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Studying the Costs of Fibre Deployment in Fixed Broadband Access Infrastructure: Evidence from the UK's National Needs Assessment

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Studying the Costs of Fibre Deployment in Fixed Broadband Access Infrastructure: Evidence from the UK's National Needs Assessment

International Telecommunications Society European Regional Conference 2016

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Abstract

There has been a concerted effort in recent years to undertake more strategic, long-term, and cross-sector assessment of national infrastructure. This paper reflects on the assessment of fixed broadband within the recent National Needs Assessment, which aims to identify options for meeting the UK's infrastructure 'needs' up to 2050. It establishes the future 'need' for different levels of fixed broadband connectivity and how much investment is required to rollout infrastructure to meet different regional coverage and capacity levels. Two key technologies are initially assessed here using a cost modelling approach, including Fibre-To-The-Premises (FTTP) utilising a Gigabit Passive Optical Network and FTTP utilising a Point-To-Point fibre connection. The results show the aggregate investment required to deliver different levels of fixed broadband access to different proportions of the population. The costs raise linearly for delivery to premises in urban areas, with total urban coverage by FTTP using a Gigabit Passive Optical Network costing £14.1 billion and FTTP using a Point-To-Point network costing £17 billion. The costs for rural and remote areas begin to rise sharply, to the extent that deployment of these technologies to the final third of premises could cost almost the same amount as deployment to the first two thirds of premises in urban areas. Deployment to rural and remote areas was estimated to cost £13.7 billion for FTTP using a Gigabit Passive Optical Network and £15.8 billion for FTTP using a Point-To-Point network. Total FTTP coverage using a Gigabit Passive Optical Network costs £27.7 billion, whereas FTTP coverage using a Point-To-Point network costs £32.8 billion. The largest aggregate investment is required in the South East, North West and East of England, due to their large population sizes. Across these technologies the lowest average marginal cost per premises was in London for urban areas, Scotland for rural areas, and Wales for remote areas.

1.0 Introduction

There has been a concerted effort in recent years to undertake more strategic, long-term, and cross-sector assessment of national infrastructure. Within fixed broadband access infrastructure there have been a wide variety of objectives set by policymakers in different countries around the world. On June the 23rd 2016 the UK voted to leave the European Union, introducing uncertainty around the expected commitments under the Digital Agenda for Europe (DAE). Had the UK voted to remain, the UK would have been expected to deliver the DAE targets of 30 Mbit/s or more to all by 2020, as well as 50% of households having access to 100 Mbit/s (European Commission, 2014).

Current statistics indicate that the UK is on the way to achieving these goals. A recent estimate showed 83% of premises have access to Superfast Broadband (SFBB) (30Mbit/s or more) (Ofcom, 2015) and the UK looks set to achieve near-ubiquitous coverage (95%) by the end of 2017. Delivery of SFBB by Broadband Delivery UK to the final 5% has recently been explored through a variety of market test pilots (Department for Culture, Media and Sport, 2016). Moreover, 46% of premises have access to download speeds over 100 Mbit/s putting the UK well on its way to achieving the second stated DAE speed target (Ofcom, 2015). The UK occupies the top ten spot in most global ICT-related rankings, having high population coverage and capacity by fixed and mobile digital communications (for example, see ITU, 2014).

The UK is similar to other European countries in that it is dominated by DSL technologies. Practically all premises (99.9%) were connected to an ADSL-enabled British Telecom (BT) exchange at the end of 2013 for fixed broadband (Ofcom, 2014), and the majority (95%) were connected to a Local Loop Unbundled (LLU) BT local exchange. The regulator estimates that under half of UK premises were able to receive Virgin Media's cable broadband services in June 2014, and 69% of UK premises were able to receive BT Openreach/Kcom's fibre broadband services. Next Generation Access[1] (NGA) access in 2014 reached 78% of UK premises. The BT exchange locations result from the previously nationalised telephone network, where there was a desire to connect every single premises regardless of cost, even in remote rural areas. In contrast, the cable network footprint developed over the last thirty years, shows that the densest urban areas were cherry-picked for the roll-out of this technology. In 2015, BT had 32% of the market share for fixed broadband, followed by Sky (22%), Virgin Media (20%), TalkTalk (14%) and EE (4%).

Access to digital connectivity services has become a popular topic in the British media, focusing especially on (invariably rural) communities poorly served by fixed broadband and mobile forms of communication. Under New Labour in 2009, the Digital Britain Report (BIS and DCMS, 2009) introduced a Universal Services Obligation (USO) which aimed to deliver 2 Mbit/s to all premises by 2012. Digital connectivity was then a top priority for the Coalition government from 2010-2015 but the date for achieving this policy was revised many times. It currently stands at 2017. Like many European countries, the UK telecommunications sector is subject to its historical legacy of having a publicly-owned telecommunications monopolist. The incumbent (BT) still owns the largest proportion of fixed infrastructure, but is subject to a variety of regulatory measures (such as LLU) to encourage increased competition in the sale of broadband services.

However, only 2% of premises currently have access to Ultrafast Broadband (UFBB) (300 Mbit/s or more), and over the long-term our fixed access needs may require us to focus on higher capacity connectivity technologies such as Fibre-To-The-Premises (FTTP)[2]. Two key technologies are initially

[1] Defined as a type of access technology that provides a significant improvement on basic broadband. This includes FTTC, FTTP and cable. Most lines enabled with NGA provide SFBB speeds, except in those circumstances where, for example, customers are connected for the final proportion over long copper lines.

[2] FTTP is used here to refer generically to both delivery to domestic consumers via Fibre-To-The-Home (FTTH) and commercial consumers via Fibre-To-The-Premises (FTTP). As defined in the methodology, 'premises' is used to refer to any building that is a Royal Mail small user delivery point.

assessed here, including FTTP utilising a Gigabit Passive Optical Network (FTTP-GPON) and FTTP utilising a Point-To-Point fibre connection (FTTP-PTP).

While many advanced economies have also exceeded the 80% threshold for Internet penetration, the UK has achieved one of the fastest growing digital economies with around 270,000 active companies (14.4% of all companies), therefore is considered to be a leading nation in this regard (Nathan et al. 2013). Conservative estimates show that the UK leads the G20 nations, with its digital economy accounting for 8.3% of total GDP in 2010, projected to increase to 12.4% by 2016 (Boston Consulting Group, 2012). The UK is one of the top economies in Europe for the proportion of sales arising from e-commerce. For example, e-commerce sales for companies in the UK non-financial sector (with 10 or more employees) amounted to 20.1% of business turnover – the equivalent of £573 billion in current prices. In 2014, by businesses, representing 20.1% of business turnover. Moreover, sales made by Electronic Data Interchange (EDI) totalled £374 billion (65% of total e-commerce sales), while the remaining £199 billion came from website sales (35%) (ONS, 2015). E-commerce sales in micro-enterprises (companies with less than 10 employees) totally £19.5 billion in 2014 (Ibid.). This is important because companies of this size are more likely to use the household consumer services which are a particular focus of this paper as their needs are not always well met by the market. In light of this information, it is therefore critical to understand the system's changing demand profile, and both current and future coverage and capacity.

The UK's decision to leave the European Union has ramifications for the provision of communications services in areas of market failure. For example, the European Regional Development Fund is one mechanism that has provided financial support to address poor connectivity with millions of pounds having been invested in projects such as Superfast Cornwall and Superfast Cymru (Wales). It is yet unknown as to what will fill this funding gap post-Brexit, and if indeed the UK decides to continue to meet existing targets set centrally in Europe, or if indeed the UK decides to takes a new divergent path.

This paper reflects on the assessment of fixed broadband within the recent National Needs Assessment, which aims to identify options for meeting the UK's infrastructure 'needs' up to 2050. The following research question has consequently been identified for investigation.

What is our future 'need' for different levels of fixed broadband connectivity and how much investment is required to rollout infrastructure to meet different regional coverage and capacity levels?

Before detailing the analysis used to answer this question, a discussion is undertaken as to how the term 'need' should be interpreted within this context. In doing so, the concept of 'need' is related to demand for fixed broadband services. It argues that the definition of 'need' is ultimately a political and not a technocratic decision, therefore this must be reflected in the costed investment options put forward to decision-makers in industry and government. Moreover, in economic theory if one has a 'need' it implies one would be willing to purchase goods and services which satisfy this demand, when in reality broadband is widely regarded as having a broken value chain.

