FUTURE BENEFITS OF BROADBAND NETWORKS

Master draft

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EXECUTIVE SUMMARY

Introduction

Frontier Economics was commissioned by the National Infrastructure Commission ("NIC") to consider the *differences* in gross economic benefits in the period to 2050 that could be enabled by investments in different forms of broadband infrastructure that could be rolled out in the coming decade. Specifically the NIC required an analysis which compared the *relative* benefits of roll out to residential premises of the following scenarios of advanced Ultra-Fast Broadband Access (UFBA) technology.

- 1. Fibre to the home/premise (FTTH/P – so called 'full fibre') with new infrastructure to 100% of households;
- 2. Fibre to the home/premise (FTTH/P) with infrastructure re-use to 100% of households (which rolls out faster than scenario 1);
- 3. Mixed Fibre to 5G and FTTP (5G to 63% of more urban premises and FTTP to the remaining 37% of more rural premises);
- 4. Mixed FTTP with Fixed to the Locale Wireless (FWA) / Long Range VDSL (LRVDSL) (FTTP in 95% of premises with FWA / LRVDSL in the 5% most rural areas); and,
- 5. G.Fast/DOCSIS 3.1 to 94% of premises with FWA/LRVDSL in the 6% of the most rural areas.

The benefits of improved broadband can include direct benefits to consumers of being able to access new innovative services or cost savings in the delivery of public services. There are also a range of indirect impacts such as economy wide productivity improvements, greater scope for innovation, enhanced labour force participation, or "externality" impacts related to improved health, wellbeing, inclusion or environmental benefits.

In order to understand the benefits that may be brought by the roll out of different technologies we need to understand the uses of broadband, over and above the existing uses supported by current networks. Making forecasts of the usage of broadband over a thirty year period is difficult for a number of reasons. Over such a long period, the recent past may not prove an accurate guide to the future development of broadband. Large increases in available bandwidth could lead to step changes in consumption rather than incremental growth in existing demand. For example, the benefits brought by the transition from dial up internet to broadband were different in nature to those brought by moving from slower broadband to faster broadband (in that each improvement enabled access to different new applications). If new innovative high bandwidth applications become commonplace, such as widespread 3D or holographic displays, this will require significantly more broadband capacity than is currently available to the majority of households. Conversely, new applications which bring significant benefits may not depend on high speeds. For example if new uses of fixed broadband are primarily to support an explosion of Internet of Things ("IoT") devices then these applications may be able to be supported on existing broadband networks.

A historical perspective informs our forecasts

In order to understand the risks associated with making long term forecasts in technology sectors we have drawn lessons from past forecasts and the Historical development of fixed and mobile broadband network markets, as well as the related PC market. These sectors illustrate that there can be a tendency to underestimate the rate at which successful new technologies are taken up initially. For example, early forecasts of mobile telephony usage consistently underestimated take up. Similarly forecasts of fixed broadband or mobile services have underestimated demand.

Given the UK's strong digital economy, its legacy network infrastructure could have supported its comparative advantage in this sector. However, we note that given the multitude of factors that can affect a country's digital economy it is difficult to isolate the impact of an existing endowment of specific digital infrastructures. Clearly some successful digital countries have very high levels of network investment (such as Korea and Japan both with near ubiquitous coverage of UFBA networks). However, other countries have very successful digital economies with lower levels of network infrastructure (such as the USA).

There were a number of factors which tended to drive demand for network capacity, which were not fully forecast and were potentially "endogenous" (in that the development of networks with advanced capabilities enabled new innovative services). There are many potential examples of innovations which were enabled as a result of developments within the wider ecosystem of related markets.

- The adoption of peer-to-peer software early in the development of broadband networks allowed users to share content. Subsequently this led to the development of new legal streaming services to satisfy demand for legal access to audio-visual content;
- The social networking applications were initially designed as a tool to communicate with peers but became a key video sharing platform;
- The rapid adoption of the internet was enabled by the existing installed base of PCs.
- The sharing of user generated content as a result of the simultaneous development of video sharing platforms, device innovations (high resolution cameras and high resolution screens on mobile handsets) and increasing capabilities of fixed and mobile networks.

The complex relationships between device, network and application markets means there can be a lag between rolling out new networks and demand developing. For example the take up and usage of third generation mobile networks was slower than predicted initially until the wider ecosystem had developed. Furthermore, the variance in take up of UFBA by country illustrates that demand is not necessarily endogenously created. For example Japan has had very high coverage of UFBA since the mid-2000s yet only has average penetration of broadband compared to peers.

Nonetheless, clearly, a lack of digital infrastructure can lead to forgone demand. In the case of demand for mobile data unmet demand can be satisfied relatively quickly after rolling out new generation mobile networks (as illustrated in the case of 4G networks where coverage increases quickly following roll out). Whereas there is a much greater risk of welfare loss in relation to unmet demand for fixed networks given the much longer roll out time scales.

A use case approach to forecast economic impacts

In making long term forecasts we have adopted a "use case" approach to assess the differences in economic output which could be enabled by different broadband infrastructures. In doing so, we attempt to understand the uses which could drive demand for increased network capabilities. Our approach considers how availability of different broadband networks directly affects economic output (or in some cases costs of delivering services), in particular by assuming that forecast demand for the use case is restricted if the broadband connection is not adequate. We have not quantified the scope for different broadband technologies to affect wider economic benefits (via productivity improvements or positive externalities). However, we assume that variation in direct economic outputs enabled by different broadband networks will correlate to variation in wider economic benefits (such as productivity improvements or the presence of positive externalities).

In conjunction with the NIC we have selected the use cases in Figure 1 as the basis for our analysis. These are all use cases which could be used in homes (and hence rely on fixed residential broadband) as residential users are likely to see the largest change in broadband quality from roll out of new mass market infrastructure[1]. The use cases studied are *not* intended to be exhaustive, but representative of the types of applications which could drive increased broadband usage. We have selected a mix of mass market applications and more niche applications.

[1] While broadband network providers serving the mass market will roll out networks to serve all premises, including business and public sector customers, larger business and public sector customers already have access to full fibre networks.

Figure 1 Use cases considered

Sector	Use case	Key technology feature
Audio visual entertainment goods and services	"Premium" audio visual display (high resolution or 3D)	Higher definition streamed video services
Computing goods and services	Virtual Reality (VR) and Augmented Reality (AR)	Higher definition streamed VR and AR video services
Economy wide	Small Office Home Office (SOHO)	Upload of large documents
Computing goods and services	Smart home applications, user generated content and next gen video communications	Upload of surveillance video, and two-way video communication
Healthcare	Teleheath and telecare	Video based remote healthcare consultation
Education	Online classrooms / MOOCs	Video based VR and AR video services
Communications	5G (support for 5G infrastructure)	Economies of scope in network roll out

Source: Frontier

As a baseline we assume that all UK customers will have access to 10 Mbps broadband connections as part of the Universal Service Obligations and the majority of homes (90%) have at least 70 Mbps connections during the period studied.

For each use case we adopt the following approach to estimate differences in benefits between technologies.

- We forecast the penetration of the use case in the period to 2050 and the resulting direct benefits in the case that there are no constraints on uptake and usage due to the network technology (i.e. an unconstrained forecast of benefits).
- For each of the use cases we have forecast the network requirements (whether bandwidth, latency, or reliability) to fully deliver the use case. We then compare the requirements of each use case (which may evolve over time) with the technical capabilities of each UFBA technology studied (and current broadband networks) to determine whether technical restrictions could constrain a household's demand for the use case.
- We then compare the forecast economic output, which may be reduced in some scenarios due to network constraints in the different rollout scenarios. For example, if the use case could not be delivered using current technology but could be fully delivered by a full fibre network, then the incremental direct benefit of a full fibre network equates to the full economic output due to the use case. Conversely, if the use case can be fully delivered using existing technology, there is no incremental benefit from investing in UFBA technologies.

Given that we deliberately do not attempt to exhaustively forecast all economy-wide economic activity in which broadband is used as an input, the output is not the absolute level of benefits generated by different technology choices. For this reason the "benefits" quoted in the report cannot be compared with costs of rolling out network infrastructure. Rather the results illustrate the relative benefits of different technologies and how these relative benefits could change depending on the assumptions on the demand for use cases that require high quality networks.

Two scenarios in evolution of use fixed broadband networks

Predicting how demand for applications that use broadband will evolve is necessarily difficult. It is uncontroversial to note that demand for fixed broadband networks has changed in ways that could barely have been predicted thirty years ago. We have therefore forecast two scenarios of how demand could develop.

