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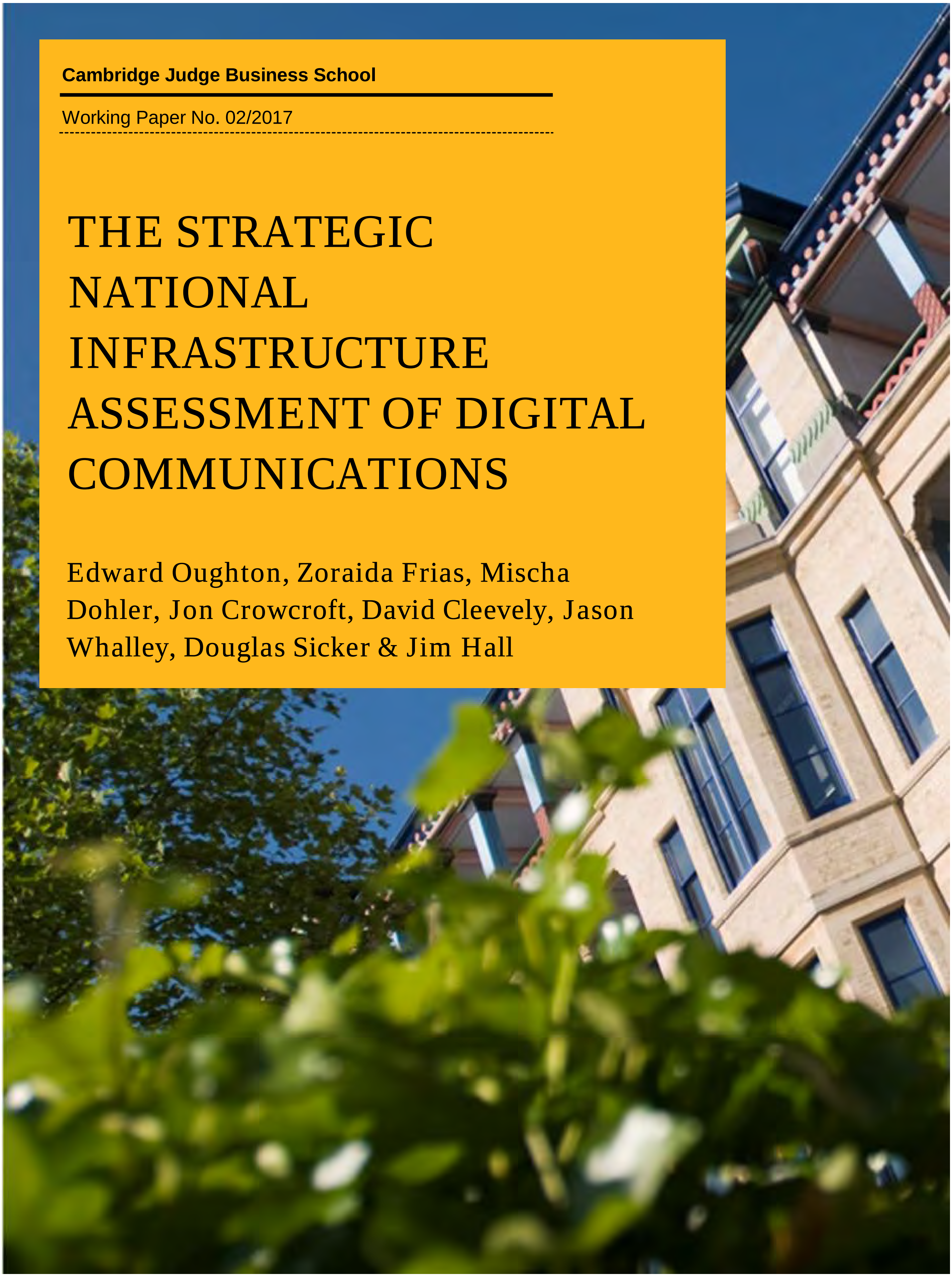

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The Strategic National Infrastructure Assessment of Digital Communications

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ITRC mistral
multi-scale infrastructure systems analytics

EPSRC
Engineering and Physical Sciences Research Council

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Abstract

This paper provides a compendium of the key issues currently facing digital communications and reviews their relevance for the UK's National Infrastructure Assessment of digital infrastructure. The methodology focuses on taking a horizon scanning approach to obtaining current information from a range of authoritative decision-makers across industry, government and academia. After structuring the issues identified, these areas are examined in detail by a multi-disciplinary research team covering engineering, economics and computer science. The key finding shows that future demand uncertainty is the major issue affecting the digital communications sector and holding back increased investment. Moreover, this uncertainty is being driven primarily by the relatively rigid willingness to pay of end-users, weak revenue, the shift from fixed to wireless forms of access, and the ongoing convergence in digital applications and services. The key contribution of this paper is not just to illustrate the issues and trends, but also to identify the need for more research on how the sensitivity of future demand affects infrastructure performance and costs under different demographic, economic and technical scenarios.

Contents

1 Introduction

The global economy is enabled by national and international infrastructure systems that move goods, people and information. A swathe of reports stating the importance of infrastructure, and indeed the decline in infrastructure investment, is commonly cited in support of this topic (see World Economic Forum, 2016 or McKinsey Global Institute, 2016). Historically, the approach to infrastructure planning and delivery has been relatively piecemeal and fragmented. Indeed, infrastructure has been as much the proverbial political football as other areas of government expenditure. A notable example in the UK includes the evidence, options and debate associated with Britain's High Speed Rail 2 decision (Tomaney and Marques, 2013; Hall, 2013; Durant, 2015) and Australia's National Broadband Network (Alizadeh and Farid, 2017).

Attempts have now begun to take a more strategic approach to infrastructure planning, coordination and delivery (Hall et al. 2016a; Hall et al. 2016b) via the introduction of the National Infrastructure Assessment. In the UK, this must be undertaken once per Parliament by a newly created independent advisory body, the National Infrastructure Commission, in an attempt to decouple infrastructure of strategic importance from the electoral cycle. The NIA should outline a strategic vision over a 30-year time horizon, and recommend how future needs should begin to be met. The hope is that this will provide a more objective direction for national infrastructure policy, based on state-of-the-art methods and the best available evidence. Industry, government and academia have responded to this, and while national infrastructure assessment has been underway in different guises for most critical national infrastructure sectors, there has still been a lack of emphasis on digital communications infrastructure (e.g. Institution of Civil Engineers, 2014). This is partly due to digital being fundamentally different to other infrastructure sectors, and while estimating future demand is hard for any infrastructure, the scale and pace of change in digital makes this endeavour much more challenging.

Many of the long-term issues explored in this paper have plagued the sector for many decades. For example, the 1990 briefing on Optical Fibre Networks by the Parliamentary Office for Science and Technology outlines the potential for the deployment of Fibre-To-The-Home (FTTH) networks, but concludes the 'the market for broadband services will grow only slowly and that narrowband links, based on a mix of coaxial and optical fibre networks, will be sufficient for the intermediate future' (p4). A similar narrative is frequently repeated. The Parliamentary Information Superhighways Research Paper (House of Commons Library, 1994: V) quotes the then Oftel Technical Director (the forerunner to Ofcom) as stating:

"*I think the development of these very expensive technologies will need to follow from customer and service demands. The future is not yet clear. One could not today determine precisely what fabric needed to be laid down in the next century until one really saw which services emerged and where there was real customer demand*."

Hence, the debate regarding the fixed fibre access network is still ongoing today, which still focuses on uncertainty in future demand. Currently, the UK is taking an incremental, predominantly mixed-access approach, using new fibre technologies combined with existing legacy copper methods.

In this paper, we aim to highlight the key issues affecting the NIA of digital communications infrastructure. The next section will outline the methodology. Section 3 and Section 4 will then report the results for Fixed networks, and Mobile and Wireless Networks, respectively. Shared issues across all sectors are then outlined in Section 5, before discussing the implications of these findings in Section 6. Finally, the paper concludes in Section 7.

2 Methodology

This section outlines the methodology applied in this paper. The first step included undertaking a workshop in Cambridge, UK, to collect structured evidence from 47 authoritative professionals from industry (23 participants), government (7 participants) and academia (17 participants) (many of whom were high-level decision makers). The workshop took place in February 2017, thereby providing the most up-to-date information for use in the NIA process. The approach used was to split participants into six groups that comprised a mixture of professionals from each sector (fixed, mobile, wireless and satellite) and from industry, government and academia. This was to maximise the interaction and discussion between those from different backgrounds, based on there being considerable value in the interaction that takes place between those traditionally pigeon-holed into either the fixed, mobile, wireless or satellite sectors. Two sessions were held where participants were asked to highlight and describe the future issues pertinent to (i) fixed networks and (ii) mobile and wireless communications.

Once complete the results were grouped based on their key dimensions, whether they were specific to one sector or more, and the spatial scale at which these issues most likely manifest. This focused on grouping by category along the following key dimensions: (i) future demand, (ii) coverage and capacity, (iii) policy and regulation, (iv) economics and business models and (v) technology. This categorical grouping is justified because future demand has a dramatic impact on the viability of delivering new digital infrastructure investment, and coverage and capacity captures the two key assessment metrics of digital infrastructure performance. Policy and regulation sets the institutional rules for telecommunications markets particularly how market failure is addressed, and economics and business models includes everything from asset prices to industry profitability. Finally, technology represents the development of new communications infrastructure components and methods that both solve, and further increase, capacity and coverage issues.

The key topics were then divided based on the subject expertise of the multidisciplinary research team, and allocated to the relevant expert. Each expert was tasked with reporting on the key areas allocated to them, and requested to write up the task in a standard format covering an explanation of the issue and the relevance for the strategic national infrastructure assessment of digital communications. We also outline potential future trends based on the different schools of thought in each area, as well as where there is general disagreement between different digital infrastructure stakeholders. An initial drafting process was carried out before undertaking an iterative redrafting exercise where all authors could access and edit the document. This took place over several months but enabled the key issues and challenges identified in the horizon scanning exercise to be framed in a clear and informative manner. The findings for each sector will now be reported.

3 Fixed Networks

Fixed networks carry the majority of Internet traffic, and although we are increasingly using wireless means to access digital services, bulk data transfer is likely to continue to take place over fixed fibre links. Currently the market share of the main Internet Service Providers (ISPs) in the UK consists of BT (32%), Sky (23%), Virgin Media (19%), Talk Talk (13%) and EE (4%) (Ofcom, 2016b). These providers deliver services using xDSL and FTTx infrastructure, except for the cable provider Virgin Media which currently uses DOCSIS 3 technology and coaxial cable. The remaining share is composed of smaller providers operating in selected areas, such as the new entrant fibre providers CityFibre or Hyperoptic. Since 2010, BT and Sky have seen a 4% and 8% increase in their market shares respectively, whereas Virgin Media and Talk Talk have seen a decrease of 3% and 7% respectively. The key issues identified will now be reviewed along the five categorical groupings articulated previously.