This paper has a number of key differences from other studies that have undertaken research on similar matters. Firstly, this piece considers how 'need' should be defined, and the different technical demand projections put forward in the literature. Secondly, this study considers the total aggregate cost across all urban, rural and remote areas as opposed to simply focusing on one spatial settlement pattern (e.g. rural) for delivering new broadband infrastructure. Thirdly, this study uses statistics on the number of premises that already receive certain services (e.g. over 300 Mbit/s) and therefore do not warrant consideration in the total aggregate costs derived here. Other studies, due to a lack of data, have excluded this. Finally, rather than focus specifically on residential demand and assuming that the market will deliver the required infrastructure to meet commercial needs, this work considers both domestic and small businesses. This is because a large number of small businesses rely on domestic consumer

services because they are cheaper then commercial leased line products, justifying their inclusion in this analysis.

2.0 Literature Review

2.1 Fixed Broadband 'Need'

The availability of high capacity, reliable digital connectivity is essential for commercial and non-commercial organisations, and domestic consumers. A lack of sufficient connectivity has a detrimental effect on business operations, affecting economic output and productivity. Large organisations purchase high-value, specialist leased lines for dedicated transmission capacity between fixed locations and generally have their needs met adequately via the market.

However, issues exist in domestic consumer services. Small and medium-sized enterprises (SMEs) also attempting to use domestic consumer services to satisfy their business connectivity needs can encounter problems. This is often because these services can be cheaper than commercial products, although they are not likely to provide the same levels of reliability. As the speed of domestic consumer products increases, we are more likely to see this happening. Until recently, the UK Government ran a voucher scheme aiming to encourage SMEs to take-up higher specification connectivity services. In some cases, there are economic productivity benefits in moving SMEs from low capacity, less reliable connections to higher capacity lines with greater resilience. Some business users may opt for taking on an additional connection via a different operator in order to provide redundancy. This paper focuses specifically on domestic consumers and SMEs, as this is where market failure most often occurs. Therefore, it is the assessment of this group that is of most interest for decision-makers in government.

The question of 'need' is an area of interesting debate within digital communications, but is central to this work. Economic theory implies that if there is a 'need' for specific goods or services, consumers will be prepared to pay for them. However, this may not always be the case, especially when it comes to those goods and services that are new to market. Broadband services are widely regarded as having a 'broken value chain'. Usually in a market, if the costs of production are higher to sell goods or services in rural or remote locations, the price can be increased to reflect this and customers are still willing to pay the purchase price. As this does not always happen, disparities occur in the provision of these services due to market failure. Consequently, the recent focus on a USO of 10 Mbit/s for fixed broadband demonstrates the UK Government's commitment to providing a sufficient level of basic digital connectivity to all members of society regardless of location.

However, ultimately USO levels are subject to political and not technocratic decision making. As the provision of digital connectivity enables users to make use of different types of content, applications and services, it is ultimately a governmental decision as to what level of provision all members of society should have access to. Bandwidth is an important component of perceived 'speed' which the USO has targeted, but we must also recognise how other factors such as latency (due to server response and network traffic) can affect user experience. While there is a large range of potential goals in this respect, we focus on two main objectives that require different levels of connectivity. The infrastructure investment needs are not the same, however, for each objective.

Objective 1: To provide equal access of economic opportunity to all by guaranteeing that basic connectivity is available for web browsing, email, basic file transfer, video calling and other services as these enable participation in a modern digital economy.

Objective 2: To provide equal access to *all* online content, applications and services regardless of location. This includes access to content that requires more bandwidth and lower latency, including High Definition (HD) and Ultra-High Definition (UHD) (4k or 8k) on-demand television services, or Virtual or Augmented Reality applications.

The UK is on its way to achieving Objective 1 in the coming years as those online services which meet this need – such as email access and web browsing – require less bandwidth and can generally be met by the current SFBB rollout. These activities also do not produce as much traffic as others, for example, when compared to entertainment services such as on-demand video. According to Ofcom (2015), the existing USO of 10 Mbit/s exceeds our needs for web browsing which only requires 0.5 Mbit/s, as well as a video call and web browsing which simultaneously only require 1.5 Mbit/s.

However, if Objective 2 is desirable and there is seen to be a need to provide the same level of digital connectivity to all citizens regardless of them being in an urban, rural or remote location, this would require additional investment. The bandwidth demand required to enable high quality online entertainment services to function – such as HD/UHD television and Virtual or Augmented Reality – is higher than for those applications and services required for achieving Objective 1. Ofcom (2015) states that catch up TV (such as iPlayer) requires 2 Mbit/s, while HD film streaming requires 6 Mbit/s. UHD will require more bandwidth unless video compression improves in coming years. However, these are potentially moving targets over the long-term.

On the other hand, some factors may reduce our future need for digital connectivity. Firstly, the developers of applications and online services are putting significant resources into ensuring their products actually function with minimal infrastructure availability, to ensure the very best user experience for their customers. This could have many positive externality effects on the network infrastructure by finding more efficient ways to deliver services, reducing demand. Moreover, fixed access use and adoption could begin to decrease as part of the ongoing shift towards mobile connectivity, affecting the long-term viability of some fixed infrastructure assets.

Although the large majority of the market are likely to have their needs met without necessary government support, it is inevitable that there may be problems at the bottom end of the market, in many rural or remote locations, as can be explored in this paper.

2.2 Technical demand forecasts

A wide variety of technical demand forecasts exist, with a prominent example of projected domestic bandwidth demand in the UK having been undertaken by the UK's Broadband Stakeholder Group (Kenny and Broughton, 2013). The key finding was that by 2023 the median household will have a requirement for 19 Mbit/s, whereas the top 1 per cent will need 35-39 Mbit/s. The methodology was anchored in the speeds required by different applications, after accounting for the expected increase or decrease in speed required over time. Households were segmented into 156 types, based on 13 different demographic profiles, 4 main usage intensities, and 3 main TV types. Importantly the study focused on 'busy hours', as bandwidth demand is driven by peaks rather than the average speed required. User satisfaction is not explicitly considered. As this focused purely on technical demand, the amount of bandwidth consumers would actually be willing to pay for via the market may be higher or lower than the presented figures.

A study by WIK (2013) for the FTTH Council also undertook a bottom-up analysis based on application bandwidth requirements, combined with individual and SME usage profiles. The study focused on the market potential for high-speed broadband in Germany up to 2025. The key finding was that by 2025, required bandwidth will range from 60 Mbit/s downstream (for entry level segments), up to 350 Mbit/s downstream (for high-end segments). The approach focused on the 'optimal user experience', so that the customer can experience the best possible usage without limitations in functionality, contrasting strongly with the approach taken by the UK's Broadband Stakeholder Group. The report expects near symmetric upstream requirements by 2025.

Dialogic and the Eindhoven University of Technology (TU/e) (2014) undertook an analysis for NLKabel and Cable Europe to examine how the speed of the Internet will develop between now and

2020. The research focused on domestic residential consumers to understand future upload and download bandwidth demand. The Compound Annual Growth Rates used in the analysis were 40% for downstream and 44% for upstream traffic demand. In 2020, the research estimates that the average user will be satisfied with 165 Mbit/s downstream, and 20 Mbit/s upstream. Kenny writing for Nesta (2015) states that this study does not provide any evidence offered for critical 'pro rata' assumptions. For example, peak bandwidth may remain constant while the traffic profile changes dramatically. If one's peak bandwidth is dependent on viewing HDTV, spending more hours watching online content will increase traffic but will have no impact on peak bandwidth.

The largest fixed broadband provider in the UK, BT (2015), has its own in-house demand forecast model which is user-centred and based on peak bandwidth demand. The approach is bottom-up, focusing on applications and domestic usage. The assumptions of the model are not made clear, but the estimates produced are that 95% of households will need less than 35 Mbit/s by 2018. Moreover, BT predict that by 2025 demand for video streaming and normal Internet usage can be supported with roughly 50 Mbit/s, with occasional demand for faster speeds in excess of 500 Mbit/s when downloading content.