- In the **moderate evolution** scenario we forecast likely changes in demand based on evolutions of existing uses and applications of broadband. This approach bases forecasts on existing usage, by application, device, or user. It makes assumptions on how existing uses will evolve over time. Such an approach is necessarily limited, as it does not attempt to forecast completely new use cases. The Historical analysis in our report illustrates the limitations of this approach. For example previous forecasts of demand for mobile networks have tended to under predict the popularity of social networks, and the consequent impact they would have on demand for data traffic (for example the sharing of videos). Similarly this approach may erroneously extrapolate recent trends. For example early forecasts of mobile broadband tended to emphasise the importance of laptops in driving demand for mobile data and did not foresee the demand that would be derived from smartphones.
- In the **ambitious innovation** scenario we attempt to account for the inherent uncertainty in forecasting future technology related use cases over a thirty year period. This uncertainty, which is explored in more detail in the Historical analysis, reflects the fact that forecasts are inevitably based on previous (recent) trends. Furthermore, forecasts often fail to predict how consumer demand grows following innovation in a number of inter-related markets. Therefore the ambitious innovation scenario deliberately posits use cases which continue the Historical trends in innovation observed in fixed and mobile markets which have, to date, driven growth in demand for higher capacity networks.

Video transmission is ultimately the key driver of network bandwidth across the use cases in both scenarios. Video is central to the use of very high resolution displays; VR and AR technologies; some smart home applications (such as uploading surveillance video); teleheath and telecare (remote healthcare consultation); and remote education. Given that existing broadband networks support video (current networks allow the majority of homes to receive HD and even UHD videostreams) then the incremental demand enabled by network investment depends to a large extent on how demand for video will evolve.

The scenarios are not intended to be an upper and lower bound. The assumptions used in both the scenarios can of course be challenged in either direction (as being too optimistic or too conservative). Some consider that demand for residential broadband may not significantly develop from current uses as demand for higher resolution video, or AR/ VR will not materially develop or advances in compression technology will offset increasing demand for higher display resolution. If this is the case then our moderate evolution scenario could overstate demand. Similarly, others would argue that change in use of broadband networks observed over the last twenty years understates the innovation that we can expect in coming years and that very high bandwidth applications, which we cannot currently foresee, will gain mass adoption. In this case even our ambitious innovation scenario may understate demand.

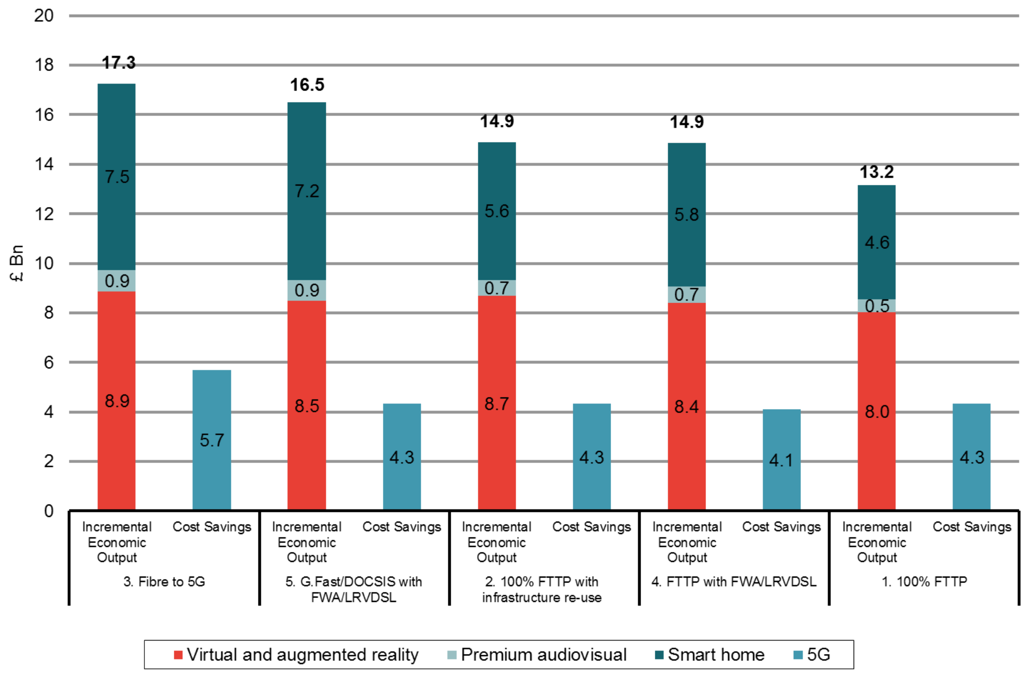
Results

The analysis considers the incremental economic output or costs saved that could be enabled in a number of vertical sectors as a result of incremental investment in broadband infrastructure (with the caveats noted above).

In the **moderate innovation scenario**, i.e. assuming demand for broadband derived from existing uses will continue to increase, investment in broadband will enable incremental economic output reflecting a number of use cases (AR/VR, smart home and “premium display”). However, the existing baseline technology could largely deliver the use case for online education or telehealth and so investments in new network technologies would be unlikely to unlock additional benefits in these sectors. Similarly incremental broadband investments could facilitate greater teleworking for those workers that are required to work with large datasets for those households that will only have a minimum 10 Mbps service in the base case but there would be little benefit to the majority of the country that has access to up to 70 Mbps. In addition roll out of new fibre networks could lead to synergies and hence cost savings in the roll out of 5G networks.

In this moderate evolution demand scenario the benefits that are enabled by UFBA investments are similar across all the technology scenarios. To the extent that there are small differences across different technology scenarios, these largely relate to the assumptions on the time taken to roll out networks. For example Fibre to 5G and G.Fast (a technology upgrade of existing infrastructure), is assumed to roll out more quickly than FTTH, and therefore benefits of G.Fast are felt sooner (and the present value of near term benefits is therefore higher).

Figure 2 Present value of direct economic output and cost savings across use sectors in the moderate evolution scenario to 2050 (£bn)



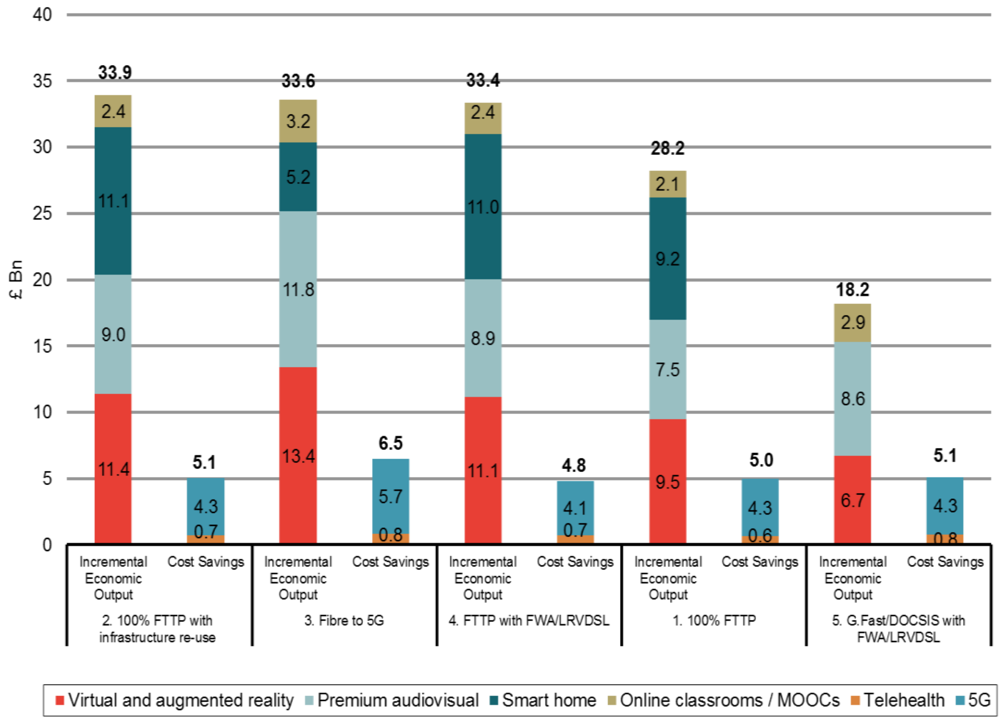
Source: Frontier

In the **ambitious innovation** scenario, as well as greater overall economic impacts from future upgrades there is a more significant differential between the different UFBA technology scenarios. This reflects that in the ambitious innovation scenario we assume use cases that require higher bandwidth than can be delivered using incremental technology upgrades of the existing copper infrastructure (G.Fast).