3.1 Future Demand

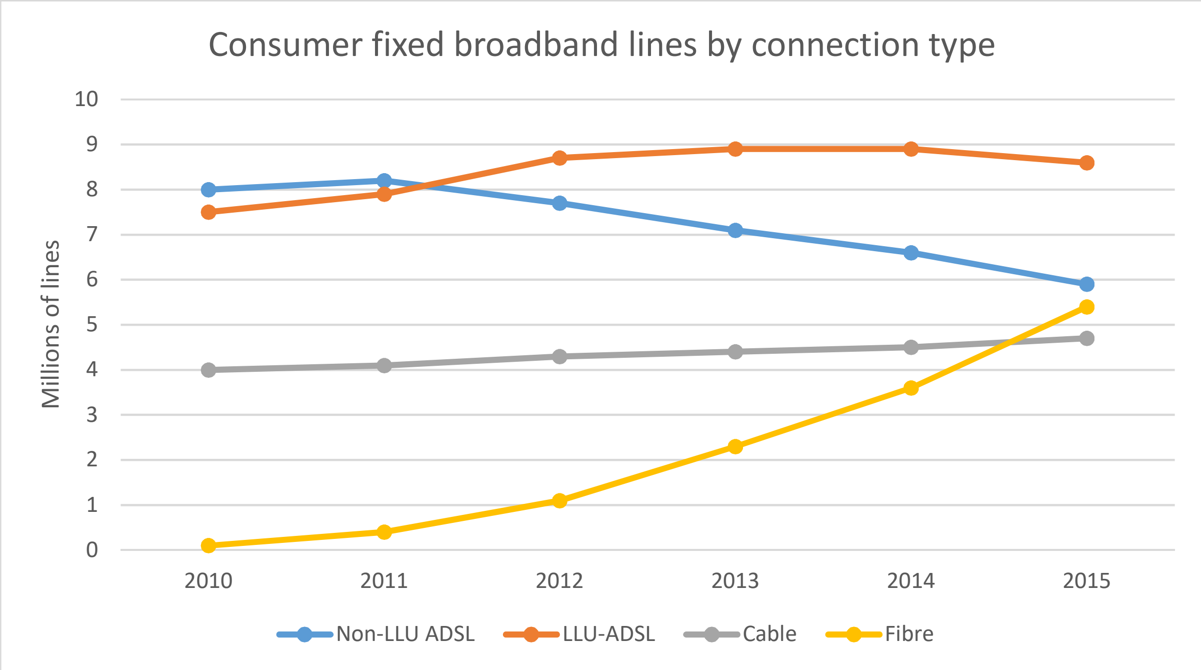
Currently over 9 million consumer premises (31%) in the UK are subscribed to superfast broadband (≥30 Mbps), although the rate of adoption for these services appears to be slowing (Ofcom, 2016a). This is concerning because the economics of density in network rollout means that low demand affects viability, making demand stimulation activities increasingly pertinent. Uncertainty in demand also significantly affects Fibre-To-The-Premise (FTTP) network architecture design (Hervet et al. 2013; Żotkiewicz and Mycek, 2016). In fact, current demand for superfast fixed broadband services is approximately a third of the total number of premises covered (Ofcom, 2016a). Take-up of ultrafast broadband (≥300 Mbps) is even lower at just 0.09% of premises, indicating future demand for higher bandwidth services will take time to evolve. Indeed, this indicates that the perceived value for consumers from the use-cases of ultrafast services is still relatively low. Angelou and Economides (2014) utilise price competition and real option analysis for an actual business case and find that when there is business uncertainty (such as in demand), delaying investment may be more attractive. In many ways, this is related to bandwidth demand and how much one actually needs, which is itself a debateable topic.

Different analyses have produced dramatically diverging estimates for future requirements (see Kenny and Broughton, 2013 versus WIK, 2013). Appendix A outlines estimates by Skouby et al. (2014) for upload and download broadband capacity requirements for different content, applications and services although these ranges are more generous than those stated by other sources. For example, Ofcom (2014:49) is more conservative stating that a total speed requirement for a peak-time household with four users is 12.5 Mbps. This is comprised of User 1 having a video call (1 Mbps), User 2 watching catch-up TV (2 Mbps), User 3 simultaneously watching IPTV and browsing (3.5 Mbps), and finally User 4 watching High Definition (HD) video-on-demand and a video call simultaneously (6 Mbps). The largest bandwidth demands are driven by video content, so the amount of future bandwidth is highly dependent on the adoption and use of IPTV and the quality of the content streamed (HD or beyond). Estimates of bandwidths for using BBC iPlayer by Chambers (2016) include 3 Mbps for Standard Definition (SD) (704x576 active pixels 50/60 fps), 6 Mbps for HD (1920x1080 pixels 50/60 fps) and 35 Mbps for Ultra-High Definition[1] (UHD) (3840x2160 pixels 50/60 fps). Currently there is a focus on providing a basic level of bandwidth (10 Mbps) to all users, but this may not provide the best quality of experience which often requires higher bandwidth.

Currently higher demanded bandwidths are more suitably met by either fibre (FTTx) or cable (DOCSIS 3) connections (instead of basic ADSL broadband). Figure 1 outlines key trends in consumer fixed broadband lines based on current take-up. Basic broadband lines via non-LLU connections have been steadily decreasing from 8 million in 2011 to under 6 million in 2015 (24%), whereas FTTx connections have been increasing at a rapid pace since that time to over 5 million in 2015 (22%). Take-up of cable connections has marginally increased in recent years but has remained under 5 million connections (19%), although Virgin's Project Lightening network expansion programme may increase this figure.

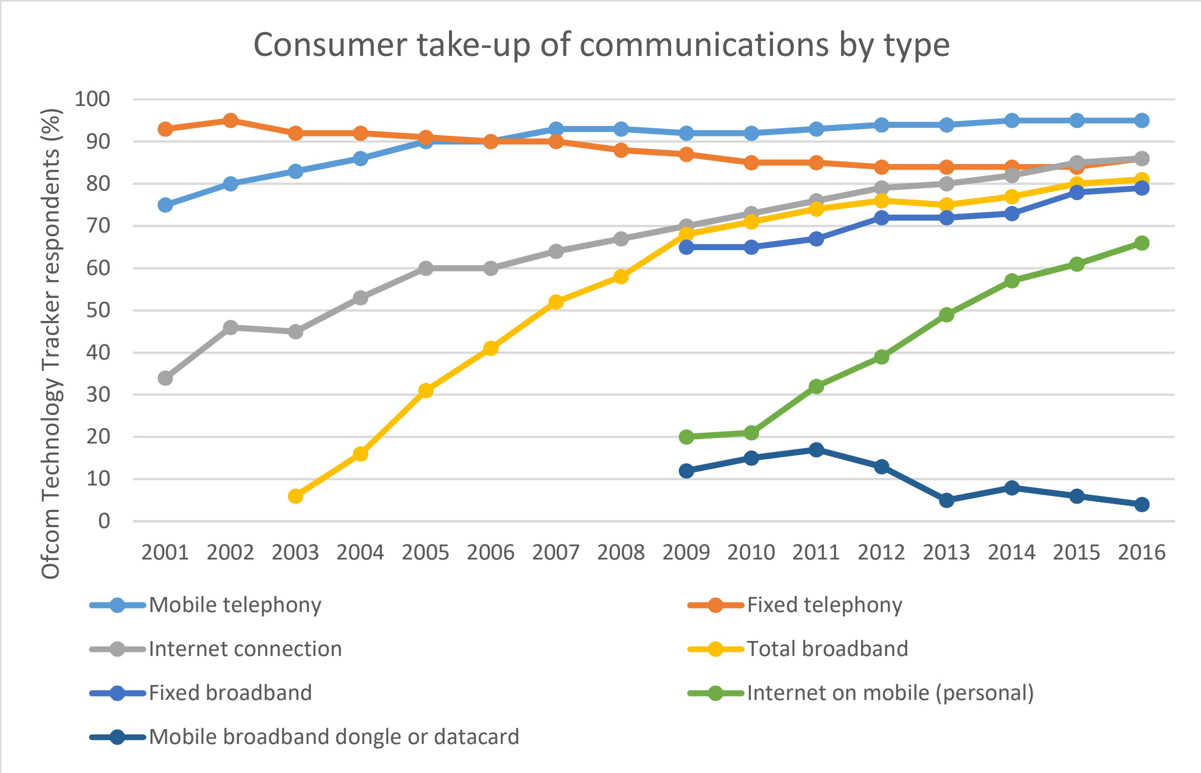
[1] BBC iPlayer does not currently offer UHD services but this bitrate was tested for the 2014 Commonwealth Games

Figure 1 Current demand in fixed broadband lines by connection type



Future demand uncertainty is not just affected by the willingness to pay of consumers, but also by changing technology trends. The increase in FTTx connections in Figure 1 is almost completely comprised of Fibre-To-The-Cabinet (FTTC) products, whereas the willingness to pay for full FTTP services is still low. The increasing capacity and use of mobile connections poses a perceived risk by fixed network operators. For example, the introduction of 4G LTE-Advanced and potentially '5G' (in whatever form '5G' may finally be once standardised) means that these wireless technologies *may* increasingly be able to compete with fixed access connections, although we currently have limited evidence. Figure 2 illustrates the dramatic rise in personal mobile Internet access in recent years, with a total increase of approximately of 45% between 2010-2016 in the Ofcom Technology Tracker data.

Figure 2 Key trends in the Ofcom Technology Tracker (Ofcom, 2016b)

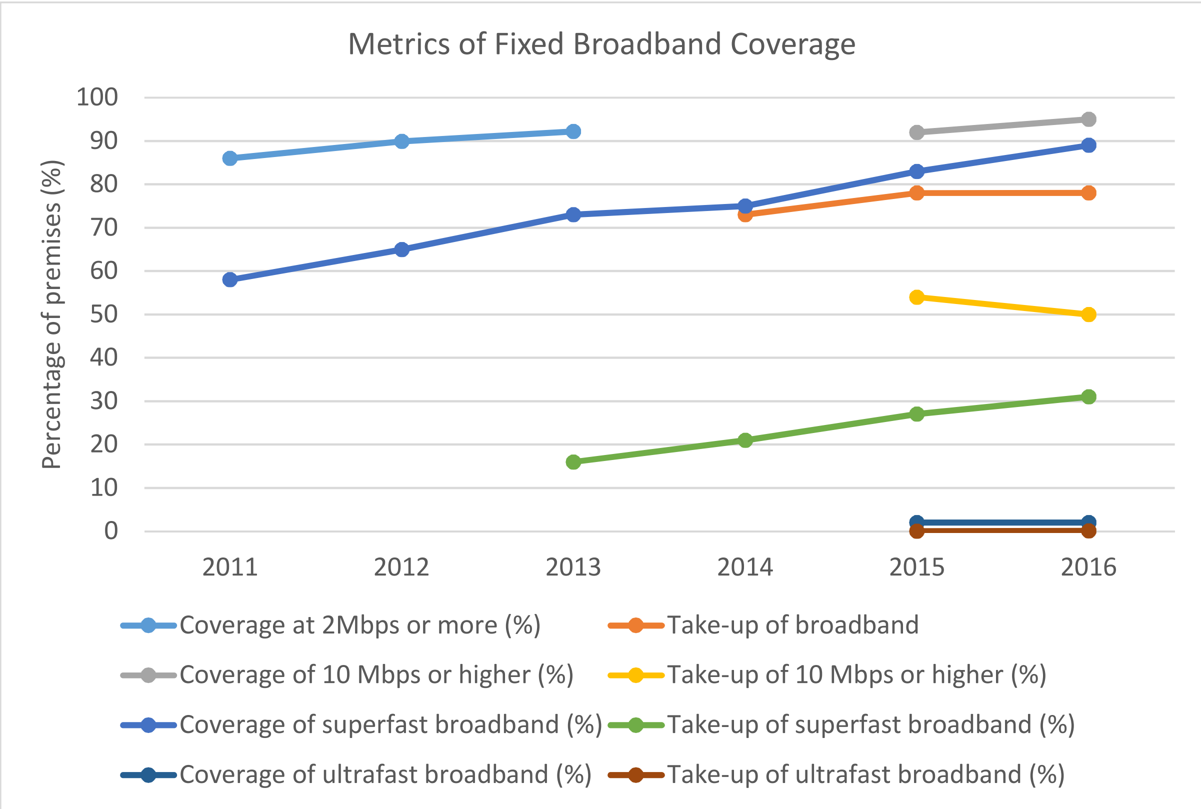


This increase in mobile internet adoption illustrated in Figure 2 has been driven by smartphone penetration, faster mobile data speeds, and an increasing range of applications and services. These latter two factors are likely to continue to drive demand over the next decade, as 5G drives speed and the increased proliferation of mobile applications and services, increase adoption and usage patterns. Importantly, one school of thought is that future demand for fixed access is uncertain over the long-term as users may increasingly moving towards using wireless access methods. The adoption of fibre services are likely to continue to rise over the next decade until FTTC is the most common access type, and early adopters move closer to full FTTP solutions.

3.2 Coverage and Capacity

In 2016, 95% of premises could achieve a broadband speed of ≥10 Mbps, leaving the final 5% to be the aspiration of the newly introduced Universal Broadband Obligation (USO). Superfast broadband speeds ≥30 Mbps were achievable by the majority of premises (89%), although only a small fraction (2%) were able to achieve Ultrafast broadband (≥300 Mbps). Figure 3 gathers useful data from Ofcom Infrastructure Reports over the past 6 years (now known as the Connected Nations report), and although there is some discontinuity in the metrics reported over this period, it provides some useful insight into capacity, coverage and willingness to pay. In this graph, 'coverage' by a specific speed indicates the ability for a premises to obtain a specific capacity over the current connection (irrespective of the amount of bandwidth paid for), hence this is an indicator of the maximum potential throughput. On the other hand, the 'take-up' of a service capable of delivering a certain speed indicates the willingness of consumers to pay for bandwidth capacity.

