications Policy, ICT developments in Africa – infrastructures, applications and policies* 41, 600–616. doi:10.1016/j.telpol.2017.05.007
- Sultanov, A., Lee, D.-J., Kim, K.-T., Avila, L.A.P., 2016. The diffusion of mobile telephony in Kazakhstan: An empirical analysis. *Technological Forecasting and Social Change* 106, 45–52. doi:10.1016/j.techfore.2016.01.020
- Thong, C., Beaven, R., Zuo, C., Birkin, M., Tyler, P., Crawford-Brown, D., Oughton, E.J., Kelly, S., 2016. Future demand for infrastructure services, in: *The Future of National Infrastructure: A System-of-Systems Approach*. Cambridge University Press, Cambridge.
- UK Government Investments, 2016. Enabling UK growth: Public sector spectrum release programme. UK Government Investments, London.
- Velickovic, S., Radojicic, V., Bakmaz, B., 2016. The effect of service rollout on demand forecasting: The application of modified Bass model to the step growing markets. *Technological Forecasting and Social Change* 107, 130–140. doi:10.1016/j.techfore.2016.03.018
- Venkatesan, R., Kumar, V., 2002. A genetic algorithms approach to growth phase forecasting of wireless subscribers. *International Journal of Forecasting, Telecommunications Forecasting* 18, 625–646. doi:10.1016/S0169-2070(02)00070-5
- Vicente, M.R., Gil-de-Bernabé, F., 2010. Assessing the broadband gap: From the penetration divide to the quality divide. *Technological Forecasting and Social Change* 77, 816–822. doi:10.1016/j.techfore.2009.12.006
- Wang, J., Lai, J.-Y., Chang, C.-H., 2016. Modeling and analysis for mobile application services: The perspective of mobile network operators. *Technological Forecasting and Social Change* 111, 146–163. doi:10.1016/j.techfore.2016.06.020
- Wymbs, C., 2004. Telecommunications, an instrument of radical change for both the 20th and 21st centuries. *Technological Forecasting and Social Change* 71, 685–703. doi:10.1016/S0040-1625(03)00062-3
- Yan, Z., Peng, M., Wang, C., 2017. Economical Energy Efficiency: An Advanced Performance Metric for 5G Systems. *IEEE Wireless Communications* 24, 32–37. doi:10.1109/MWC.2017.1600121WC
- Yang, L., Yang, S.H., Plotnick, L., 2013. How the internet of things technology enhances emergency response operations. *Technological Forecasting and Social Change, Planning and Foresight Methodologies in Emergency Preparedness and Management* 80, 1854–1867. doi:10.1016/j.techfore.2012.07.011
- Yoo, S.-H., Moon, H.-S., 2006. An estimation of the future demand for portable Internet service in Korea. *Technological Forecasting and Social Change* 73, 575–587. doi:10.1016/j.techfore.2005.07.009

- Zander, J., 2017. Beyond the Ultra-Dense Barrier: Paradigm Shifts on the Road Beyond 1000x Wireless Capacity. *IEEE Wireless Communications* 24, 96–102. doi:10.1109/MWC.2017.1500377WC
- Zanni, A.M., Goulden, M., Ryley, T., Dingwall, R., 2017. Improving scenario methods in infrastructure planning: A case study of long distance travel and mobility in the UK under extreme weather uncertainty and a changing climate. *Technological Forecasting and Social Change* 115, 180–197. doi:10.1016/j.techfore.2016.10.002

Appendix A

Year	Name	Region	Capacity Margin (Mbps km ²)	Strategy	Population Share (%)
2016	Isles of Scilly	South West	-0.63	Minimal Intervention	0.01
2016	Moray	Scotland	-0.12	Minimal Intervention	0.14
2016	Powys	Wales	-0.09	Minimal Intervention	0.22
2016	Orkney Islands	Scotland	-0.07	Minimal Intervention	0.03
2016	Shetland Islands	Scotland	-0.05	Minimal Intervention	0.04
2020	London	London	-1,807.10	Minimal Intervention	13.13
2020	Norfolk	East of England	-9.57	Minimal Intervention	1.48
2020	Rhondda Cynon Taf	Wales	-5.83	Minimal Intervention	0.37
2020	Hampshire	South East	-5.27	Minimal Intervention	2.15
2020	Blaenau Gwent	Wales	-4.50	Minimal Intervention	0.11
2025	London	London	-8,224.63	Minimal Intervention	13.16
2025	Hampshire	South East	-309.13	Minimal Intervention	2.16
2025	Surrey	South East	-296.57	Minimal Intervention	1.87
2025	Hertfordshire	East of England	-262.50	Minimal Intervention	1.86
2025	Essex	East of England	-260.84	Minimal Intervention	2.47
2030	London	London	-14,946.76	Minimal Intervention	13.10
2030	Surrey	South East	-662.94	Minimal Intervention	1.88
2030	Hampshire	South East	-631.00	Minimal Intervention	2.17
2030	Hertfordshire	East of England	-610.32	Minimal Intervention	1.87
2030	Essex	East of England	-545.34	Minimal Intervention	2.50
2016	Isles of Scilly	South West	-0.63	Spectrum Integration Strategy	0.01
2016	Powys	Wales	-0.09	Spectrum Integration Strategy	0.22
2016	Orkney Islands	Scotland	-0.07	Spectrum Integration Strategy	0.03
2016	Shetland Islands	Scotland	-0.05	Spectrum Integration Strategy	0.04
2016	Na h-Eileanan Siar	Scotland	-0.03	Spectrum Integration Strategy	0.04
2020	North Tyneside	North East	-1.79	Spectrum Integration Strategy	0.33
2020	Merthyr Tydfil	Wales	-0.27	Spectrum Integration Strategy	0.09
2020	Southampton	South East	0.03	Spectrum Integration Strategy	0.41
2020	Rhondda Cynon Taf	Wales	0.93	Spectrum Integration Strategy	0.37
2020	Isles of Scilly	South West	1.10	Spectrum Integration Strategy	0.01
2025	London	London	-2,262.84	Spectrum Integration Strategy	13.13
2025	Southampton	South East	-106.29	Spectrum Integration Strategy	0.41
2025	Sandwell	West Midlands	-63.66	Spectrum Integration Strategy	0.47
2025	Walsall	West Midlands	-50.39	Spectrum Integration Strategy	0.40
2025	Bournemouth	South West	-47.72	Spectrum Integration Strategy	0.26
2030	London	London	-8,257.23	Spectrum Integration Strategy	13.16
2030	Southampton	South East	-252.43	Spectrum Integration Strategy	0.41
2030	Sandwell	West Midlands	-171.62	Spectrum Integration Strategy	0.47
2030	Walsall	West Midlands	-136.29	Spectrum Integration Strategy	0.40
2030	Leicester	East Midlands	-136.13	Spectrum Integration Strategy	0.55
2016	Isles of Scilly	South West	-0.63	Small Cell Strategy	0.01