Analysys Mason (2013) present a simplified illustration based on the likely key drivers of bandwidth, which include media services such as YouTube, and other online, on-demand video content. The two factors influencing this development are the bandwidth requirements per stream and the number of streams per household. While media services are the focus of household demand, for example the bandwidth required for HDTV, additional bandwidth is allocated for other services based on 50% of the total bandwidth required for concurrent media streams. The estimated bandwidth requirement range from 15 Mbit/s to 52.5 Mbit/s by 2018 for different households.

Many of these studies use different methods with diverse assumptions. However, there is broad agreement between the work of the BSG (2013), BT (2014) and Analysys Mason (2013). These approaches focus on taking the technical bandwidth requirements for various applications and place less of an emphasis on user experience, contrasting with the report by WIK (2013) which specifically included the aspiration of providing the very best customer experience without any limitations in functionality. This has a large impact on expected bandwidth demand. It is an important question as to whether customer satisfaction should or should not be included in demand forecasts, as these projections are used for informing a variety of industrial and governmental decisions. Kenny writing for Nesta (2015) states that customer satisfaction is fundamentally a private benefit and therefore less relevant when discussing policy interventions.

The current approach to broadband delivery in the UK has been to focus on providing near-ubiquitous fixed broadband access between 10-100 Mbit/s via SFBB, rather than trying to provide UFBB services via FTTP. In many ways this is a form of utilitarian broadband provision, providing sufficient connectivity for the majority, while being unlikely to meet the needs of the few with very high bandwidth demand. Therefore operators have been focused on meeting the demand of the median user at the lowest possible price (driven by Ofcom's consumer-focused regulatory regime), rather than delivering more UFBB connectivity which only a few users may actually utilise. In the case of the latter, the delivery of UFBB connectivity would undoubtedly push up consumer broadband prices.

2.3 Demand-side factors in delivery

Local factors can have a very large influence over the demand for fixed access broadband, and due to the great deal of heterogeneity associated with the economic, socioeconomic, geographic and technical characteristics of different places, the quality of broadband availability for premises has often been referred to as a 'lottery'. The expected demand for fixed broadband services influences the investment decisions of network operators, leading to disparities in provision of a fixed factor of production. Considerable work has been undertaken which has analysed the key demand-side determinants, and here key quantitative studies are reviewed.

Belloc et al. (2012) analyses both supply-side and demand-side policies for previous generations for broadband and found that the effectiveness of these two approaches depends on the stage of technology diffusion. Once a mature stage has been reached, only demand-side policies are able to generate further positive effects. This is relevant to the UK given its mature fixed broadband penetration rate. It is also found that the share of adoption of both fixed and mobile broadband is positively associated with the share of service sector employment.

Haucap et al. (2015) undertook analysis of over 1000 fixed-line broadband tariffs in a cross-country sample of 82 OECD and non-OECD states to understand how diversity can affect fixed broadband penetration. The authors report finding that price-related and socio-economic factors affect broadband demand the most. Income is the key component here, because ultimately there is an economic requirement for customers to be able to pay for desired services. This is similar to previous work undertaken by Jakopin and Klien (2011) which found that economic prosperity (measured as purchasing power parity adjusted GDP per capita across countries), and computer penetration had the largest influence on broadband take-up.

Lin and Wu (2013) identify the determinants of broadband adoption by diffusion stage in OECD countries using an Arellano-Bond GMM dynamic panel method to capture the dynamics of broadband diffusion while also solving the endogeneity problem associated with estimates in previous studies. Income, education and available content most influence early adoption. The adoption by the 'early majority' is most associated with platform competition and the previous broadband penetration. Finally, adoption by the 'late majority' and 'laggards' is associated with broadband price effects.

Grubesic (2006) undertakes Principle Components Analysis of broadband markets in the USA to highlight the socioeconomic and demographic factors affecting broadband provision. Favourable demand conditions relate to high incomes and high levels of education, while unfavourable demand conditions are associated with low incomes, older populations and smaller household sizes. In another piece, Grubesic (2008) examines the spatial distribution of broadband providers in the USA using longitudinal analysis and spatial statistical techniques. The paper demonstrates that the geographic heterogeneity in provision is able to be explained using a set of demand-side determinants. Household density is used as a measure of market demand, along with average household size to differentiate intensity of usage. Other indicators of demand relate to ethnicity, median age, median income. Moreover, business counts are also used for two key sectors (i) professional, scientific and technical services, and (ii) educational services. The supply-side factors in delivery will now be reviewed.

2.4 Supply-side factors in delivery

Supply-side factors include the use of *ex ante* regulation to encourage market competition, as well as subsidies, regulatory holidays and tax breaks. Much analysis has been undertaken to date, focusing on quantifying investment and adoption (penetration) under certain supply-side conditions. There have also been qualitative reviews of the theoretical and empirical literature on how supply-side policies such as regulation affect investment in infrastructure (Cambini and Jiang, 2009).

Briglauer (2014) employs both static and dynamic model specifications to examine the key determinants of the adoption of fibre-based broadband services, using panel data from the European Union member states between 2004 and 2012. A key finding is that the degree of regulation placed on wholesale broadband access regulation for the incumbent's first-generation DSL infrastructure is negatively correlated with NGA adoption. Mobile networks also affect NGA adoption in a non-linear way. The paper concludes by suggesting that the DAE targets can be best achieved by focusing on supply-side rather than demand-side policies. This includes deregulation, and encouraging favourable competitive market conditions. This judgement is informed by the majority of previous literature, the results indicated in the paper, and historical evidence. Briglauer suggests that the supply and demand dynamic for encouraging NGA delivery is the classic 'chicken and the egg' problem. What comes first, the infrastructure or the end-use applications and services? Historically we have seen that the market

has developed and delivered end-use applications once new infrastructure has been delivered, and therefore this supports his conclusions in this regard.

Gruber and Koutroumpis (2013) analyse data from 167 broadband markets over 11 years to understand efficient and effective competition-enhancing policies in regulating broadband networks. The study provides insight into the theoretical propositions of the regulatory debate based on different levels of infrastructure competition. Forms of intra-platform competition on the incumbent's network had a positive impact on accelerating the adoption of broadband, highlighting the importance of reducing the market power of the incumbent. In contrast, there was little evidence to suggest that forms of inter-platform competition across different technology platforms were effective (e.g. DSL versus cable). This finding was similar to other work that found that light-touch Local Loop Unbundling (LLU) was associated with high levels of fixed broadband diffusion (e.g. Lee et al. 2011).

Nardotto et al. (2015) studies the impact of access regulation in the UK on total demand (penetration rate) and quality of service in broadband telephone exchange areas. No evidence was found that unbundling increased adoption, except for in early years before the market reached maturity. The data instead found that inter-platform competition from cable always leads to market expansion. This is comparable with the work of Oughton et al. (2015) who also found that inter-platform competition had the largest effect on network investment in the UK. These studies used spatially granular data in their analysis which is more effective at identifying local trends given the great geographic heterogeneity in provision within countries such as the UK, explaining why these results are different to other studies such as Gruber and Koutroumpis (2013) which took a more aggregate approach.

Götz (2013) examines the effect of different regulatory regimes on both penetration and coverage of broadband access to the Internet. This included exploring the impact of regulated monopolies, facilities-based competition, and the subsidisation of broadband investment and access, on the trade-off between penetration and coverage, while taking into account differences in population density. Strong and well-informed regulatory approaches did not perform much better than the unregulated benchmark. Indeed, light-touch regulatory approaches such as uniform pricing may therefore be more appropriate given that regulators may lack desired information to thoroughly inform regulatory strategies. Due to the degree of rapid innovation in connecting technologies on the demand-side, adding uncertainty to future system states, the analysis found a lack of evidence to suggest that strong regulatory approaches were superior. Light-touch approaches were favoured.

Bouckaert et al. (2010) investigated broadband penetration in OECD countries based on differences in the use of three types of competition. These include inter-platform competition, facilities-based intra-platform competition and service-based intra-platform competition. Based on the data analysed for OECD nations, the main driver of broadband penetration was inter-platform competition, contrasting with the later work of Gruber and Koutroumpis (2013). Intra-platform competition in this analysis had a considerably smaller effect on broadband penetration. The authors consequently advocate the avoidance of extensive mandatory access obligations on DSL incumbents. Conclusions will now be drawn from this review.