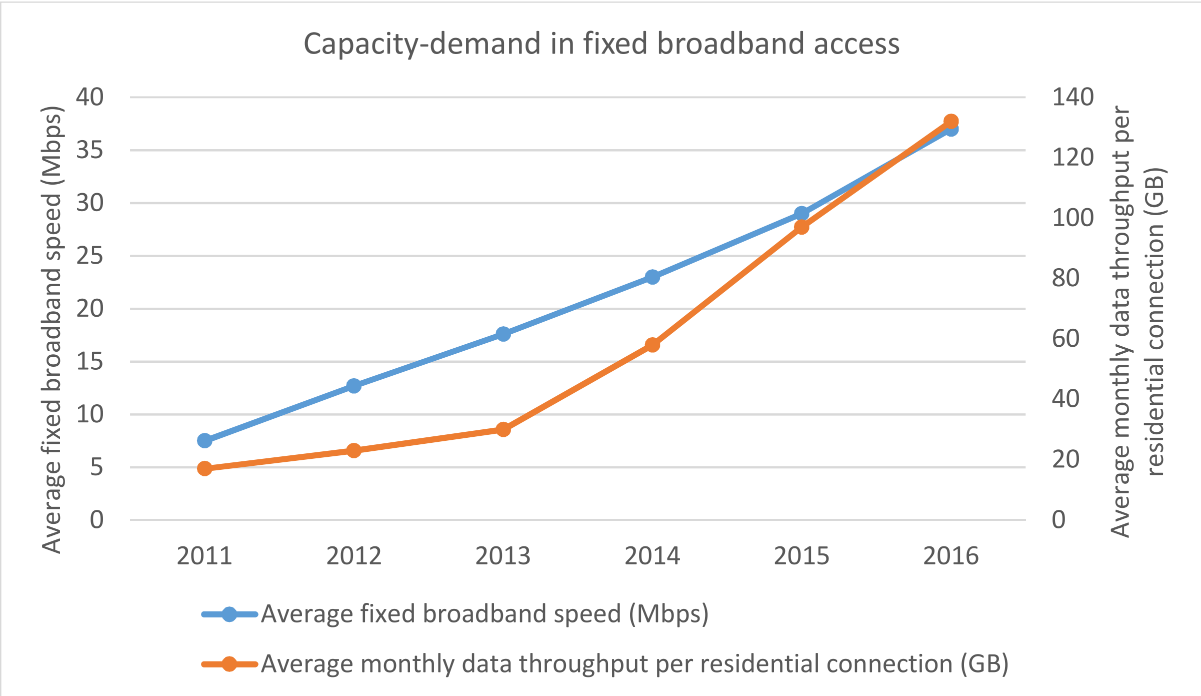
Figure 3 Fixed broadband coverage by speed target 2011-2016



Coverage of superfast broadband has increased considerably between 2011-2016 by roughly 20%, to just below 90% of premises, however coverage of ultrafast broadband remains very low. In terms of take-up, almost 80% of premises have a basic broadband connection, and approximately 50% pay for a service that delivers more than (≥10 Mbps). Whereas over the past ten years, coverage and capacity has been focused on the number of premises receiving 2 Mbps (the old USO), and 30 Mbps (superfast broadband), now that the speed distribution has shifted, the current concern will be 10 Mbps (the new USO) and 300 Mbps (ultrafast broadband). In the future, this will rise as bandwidth demand increases, and we could plausibly see a 30 Mbps USO and a 500 Mbps standard connection speed introduced in future decades.

Over the past six years there has been a considerable increase in average fixed broadband speed due to investment in FTTx and DOCSIS 3, and this has simultaneously driven data demand due to the relative ease of dealing with the transfer of what was traditionally regarded as large amounts of data. Figure 4 illustrates that the average fixed broadband speed has increased from approximately 7 Mbps in 2011 to 37 Mbps in 2016, and that this speed increase has taken place in a relatively linear manner. The average monthly data throughput per residential connection however saw modest growth between 2011-2013, whereas it increased rapidly from 2014 onwards, most probably due to the adoption and use of IPTV services. As just one example over this period, in February 2011 there were 117 million monthly requests for TV content via BBC iPlayer which then increased in 2016 to 239 million (BBC, 2017). In February 2017 this increased to 277 million BBC iPlayer requests.

Figure 4 Capacity-demand in fixed broadband access 2011-2016



The key message in Figure 4 is that as fixed broadband speeds continue to grow, demand across the connection in terms of data throughput is likely to similarly grow, potentially even at a faster rate.

Indeed, recently the idea of a 'capacity crunch' in optical fibre communications networks has been explored. The key concern relates to whether technological capabilities are keeping pace with dramatic increases in demand, as optical fibre has a finite information flow. The three methods for expanding capacity (which each have limits) include (i) increasing the channel spectral window, (ii) improvements in spectral efficiency, and (iii) raising injected power levels to obtain an improved Signal-to-Noise Ratio (SNR) (Ellis et al. 2016).

Although research is still exploring if a limit exists to the capacity of optical communication (e.g. Bayvel et al. 2016), if a practical limit was reached there would need to be increased parallelism in communications networks, requiring more fibre infrastructure (Kilper and Rastegarfar, 2016). This would have a significant impact on both capital expenditure (equipment costs) and operational expenditure (energy consumption), influencing the overall economic viability of new capacity.

3.3 Policy and Regulation

The policy and regulatory aspects of fixed broadband networks continues to be a heated area of debate, due to issues in how best to push a previously nationalised network industry towards more competitive dynamics for each major generational upgrade. As identified in the Digital Communications Infrastructure Strategy (DCMS and HM Treasury, 2015), a core part of the UK's success in attractive investment and ensuring competitive markets, stems from strong, transparent and independent regulation. The UK has long favoured market-based policies in the telecoms sector, with a prudent mix of supply-side (e.g. Broadband Delivery UK's Superfast Broadband Programme) and demand-side (e.g. Broadband Connection Voucher Scheme) policy instruments where the market has failed to deliver adequate digital infrastructure. Some of these schemes have had mixed results, however.

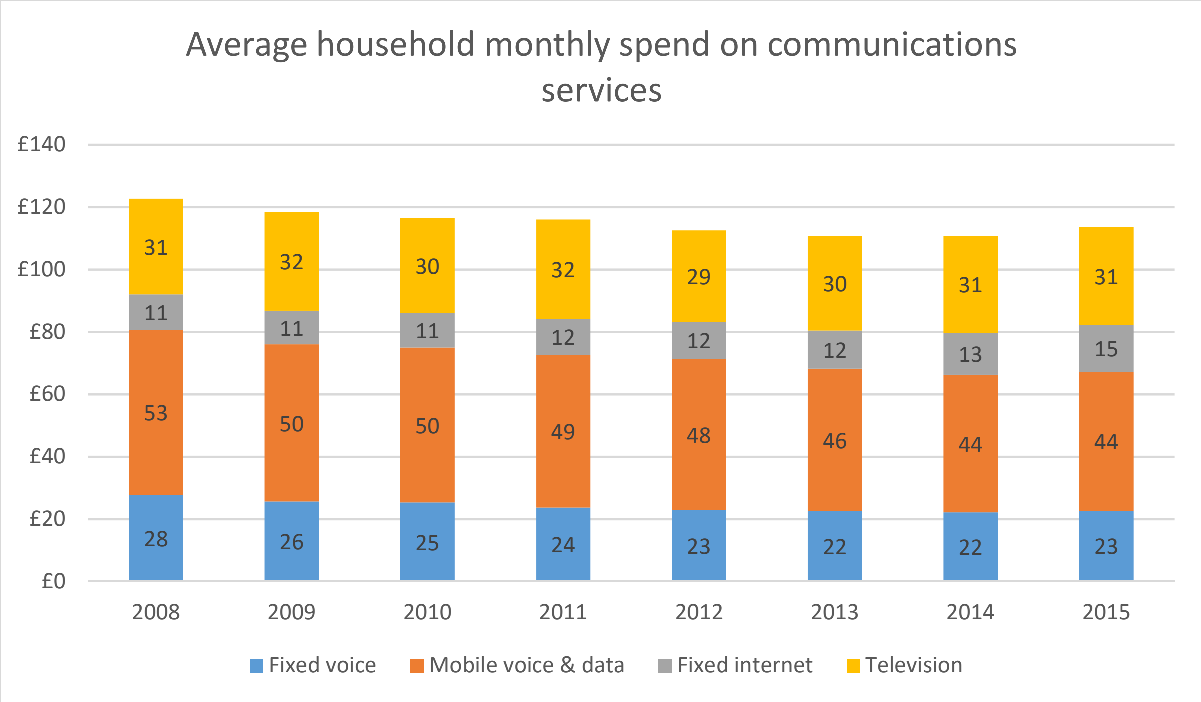
In terms of encouraging more investment into fixed networks, the UK has pursued a Local Loop Unbundling strategy over almost two decades. Evidence suggests that this approach can have a positive impact when introduced, but has less and less impact as markets start to mature (see Nardotto et al. 2015). Inter-platform competition, therefore, will have more of a positive impact in terms of penetration and quality moving forward, and will be increasingly important for UK digital infrastructure rollout. The key inter-platform competitor to the incumbent is from Virgin Media, although the Project

Lightening network expansion will generally target only the infill development within its existing urban-centric footprint. New full fibre entrants such as Gigaclear and Hyperoptic will also be key in driving the benefits of inter-platform competition, although it is unclear if a third ultrafast broadband operator is able to compete with Openreach and Virgin Media. International evidence suggests that ensuring open access for new entrants to the incumbent's infrastructure facilities is associated with high-quality broadband infrastructure networks (Rajabiun and Middleton, 2013). Ofcom is currently pursuing how to increase physical infrastructure access for communications providers, as part of the Wholesale Local Access Market Review.

3.4 Economics and Business Models

Issues pertaining to the economics of FTTP networks are not new (see Frigo et al. 2004; Monath et al. 2003; Weldon and Zane, 2003), as making the case for large-scale deployment can be challenging without a defined set of use-cases for fibre, or significant changes in public policy or industrial organisation. The two key issues affecting the economics of deployment are firstly the large fixed costs associated with deployment and secondly the uncertainty in future demand. Considerable emphasis is placed on supply-side market failures, but less focus is placed on demand-side issues such as willingness to pay, the ability to adopt new services and demand stimulation activities. By increasing the willingness to pay and aggregate demand for higher bandwidth services, it not only provides more certainty to operators making major investments but also reduces the average cost of delivery per user due to scale economies (Katz and Berry, 2014). Importantly, we need to do more to understand the potential positive effects that demand-side policies may have on increasing the coverage and capacity of ultrafast fixed broadband networks. Figure 5 illustrates average monthly communications spending by service.

Figure 5 Average household monthly spend on communications services by key sector



As illustrated in Figure 4, between 2008-2014 there was roughly a 10% decrease from £123 in 2008 to £111 in 2014. In 2015 we saw a slight increase overall to £114, mainly due to expenditure increases in fixed Internet services. The reason for the increase in fixed internet revenue is that consumers are willing to pay more to upgrade to superfast broadband services, and gain the benefits of greater bandwidth. As more households move to adopt these services, this average monthly figure will continue to rise, which may also positively impact the viability of future fixed network investment.

3.5 Will technology save the day?

Technology and software development is driving major change in the fixed access, metro and core networks. Due to the civil engineering and planning costs of laying full fibre solutions in the access network, new technologies such as G.fast (offering up to 1 Gbps) or XG-fast (offering up to 10 gbps) have attempted to make DSL technology competitive with FTTP (Timmers et al, 2013; Coomans et al. 2015). Using advanced crosstalk cancellation techniques (vectoring), 500 Mbps has been achieved over 250m (Oksman et al. 2013). Additionally, in cable access the DOCSIS 3.1 specification has been developed with the aim of providing subscribers with speeds of up to 10 Gbps downstream and 1 Gbps upstream (Hamzeh et al. 2015). The delivery of these technologies will hamper (or at least delay) the case for full FTTP solutions as they are likely to cost more.

A series of new technologies termed Network Function Virtualisation (NFV) can enable the core network's high-volume packet-processing functions to be virtualised to run on cloud computing platforms (Joshi and Benson, 2016). In communications networks, this has been proposed as a way of increasing the flexibility of network service provision, including reducing the deployment time for new digital applications and services (Han et al. 2015). NFV is commonly referred to in tandem with Software Defined Networking (SDN) which is an approach capable of separating the underlying data plane in the network from the control plane, consolidating control functions in a logically centralised controller (Thyagaturu et al. 2016). These tools will provide greater flexibility and efficiency to infrastructure network operators in the future (Nunes et al. 2014), and are hoped to be able to reduce both capital and operational expenditure (Mijumbi et al. 2016), potentially making new infrastructure delivery more viable.