In this scenario the economic impacts for the scenario with highest benefit (FTTP with infrastructure re-use) are almost double those for the G.Fast scenario, based on a technology upgrade of the existing infrastructure. The use cases driving these differentials are premium displays, VR AR services, and Smarthome devices (such as video monitoring). In addition in the ambitious innovation we assume that demand for healthcare (remote diagnosis with very high resolution 3D images) or teleworking that require high bandwidth could be developed. In this case investments in UFBA networks would deliver cost savings and support a greater degree of home working.

However, the absolute benefits a dependent on complex relationship between assumptions on technical requirements of the use cases, the UFBA roll out assumptions, and the technical capabilities of different networks. For example the Fibre to 5G scenario enables larger benefits for Premium display than FTTP since 5G rolls out faster than FTTH (and therefore benefits are felt sooner). However, the Fibre to 5G scenario realises lower benefits of smart home use cases since these are not supported by 5G networks in our analysis.

Figure 3 Present value of direct economic output and cost savings across use sectors in the ambitious innovation scenario to 2050 (£bn)



Source: Frontier

Across both scenarios the results are sensitive the assumptions used in the forecasts. There are a number of key uncertainties that affect the results which we explore in the sensitivity testing.

First, clearly an important assumption is the capabilities of networks and the technical requirements (principally bandwidth) of the use cases. If advances in technology mean that use cases can be delivered using lower bandwidth, then UFBA technologies with lower capabilities (such as G.Fast) might realise greater benefits than we forecast. Though if advances in technology mean that use cases can be delivered using existing networks then ultimately the value of further investment in all the UFBA network scenarios will be diminished.

Second, the time to roll out new UFBA networks has a significant impact on the results. Networks that roll out faster (such as G.Fast and the 5G network[2]) realise benefits sooner than FTTP networks, which we assume roll out over a longer time period.

Third, the evolution of demand obviously affects the benefits. We assume that for all use cases demand evolves gradually reaching market maturity after 15 years. However, faster increases in demand will obviously increase the economic impact of broadband investments and slower increases in demand will reduce the economic impact of broadband.

2 In scenario 3 5G is rolled out to 63% of premises.

Fourth assessing how network bandwidth constraints affect demand for the use cases is important. We assume that if a network is unable to support a use case, an alternative “lower quality” service can be provided. Hence, in the presence of bandwidth constraints, demand for a use case is *reduced* but not eliminated. However, it is not possible to predict whether a significant degree of differentiation will emerge between high bandwidth use cases and low bandwidth use cases. If so, the impact of network bandwidth constraints will be greater than we assume in our base case.

Finally we note that fibre based broadband access technologies may be marginally more reliable than copper based broadband access technologies. However, in practice, a household’s experience of reliability depends on more factors than the access technology (for example it also depends on the household’s equipment, Wi-Fi interference etc.). Therefore we assume that network reliability does not have a significant impact on difference in economic impact of different UFBA networks. However, we recognise that reliability of the access network might become more important if users rely on it to a greater degree (for example in rural areas where it enables access to services).

Commentary on results

Based on the use cases in the *moderate evolution* scenario, there does not appear to be a strong demand side case to invest widely in FTTP infrastructure. Indeed, assuming a moderate evolution of broadband applications and services it is conceivable that existing networks could support most (but not all) of the use cases described in this report. For use cases which are not supported on current networks the magnitude of benefits are related to the speed of UFBA roll out rather than the quality of the specific UFBA network. Therefore G.Fast applications (if widely available) would generate larger benefits than FTTH networks with longer rollout profiles.

However, demand forecasting is intrinsically uncertain over this timescale. The Historical use case analysis reveals how demand for technology can evolve in unexpected ways in much shorter time scales than we consider here. Reflecting this uncertainty, the assumptions in the ambitious innovation scenario deliberately consider how services and applications that use broadband might develop with currently unused or unknown use cases. These necessarily rely on more innovative technological and application developments. In this scenario, widespread investments in UFBA would lead to large benefits and the quality of the network would become critical, with FTTP infrastructure leading to significant incremental direct benefits (which may lead to indirect impacts elsewhere in the economy and welfare impacts for consumers).

The inherent uncertainty in how demand could evolve leads to significant risks related to either over-investment or under-investment. The risks of over- and under-investing are accentuated by high level of sunk costs (which increase the cost associated with making investment which lie underutilised) and the time required to roll out (which increases the costs of a wait and see approach).

However, these risks are not necessarily symmetric in nature or magnitude. Depending on the costs of infrastructure roll out, the deadweight loss due to inefficient investment may be smaller than the risk of foregone welfare if users cannot access applications that they value highly. Furthermore, given the broadband is part of a wider ecosystem of related network, device and application markets there could be wider impacts in related markets if there is under investment in networks.

With significant demand uncertainty a “real options” view would indicate there could be value in waiting for more information, even if the central case suggested there were benefits in investing now. Similarly an iterative approach, investing first in geographic areas of lower cost (e.g. dense urban areas), or in areas where the wider benefits of better broadband are likely to be greater (e.g. rural areas) could be optimal. This is because a decision to invest ‘now’ foregoes the real option value of ‘wait and see’ or maintaining flexibility (i.e. not committing to a single project covering the whole of the UK).

1 INTRODUCTION

This report, commissioned by the National Infrastructure Commission (NIC), considers the economic benefits that could be enabled by investments in different fixed broadband infrastructures.

We set out below:

- the terms of reference for the study;
- the context of the NIC report; and,
- the structure of the rest of the report.

1.1 Terms of reference

Frontier Economics was commissioned by the NIC to consider the differences in demand side economic benefits that could be enabled by investments in different fixed broadband infrastructures in the period to 2050. Specifically the NIC required an analysis which compared the relative benefits of rolling out to residential premises the following forms of Ultra-Fast Broadband Access (UFBA) technology:

- Fibre to the home/premise (FTTH/P);
- G.Fast (and subsequent copper based technological advancements);
- DOCSIS 3.1 (and subsequent cable based technological advancements); and,
- Fixed Wireless Access to the local area (FWA).

The project had three strands of work.

First, in order to provide a context to the forecasts of potential benefits of broadband infrastructures the project included a historical assessment of how previous demand forecasts for analogous technologies (PC, mobile and broadband) were made and how these forecasts compared with the market outturn.

Second, we estimated the likely *relative* economic impacts that could be realised by different broadband technologies. In estimating the relative benefits of different technologies we considered the assumptions on network coverage (by geotype), and technology roll out (time) profiles for different technology rollout scenarios, and the potential take-up assumptions of new uses for broadband technologies. In making this assessment we consider those future uses which might be considered innovative.

Third, the NIC requires the analysis to consider those uses which are currently unknown, yet reasonably foreseeable. These relate to potential uses of broadband which may not relate to existing uses (or wider roll out of existing usage), but instead relate to technologies or services which are not as yet developed or adopted.

1.2 Context of this report

The NIC is required to provide impartial, expert advice on major long-term infrastructure challenges to the parliament. This includes the NIC having to consider the UK's infrastructure requirements to support digital communications.

Therefore the NIC wishes to assess the potential benefits that could be enabled by investments in different fixed broadband infrastructures.

The infrastructure assets required to deliver fixed broadband services are costly, have a long lifespan and are sunk. This means decisions on whether to invest in new or enhanced technologies or to continue developing existing assets need to take account of future demand for services. There are significant risks associated with both investing in new assets where development of existing assets could meet demand at lower costs at a later date or conversely being unable to meet future demands in a timely or efficient fashion because the available infrastructure is not fit for purpose.

Fixed broadband services have already evolved significantly over time with the standard broadband services (SBB) delivered over ADSL and CATV networks. These have been complemented by superfast broadband services (SFBB), which are based on either fibre to the cabinet (FTTC) VDSL technology over BT Openreach network or DOCSIS 3.0 offered over Virgin Media's network. Currently coverage of superfast broadband (with a bandwidth speed greater than 24 Mbps) covers the large majority of households. These lines can offer on average 74 Mbps based primarily on a mix of FTTC and DOCSIS3.0.[3]

Figure 4 SFBB and UFBA Broadband Technology Options

	Current Coverage
FTTC/VDSL	Over 90%
DOCSIS3.0	45%
G.Fast	Negligible
5G	None
FWA/LRVDSL	Negligible
FTTP	2%

Source: Ofcom Connected Nations 2016, Frontier assumptions

Note: many FTTC lines do not receive 70 Mbps as they are located a long distance from a cabinet

Operators currently indicate that they have plans to increase investment in broadband infrastructures in coming years. These include operators such as Cityfibre, Gigaclear, as well as Virgin Media and BT. Therefore it is likely some of such investments will increase the coverage of UFBA networks in the coming years. However, this analysis assesses the economic impacts of further investments over current level of coverage. The NIC has commissioned a separate study on the costs of roll out of different UFBA technologies, therefore the UFBA technologies assessed in this report are consistent with the with those in the complementary report on costs.