2.5 Conclusions from the literature review

The concept of 'need' for fixed broadband services is an ambiguous term. To date, UK broadband policy has focused on ensuring that all premises have satisfactory broadband access as specified by the USO targets, focusing more on avoiding social exclusion than providing very high capacity connectivity to enable more intensive, online entertainment content. There are a variety of different studies that have analysed anticipated technical demand for bandwidth in coming years, with the main difference being whether user experience is taken into account in the analysis. If it is, then much higher bandwidth is required. There has been considerable research in the supply and demand factors which influence the delivery of broadband infrastructure, as examined in the review undertaken here. Conflicting evidence

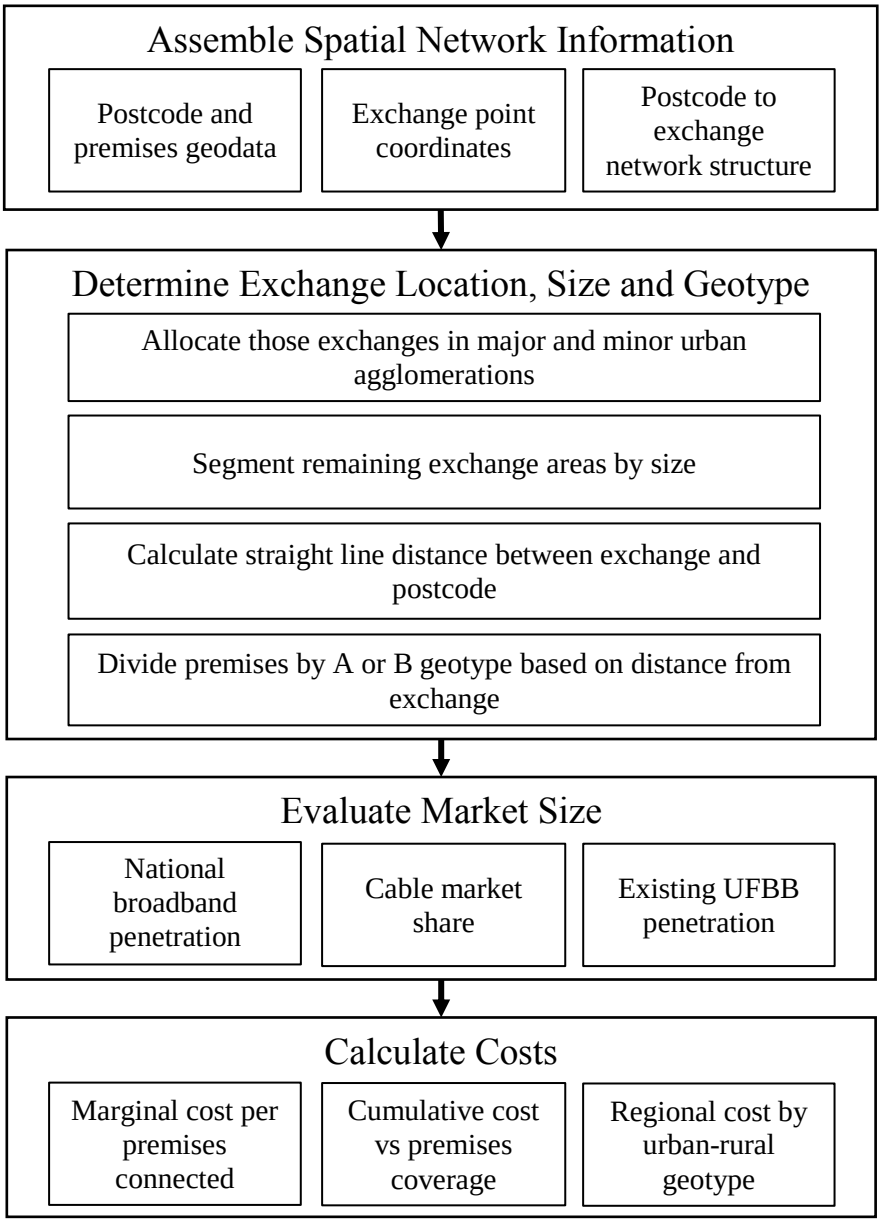
has been identified as to whether supply or demand-side factors have the largest impact on broadband infrastructure delivery, with this often arising due to the level of spatial disaggregation used within the analysis. The insights provided by this review will be used to inform the subsequent investigation.

3.0 Methodology

The approach taken in this paper is aimed at providing a broad picture of the total investment costs associated with rolling out FTTP technologies to different levels of the population. The total investment costs are determined by calculating technology costs (optical distribution frame, active equipment and splitters), civil engineering costs (up to the final drop, and including the final drop), in-building wiring costs and required customer premises equipment.

The methodology consists of four key parts detailed in Figure 1, including (i) assembling the necessary spatial network information, (ii) determining exchange location, size and geotype, (iii) evaluating the market size present, and finally (iv) calculating the costs per premises, cumulative coverage costs and heterogeneity across urban-rural locations.

Figure 1 Box diagram illustrating key steps in the methodology



This cost modelling approach takes inspiration from the methodology used in report undertaken for the UK's Broadband Stakeholder Group by Analysys Mason (2008), entitled *The Costs of Deploying Fibre-Based Next-Generation Broadband Infrastructure*. In doing so, the methodology has been updated using 2015 connectivity data for roughly 30 million premises in more than 1.6 million postcodes across England, Scotland and Wales (Ofcom, 2015). The cost structure has also been updated to 2016. Originally, this method was developed in association with a technical steering group comprising industry experts from the membership of the Broadband Stakeholder Group, thereby justifying this methodology. Recently, Rendon Schneir & Xiong (2016) have utilised this methodology in a similar study to assess fixed access in rural areas.

Firstly, the necessary spatial network information is assembled, which includes using (i) postcode and premises geodata, (ii) telephone exchange point coordinates data, and (iii) information on the exchanges that different postcodes are connected to. Using Ordinance Survey Codepoint it is possible to identify the latitude and longitude coordinates of the centroid of each postcode, as well as the number of premises in each postcode. Postcodes are also identified by Royal Mail as being either a small user or

large user. Premises identified as small users are used in this paper to represent households and small businesses as they are most likely to use consumer broadband offerings and be susceptible to disparities in infrastructure provision. Exchange point coordinates are also obtained using SamKnows data, where the postcode of each exchange has been provided. As we do not have the exact coordinates for the exchange, the postcode centroid is taken instead, as this provides a reasonable degree of accuracy and is satisfactory for the purpose utilised here. Finally, information gathered from multiple sources is used to represent the fixed access network structure. We do not have openly accessible information which accurately details which postcodes are attached to which exchange, but the large majority of the postcode-to-exchange linkages can be worked out from using information made publicly available by BT on the rollout and availability of SFBB. Where information is not available Voronoi polygons have been used for the postcode exchange areas, and the postcodes which either fall within, or intersect with, the telephone exchange area boundary are classed as being served by that exchange.

Secondly, we need to determine the exchange location, number of lines connected and finally how many premises fall into Geotype A or Geotype B. Overall, there are 13 different geotypes that represent areas with specific attributes, ultimately affecting the financial aspects of deployment for each premises. In this case, the key characteristics chosen that have the largest impact on cost are whether the exchange is within a major or minor urban agglomeration, the number of lines served by each exchange, and finally the (straight-line) distance between the customer premises and the telephone exchange. The first two factors have a large impact on the degree of economies of scale, bringing infrastructure capital expenditure down, particularly if the premises are clustered close to the exchange and do not require long feeder segments. With regard to the latter point, we need to identify those premises that are located either close to, or far from, the exchange.

Different fixed costs are assumed for those premises in either major or minor urban agglomeration, and Table 1 and Table 2 represent cities in each agglomeration category. Inner London has also been given its own category with one of the lowest cost structures. The ONS 'built-up' area definition is used for each city, as this most closely represents the true extent of the built environment.