4 Mobile and Wireless Networks

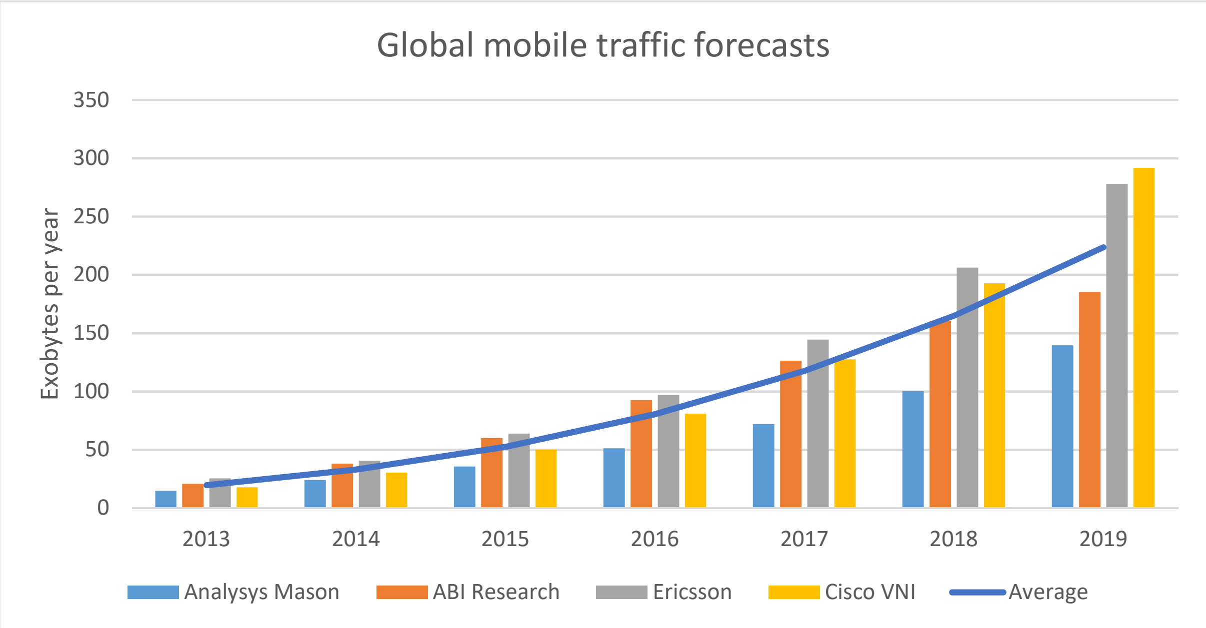
In terms of revenue and the subscriber numbers, the UK mobile sector is one of the largest in Europe. Mobile Network Operators (MNOs) with major market shares include EE (inc. Orange and T-Mobile) (29%), O2 (inc. GiffGaff) (27%), Vodafone (inc Talkmobile) (19%), and Hutchinson Three (11%) (Ofcom, 2016b). Other Mobile Virtual Network Operators (MVNOs) comprise the remaining 15%, mainly offering alternative low-cost offers. Currently 2G, 3G and 4G technologies are in operation across the UK by the majority of major operators, although 4G rollout is still taking place and is yet to cover many rural areas. Although premises coverage of both 3G and 4G is over 70%, geographic coverage lags behind with 4G at approximately 40% of UK landmass. With the increased proliferation of 4G, the average data consumption per user is increasing rapidly which is now over 1 GB.

Considerable policy emphasis has been put on the mobile and wireless industry in recent years for three key reasons. Firstly, mobile signal can be poor at times in both urban and rural areas even for voice calls. Given the UK is a major economy with one of the fastest growing digital economies, this is surprising and concerning. The operators state that they struggle to get new sites for basestations through planning. Others blame the operators for underinvesting. Either way, there is a desire by government to try and improve the current level of mobile connectivity. Secondly, as the UK was sluggish at gearing up for, and delivering, 4G rollout there has been significant interest in making sure that the UK does not repeat the same mistake with 5G. In 2016, the incumbent chancellor announced the ambitious aim to make the UK a world leader in 5G. This includes deployment taking place by 2020 which will no doubt be challenging. Thirdly, the UK thankfully avoided high unemployment throughout the great recession, unlike many of its counterparts. However, over the past decade there has been increasing concern regarding productivity, as national indicators of this metric have essentially remained static with little improvement. Therefore, 5G is hoped to be one such tool that can drive increases in labour productivity as well as the wider economy. In short, this future ambition is motivated by the desire to use 5G as part of a national industrial strategy, to drive both improvements in productivity and overall economic output.

4.1 Future Demand

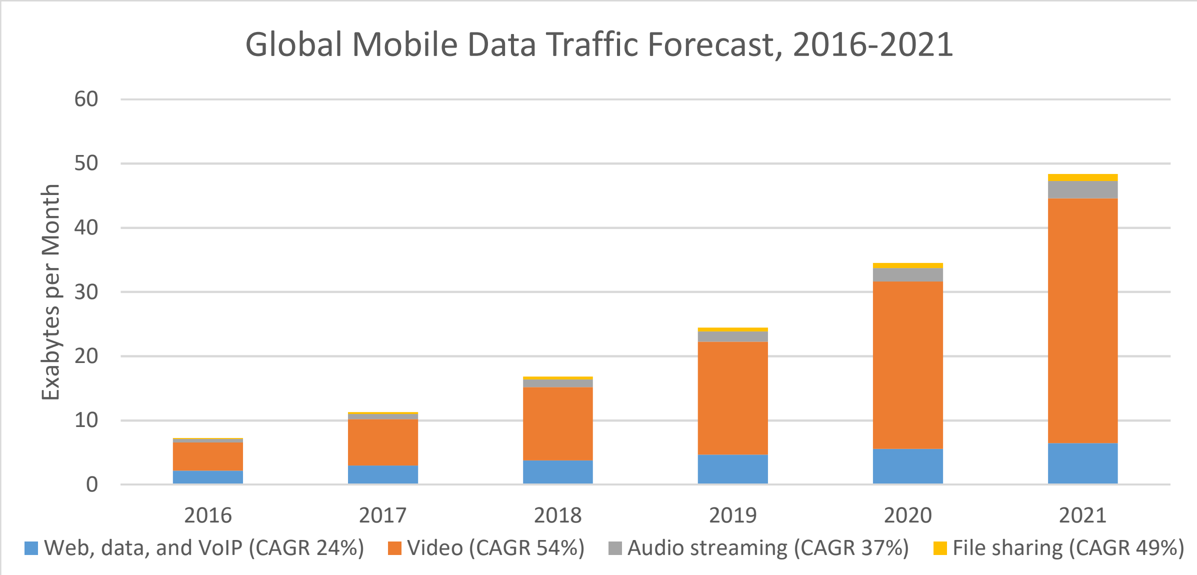
There are currently 91.5 million UK mobile subscriptions, of which 39.5 million are 4G, with approximately 93% of adults using mobile phones. Smartphones are currently used by 71% of all adults and are the key technology driving the demand for more access capacity and data throughput, as they enable a wide range of content, applications and services including wireless HD video access. A synthesis of global mobile traffic forecasts are presented in Figure 6, including the average growth trend.

Figure 6 Global mobile traffic forecasts (GSMA, 2015)



Over the past five years, mobile data traffic has grown by up to 18 times, with mobile video traffic accounting for 60% of total mobile traffic in 2016 (Cisco, 2017). Figure 7 illustrates the most recent Cisco mobile traffic forecast for 2016-2021, which illustrates that video is driving the overall long-term trend with a Compound Annual Growth Rate (CAGR) of 49%. Fixed traffic is expected to fall from 52% of total IP traffic in 2015 to 33% by 2020, as mobile and wireless grow at a rapid rate and increasingly take up larger shares of the total. Assessment of IP traffic by access technology shows that by 2020, 17% will be from mobile data, 29% will be from fixed/Wi-Fi from mobile devices, 20% from fixed/Wi-Fi from Wi-Fi-only devices, and 33% from Fixed/Wired technologies.

Figure 7 Global mobile traffic forecast 2016-2021 (Cisco, 2017)



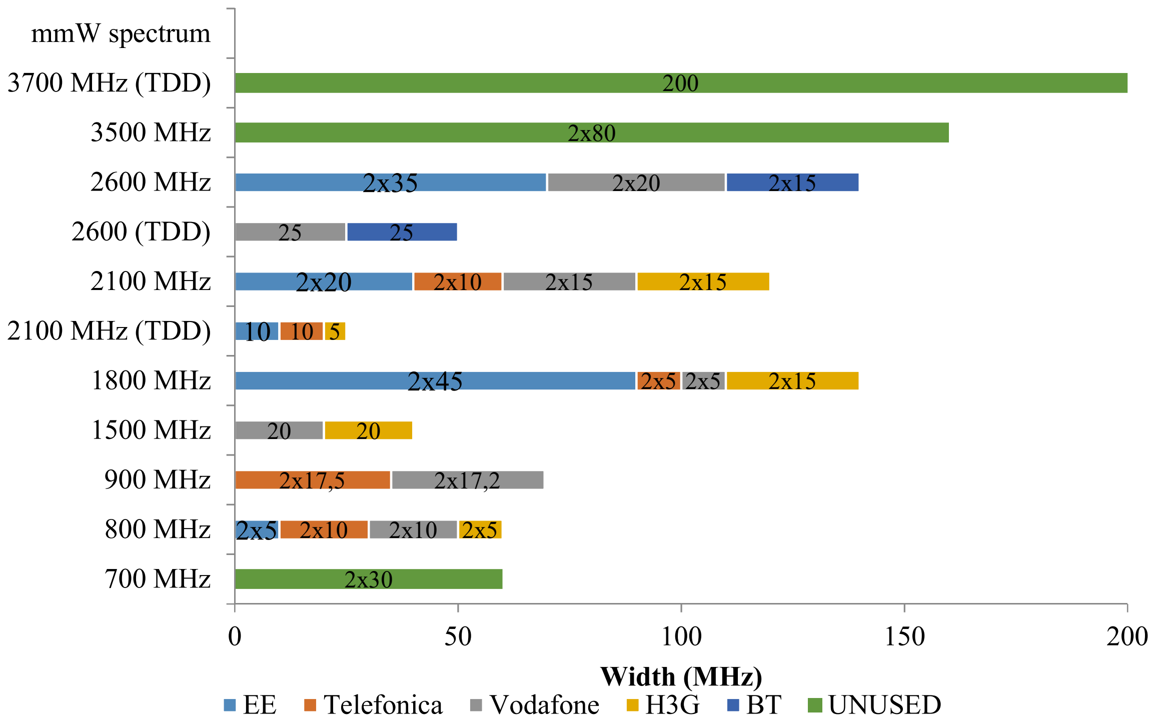
Analysis by Feijoo et al. (2016) modelled various future scenarios by segmenting demand by service type in Spain. Baseline demand, defined as the average data throughput per user, was estimated by calculating (i) the number of mobile broadband subscribers, (ii) number of users and technical evolution requirements, and (iii) combined service usage. Between 2013 and 2020 the baseline saw average annual growth rate of 31%, which is generally more conservative than other forecasts, such as those shown in Figures 7 and 8. Regardless, it demonstrates that mobile data demand is no longer driven by supply, meaning operators must make more capacity available to merely keep up with market expectations (even without additional revenue).

As already highlighted, the future demand for 5G is an issue. Merely because government wishes to deploy 5G infrastructure expediently, it does not mean businesses or consumers will be willing to pay extra for these services. This partly relates to use-cases for the additional services as consumers are only willing to increase spending if there is a perceived additional benefit. According to work by Real Wireless (2016), the probable 5G use-cases include connected vehicles, railways, preventative health and remote care, smart utilities, supply chain monitoring and delivery, and media and cloud everywhere. Hence, unless these usage benefits are clearly perceived by consumers there will be reluctance to pay increased additional money for services marketed as ‘5G’, introducing added uncertainty to future demand. Reflecting on 4G deployment in the UK, consumers showed how price conscious they are with the large majority of customers eventually being given the 4G service as a free upgrade, rather than paying additional revenue. As illustrated already in Figure 6, average monthly revenue on mobile voice and data has decreased quite significantly between 2008-2015.