[3] Ofcom (2016) Connected Nations; https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2016

In order to understand whether what might be the potential benefits of broadband infrastructure it is necessary to understand how these networks will be used over their lifetime of the assets. Therefore the assessment considers how improvements in the capabilities of networks could enable incremental economic activity, and alternatively, how network constraints imposed by certain UFBA networks could limit the potential economic activity.

1.3 Structure of this report

The structure of the remainder of the report is as follows.

- Section 2 sets out a historical analysis of the patterns of usage of key technologies (broadband, mobile services and PCs);
- Section 3 describes the approach for assessing relative benefits of from investing in different broadband future digital infrastructures options;
- Section 4 sets out the assessment of future demand for broadband in the studied use cases;
- Section 5 sets out the results of our combinatorial usage analysis where households use several services that rest on the availability of broadband technology ; and,
- Section 6 presents out our conclusions.

The report contains a number of supporting annexes.

- Annex A contains a historical analysis of the developments of the mobile communications market.
- Annex B contains a historical analysis of the developments of the broadband market.
- Annex C contains a historical analysis of the developments of the personal computer (PC) market.
- Annex D contains the results of a sensitivity analysis of our economic benefits forecast.
- D.1 contains the assumptions common to all use cases.
- Annex F contains the assumptions specific to the use cases.
- Annex G contains assumptions on household segmentation.
- Annex H contains a review of recent literature which examines future demand for residential broadband data.

2 HISTORICAL ANALYSIS OF THE PATTERNS OF USAGE OF KEY TECHNOLOGIES (BROADBAND, MOBILE SERVICES AND PCS)

This section summarises the evidence gathered in the historical reviews of development of the mobile, broadband and PC markets (set out in full in the Annex)[4].

Projecting future consumer demand for the applications and services that will use broadband is necessarily uncertain. The forecasts are made over long time periods and in rapidly evolving technology markets. Recognising this uncertainty, this section considers the lessons that can be learnt from similar exercises carried in the past and when considering the future demand for broadband over a 30 year time horizon.

Forecasts often extrapolate from existing uses since these are the “known unknowns”. While such forecasts may be reasonably accurate in the short term, over a longer time period they can suffer from two errors related to life cycle effects. First forecasts can miss innovative uses which are non-existent or immaterial at present but which could create new material demand in the longer term if they become mass market. Second extrapolating current trends in usage, assuming demand will continue growing exponentially not taking account of life-cycle effects for mature uses which may enter periods of lower growth and potentially decline due to substitution by innovative uses.

The annexes containing the full analysis consider a number of aspects in relation to the development of the markets.

- Whether forecasts in terms of penetration, usage and applications were accurate.
- Whether quantitative forecasts of demand were made prior to investment decisions.
- The extent to which forecast errors impacted on the development of markets, for example in leading to over-investment or under-investment, which in turn led to poor customer outcomes.

These historical analyses can therefore provide insights which can provide useful context when making forecasts of benefits for UFBA. This section considers how the inter-related eco-system of markets affect demand forecasts; and illustrates the difficulties in making demand forecasts.

[4] See Annex A, Annex B and Annex C.

2.1 Inter-linked ICT sectors and convergence

The demand for UFBA is a function of the supply of (and demand for) other complementary services, applications and devices that use the network.

Lags between developments in different markets

The complex linkages between device, network and application markets mean that forecasts of the adoption of new technologies or applications is uncertain. The wide adoption of new services requires developments to be made across an eco-system of inter-related markets. For example in the 1990s it became clear that there would be widespread demand for mobile data services in the long term given the successes of both mobile voice services and fixed Internet services. However, the industry underestimated the barriers to adoption in terms of usable devices, deployment of network technology and infrastructure. As a result networks were rolled out from 2003 well in advance of significant user adoption and hence were underutilised for a period.

Device technology and network capacity was able to support smartphones in the early 2000s to meet demand for mobile data services. [5] However, this was not sufficient to promote take-up. This is because there were a number of limiting factors to the devices: memory, screen size and battery life.

In fact smartphones did not gain significant traction with consumers until the iPhone and later Android handsets were introduced after 2008. The form factors of these new devices (larger screens and user interfaces built around touch screen controls) differed significantly from earlier iterations. They were designed specifically as devices to consume audio-visual content (on large screens) and browse the internet. These devices led to the development of a wider ecosystem of devices, applications and services which stimulated demand for data networks.

From 2007, demand on 3G mobile networks exceeded supply in urban areas for long periods of the day, with supply effectively being rationed between users by the network. The balance between supply and demand was better achieved as more capacity was added as 4G network were rolled out, although data usage is still capped for most subscribers to prevent excessive demand. This implies that a constraint on one market (for example constraining the capacity on fixed or mobile networks) could limit potential developments in other markets.

Forecasting demand depends on innovations in a wide range of related markets

Forecasting demand is difficult as users combine products and services from a range of distinct but linked markets (categorised as networks, devices, or applications and services). Therefore, developments in one market depend on changes in technology and consumer demand in related markets. Technological change in device markets occurs gradually and depends on innovations made in many separate input markets.

[5] Early smart phones included Sony Ericsson P900 (2004), or, Nokia 3650 (2003). Nokia Communicator (2004).

Identifying the “killer app” is not easy as demand for new features evolves in unpredictable ways and depends on the (equally unpredictable) evolution of device technology. For example push notifications, have changed how we use devices, and arguably have supported the rise of social networks, which were initially only available on business focused devices (such as Blackberry handsets) as a business specific tool. However, the popularity of such features quickly spread such that other providers of devices and operating systems adopted these same features. As manufactures try to incorporate new features into handsets, demand only takes hold once apps and services which use the features are created. For example, inbuilt front and rear cameras or GPS sensors are now integral to all mobile handsets and apps. In contrast other features which were tried in some smartphone devices have not proved as enduring, for example in built projector function[6], 3D screens[7], and gaming console interfaces[8] were tried, but ultimately did not gain traction.

While the nature of innovation is difficult to predict competition between providers incentivises and advances innovation. In fixed networks markets competition between providers is difficult to achieve, absent government intervention. For example the 2000s broadband markets were characterised by high levels of service based competition. This benefited consumers as prices fell and services improved, and led to the high rates of adoption of fixed broadband in the UK. In device markets, consumers have benefited from strong competition between device, and application manufacturers and suppliers.

The inter-related nature of network, device and service markets can affect the consumer take-up cycle for new technologies. Demand for new services can quickly grow where there is an existing stock of compatible devices. For example consumer take up of the internet grew relatively quickly since there was a stock of devices (home PCs) that could be used to access the internet. Therefore potentially the demand for UFBA access can similarly be expected to grow in unexpected ways given that there is currently a stock of a wide range of devices that would use the UFBA (TVs, gaming consoles, mobile phones, wearable devices etc.).

Consumer demand evolves in unpredictable ways

Changes in consumer demand can be more difficult to predict. For example in mobile markets the “smartphone” had existed long before Apple’s iPhone launched. However, feature phones (with limited functionality) were sufficient to meet consumer demand given the limited apps and services that were available at the time, and the existing 2G networks were not capable of carrying significant quantities of data. Similarly there are examples of technological advances (such as 3D TV or wearable AR displays such as Google Glass) which have not led to wide consumer take up, despite significant investments by suppliers.

There are a number of barriers which can restrict consumer demand for new services in unpredictable ways. The most obvious might be consumers’ reticence

[6] Featured on the Samsung Galaxy Beam.

[7] Featured on the LG OPTIMUS 3D VR

[8] For example the Sony Xperia Play.

to try new services. For example the “internet” (and to a degree faster broadband speed) are potentially “experience goods”: their value can only be truly determined by consuming or experiencing them, as a result it took time for consumers to access these new services.