Table 1 List of major cities

Major Agglomerations		
Bristol	Liverpool	Newcastle
Glasgow	Nottingham	Birmingham
Manchester	Sheffield	Leeds

Table 2 List of small cities

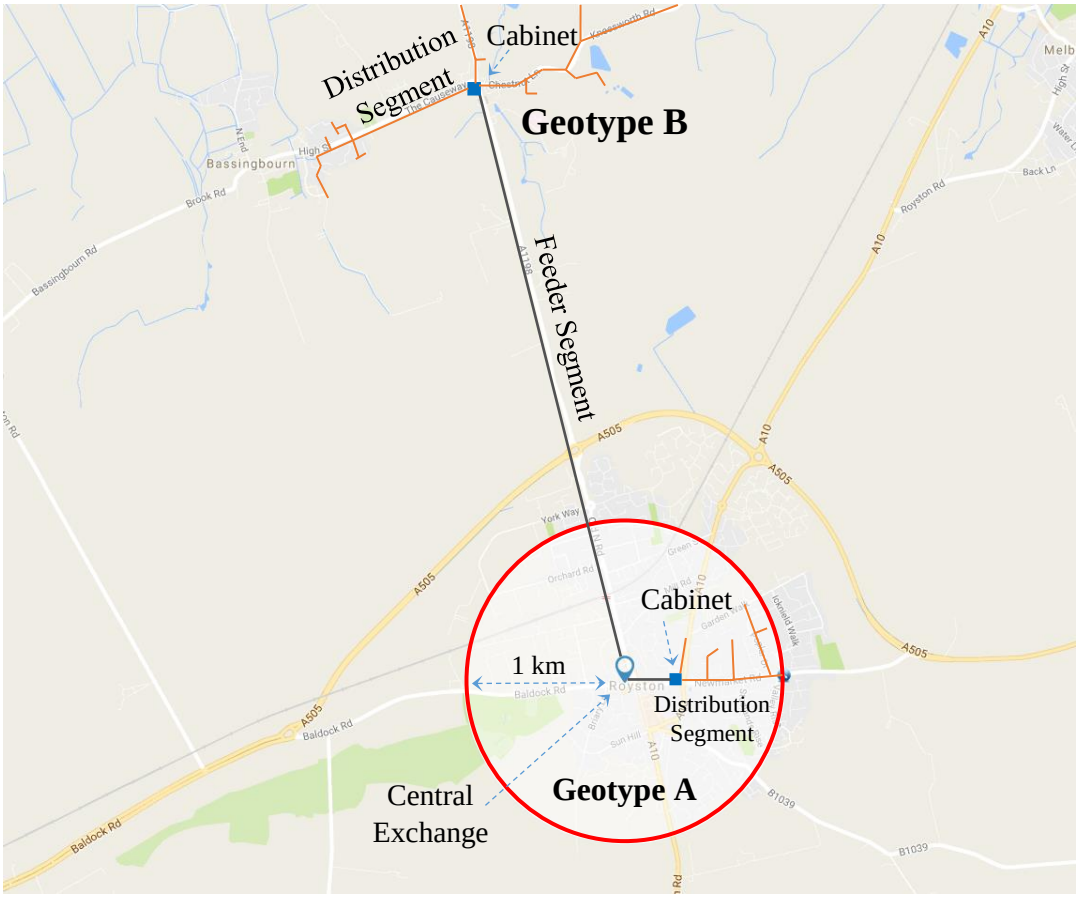
Minor Agglomerations			
Aberdeen	Coventry	Northampton	Southend
Aldershot	Barnsley	Norwich	Swansea
Birkenhead	Derby	Plymouth	Middlesbrough
Blackpool	Edinburgh	Portsmouth	Gillingham
Bournemouth	Kingston	Preston	Stoke-on-Trent
Brighton	Leicester	Reading	
Cardiff	Luton	Southampton	

Next, the sum of the premises within each exchange is taken to indicate the number of lines connected to each exchange. It is assumed that each premises is connected via one line. This is a reasonable assumption to make given that the historical network structure dates back to when voice was the main use of fixed communications infrastructure, and to this day BT is still obliged to provide a fixed telephone line to any premises in the UK that requests one under the incumbent's voice USO.

The straight line distance[3] is then calculated between the geographical coordinates of each telephone exchange, and each individual connected postcode. The measured distance is then allocated uniformly to each of the premises within a postcode, ready for the next step.

In many rural areas there are significant numbers of premises in relatively dense clusters close to telephone exchanges, and therefore it is essential that this clustering be taken into account, as illustrated in Figure 2 below. The telephone exchange in Royston, Hertfordshire, UK, serves roughly 9,500 lines where the majority are located in Royston town centre.

Figure 2 Examples of network elements in Geotype A and Geotype B emanating from the central telephone exchange in Royston, Hertfordshire, UK



Premises within 1 kilometre of the exchange are classed as falling within Geotype A (within the red circle in Figure 2), whereas those outside are classed as falling into Geotype B (outside the red circle in Figure 2). The feeder segment would be longer in Geotype B, and potentially also the distribution segment, therefore incurring more cost which would push up the required capital expenditure for delivery.

Table 3 provides summary statistics for each geotype used for England, Scotland and Wales, including the total number of premises, the percentage of premises, and the number of premises without NGA or UFBB (as of 2015)[4].

3 This does not account for the curvature of the Earth.

4 UFBB is defined by Ofcom (2015) based on actual modem sync speed measurements for all premises.

Table 3 Summary of Geotypes

Geotype	Classification	Total premises	Percentage of premises	Premises without NGA	Premises without UFBB
Inner London	Inner London	1,355,827	4.4	110,508	1,328,448
>500k pop	Major City (pop = 500k+)	4,993,951	16.3	327,286	4,969,496
>200k pop	City (pop = 200k+)	3,906,347	12.7	227,605	3,813,358
>20k lines (a)	>20,000 lines, <2km from the exchange	4,294,930	14.0	168,752	4,198,953
>20k lines (b)	>20,000 lines, >2km from the exchange	866,005	2.8	166,627	814,074
>10k lines (a)	>10,000 lines, <2km from the exchange	6,013,957	19.6	323,546	5,889,371
>10k lines (b)	>10,000 lines, >2km from the exchange	532,188	1.7	44,627	520,602
>3k lines (a)	>3,000 lines, <1km from the exchange	2,147,128	7.0	253,348	2,106,490
>3k lines (b)	>3,000 lines, >1km from the exchange	3,304,520	10.8	381,178	3,235,593
>1k lines (a)	>1,000 lines, <1km from the exchange	690,061	2.2	170,322	668,954
>1k lines (b)	>1,000 lines, >1km from the exchange	1,648,834	5.4	511,532	1,566,865
<1k lines (a)	<1,000 lines, <1km from exchange	150,769	0.5	51,313	143,289
<1k lines (b)	<1,000 lines, >1km from exchange	769,296	2.5	352,331	701,620

Thirdly, we need to evaluate the market size, as only new customers will be connected to the network. Broadband penetration is based on the national average of 80%. Moreover, it is assumed that the national market share of cable broadband remains constant at ~21% based upon coverage by Virgin Media's network in each geotype. Virgin Media provide at least some cable coverage in approximately 60% of postcode areas, although only about 45% of premises are actually passed. Within the 60% coverage areas, this corresponds to a market share of around 35%[5]. This leads to an overall take-up rate of 31% of all lines nationally. Finally, premises which already have access to UFBB (>300Mbit/s) are excluded from the analysis to avoid double counting.

Finally, utilising the cost structure from the Analysys Mason (2008) report, there was on average an 80:20 split between civil engineering costs and technology costs. Hence, the civil engineering component of the cost structure was updated using an inflation rate of 19.6% representing the change in the Retail Price Index between September 2008 and April 2016. Technology costs are assumed to be roughly the same. In reality the technology component, as a result of technological and organisational efficiencies, is likely to have induced cost savings, therefore the figures presented here represent the upper bound of the potential cost.

[5] Virgin Media's Project Lightening will extend the existing cable network to passing 16 million premises in total by 2020, although this is still ongoing. This is an addition of roughly 3 million new premises, potentially increasing their market share.

4.0 Results

This section will first examine the average marginal cost per premises by region and geotype, secondly illustrate the cumulative cost for providing coverage to different proportions of the population, and finally show the aggregate costs by region and geotype.