4.2 Coverage and Capacity

In June 2016, a total of 106 PB were sent across all mobile networks which was almost a 50% increase on the previous year, although this still only represents about 4% of the data sent across fixed networks (Ofcom, 2016a). For capacity to meet this growing demand there are three options which include integrating newly available spectrum, densification of the network and increasing the spectral efficiency of the basestation technology (Clarke, 2014). To meet long-term data demand it is likely that a combination of all of these capacity-enhancing techniques will be required, but the main gains will be made in small cell network densification and additional spectrum integration. As spectrum availability is potentially a key capacity limitation for wireless infrastructure it deserves significant attention. The current spectrum bands have been outlined in Figure 8 according those held by each network operator.

Figure 8 Licensed spectrum bands by operator (Oughton and Frias, 2016)



Kassem and Marina (2015) evaluate the UK's approach to future spectrum use below 6 GHz. Currently the four drivers for additional sub-6 GHz spectrum in the UK are the need to expand network capacity (especially indoors), improve coverage, meet the demand for new machine-to-machine applications and rollout more wireless backhaul links in ever denser networks. The authors argue that unlike current allocations, most new spectrum (approximately 80%) would be shared spectrum accessed via Licensed Shared Access (LSA) or Opportunistic Spectrum Access (OSA). The UK has committed to releasing 750 MHz of sub-10 GHz spectrum by 2022, with 500 MHz being available by 2020 (UK Government Investments, 2016), as outlined in Figure 9. Ultimately, the choice of future spectrum bands themselves will be a key driver for the *type* of infrastructure likely to be delivered by the market, as the characteristics of different bands will affect capacity and coverage.

Figure 9 UK public sector spectrum release 500 MHz target

Category	**Frequency band**	**Lead department**	**Target release**	**Quantity (MHz)**
Completed releases (Total: 384 MHz)	70.5-71.5 MHz, 80-87.5 MHz, 138.0875-138.3125 MHz	HO	2012	9
	1668-1670 MHz, 1698-1700 MHz	HO	2012	4
	870-872 MHz, 915-917 MHz	MOD	2014	4
	960-1165 MHz	CAA	2016	92
	2025-2070 MHz	MOD	2015	45
	Upper 2.3 GHz (2350-2390 MHz)	MOD	2015	40
	3.4 GHz (3410-3600 MHz)	MOD	2015	190
Target priority bands below 5 GHz	380-385 MHz, 390-395 MHz	MoD	2021	Up to 10
	406-430 MHz	MoD	2018	Up to 5
	1427-1452 MHz	MoD	2018	Up to 20
	Lower 2.3 GHz	MoD / HO	2020-2022	Up to 40
	4.8-4.9 GHz	MoD / HO	2016-2018	Up to 55
Priority bands >5 GHz	5350-5470 MHz, 5725-5925 MHz	MoD/BIS/DfT	2017-2022	Up to 245
	7.9-8.4 GHz	MoD	2016-2017	Up to 168
Public sector to public sector sharing	2.7-2.9 GHz	CAA/DfT	2016-2020	Up to 100

Three pioneer bands have been earmarked for 5G by the EU's Radio Spectrum Policy Group (RSPG) which include 700 MHz, 3.4-3.8 GHz and 26 GHz. These spectrum choices have been selected as options for providing significant performance improvement in current wireless networks. Firstly, while 700 MHz is constrained by the bandwidth available, it is the only band of the three capable of delivering reliable national coverage, especially as it could significantly improve reach into and around buildings. Secondly, 3.4-3.8 GHz has the potential to deliver Gbps to mobile users via dense clusters of small cells (predominantly in urban areas). However, the expectation is that it will not be economically feasible beyond urban areas (see Oughton and Frias, 2016). Finally, hotspot locations with very high footfall could make use of 26 GHz which is capable of delivering multiple Gbps. These spectrum choices will end up making 5G infrastructure a "layered cake" of three new networks on top of existing infrastructure, with the aim of advancing fixed wireless capacity, mobile wireless capacity and mobile wireless coverage.

International perspectives are highly useful to provide context for the UK. In the USA, there are two different schools of thought regarding the availability of adequate spectrum. On one hand, there are those who believe the USA faces no spectrum shortage. On the other hand, some argue that the USA has inadequate spectrum to accommodate future demand growth. For example, Clarke (2014) quantified the capacity expansion potential of 4G LTE and LTE-Advanced with traditional spectrum reuse and made comparisons with future demand forecasts, concluding that without significantly increasing current spectrum allocations by 560 MHz over 2014-2022, wireless capacity will be inadequate. More quantitative analysis of UK capacity-demand and spectrum availability would be highly useful to increase our understanding of future capacity limits.

In terms of UK coverage, there is potential that future generations of technologies (e.g. 5G) may well make coverage and capacity disparities worse, rather than better (see Oughton and Frias, 2016). This is due to small cell deployments with 100-200m radii (Murdock et al. 2012; Akdeniz et al. 2014) which will only be viable to deliver in urban areas. Some have looked to 5G to 'fix' the coverage issues currently present in the UK, but this seems unlikely. There is growing concern regarding the disparity between areas that are stated to have coverage by operators, but in fact the user can struggle to obtain the desired level of service leading to a poor user experience. This is emphasised when comparing coverage via Ofcom's coverage checker, and actual connectivity data from OpenSignal. Hence, there has been increasing awareness of the need to shift from Quality of Service metrics, which are purely technocratic, to Quality of Experience metrics that include the subjective satisfaction of the end-user (Liotou et al. 2015; Tsolkas et al. 2017; Agboma and Liotta, 2012; Reiter et al. 2014). A shift moving forward, placing more emphasis on user experience, will improve the ease of use of digital applications and services. However, doing so would have many ramifications for the design and delivery of digital infrastructure in the future.

4.3 Policy and Regulation

Increasing infrastructure deployment costs combined with declining ARPU have led to increased consolidation across the mobile industry in the UK and Europe. However, the degree to which M&A activity has been allowed to take place has been heavily influenced by the regulatory stance of each country. Curwen and Whalley (2016) examine the decision to block the acquisition by 3UK (Hutchinson) of O2 Telefónica, despite a similar reduction to three networks in Germany (with stringent conditions attached however). The key issue is whether consolidation is beneficial or detrimental to prices and infrastructure investment. Some industry analysts believe there would be positive network investment effects from this activity (see Frontier Economics, 2014 and HSBC, 2015), although others disagree, stating that there is little historical evidence this would take place (i.e. WIK-Consult, 2015). We must wait for further evidence to undertake a thorough evaluation of the long-term investment impacts due to recent European M&A activity, but there appears to be opposing views held by different stakeholders regarding the optimal industrial structure of the UK mobile industry.

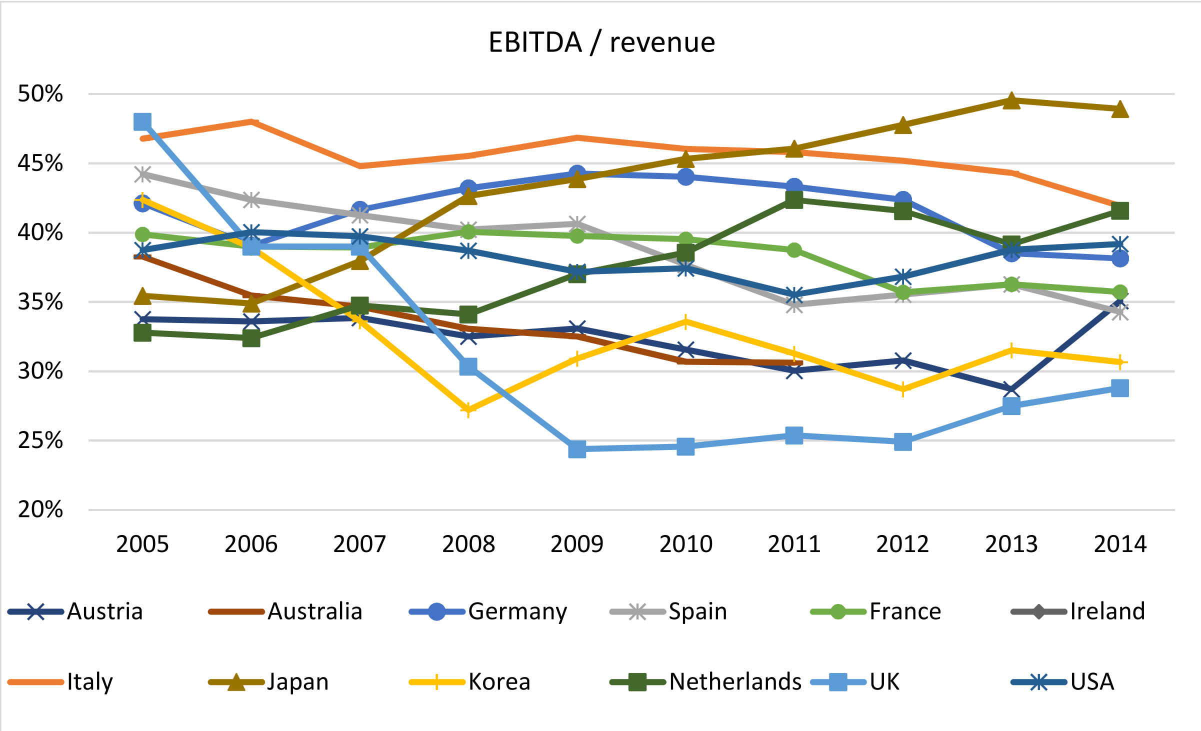
If the UK is to embark on early 5G deployment, numerous planning reforms may need to be implemented for effective and efficient small cell infrastructure deployment. Current local planning regimes can be prohibitive for deploying digital infrastructure, with examples including limits on the heights of basestation antennas, as well as the challenges of obtaining planning permission for new sites that are not within permitted development. Hence, planning issues have a significant impact on the available coverage and capacity for users and may further require reform. If 5G is to be driven by small cell deployment, which is highly likely given the desired capacity enhancements mooted by various sources (Andrews et al. 2014), this process must be able to take place swiftly and cheaply.

Indeed, Brake (2016) makes policy recommendations regarding the rollout of 5G networks in the US. Firstly, this includes the allocation of more spectrum to mobile, not only high-band but also low and mid-band. Secondly, streamlining access to rights-of-way, dig-once policies, consolidated paperwork, and a single point-of-contact for planning. This would require more cooperation between UK industry and local government, with local authorities understanding the importance of digital infrastructure rollout. Unnecessary additional taxation on infrastructure delivery would constrain rollout.

4.4 Economics and Business Models

As already illustrated in Figure 5, average monthly spend on mobile voice and data services has decreased significantly over the past decade. Falling Average Revenue Per User (ARPU) is also reflected in the general profitability of the UK mobile sector, which has declined since 2005. Two key metrics that represent 'profitability' include Earnings Before Interest, Tax, Depreciation and Amortisation (EBITDA), and Post-Tax Return On Capital Employed (ROCE). Firstly, Figure 10 shows between 2005-2014, the EBITDA for 11 countries, where by the end of this period, the UK was lowest.