Similarly there can be cultural or regulatory barriers to which can constrain demand. Many forecasts have considered health and education to be key drivers of demand for data, however, in practice these use cases have not developed in the way that was foreseen. In many early forecasts health and education were considered key uses of fixed and mobile broadband networks. While communications networks play a role in new health and education services (such as wearable devices in the case of health, or provision of education materials and applications in the case of education), investments in communications networks have not led to a structural change in how these services are delivered. In practice both sectors make relatively little contribution to user demand for broadband.

2.2 Accuracy of forecasting

Commentators, industry and government stakeholders all have an interest in understanding future demand for data networks. The historical analysis examined forecasts made of fixed and mobile demand. These revealed some common themes which are relevant to the assessment of benefits of UFBA networks.

In the forecasts of household demand for broadband services, there is evidence of a bias to under-forecasting the level of demand. Early forecasts of mobile demand under-forecasted the *take up* of mobile services[9]. Similarly ITU compared a range of forecasts made in the 2005 on mobile data growth. All these forecasts have turned out to under-forecast demand for data[10]. Analysis of Cisco five-year forecasts of fixed services showed a bias to under-forecast in some years for the period 2006 to 2010 (though less so in more recent forecasts)[11].

Forecasts tend to project forward existing uses of technology. This implies that it is difficult to fully anticipate all uses of the technology. For example recent studies recognise the contribution that social network applications has had on demand for data, as they have been a tool to share video and pictures, including large volumes of user generated content. While early forecasts recognised that sharing photos and one-to-many communications were likely to be drivers of mobile demand even before “social networks” were popular tools, they could not predict the volume of data that these applications would generate.

Equally, basing forecasts on recent trends can lead to overestimates of demand for some applications. For example mobile forecasts made around 2010 highlighted the importance of “dongles” as an important driver of mobile data demand. These forecasts reflected the previous growth of use of these services. However, in practice the wide spread adoption of smartphone handsets and

9 See A.2.1.

10 See A.4.3.

11 See B.7.

growing availability of WiFi limited the contribution of dongles and connected devices to data demand. Similarly before 2010, IPTV (i.e. managed TV services transmitted over broadband networks) were considered to be an important driver of fixed demand for broadband. In fact the growth of unmanaged video services (including paid subscription services such as Netflix and Amazon, as well as other free services such as YouTube) were far more important drivers of demand, and managed IPTV services had largely disappeared by the early 2010s.

Video is a key driver of demand for data networks. All forecasts for broadband and mobile data demand have acknowledged that video entertainment would be a key driver of demand. Indeed as far back as the 1980s when considering on the potential of fixed fibre broadband, a US study noted that the *only* identified use case was audio-visual entertainment. Later forecasts all noted that audio visual entertainment was a key driver of demand for increasing speed of connection. However, the volume of video data was generally under-forecast.

Looking forward, it remains to be seen whether video will continue to be a significant driver of bandwidth, which in turn will depend on whether consumers are interested in higher resolution displays.

Unsurprisingly there is greater uncertainty as for the penetration of new applications when compared to usage of mature applications. Forecasts of mobile demand made in the early 1990s, (which were based on existing usage) underestimated future demand for mobiles because there was an assumption that mobile phones would remain a premium service. In fact technological developments, competition and economies of scale resulted in device and network costs falling more rapidly than foreseen and as a result a quicker widespread adoption of mobile than predicted. In contrast medium term forecasts of usage in mature markets, have been more accurate in predicting demand growth over time.

Finally we note that making forecasts of use of technology is uncertain as the use of technology changes in unexpected ways. For example home PCs had been bought in the 1980s, and 1990s primarily as gaming devices, and devices to support home administration applications (principally word processing but also spreadsheet based tools). This installed base of devices (PCs) supported the adoption of internet by households. As demand for internet grew so demand for PCs used to access the internet grew. But the fortunes of PC changed. As new devices such as smartphones and tablet computers were adopted as the key technologies to access the internet, demand for PCs fell.

2.3 The role of digital infrastructure in the digital economy

There is no doubt that suitable network infrastructure is a necessary input for modern economies. Broadband technology has become an essential part of modern life for both residential and business users. It has transformed how we communicate, shop, or consume audio-visual content. It has had an equally dramatic effect on businesses. Broadband and ICT in general have brought markets together via online platforms, reduced barriers to entry, lowered shopping costs, and increased the value that can be extracted from aggregated data collected.

The UK has a relative strong position in the share of its economy that is attributable to the digital economy relative to other comparator countries. Therefore, drawing on the evidence of the historical analysis, it is relevant to consider whether its strong position is as a result of a legacy endowment of digital infrastructure (for example wide penetration of PCs or early adoption of broadband or digital mobile infrastructure). Furthermore, investments in digital infrastructure could enable “first mover” economic advantages, i.e. advantages later adopters are unable to replicate.

We discuss below:

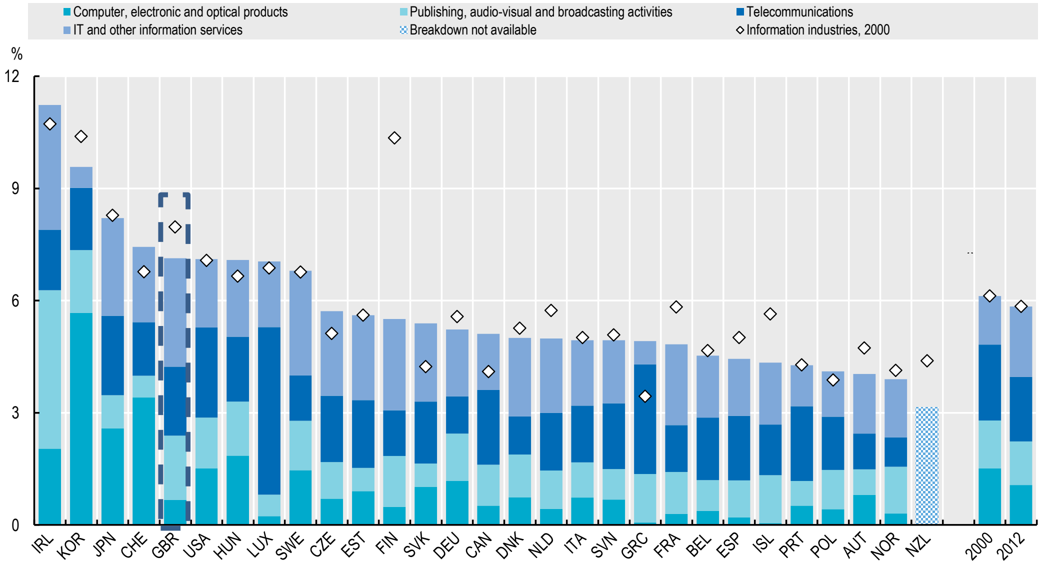
- the UK’s relatively advanced position in the digital economy;
- evidence from the historical analysis on the UK’s relative performance in the provision digital infrastructure (broadband, mobile and PCs) and the potential link to the UK’s digital economy;
- whether investments in UFBA are likely to lead to first mover advantages in the digital economy.

2.3.1 The UK’s relatively advanced digital economy

There are many potential indicators which illustrate the UK’s relatively strong position in the digital economy. It is beyond the scope of this report to exhaustively consider all potential measures of a “digital economy”. Rather we have illustrated the UK’s relatively strong performance using a number of indicators.

The proportion of value added that is allocated to information industries is a measure of the how each country’s economy is focused on the digital economy. The UK ranks 4th, behind Ireland, Korea and Japan.

Figure 5 Value added of information industries as a percentage of total value added at basic prices 2000 and 2012

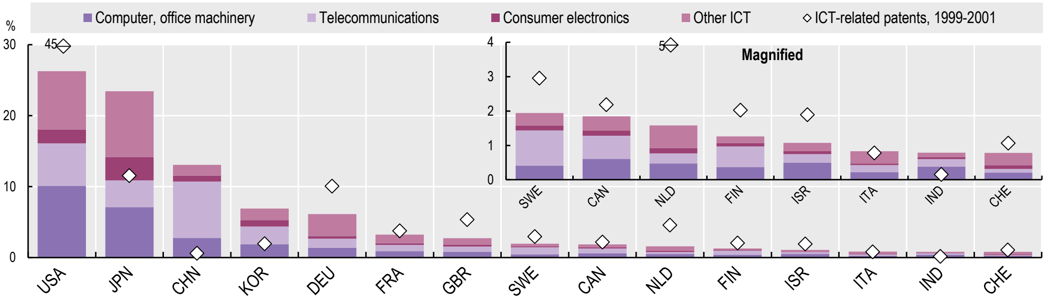


Source: OECD, ICT Database; Eurostat, Information Society Statistics and national sources, July 2014.