The cost structure for delivering FTTP when plotted against population density resembles a U-shaped curve. In dense urban areas the costs can be high because it is expensive to close streets in city centres as it requires numerous permits, the work may need to be carried out at night when streets are less busy, and any disturbance to the road or pavement need to be replaced like-for-like. As you move to the suburbs the costs drop as there is more space for new ducting, but premises are close enough together to provide economies of scale for expenditure on fixed capital assets. In rural or remote areas, the costs of digging fibre are less but the low density increases the overall cost per premises, particularly as feeder segments and new ducting may need to be run for long distances. Figure 3 and Figure 4 show the average marginal cost per premises by geotype for each region. The cost differences between the urban-rural geotypes are due to these outlined differences, as the costs increased in areas of lower population density. The small differences between the average marginal cost per premises by geotype between each region, represent the fact that each region has its own unique set of settlement patterns, leading to a different number of premises in either urban, rural or remote areas.

Figure 3 FTTP-GPON average marginal cost per premises connected by region and geotype

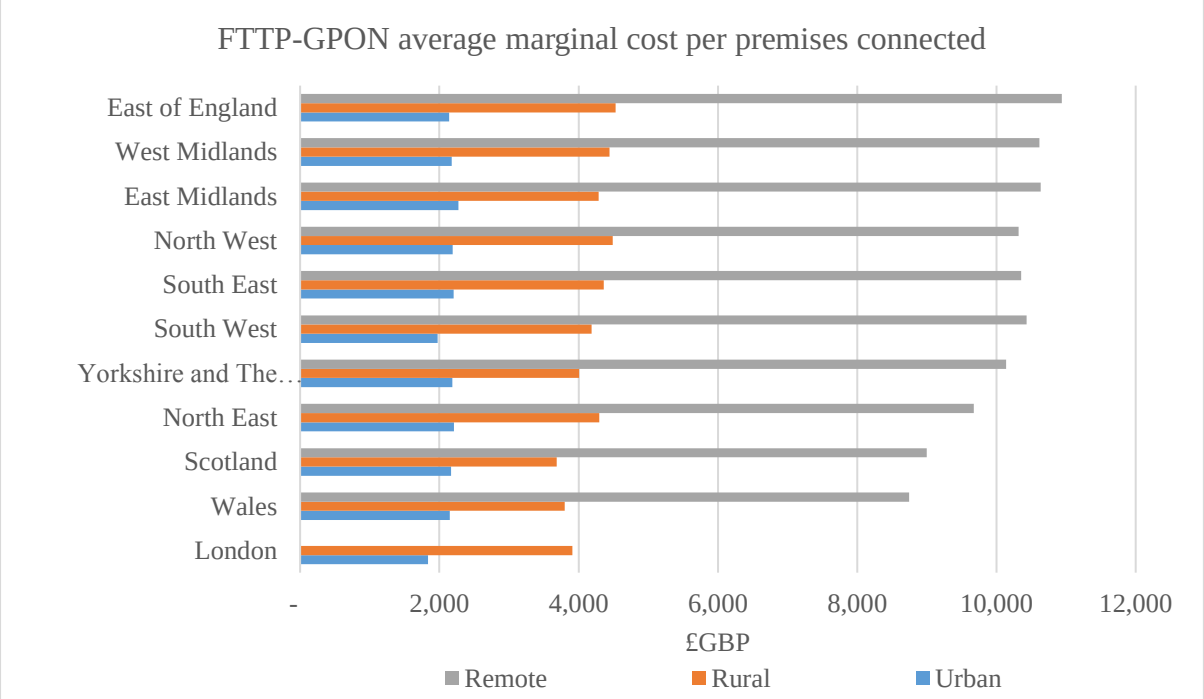
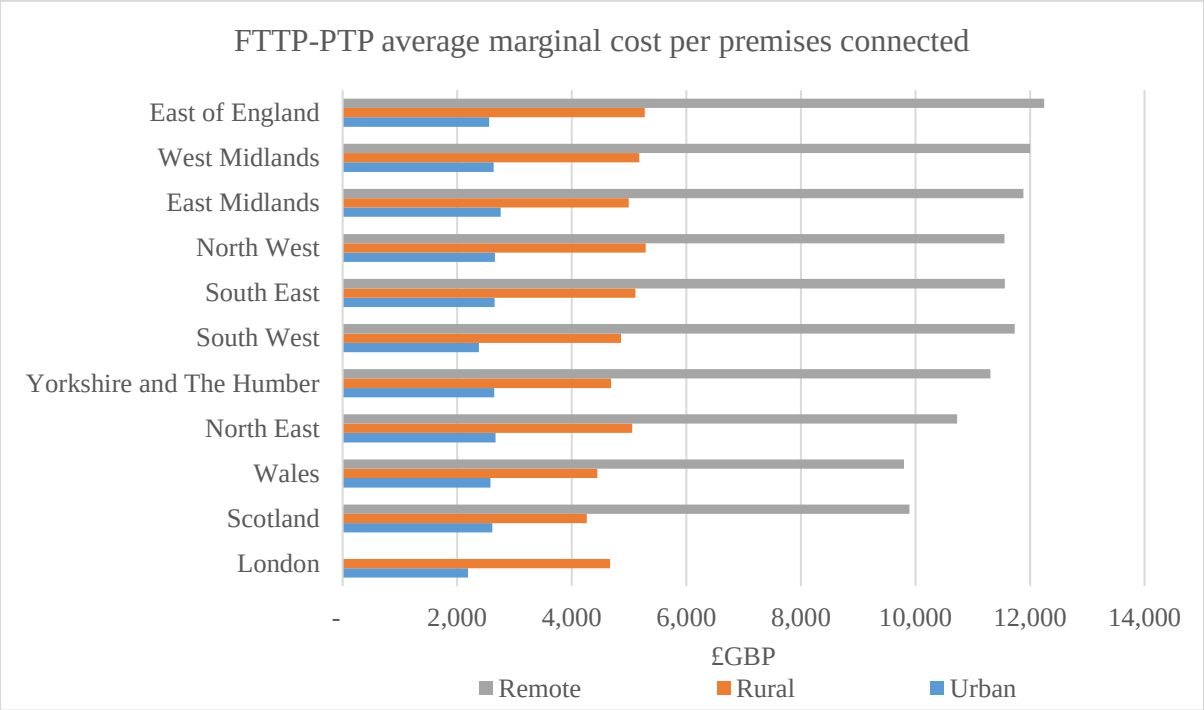


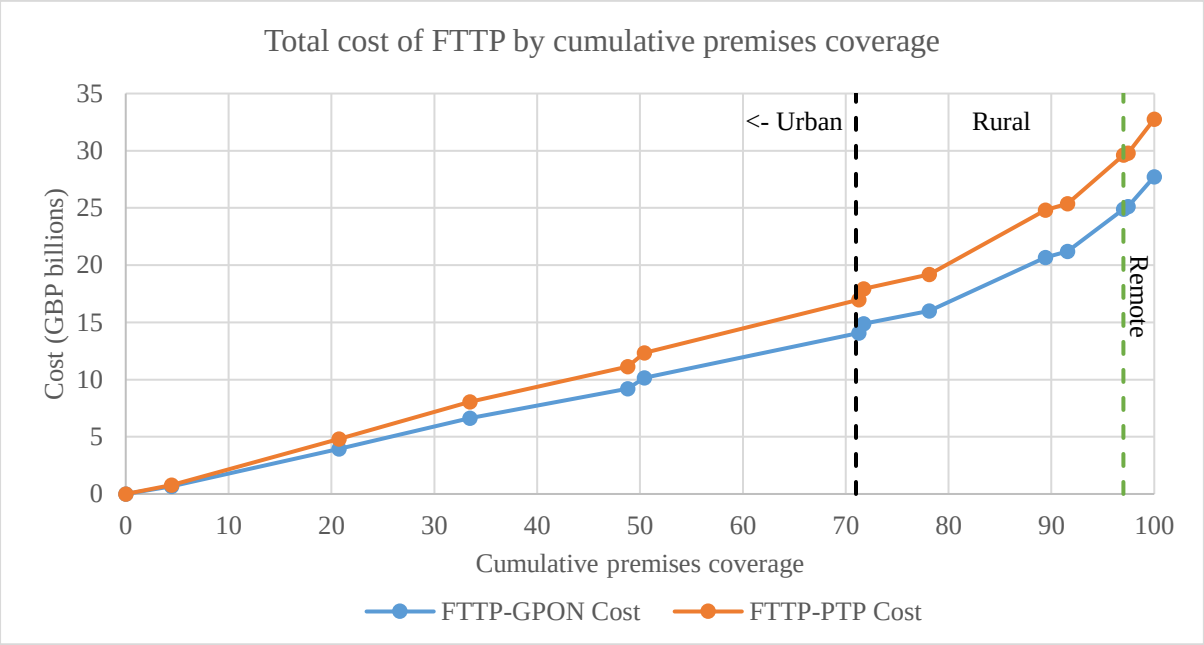
Figure 4 FTTP-PTP average marginal cost per premises connected by region and geotype



The average marginal cost per premises is roughly similar, but with FTTP-PTP proving more expensive. This is because each premises requires its own dedicated fibre connection all the way to the exchange, whereas FTTP-GPON uses a shared fibre connection between the exchange and the cabinet. Due to the increased space required for numerous fibre-optic cables, there is also a lower reuse rate, requiring more new ducting to be installed.