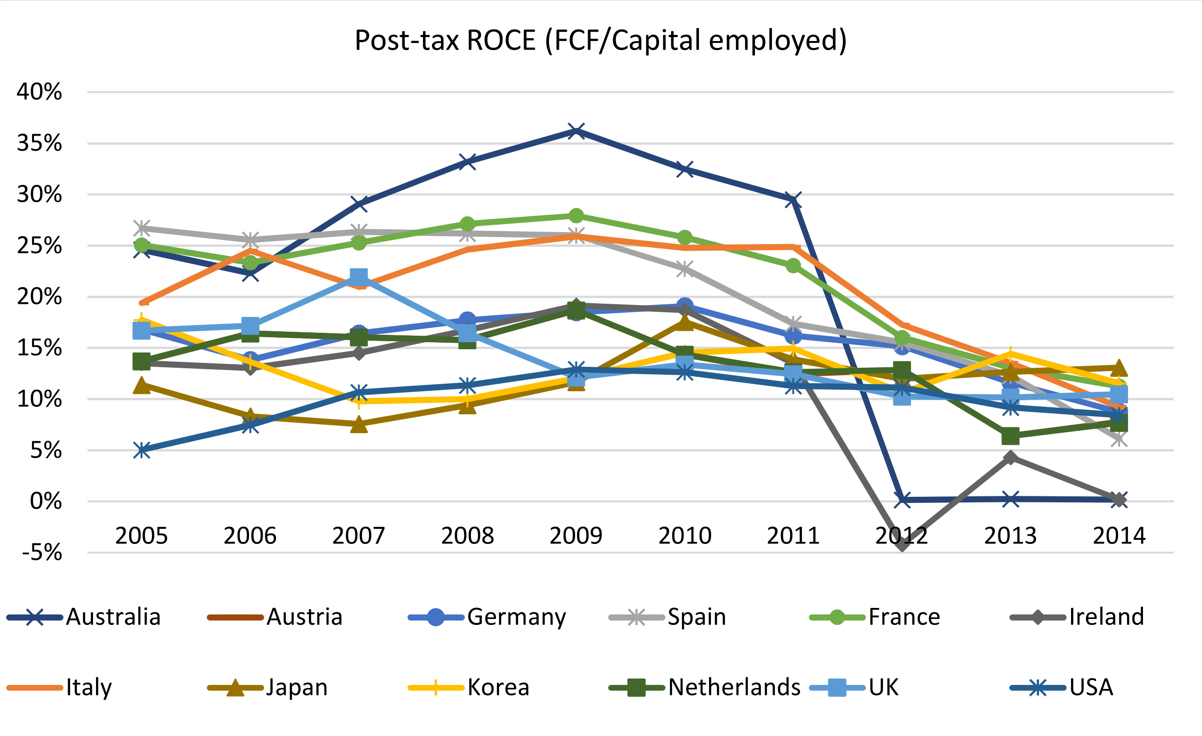
Figure 10 EBITDA / revenue of mobile operators in major countries 2005-2014 (New Street Research, cited in WIK-Consult, 2015)



While countries such as Spain and Korea have also seen declining EBITDA, others have seen a positive increase, such as Japan and the Netherlands. Little change has taken place in the mobile markets of the USA, France and Austria with the EBITDA margin remaining around 35%.

Secondly, Figure 11 shows for the same period the Post-Tax ROCE. The UK mobile sector was in the middle of the distribution in 2015 at 10-11% return. In comparison with other countries, this shows that the UK mobile sector has potentially low investment attractiveness moving forward, which may detrimentally affect infrastructure investment.

Figure 11 Post-tax ROCE of mobile operators in major countries 2005-2014 (New Street Research, cited in WIK-Consult, 2015)



The desire in the UK to expedite the delivery of '5G' is due to the possibility that it could be a key element of the national industrial strategy, as some have predicted there could be large economic benefits due to a range of end-uses, including increased automation (leading to the so-called '5G industrial revolution'). ICT capacity does have an impact on economic development, but certain variables such as education and prices can mediate any impacts (Jin and Cho, 2015). Indeed, technology usage is ultimately the key driver of change, not merely delivery of the infrastructure (Mack and Faggian, 2013). A review of the empirical literature found that ICT generally has a positive and significant impact on productivity (Cardona et al. 2013), but it is worth being aware that the benefits of infrastructure rollout begin to reduce as more and more capacity is added. The largest economic benefits have accrued with past generations of communications technologies at near-ubiquitous coverage (Röller and Waverman, 2001), suggesting it is better to aim for total coverage with modest capacity, rather than large capacity only in a few places.

4.5 Will technology save the day?

Delivering ultra-dense networks will be essential for meeting the capacity-demand evolution of wireless networks in future decades, and will include both densification of small cell deployments and utilising larger portions of diverse radio spectrum bands (Bhushan et al. 2014). The use of high-frequency millimetre wave (mmW) spectrum is seen by some as an increasingly important technical solution to future 5G networks. Despite experiencing much higher path loss than microwave signals, there is an increased availability of spectrum at this frequency range. The potential benefit of this solution would be to offer multi-Gbps data rates at a lower marginal cost than previous technologies (Murdock et al. 2012). Figure 12 illustrates the potential 5G technologies and methodologies that could be used to develop the needs of a network capable of dealing with future demand.

Figure 12 Summary of technologies and methods for 5G (Panwar et al. 2016)

Method	Increasing data rate	Increasing network capacity	Massive device support	Energy-efficiency	Low latency	Economic viability	Security and privacy	Interference	Mobility support
Small cells	✓	✓		✓		✓^{P}			
Mobile small cells	✓	✓		✓		✓^{P}			✓
Cognitive Radio Networks (CRN)		✓				✓			
Device-to-Device (D2D)	✓^{P}		✓^{P}	✓		✓^{P}		✓^{P}	
C-RANs	✓	✓	✓	✓		✓		✓	✓
Full duplex radio		✓						✓	
Advance receiver		✓						✓	
Self-Interference Cancelling (SIC)		✓			✓^{P}			✓	✓^{P}
Downlink and Uplink Decoupling (DUD)		✓^{P}		✓					
Milimeter Wave (mmWave)	✓	✓	✓	✓	✓				
Massive MIMO (mMIMO)	✓	✓	✓	✓	✓				
Visual Light Communication (VLC)	✓			✓	✓	✓	✓		
Content Centric Networking (CCN) Fast caching						✓			

✓^{P} Partial support

5 Shared Issues Across Digital Communications

Having reviewed and outlined individual digital communications sectors, we will now examine the technical, economic and governance issues that are shared across the whole industry.

5.1 Brexit

The UK has one of the largest telecoms industries in Europe, which comprises a major part of the UK's total service exports. In 2012, 18.8% of value-added in the EU-28 telecommunications industry (EUR 31.8 billion) was generated by the UK (Eurostat, 2015). Ensuring a free-trade agreement that works for the UK telecommunications industry will be essential to guarantee domestic digital infrastructure provision, as well as ensuring international export opportunities are not determinately affected over the long term. Currently, many of the powers under the UK's Communications Act 2003 originate from the EU Regulatory Framework for Communications (Broadband Stakeholder Group, 2017). Hence, the overarching regulatory framework governing UK digital communications is now under review and there will be considerable uncertainty moving forward in the coming years as a result. At least in the medium term it would be sensible to align the UK's regulatory framework with the EU's, in order to avoid a cliff-edge change that could affect investment, operations and hurt consumers. To ensure the viable delivery of digital communications infrastructure, investors require a high degree of predictability. After Brexit, the UK will have the possibility to consider changing the State Aid rules which currently affect the range of options available for resolving coverage and capacity issues in digital infrastructure, although this would need careful thought. Moreover, many areas of the UK currently receive support from the European Regional Development Fund, such as Superfast Cornwall and Superfast Cymru, to encourage rollout of broadband in rural and remote areas. To ensure future infrastructure delivery in areas of market failure, this source of European funding will need to be replaced domestically, otherwise it may detrimentally affect connectivity in less viable places.

5.2 Remote Areas

The issue of delivery in remote areas is a challenge for all infrastructure sectors including transport, energy, water and waste, not just for digital. Ultimately digital infrastructure delivery and operation is a network industry and therefore there are large fixed capital costs associated with building a network capable of delivering even basic services. Broadband services are widely regarded as having a 'broken value chain'. So even if the costs of production are higher to deliver broadband access services in remote areas, users are generally not willing to pay the additional costs to cover the rollout. Hence, demand stimulation activities are essential, as this can help to make investment viability more plausible. Statistical analysis by Whitacre et al. (2015) found that approximately a third of the difference in broadband adoption between urban and rural areas in the US could be explained due to infrastructure disparities. The remaining amount was largely explained by differences in education and income highlighting the importance of demand-side policies to stimulate take-up. On the supply-side, as digital access is increasingly being regarded as a 'merit good' by government, we have seen an increase in the USO for fixed broadband access, which could increase again in the future.

In fixed access, Broadband Delivery UK recently reported on the emerging findings from the Market Test Pilots (DCMS, 2016) which explored new ways for delivering superfast broadband services to the least commercially viable parts of the UK (the last 5% of premises). The technologies deployed were a mixture of satellite, fixed wireless, and mixed fibre and fixed wireless access, with a key finding being that non-fibre access technologies can be a key component in delivering reliable, superfast-capable speeds that satisfy the majority of customers. However, future demand over the next decade may well exceed the capabilities explored in these initial test pilots, and there may be a long-term increase in the USO in coming decades. Hence, the activity of exploring different technology configurations must be sustained after this period with a view to meeting the challenge of long-term demand in the most remote places in the UK.

5.3 Single vs Multiple Infrastructure Networks

Digital communications is not the only infrastructure sector that has been trying to tackle the question of whether to build multiple networks, or a single infrastructure. Many previously nationalised network industries have had to address issues pertaining to competition in the delivery of infrastructure services and deliberate over whether building multiple networks is an efficient use of limited capital. The key issue is that broadband diffusion in OECD countries has been found to be affected by (a) competition variables (inter, facility, and services-based platform competition); (b) broadband service variables (speed and price), and (c) market demographics (population density, population dispersion, GDP, and device penetration) (Bouckaert et al. 2010). The results suggest that inter-platform competition has been the key driver of broadband penetration, while intra-platform competition has had more modest effects. Additionally, this study demonstrates that competition and service variables in the supply of infrastructure combine with demand-side factors to influence investment. In deciding whether to progress with single or multiple networks, one must also deeply consider the investment (and resulting price) implications. Therefore, on one hand there may be a single dominant infrastructure network with an owner providing access to competitors, requiring relatively modest investment (and keeping prices stable). While on the other, there may be multiple operators with greater competitive dynamics, but the investment requirements may be higher which could have a knock-on effect on prices.

In fixed networks, LLU has been a way to enable facilities-based intra-platform competition between the incumbent and new entrants, and the UK took this approach because it would not be efficient to use capital to build a duplicate local access infrastructure at great expense, when the value of the service delivered to consumers would essentially be similar. Increasingly however, inter-platform competition is becoming favoured for full fibre access solutions as new entrants compete with the incumbent by offering FTTP.

In the mobile and wireless industry, the UK currently has multiple networks although the actual coverage and capacity delivered is different between operators. Due to the industrial supply and demand cost pressures already articulated in this paper, we have seen increased consolidation in the sector, in combination with site sharing agreements between operators. The question has arisen however, as to how to deliver the number of required small cells to enable the types of capacity increases required to meet growing demand. One option on the table is by using a shared small cell infrastructure to reduce cost. Indeed, in an economic analysis of spectrum and infrastructure sharing in cellular networks, Fund et al. (2016) concludes that 'open' deployments of neutral small cells serving subscribers of any service provider encourage market entry by making it easier for networks to get closer to critical mass. This is one option that requires greater analysis moving forward given that ARPU has been decreasing.

5.4 Security

There is growing concern regarding potential cyber-attacks on critical national infrastructure. Digital communications plays two roles here, firstly as a transport medium enabling these attacks via the Internet, and secondly, as being vulnerable to disruption itself from malicious activity. Cyber-attacks may be carried out by range of threat actors including nation states, terrorists, hacktivists and disgruntled insiders (Rudner, 2013). Some telecoms companies have been the target of hackers trying to steal customer information, such as those experienced by Vodafone and Talk-Talk. However, our major concern here is the impact of network failure due to cyber-attacks, as we move further towards an increasingly virtualised digital infrastructure network. More and more assets consequently may become exposed and vulnerable to disruption.

Data on the primary causes of network disruption incidents reported to Ofcom show that hardware failure is the major cause year-on-year (Ofcom, 2014; 2015; 2016). Indeed, these statistics show only one or two reported outages attributed to cyber-attacks taking place annually, although attribution can often be hard to determine. However, we have seen major attacks on telecoms operators, such as the Mirai worm that infected Deutsche Telekom's routers in 2016, causing disruption to 900,000 customers. The key issue with cyber is the scalability of the attack. Whereas a hardware fault or flooded telephone exchange may take down a relatively small number of localised customers, hacks such as Distributed Denial of Service (DDoS) have been increasing in size annually, which has the potential to lead to a proportional increase in the number of customers affected. One of the largest DDoS attacks to-date was on Dyn's servers which was in the magnitude of Tbps. Until Mirai hit Deutsche Telekom a cyber-attack of this size had not affected such a large number of customers, but this is starting to become a more plausible reality, especially over the time horizon of the NIA. Greater emphasis needs to be placed on the cyber security of key digital infrastructure assets, by both industry and government, as there are a range of threat actors with the potential to cause major disruption to UK digital communications, and this threat is increasing.