Note: See OECD (2014) Measuring the Digital Economy for full notes.

In relation to the share in ICT-related patent applications the UK is 7th position (close to the UK's rank in term of GDP (5th)) (Figure 6). Korea is a strong performer in terms of ICT patents (4th position compared with 11th ranked by GDP). Similarly Sweden is ranked 8th in terms of ICT patents (but 22nd by GDP).

Figure 6 Top 15 countries' share in ICT-related patent applications, 1999-01 and 2009-11

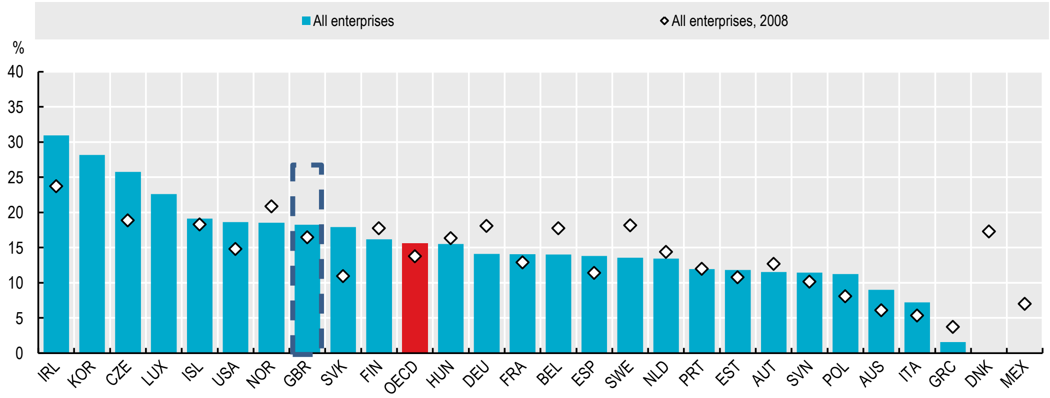


Source: OECD, Patent Database

Note: See OECD (2014) Measuring the Digital Economy for full notes.

While another measure indicating a country's relative propensity to for consumers adopt digital economy practices is the turnover from e-commerce where the UK ranks 7th (behind Ireland, Korea, and the USA).

Figure 7 Turnover from e-commerce, by size, 2008 and 2012



Source: OECD, ICT Database; Eurostat, Information Society Statistics and national sources, July 2014.

Note: See OECD (2014) Measuring the Digital Economy for full notes.

2.3.2 Assessment of whether the UK's legacy digital infrastructure enabled growth of the digital economy

In practice there are a wide number of factors that will influence an economy's ability to grow the digital sector of its economy. These will include many factors such as labour market indicators, education institutions and attainments, institutional framework, R&D investments digital infrastructure as well as availability, use and diffusion of ICT infrastructure.

Indeed there are a number of international indicators which measure the factors which go to explain a country's relative performance in the digital economy. For example the ICT Development Index[12], where the UK ranks 5th, monitors and compares developments in information and communication technology (ICT). The Network Readiness Index[13] where the UK is ranked 8th position, measures how economies use opportunities offered by information and communications technologies for increased competitiveness and well-being.

Furthermore measuring the relationships between an economy's strength in the digital economy and the contributory factors explaining this outcome is complex. This is not just due to the large number of variables involved but as there is a complex relationship between cause and effect between inputs and outputs. Put simply it is difficult to know the extent to which investment in digital infrastructure causes economic benefits which result in positive outcomes in the digital economy, or whether an economy which is relatively highly specialised towards the sector ICT *causes* investments digital infrastructure. In practice the causality between economic performance and investment in digital infrastructure is likely to go both ways.

Nonetheless it is helpful to consider the extent to which the UK's legacy infrastructure contributed to its current relatively strong performance as a digital economy.

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[12] Developed by the ITU. See: http://www.itu.int/en/ITU-D/Statistics/Pages/publications/mis2017/methodology.aspx

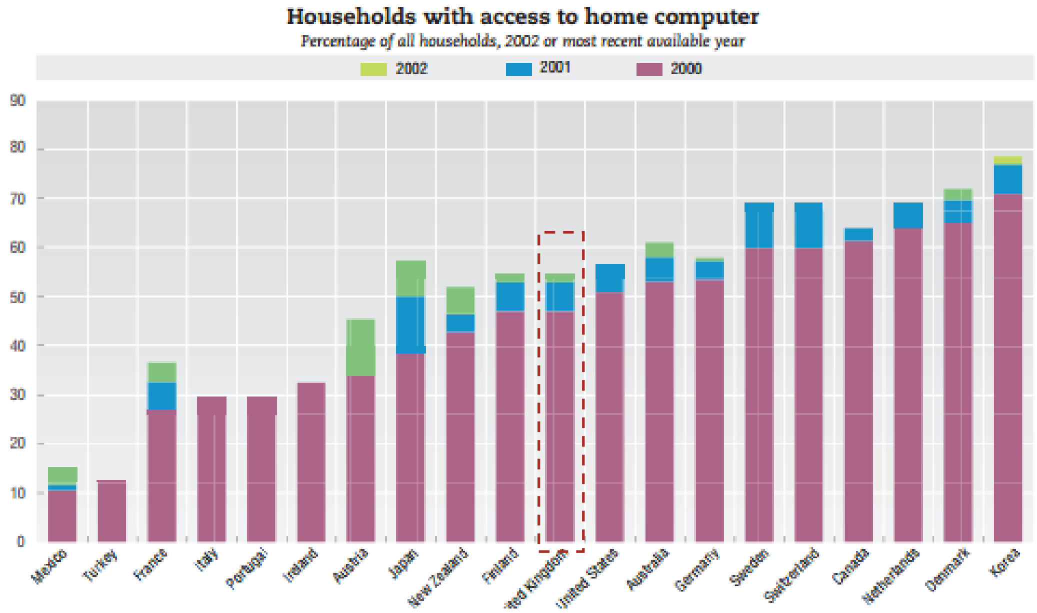
[13] Developed by the World Economic Forum. See: http://reports.weforum.org/global-information-technology-report-2016/

PC penetration

In relation to PC penetration, the historical analysis noted that at an early stage of development the UK was relatively advanced in the development of home computers. In the early stages of the sector's development, like the US, the UK had a number of small developers and manufacturers who were developing services for the home market as well as for exports. Ultimately the sector standards coalesced around the PC standard (developed by IBM in the US).

By 2002 the UK was approximately in the middle of comparator countries in the household penetration of PCs. In 2000 it was ahead of Japan, and on a par with the US. By 2002 Japan was slightly ahead of the UK. Other advanced digital economy countries, such as Ireland were lower.

Figure 8 PC penetration 2000 - 2002



Source: OECD

See: http://www.oecd.org/publications/factbook/34416149.pdf for notes

Broadband penetration

The annex noted that while initially (2002) the UK was a relative laggard in take up of broadband among OECD countries. However, it quickly became a relatively strong performer in terms of penetration of broadband services, ahead of many comparator OECD countries in the OECD (see: Figure 69).

Mobile data services

In relation to mobile data services the UK was one of the first to auction spectrum for 3G services and "Three" was one of the first mobile networks to launch 3G services. However as noted above, there was a lag between the availability of 3G services and their use in the UK. This resulted in excess capacity on UK networks in the initial period following launch until the wider ecosystem had developed (prompted by the launch of the iPhone and Android handsets).