Figure 5 show the estimates produced by the cost model for FTTP-GPON and FTTP-PTP versus the cumulative percentage of premises reached. The circular points on each line represent the number of premises and associated costs for each of the 13 geotypes, which have been ranked based on their density (1% being the most dense, and 100% being the least dense). Therefore, Figure 5 indicates that almost 35% of premises are located within the built up areas of either major or minor urban agglomerations (the first three geotype segments outlined in Table 3). Roughly the next 35% contain premises connected to large exchanges (the next three geotypes outlined in Table 3). Finally, the least dense 7 geotypes covering rural and remote areas contain approximately 30% of premises.

Figure 5 Total cost of FTTP technologies vs. premises coverage



The costs raise linearly for delivery to premises in urban areas, with total urban coverage by FTTP-GPON costing £14.1 billion and FTTP-PTP costing £17 billion. The costs for rural and remote areas begin to rise sharply, to the extent that deployment of these technologies to the final third of premises could cost almost the same amount as deployment to the first two thirds. Deployment to rural and remote areas was estimated to cost £13.7 billion for FTTP-GPON and £15.8 billion for FTTP-PTP. Total coverage predicated on the aforementioned assumptions totals £27.7 billion for FTTP-GPON and £32.8 billion for FTTP-PTP.

Finally, the aggregate investment required to deliver ubiquitous fixed FTTP broadband access is illustrated graphically in Figure 6 and Figure 7 below. The largest aggregate investment is required in the South East, North West and East of England. Across these technologies the lowest average marginal cost per premises was in London for urban areas, Scotland for rural areas, and Wales for remote areas.

Figure 6 FTTP-GPON total costs per region and geotype

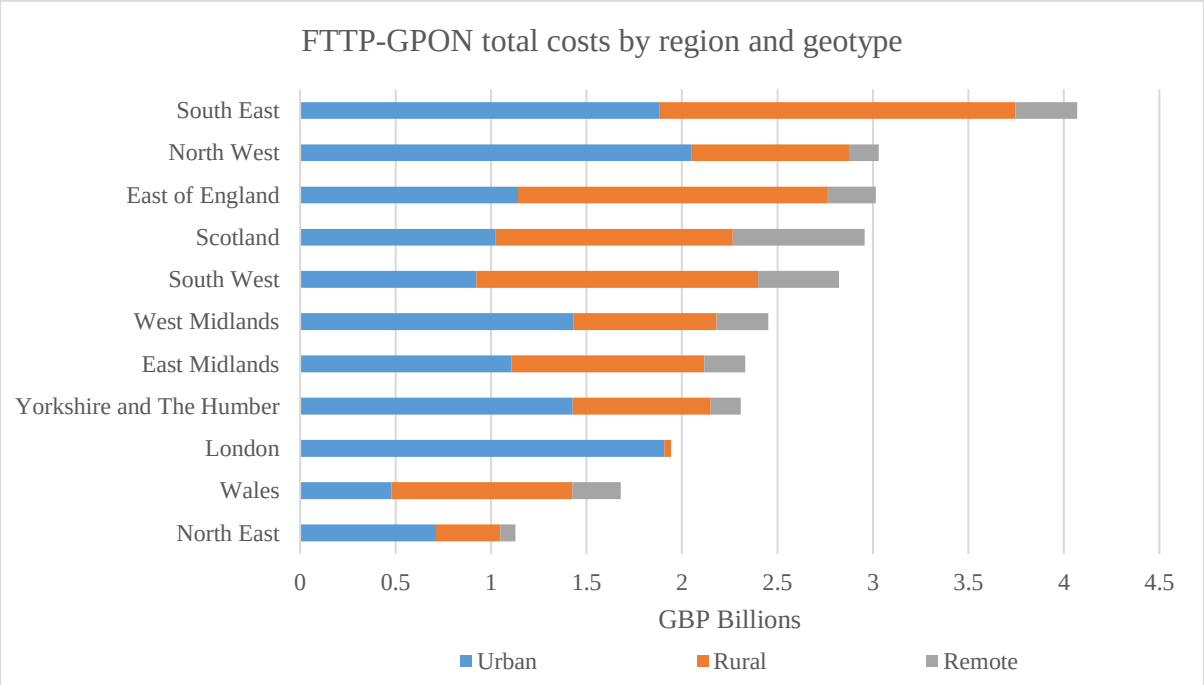
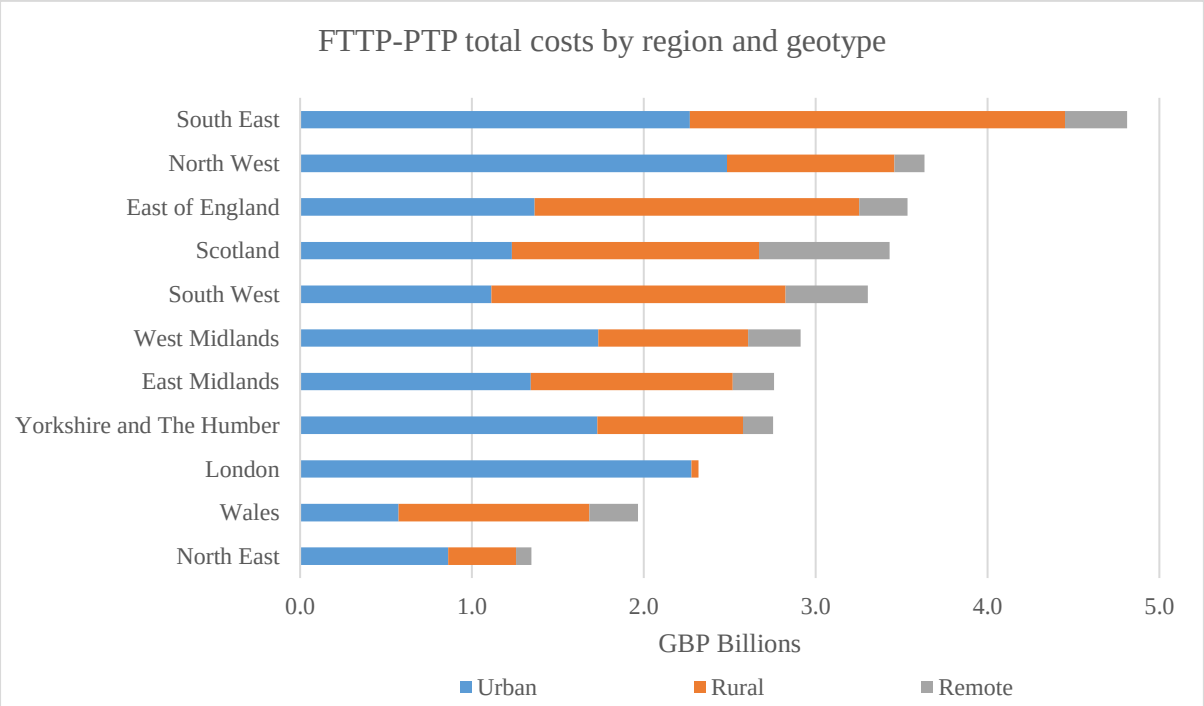


Figure 7 FTTP-PTP total costs per region and geotype



The size of each region has a large impact on total investment. For example, the South East is the largest region in the UK and therefore it will cost more to connect all premises via these technologies. When examining the geotype breakdown, the South East not only has the third highest number of urban premises, but also the largest number of rural premises. This contrasts with the North West region that has the second highest number of premises in the urban segment, but only the eighth and tenth highest number of rural or remote premises respectively. One region with a particularly high number of rural

premises is the East of England that ranks second after the South East. At the other end of the scale is the North East that ranked eleventh out of the twelve regions on the number of premises in urban, rural or remote geotypes, indicating how small the region is comparatively. Wales has the smallest number of urban premises overall, but has a reasonable number of premises located in rural or remote geotypes. Finally, London is more of an outlier in this case, with aggregate total investment being lower because in reality it is a 'city-region' and not a region, as indicated by its largely urban premises. It has the lowest number or rural premises out of all regions, and no premises fall within the remote segment. Having now examined the results they will be discussed and related to their relevance for policy.