6 Discussion

The results obtained highlighted two key issues including uncertainty in demand and increasing convergence between sectors, and these two issues are highly interrelated. Currently the demand for many of the technologies featured in the media limelight remains inconclusive (e.g. for 5G, gigabit fixed access, connected vehicles etc.), highlighting issues associated with investment viability and risk exposure for those companies who bring them to market. Moreover, convergence between sectors adds additional uncertainty to this issue. Some operators are being relatively risk-averse and attempting to avoid long-term stranded assets by prudent incremental delivery. Opponents of this approach however believe this is deliberately sweating existing assets and therefore holding back new infrastructure delivery. Additional uncertainty is produced when we consider the Over The Top (OTT) threat, as operators may continue to fail at taking a proper slice of an evolving value chain. This may detrimentally affect future infrastructure investment and delivery. Hitherto, fixed and wireless infrastructure have been largely complementary technologies, however the degree to which wireless services will instead become substitutionary may increase in coming years, affecting fixed revenue.

We have found that considerable emphasis is continually placed on supply-side market failures, but less focus is placed on demand-side issues such as willingness to pay, the ability to adopt new services and demand stimulation activities. In the UK, the trends shown in current ARPU and EBITDA illustrate that infrastructure operators may continue to be ‘squeezed’ moving forward (particularly in mobile and wireless), which may fundamentally affect the ability to deliver the capacity and coverage of digital infrastructure that we require when data demand continues to increase annually. Therefore, we need more analysis on the effectiveness of demand-side interventions and policies in areas of market failure, as well as greater quantification of the positive externality impacts that could accrue for both users and the wider economy if increased adoption takes place.

We find that there are two aims embodied in the National Infrastructure Assessment of digital communications, firstly relating to the ‘digital divide’, and secondly relating to the UK’s national industrial strategy over coming decades. Disparities in digital infrastructure frequently feature in the media, as consumers and businesses highlight their discontent with current fixed broadband access and mobile coverage, and there is desire in government to address these ‘digital divide’ issues for both equity and economic reasons. Additionally, the UK’s lack of progress in labour productivity over the past decade has prompted focus on how technology may help to make industry more internationally competitive. Indeed, the UK’s approach to expediting ‘5G’ is increasingly seen as part of the nation’s current and future industrial strategy, where on one hand this is an attempt to boost productivity via potential automation benefits, and on the other, the recognition that existing industries such as car manufacturing need to stay competitive by having the capability to conduct R&D and testing of autonomous vehicles on British roads. However, these two objectives are not necessarily complementary to each other. For example, evidence to-date on the cost and rollout of 5G infrastructure shows that rather than solving ‘digital divide’ coverage issues, it may well make infrastructure disparities *worse*, as delivery of small cell infrastructure will only be viable in urban areas.

If the traditional boundaries between digital sectors are becoming increasingly blurred due to convergence and substitution, this justifies the need to move away from silo-based approaches to infrastructure assessment in fixed, mobile, wireless and beyond. Hence, cross-sector national infrastructure assessment has the potential to be a useful tool if the strategic vision it produces can be implemented across government, and consequently by industry. But serious challenges do exist in undertaking this endeavour, primarily in attempting to take a long-term 30-year time horizon in a sector experiencing rapid innovation. This sets digital apart from other more stable sectors such as water, waste or transport as they more closely follow demographic and economic trends.

7 Conclusion

Digital infrastructure operators have a thorough understanding of their current networks, and the costs involved with new infrastructure delivery and operation, but the uncertainty in future demand is the key unknown quantity which is holding back future infrastructure investment. This uncertainty is compounded by the fact that the sector is experiencing declining revenue, increasing convergence in digital services, as well as growing fixed-mobile substitution. In evaluating those areas pertinent to the national infrastructure assessment of digital communications, we have covered the key engineering, economic and policy issues that will affect the future of the industry. In the large majority of cases, it is highly likely that the market will provide the required infrastructure assets and therefore we have focused on the issues that might constrain this process. We believe that there is considerable emphasis continually placed on supply-side market failures in the delivery of digital infrastructure, but less focus is placed on demand-side issues such as willingness to pay, the ability to adopt new services and demand stimulation activities. If market-based methods continue to be the main way to organise the allocation of limited resources in digital communications, which seems to be the case, then there is only so far operators can be 'squeezed' by government before there is a detrimental effect on infrastructure investment. Hence, demand-side methods play a very important role in providing additional certainty and risk reduction, to operators attempting to bring new digital infrastructure to market. More research needs to be undertaken which explores the sensitivity of future demand in relation to infrastructure performance and cost, under different demographic, economic and technical scenarios.

8 References

Agboma, Florence, and Antonio Liotta. 2012. 'Quality of Experience Management in Mobile Content Delivery Systems'. *Telecommunication Systems* 49 (1): 85–98. doi:10.1007/s11235-010-9355-6.

Akdeniz, Mustafa Riza, Yuanpeng Liu, Mathew K. Samimi, Shu Sun, Sundeep Rangan, Theodore S. Rappaport, and Elza Erkip. 2014. 'Millimeter Wave Channel Modeling and Cellular Capacity Evaluation'. *IEEE Journal on Selected Areas in Communications* 32 (6): 1164–1179.

Alizadeh, Tooran, and Reza Farid. 2017. 'Political Economy of Telecommunication Infrastructure: An Investigation of the National Broadband Network Early Rollout and Pork Barrel Politics in Australia'. *Telecommunications Policy* 41 (4): 242–52. doi:10.1016/j.telpol.2017.02.002.

Angelou, Georgios N., and Anastasios A. Economides. 2014. 'Investment Flexibility and Competition Modeling for Broadband Business'. *Telecommunications Policy*, Special issue on : Selected papers from the 10th Conference in Telecommunications, Media and Internet Techno-economicsSpecial issue on : The development of public e-services: Empirical analysis and policy issues, 38 (5–6): 438–48. doi:10.1016/j.telpol.2014.02.005.

Bayvel, Polina, Robert Maher, Tianhua Xu, Gabriele Liga, Nikita A. Shevchenko, Domaniç Lavery, Alex Alvarado, and Robert I. Killey. 2016. 'Maximizing the Optical Network Capacity'. *Phil. Trans. R. Soc. A* 374 (2062): 20140440.

BBC. 2017. 'BBC iPlayer Monthly Performance Report - February 2017'. London: BBC. http://downloads.bbc.co.uk/mediacentre/iplayer/iplayer-performance-feb17.pdf.

Bhushan, N., J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. T. Sukhavasi, C. Patel, and S. Geirhofer. 2014. 'Network Densification: The Dominant Theme for Wireless Evolution into 5G'. *IEEE Communications Magazine* 52 (2): 82–89. doi:10.1109/MCOM.2014.6736747.

Bouckaert, Jan, Theon van Dijk, and Frank Verboven. 2010. 'Access Regulation, Competition, and Broadband Penetration: An International Study'. *Telecommunications Policy* 34 (11): 661–71. doi:10.1016/j.telpol.2010.09.001.

Brake, D. 2016. '5G and next Generation Wireless: Implications for Policy and Competition'. Washington D.C.: Information Technology & Innovation Foundation. https://itif.org/publications/2016/06/30/5g-and-next-generation-wireless-implications-policy-and-competition.

Broadband Stakeholder Group. 2017. 'Implications of Brexit on the Digital Communications Sector'. London: Broadband Stakeholder Group. http://www.broadbanduk.org/wp-content/uploads/2017/04/Implications-of-Brexit-on-the-digital-communications-sector-FINAL.pdf.

Cardona, M., T. Kretschmer, and T. Strobel. 2013. 'ICT and Productivity: Conclusions from the Empirical Literature'. *Information Economics and Policy*, ICT and Innovation, 25 (3): 109–25. doi:10.1016/j.infoecopol.2012.12.002.

Chambers, C. J. 2016. 'Future Traffic Demands and Characteristics from a Media Perspective'. *Phil. Trans. R. Soc. A* 374 (2062): 20140433. doi:10.1098/rsta.2014.0433.

Cisco. 2017. 'Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021'. San Jose, CA: Cisco American Headquarters. http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.pdf.

Clarke, Richard N. 2014. 'Expanding Mobile Wireless Capacity: The Challenges Presented by Technology and Economics'. *Telecommunications Policy*, Special issue on Moving Forward with Future Technologies: Opening a Platform for AllSpecial issue on Papers from the 41st Research Conference on Communication, Information and Internet Policy (TPRC 2013), 38 (8–9): 693–708. doi:10.1016/j.telpol.2013.11.006.

Coomans, W., R. B. Moraes, K. Hooghe, A. Duque, J. Galaro, M. Timmers, A. J. van Wijngaarden, M. Guenach, and J. Maes. 2015. 'XG-Fast: The 5th Generation Broadband'. *IEEE Communications Magazine* 53 (12): 83–88. doi:10.1109/MCOM.2015.7355589.

Curwen, P., and J. Whalley. 2016. 'European Mobile Markets and the Doctrine of "4 Networks Good, 3 Networks Bad"'. *Info* 18 (5): 1–23. doi:10.1108/info-05-2016-0021.

Department for Culture, Media and Sport. 2016. 'Emerging Findings from the BDUK Market Test Pilots'. London: Department for Culture, Media & Sport.

Department for Culture, Media and Sport, and HM Treasury. 2015. ‘The Digital Communications Infrastructure Strategy’. https://www.gov.uk/government/publications/the-digital-communications-infrastructure-strategy/the-digital-communications-infrastructure-strategy.

Durrant, Daniel William. 2015. ‘The Controversial Discourse on Speed in the Case of HS2’. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning* 168 (5): 241–50. doi:10.1680/udap.14.00050.

Ellis, A. D., N. Mac Suibhne, D. Saad, and D. N. Payne. 2016. ‘Communication Networks beyond the Capacity Crunch’. *Phil. Trans. R. Soc. A* 374 (2062): 20150191. doi:10.1098/rsta.2015.0191.

Eurostat. 2017. ‘Telecommunications Services Statistics - NACE Rev. 2 - Statistics Explained’. Luxembourg: Eurostat. Accessed April 16. http://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Telecommunications_services_statistics_-_NACE_Rev._2#Country_analysis.

Feijóo, Claudio, José Luis Gómez-Barroso, and Sergio Ramos. 2016. ‘Techno-Economic Implications of the Mass-Market Uptake of Mobile Data Services: Requirements for next Generation Mobile Networks’. *Telematics and Informatics* 33 (2): 600–612. doi:10.1016/j.tele.2015.10.001.

Frigo, Nicholas J., Patrick P. Iannone, and Kenneth C. Reichmann. 2004. ‘A View of Fiber to the Home Economics’. *IEEE Communications Magazine* 42 (8): S16–S23.

Frontier Economics. 2014. ‘Assessing the Case for in-Country Mobile Consolidation’. Report prepared for the GSMA. London: Frontier Economics.

GSMA. 2015. ‘Data Demand Explained’. London: GSMA. http://www.gsma.com/spectrum/wp-content/uploads/2015/06/GSMA-Data-Demand-Explained-June-2015.pdf.

Hall, Jim W., Scott Thacker, Matt C. Ives, Yue Cao, Modassar Chaudry, Simon P. Blainey, and Edward J. Oughton. 2016. ‘Strategic Analysis of the Future of National Infrastructure’. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, November, 1–9. doi:10.1680/jcien.16.00018.

Hall, Jim W., Martino Tran, Adrian J. Hickford, and Robert J. Nicholls. 2016. *The Future of National Infrastructure: A System-of-Systems Approach*. Cambridge, UK: Cambridge University Press.

Hall, Peter. 2013. ‘High Speed Two: The Great Divide’. *Built Environment* 39 (3): 339–54. doi:10.2148/benv.39.3.339.

Hamzeh, B., M. Toy, Y. Fu, and J. Martin. 2015. ‘DOCSIS 3.1: Scaling Broadband Cable to Gigabit Speeds’. *IEEE Communications Magazine* 53 (3): 108–13. doi:10.1109/MCOM.2015.7060490.

Han, B., V. Gopalakrishnan, L. Ji, and S. Lee. 2015. ‘Network Function Virtualization: Challenges and Opportunities for Innovations’. *IEEE Communications Magazine* 53 (2): 90–97. doi:10.1109/MCOM.2015.7045396.

Hervet, Cedric, Alain Faye, Marie-Christine Costa, Matthieu Chardy, and Stanislas Francfort. 2013. ‘Solving the Two-Stage Robust FTTH Network Design Problem under Demand Uncertainty’. *Electronic Notes in Discrete Mathematics* 41 (June): 335–42. doi:10.1016/j.endm.2013.05.110.