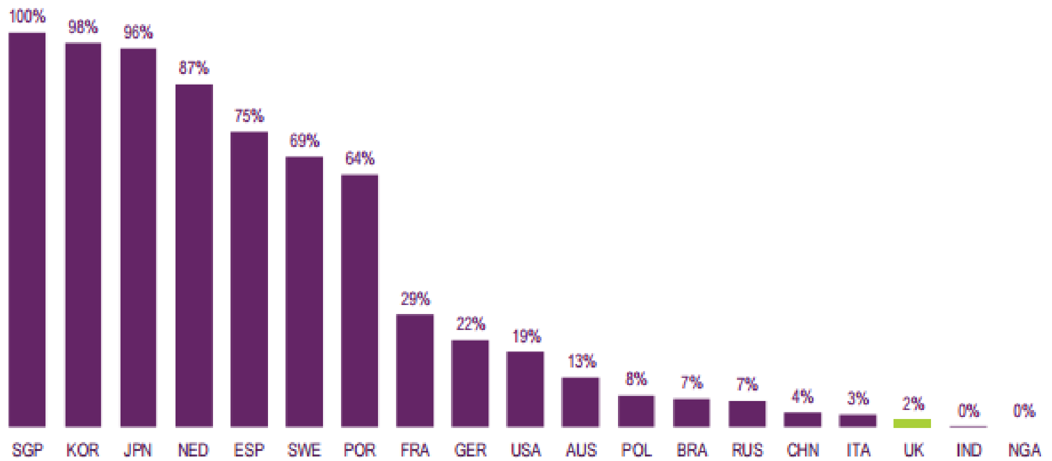
In relation to LTE, rollout began in 2010 in Japan and was later in the UK (partly as a result of the effect of legal action which delayed the auction of 4G spectrum[14]. While EE launched LTE services late in 2012, the 4G spectrum auction was ultimately delayed until February 2013 (four years later than planned). By that time, 4G networks were rolled out in most countries in Western Europe and 4G coverage in Germany reached 75%. By the time that 4G launched in the UK demand for data grew quickly.

2.3.3 Has investment in UFBA infrastructure enabled fist mover advantages?

Therefore the UK had some advantages in its digital infrastructure: an early leads in the development of home computers, relatively early launch of 3G mobile data services, though it was slower launch of 4G. There are no clear parallels which indicate these were strongly related to its high performance of the UK's digital economy.

A more recent indicator of country's digital infrastructure is the coverage of UFBA. However, as noted in [Annex B] the UK has one of the lowest levels of coverage of UFBA networks. Some countries with strong "digital economies" such as Singapore, Korea, and Japan have very high coverage of UFBA. While there are some countries who have strong digital economies which, in common with the UK, have much lower levels of UFBA (such as the USA).

Figure 9 Percentage of households in areas served by UFBA products (with advertised speeds of 300Mbit/s or more): September 2016



Source: *Ofcom iCMR 2016 Figure 3.34*

Note: *NGA is the country code for Nigeria, and does not refer to next generation access technologies. All figures have been rounded to the nearest whole number.*

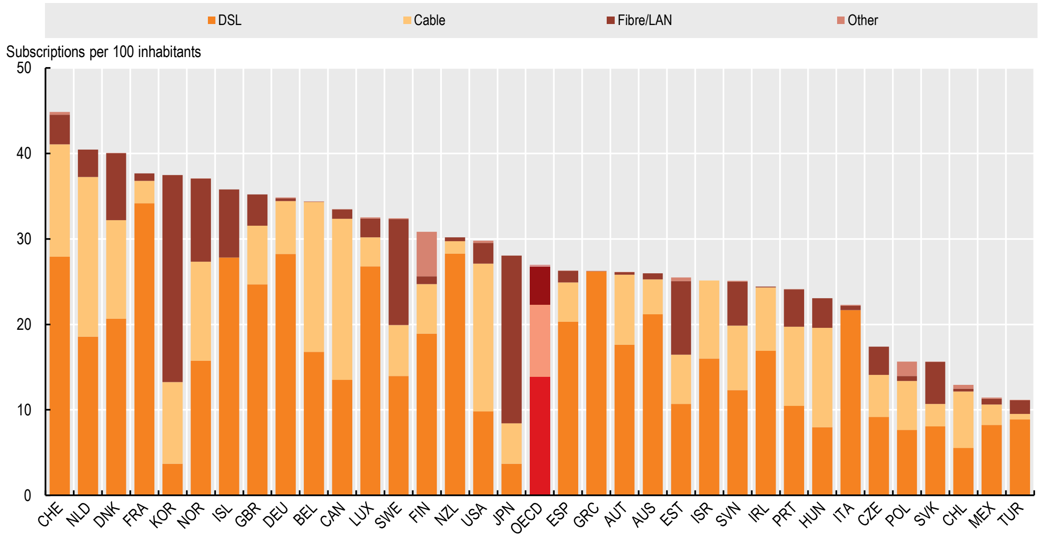
Furthermore we note the degree to which demand is "endogenous" is difficult to ascertain. For example as set out Figure 10 despite being an early leader in the roll out of fibre based broadband (Japan's UFBA coverage reaching 80% by 2008[15]), Japan only has penetration of broadband which is close to the OECD

[14] See section A.4.7.

[15] See: http://www.soumu.go.jp/main_sosiki/joho_tsusin/eng/presentation/pdf/091019_1.pdf

average (well below the UK). The high availability of high quality broadband has not obviously stimulated demand.

Figure 10 Fixed (wired) broadband penetration by technology, December 2013



Source: OECD, Broadband Portal, www.oecd.org/sti/broadband/oecdbroadbandportal.htm, July 2014. See: http://www.oecd.org/publications/factbook/34416149.pdf for notes

Therefore we note that given the multitude of factors that can affect a country's digital economy it is difficult to isolate the impact of an existing endowment of specific digital infrastructures. Clearly some successful digital countries have very high levels of digital infrastructure (such as Korea and Japan). However, other countries have very successful digital economies with lower levels of digital infrastructure (such as the USA). Finally, the variance in take up of UFBA illustrates that demand is not necessarily endogenously created. Nonetheless, clearly a lack of digital infrastructure can lead to forgone demand. In the case of unmet demand for mobile networks unmet demand can be satisfied relatively quickly after rolling out new generation mobile networks (as illustrated by the UK and Ireland who were relatively slow to roll out 4G but where increased coverage quickly met demand). Whereas there is a much greater risk of welfare loss in relation to unmet demand for fixed networks given the much longer roll out time scales.

2.4 Implications for forecasts of benefits of UFBA networks

The historical analysis revealed a number of factors which are relevant to the assessment of economic benefits that can be enabled by UFBA investments.

The complexity of the various inter-related markets made it difficult to reliably forecast demand. Consumer demand depends on technological developments across many markets. Furthermore, the factors that drive demand are difficult to predict.

Quantitative forecasts (made during an earlier phase of the development of network markets) appear to show a bias to "under-forecast" demand. While forecasts correctly identified the uses driving demand for networks, precisely predicting demand is more difficult. Video was a key "use case" for mobile and fixed networks, however, particularly in the context of mobile its use was under-forecast. Similarly, cultural or other barriers to adoption should not be underestimated. For example wide spread uptake of data application to support healthcare provision have been predicted for decades, yet are still to materialise to a significant degree.

However there are important differences in the markets studied as part of the historical analysis compared with UFBA markets which should be remembered. As noted above, investment in UFBA, such as fibre to the premises (FTTP) has a very long investment cycle with the majority of the assets that are installed to support the network (the physical ducts, and fibre optic cable) with a substantial long asset life of at least fifty years. In contrast the investment cycles for mobile, PC and previous iterations of broadband technologies are much shorter and typically between three to five years.

- Mobile investment cycles broadly reflect the iterative generations of mobile technology from analogue; 2G GSM; 2G GPRS and EDGE; 3G; 3G HSPA; and 4G LTE and LTE+. Typically mobile operators (as well as consumers and device manufactures) make upgrades to the new standard every five years or so.
- PC investment cycles reflect competition in the design and manufacturing market where providers compete to offer new more powerful devices. The investment cycle for such investments could be three years reflecting the growth in new chip processers.
- Previous iterations of broadband technologies (DSL, ADSL, ADSL2, VDSL and potential upcoming G.Fast technology) are on a five year investment cycle.

Therefore, the much longer time frame for the forecasts in this analysis compared to those in mobile, broadband and PC markets, reinforces the difficulties and limitations of the forecasts of UFBA markets.

Furthermore given the complex inter-linkages between different markets, as demonstrated by the development of PC, mobile and broadband markets, the results in this analysis should be interpreted with caution. An analysis which assesses individual use cases in isolation will fail to capture the value of "spill-over" impacts generated by adoption of technologies which are used in multiple markets.

3 APPROACH FOR ASSESSING RELATIVE BENEFITS OF FUTURE DIGITAL INFRASTRUCTURE OPTIONS

3.1 Introduction

In this section we set out our methodology for forecasting the incremental benefits that could be enabled by investments in different broadband technologies.

Forecasting demand over a long period for rapidly evolving technologies is necessarily uncertain. As noted in section 2 communications technologies develop in ways that cannot be accurately predicted over a ten year period and much less so over longer periods. Therefore in assessing the differences in the economic impacts enabled by different forms of investment this study has to overcome a number of methodological issues.