5.0 Discussion and policy relevance

Having reviewed the relatively limited literature on the concept of bandwidth 'need' and future demand, this appears to be a highly under-researched area. To date, there have been a number of industry reports on bandwidth demand but they have been commissioned by organisations with a vested interest in the degree of investment in fixed access. Much of the content in these reports does not make it into peer-reviewed academic journals, leaving a relatively sparse literature landscape on this important topic. For example, governments have a key interest in capacity planning and therefore surely this topic is paramount for effective formulation of broadband policy and regulation, but hitherto this activity has been left up to industry where it either forms part of their analysis of future market size or of their policy lobbying toolkit. One key aspects that arose in the review is whether customer satisfaction and user experience should be taken into account in this analytical process, and how that should feed through to decisions that are made at the policy level.

In the literature review, two potential objectives were outlined from a range of infrastructure investment options that may be important political objectives for delivering fixed access. They are as follows:

Objective 1: To provide equal access of economic opportunity to all by guaranteeing that basic connectivity is available for web browsing, email, basic file transfer, video calling and other services as these enable participation in a modern digital economy.

Objective 2: To provide equal access to *all* online content, applications and services regardless of location. This includes access to content that requires more bandwidth and lower latency, including High Definition (HD) and Ultra High Definition (UHD) (4k or 8k) on-demand television services.

The UK's current USO of 10 Mbit/s is in an implementation stage and will require ubiquitous delivery to the last 5% of premises that currently do not achieve this. However, in doing so one of the primary objectives will be overcoming the social exclusionary effects associated with not having access to key content, applications and services required for equality of economic opportunity, thereby meeting Objective 1. This is predicated on key services working to a sufficient level at 10 Mbit/s, although this speed may not provide the best user experience and highest customer satisfaction. Moreover, if SFBB speeds can also be delivered ubiquitously to the last third of premises, then that will contribute considerably to achieving Objective 2 and enabling access to content, applications and services that demand more bandwidth for all in our society, at least over the short to medium term.

The UK's Broadband Delivery UK recently reported on the emerging findings from the Market Test Pilots (DCMS, 2016) which explored new ways for delivering SFBB services to the hardest to reach and least commercially viable parts of the UK (such as 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, SFBB-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. Hence, the activity of exploring different technology configurations must be sustained after this period but with a view to meeting long-term demand in the most challenging places in the UK.

Although FTTP will future-proof our needs, it is very expensive. One near-term solution seen as a 'halfway house' is other types of fibre rollout which focuse on getting fibre as close to the end consumer as possible without absorbing the costs associated with full fibre deployment. For example, Fibre-To-The-Distribution-Point (FTTDP) may play an important role in meeting our future bandwidth and traffic needs, whereby fibre runs from the cabinet to a street close to the customer's premises, or to a shared building. The remaining link still utilises legacy copper cabling. FTTDP with the technology G.fast, using a GPON architecture, enables theoretical transmission rates of 1Gbit/s in download and upload channels over a 100 m distance. The ITU has now approved the G.fast standard, the technology is on the market and operators are in receipt of compliant equipment. Rendon Schneir & Xiong (2015) report the cost per premises for deploying FTTDP and G.Fast as roughly 17% lower than FTTP. This is because it eliminates the need to get the necessary permissions for indoor fibre deployment that can be considerably time consuming. For example, even if a municipality or residents' association gives permission to install fibre in a building, permission also needs to be obtained to install the final fibre connection into each individual dwelling. The key issue associated with this type of incremental development is defining exactly what we may forgo by not moving to complete FTTP rollout. Very few applications currently require the additional uplift in speed delivered by FTTP, that cannot already function using existing SFBB, but this may change in the future.

The analysis conducted here is an aggregate estimate of required investment across UK regions and urban-rural geotypes. Detailed network planning is still required to gain an accurate understanding of cost at the local level, particularly for civil engineering costs which are affected by whether new ducting needs to be installed and the ease at which this can take place (e.g. narrow streets make construction challenging and require traffic to be rerouted). Future research must focus on those locations which are not likely to have their demand met via the market and are therefore likely to suffer from market failure. This would enable decision makers to have greater insight into the role that policy should play in supporting the UK's digital economy across all regions. Those places that do not have their demand met by the market may need additional state support, although there is uncertainty affiliated with this because as the UK it set to leave the European Union access to the Regional Development Fund will cease. Regardless, further research must be able to provide enhanced understanding of the interactions between fixed broadband, and other types of mobile, wireless and satellite broadband, including the substitutionary effects of these technologies in meeting technical demand.

In light of this, it is tantamount to consider not just fixed on its own as an individual subsystem, but the whole digital communications system which is comprised of fixed, mobile, wireless and satellite access. Indeed, these do not function in a closed manner but are highly integrated with these other systems, and indeed consumers are increasingly becoming more willing to explore how their demand can be met by other technologies than purely a fixed connection. Inevitably, the roll of 5G will therefore influence future demand for fixed fibre, particularly as the economics of delivering high bandwidth connectivity via mobile and wireless become more viable. Some may argue this diminishes the importance of fixed access. However, in reality, while we may move to a future where access utilises more mobile and wireless connectivity, existing and future fibre connections will play a pivotal role in enabling small cells to actually deliver the benefits of 5G including enhanced mobile broadband, massive machine-type communications, and ultra-reliable and low-latency communications. Indeed, the future of the digital communications system is now widely regarded as likely to be a heterogeneous network (the 'HetNet'), which will in essence be a highly complex and adaptive multi-layered network consisting of not just macrocells, but also a variety of small cells enabling millions of connected devices to function (smartphones, wearable technology, autonomous and connected vehicles, drones, smart buildings, smart infrastructure and endless applications via the Internet of Things).

6.0 Conclusion

This paper explored the aggregate investment required to deliver different levels of fixed broadband access to different proportions of the population via two different technologies, FTTP-GPON and FTTP-PTP. Total urban coverage (equating to the first two thirds of premises) has been estimated to cost £14.1 billion by FTTP-GPON and £17 billion for FTTP-PTP. Delivery to the final third of premises residing in rural and remote areas was estimated to cost 13.7 billion for FTTP-GPON and £15.8 billion for FTTP-PTP. Hence, the costs for rural and remote areas rise sharply, to the extent that deployment of these technologies to the final third of premises could cost the same as deployment to the first two thirds of premises in urban areas. Total coverage would therefore be £27.7 billion for FTTP-GPON and £32.8 billion FTTP-PTP.

In addition to the estimates derived, this paper also identified a number of important points. Firstly, there is relatively little research that tries to forecast the future demand for bandwidth, which is surprising given that this is important information for supporting policy formulation. Where this has been undertaken, predominantly in industry-sponsored reports, there are a number of diverging assumptions underlying the modelling process. Critically, whether user experience and customer satisfaction is taken into account, has a large influence over future bandwidth demand. Whether customers would be willing to pay for the costs associated with UFBB (or beyond) are as yet unclear. The current rollout of SFBB may meet our short to medium term needs, but if fibre is to play an increasingly important role in local access between the cabinet and the customer, it is likely that the cost needs to be brought down further, potentially via business model innovation.

Finally, too often we attempt to analyse parts of the digital communications system in isolation, whether the focus be on either fixed, mobile, wireless or satellite connectivity. Yet this not only misses out the interactions between these subsystems, but also the substitutionary effects between them. Therefore, future research needs to pay more attention to the cross-sectoral impacts between supply and demand in digital communications markets, especially as the technologies that we use to connect are rapidly changing. While we may move to a future that sees a larger role for mobile and wireless technologies, that does not make fixed access redundant. In reality, fixed access will be essential for enabling the small cell 5G future that we are moving towards.

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