House of Commons Library. 1994. ‘Information Superhighways’. London: House of Commons Library. https://ntouk.files.wordpress.com/2015/06/1994-information-superhighway.pdf.

HSBC. 2015. ‘Supersonic: European Telecoms Mergers Will Boost Capex, Driving Prices Lower and Speeds Higher’. London: HSBC. https://www.orange.com/fr/content/download/33263/1086075/version/2/file/Supersonic+13.04.15.pdf.

Institution of Civil Engineers. 2014. ‘State of the Nation: Infrastructure 2014’. London: Institution of Civil Engineers. https://www.ice.org.uk/media-and-policy/policy/state-of-the-nation-infrastructure-2014.

———. 2016. ‘National Needs Assessment - A Vision for UK Infrastructure’. London: Institution of Civil Engineers. https://www.ice.org.uk/media-and-policy/policy/national-needs-assessment-a-vision-for-uk-infrastr.

Jin, Sangki, and Cheong Moon Cho. 2015. ‘Is ICT a New Essential for National Economic Growth in an Information Society?’ *Government Information Quarterly* 32 (3): 253–60. doi:10.1016/j.giq.2015.04.007.

Joshi, K., and T. Benson. 2016. ‘Network Function Virtualization’. *IEEE Internet Computing* 20 (6): 7–9. doi:10.1109/MIC.2016.112.

Kassem, M. M., and M. K. Marina. 2015. ‘Future Wireless Spectrum below 6 GHz: A UK Perspective’. In *2015 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 59–70. doi:10.1109/DySPAN.2015.7343850.

Katz, Raul L., and Taylor A. Berry. 2014. ‘Strategies to Promote Broadband Demand’, 295–305. doi:10.1007/978-3-319-07197-8_8.

Kenny, R., and T. Broughton. 2013. ‘Domestic Demand for Bandwidth: An Approach to Forecasting Requirements for the Period 2013-2023’. London: Broadband Stakeholder Group. http://www.commcham.com/pubs/2013/11/6/forecasting-domestic-uk-broadband-demand-2013-2023.html.

Kilper, Daniel C., and Houman Rastegarfar. 2016. ‘Energy Challenges in Optical Access and Aggregation Networks’. *Phil. Trans. R. Soc. A* 374 (2062): 20140435. doi:10.1098/rsta.2014.0435.

Liotou, E., D. Tsolkas, N. Passas, and L. Merakos. 2015. ‘Quality of Experience Management in Mobile Cellular Networks: Key Issues and Design Challenges’. *IEEE Communications Magazine* 53 (7): 145–53. doi:10.1109/MCOM.2015.7158278.

Mack, Elizabeth, and Alessandra Faggian. 2013. ‘Productivity and Broadband the Human Factor’. *International Regional Science Review* 36 (3): 392–423. doi:10.1177/0160017612471191.

McKinsey Global Institute. 2016. ‘Bridging Global Infrastructure Gaps’. Brussels: McKinsey Global Institute. http://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/bridging-global-infrastructure-gaps.

Mijumbi, R., J. Serrat, J. L. Gorricho, N. Bouten, F. De Turck, and R. Boutaba. 2016. ‘Network Function Virtualization: State-of-the-Art and Research Challenges’. *IEEE Communications Surveys Tutorials* 18 (1): 236–62. doi:10.1109/COMST.2015.2477041.

Monath, Thomas, N. Kristian, Philippe Cadro, Dimitris Katsianis, and Dimitris Varoutas. 2003. ‘Economics of Fixed Broadband Access Network Strategies’. *IEEE Communications Magazine* 41 (9): 132–139.

Murdock, James N., Eshar Ben-Dor, Yijun Qiao, Jonathan I. Tamir, and Theodore S. Rappaport. 2012. ‘A 38 GHz Cellular Outage Study for an Urban Outdoor Campus Environment’. In *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, 3085–3090. IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6214335.

Nardotto, Mattia, Tommaso Valletti, and Frank Verboven. 2015. ‘Unbundling the Incumbent: Evidence from Uk Broadband’. *Journal of the European Economic Association* 13 (2): 330–62. doi:10.1111/jeea.12127.

Nunes, B. A. A., M. Mendonca, X. N. Nguyen, K. Obraczka, and T. Turletti. 2014. ‘A Survey of Software-Defined Networking: Past, Present, and Future of Programmable Networks’. *IEEE Communications Surveys Tutorials* 16 (3): 1617–34. doi:10.1109/SURV.2014.012214.00180.

Ofcom. 2014. ‘Infrastructure Report 2014: Ofcom’s Second Full Analysis of the UK’s Communications Infrastructure’. London: Ofcom.

———. 2015. ‘Connected Nations 2015’. London: Ofcom. http://stakeholders.ofcom.org.uk/market-data-research/market-data/infrastructure/connected-nations-2015/.

———. 2016a. ‘Connected Nations 2016’. London: Ofcom. http://stakeholders.ofcom.org.uk/market-data-research/market-data/infrastructure/connected-nations-2015/.

———. 2016b. ‘The Communications Market Report 2016’. London: Ofcom. https://www.ofcom.org.uk/research-and-data/cmr/cmr16.

Oksman, V., R. Strobel, X. Wang, D. Wei, R. Verbin, R. Goodson, and M. Sorbara. 2016. ‘The ITU-T’s New G.fast Standard Brings DSL into the Gigabit Era’. *IEEE Communications Magazine* 54 (3): 118–26. doi:10.1109/MCOM.2016.7432157.

Oughton, E.J., and Z. Frias. 2016. ‘Exploring the Cost, Coverage and Rollout Implications of 5G in Britain: A Report for the UK’s National Infrastructure Commission’. Cambridge: Centre for Risk Studies, Cambridge Judge Business School. https://www.gov.uk/government/publications/connected-future.

Panwar, Nisha, Shantanu Sharma, and Awadhesh Kumar Singh. 2016. ‘A Survey on 5G: The next Generation of Mobile Communication’. *Physical Communication*, Special Issue on Radio Access Network Architectures and Resource Management for 5G, 18, Part 2 (March): 64–84. doi:10.1016/j.phycom.2015.10.006.

Parliamentary Office for Science and Technology. 1990. ‘Optical Fibre Networks’. London: Parliamentary Office for Science and Technology.
Rajabiun, Reza, and Catherine A. Middleton. 2013. ‘Multilevel Governance and Broadband Infrastructure Development: Evidence from Canada’. *Telecommunications Policy*, Papers from the 40th Research Conference on Communication, Information and Internet Policy (TPRC 2012)Special issue on the first papers from the ‘Mapping the Field’ initiative., 37 (9): 702–14. doi:10.1016/j.telpol.2013.05.001.
Real Wireless. 2016. ‘Future Use Cases for Mobile Telecoms in the UK’. Pulborough: Real Wireless. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/581437/Real_Wireless_Future_Use_Cases_for_Mobile_UK.pdf.
Reiter, Ulrich, Kjell Brunnström, Katrien De Moor, Mohamed-Chaker Larabi, Manuela Pereira, Antonio Pinheiro, Junyong You, and Andrej Zgank. 2014. ‘Factors Influencing Quality of Experience’. In *Quality of Experience*, edited by Sebastian Möller and Alexander Raake, 55–72. T-Labs Series in Telecommunication Services. Springer International Publishing. doi:10.1007/978-3-319-02681-7_4.
Röller, Lars-Hendrik, and Leonard Waverman. 2001. ‘Telecommunications Infrastructure and Economic Development: A Simultaneous Approach’. *The American Economic Review* 91 (4): 909–23.
Rudner, Martin. 2013. ‘Cyber-Threats to Critical National Infrastructure: An Intelligence Challenge’. *International Journal of Intelligence and CounterIntelligence* 26 (3): 453–81. doi:10.1080/08850607.2013.780552.
Skouby, Knud Erik, Morten Falch, Anders Henten, and Reza Tadayoni. 2014. ‘Need for Broadband Infrastructure in a 2020 Perspective’. *Wireless Personal Communications* 76 (2): 271–89. doi:10.1007/s11277-014-1688-0.
Temprana, E., E. Myslivets, B. P.-P. Kuo, L. Liu, V. Ataie, N. Alic, and S. Radic. 2015. ‘Overcoming Kerr-Induced Capacity Limit in Optical Fiber Transmission’. *Science* 348 (6242): 1445–48. doi:10.1126/science.aab1781.
Thyagaturu, A. S., A. Mercian, M. P. McGarry, M. Reisslein, and W. Kellerer. 2016. ‘Software Defined Optical Networks (SDONs): A Comprehensive Survey’. *IEEE Communications Surveys Tutorials* 18 (4): 2738–86. doi:10.1109/COMST.2016.2586999.
Timmers, M., M. Guenach, C. Nuzman, and J. Maes. 2013. ‘G.fast: Evolving the Copper Access Network’. *IEEE Communications Magazine* 51 (8): 74–79. doi:10.1109/MCOM.2013.6576342.
Tomaney, John, and Pedro Marques. 2013. ‘Evidence, Policy, and the Politics of Regional Development: The Case of High-Speed Rail in the United Kingdom’. *Environment and Planning C: Government and Policy* 31 (3): 414–27. doi:10.1068/c11249r.
Tsolkas, Dimitris, Eirini Liotou, Nikos Passas, and Lazaros Merakos. 2017. ‘A Survey on Parametric QoE Estimation for Popular Services’. *Journal of Network and Computer Applications* 77 (January): 1–17. doi:10.1016/j.jnca.2016.10.016.
UK Government Investments. 2016. ‘Enabling UK Growth: Public Sector Spectrum Release Programme’. London: UK Government Investments. https://www.gov.uk/government/publications/enabling-uk-growth-public-sector-spectrum-release-programme.
Weldon, Marcus K., and Francis Zane. 2003. ‘The Economics of Fiber to the Home Revisited’. *Bell Labs Technical Journal* 8 (1): 181–206.
Whitacre, Brian, Sharon Strover, and Roberto Gallardo. 2015. ‘How Much Does Broadband Infrastructure Matter? Decomposing the Metro–non-Metro Adoption Gap with the Help of the National Broadband Map’. *Government Information Quarterly* 32 (3): 261–69. doi:10.1016/j.giq.2015.03.002.
WIK-Consult. 2015. ‘Competition & Investment: An Analysis of the Drivers of Investment and Consumer Welfare in Mobile Telecommunications’. Bad Honnef, Germany: WIK-Consult. http://www.wik.org/fileadmin/Studien/2015/Competition_and_investment_mobile_telecommunications.pdf.
World Economic Forum. 2016. ‘The Global Competitiveness Report 2016-2017’. Geneva, Switzerland: World Economic Forum. http://www3.weforum.org/docs/GCR2016-2017/05FullReport/TheGlobalCompetitivenessReport2016-2017_FINAL.pdf.

Żotkiewicz, M., and M. Mycek. 2016. 'Impact of Demand Uncertainty Models on FTTH Network Design'. In *2016 18th International Conference on Transparent Optical Networks (ICTON)*, 1–4. doi:10.1109/ICTON.2016.7550445.

Appendix A

Capacity requirements for different applications and services

Service	Download capacity requirements	Upload capacity requirements
Browsing	3-10 Mbps	-
Music streaming	1 Mbps	-
Music download	10 Mbps	1-2 Mbps
E-mail	10 Mbps	1-10 Mbps
Social networking	10 Mbps	1-10 Mbps
Cloud drive*	10-100 Mbps	10-100 Mbps
Home office*	10-100 Mbps	10-100 Mbps
File sharing/download*	10-100 Mbps	10-100 Mbps
Video on demand*	10-100 Mbps	-
Software distribution and update*	10-100 Mbps	-
E-mail download	1-3 Mbps	-
Online video game	3 Mbps	1-3 Mbps
Cloud video game*	10-100 Mbps	-
Home surveilllance	2 Mbps	2 Mbps
E-learning**	10-100 Mbps	2-10 Mbps
E-health-user	10-100 Mbps	2-10 Mbps
E-health-provider	10-100 Mbps	10-100 Mbps
AAL applications	10-100 Mbps	1 Mbps
E-shopping	10 Mbps	2-10 Mbps
Augmented reality applications	20 Mbps	-

* Capacity requirement depends on the size of the files and what is deemed a reasonable waiting time

** Capacity requirement depends on the size of the files and what is deemed a reasonable waiting time

(Adapted from Skouby et al. 2014)