Making forecasts of the usage of broadband over a thirty year period is difficult for a number of reasons. Over such a long period, the recent past may not prove an accurate guide to the future development of broadband. Large increases in available bandwidth could lead to step changes in consumption rather than incremental growth in existing demand. For example, the benefits brought by the transition from dial up internet to broadband were different in nature to those brought by moving from slower broadband to faster broadband (in that each improvement enabled access to different new applications). If new innovative high bandwidth applications become commonplace, such as widespread 3D or holographic displays, this will require significantly more broadband capacity than is currently available to the majority of households. Conversely, new applications which bring significant benefits may not depend on high speeds. For example if new uses of fixed broadband are primarily to support an explosion of Internet of Things (“IoT”) devices then these applications may be able to be supported on existing broadband networks.

Therefore the approach adopted in this study considers how broadband will be used as an input to deliver services in a number of vertical sectors over a thirty year period, and whether different broadband technologies will constrain these uses. This approach forecasts the relative economic output related to each use case, which could be enabled by different broadband choices.

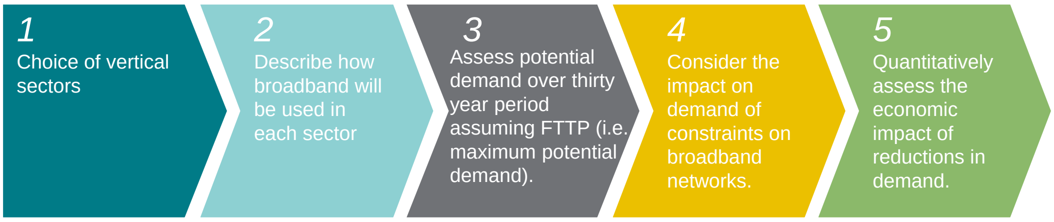
The relativities in the wider economic benefits associated with different broadband technologies (such as economy wide productivity, or positive externalities) can be inferred from the differences in economic impacts enabled by each broadband technology.

In summary, making long term forecasts of demand in markets subject to rapid change is necessarily uncertain. However, while the absolute magnitude of economic output in each use case is uncertain, the relativities of economic outputs enabled by the different technologies can be estimated with greater confidence.

3.2 Description of the use case approach

We set out in Figure 11 below the approach taken in this project to considering how choices of different broadband infrastructure can affect potential benefits of broadband.

Figure 11 Methodology overview



The five stages of this methodology are as follows:

1. A number of vertical sectors are chosen to assess how broadband will be used.
2. For each vertical sector the key use cases which will rely on broadband networks are identified.
3. For each use case forecasts of potential economic demand are modelled (assuming broadband networks do not constrain demand).
4. The model forecasts how the constraints of different broadband technology options affect demand for the use cases.
5. Based on the demand forecasts the model estimates the incremental economic output as a result of UFBA options.

3.2.1 Choice of use cases

The analysis identified a long list of potential use cases across a number of different vertical sectors, specifically: healthcare, media / entertainment, energy, education, retail, communications and IT, public sector, home, transport and support for 5G. The review of the long list also identified key technologies that generically enable or facilitate a number of use cases across different vertical sectors. Along with NIC we identified potential uses which we have analysed in depth in this report.

The use cases studied are deliberately not intended to be exhaustive. In practice broadband networks will be used as an input in almost all conceivable consumer and business activities. However, the purpose of this study was not to exhaustively identify all potential use cases where broadband is an input but rather to choose a range of different use cases which illustrate how choice of broadband network investment can affect demand.

Broadband network providers will monetise investments from a range of different customers including residential and small business customers, public sector clients and large corporate customers. However, for the purposes of this analysis we have focused on residential use cases where the likely *differences* in capabilities between different uses will occur. We deliberately exclude from the analysis the use of networks from larger commercial or public sector organisations. This is because the supply of high capacity connectivity which is required by such large organisations (generally concentrated in urban locations) is likely to be similar across all the technologies studied. By contrast the capabilities of *residential* broadband networks will vary significantly by technology used.

The project team and NIC narrowed the long list of potential use cases down to seven potential broad use cases using the following criteria.

- The use cases should rely to a significant degree on the roll out of Ultra-Fast Broadband Access technology UFBA technology to residential premises.
- The use cases should come from different vertical sectors.
- The use cases should include both mass market applications and applications relevant to a particular segment of users.
- The use cases should be a mix of cases that require different technical requirements (for example: some require high bandwidth, others require low latency, whilst others might require high reliability).
- The use cases should be a mix of cases that may have different types of economic impacts. Some will have direct impacts on consumer demand, while others may also lead to positive economic externalities[16].

The use cases chosen are set out in Figure 12.

Figure 12 Use cases considered

Sector	Use case	Key technology feature
Audio visual entertainment goods and services	"Premium" audio visual display (high resolution or 3D)	Higher definition streamed video services
Computing goods and services	Virtual Reality (VR) and Augmented Reality (AR)	Higher definition streamed VR and AR video services
Economy wide	Small Office Home Office (SOHO)	Upload of large documents
Computing goods and services	Smart home applications, user generated content and next gen video communications	Upload of surveillance video, and two-way video communication
Healthcare	Teleheath and telecare	Video based remote healthcare consultation
Education	Online classrooms / MOOCs	Video based VR and AR video services
Communications	5G (support for 5G infrastructure)	Economies of scope in network roll out

Source: Frontier

Ultimately the key driver of network bandwidth across the use cases is video. Video is central to the delivery of premium displays, Virtual Reality (VR) and Augmented Reality AR, some smart home applications (upload surveillance

[16] Economic externalities refer to the concept of economic benefits which result from an economic activity but which are not enjoyed solely by the buyer or seller of the economic activity.

video), telecare (remote healthcare consultation), and online class rooms (remote education). Given that existing networks support video (form the majority of premises) then the incremental demand enabled by network investment will depend on how demand for video will evolve.

There is inherent uncertainty when selecting future use cases which will rely on broadband. This uncertainty is mitigated to a degree as all the future use cases in our analysis extend the *current* uses of broadband networks. Indeed forecasts of use of broadband networks in the broad vertical sectors map closely to Historical forecasts of broadband use, suggesting that at least at a high level it is possible to identify the key sectors that will make use of broadband technology (see for example Figure 80 that sets out the forecast use cases for broadband as was imagined in the early and mid-1990s in the UK).[17]

One the one hand basing forecasts on existing use cases could be criticised for being too conservative since it necessarily omits those use cases which cannot be imagined (though as we note below, our analysis does attempt to factor in more potential innovative evolutions of these use cases). On the other hand assuming greater use of *existing* use cases to forecast future use of broadband can exaggerate demand. For example, some Historical forecasts posited demand for mobile networks would be derived from mobile "dongles" which provide connectivity to laptops for business purposes, whereas in fact it was smart phones and consumer tablets that drove demand for mobile networks. As broadband technologies reach maturity, the pace of further innovation in demand may be reduced.[18]

Similarly, forecasts of use cases can fail to predict barriers to take up which then exaggerate potential demand (such as with telehealth noted above). Our forecasts assume that these cultural barriers are overcome, to a degree, and greater use of broadband is made to deliver these services.

This uncertainty in *how* broadband networks will be used in the future was illustrated by a former Ofcom Chief Executive in 2011, in a speech about investment in new broadband networks, when he noted that:

> *"Amid a cornucopia of entertainment and information services, and the promise of advanced telemetry, e-health and interactive education, it is interesting that the only 'killer app' we have so far is the presence of teenage children. Social networking, streaming and sharing from the teenage bedroom,* […] *seems to be among the strongest reasons for adopting superfast broadband.*
>
> […] *So there remains uncertainty within the sector about the level of demand for superfast services and of course willingness to pay. Yet it is clear that consumption of data continues to surge."*[19]

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[17] In annex section B.7.

[18] See Figure 80 and section B.7.

[19] http://webarchive.nationalarchives.gov.uk/20160702191620/http://media.ofcom.org.uk/speeches/2011/competition-and-investment-in-superfast-broadband/, accessed on 21 September 2017.

3.2.2 Assessment of the use of broadband networks in each vertical sector

For each vertical sector we consider how broadband usage may develop. This was based on a desk based review of the relevant literature, and workshops attended by experts in technology and telecoms networks, interviews with experts in the field. The assumptions on growth in demand for the use cases are set out in full in section 4.

Given the inherent uncertainty in long run forecasts we set out two scenarios:

- more moderate assumptions (based on evolution of current uses, i.e. “moderate evolution”); and,
- more ambitious scenario (which may include as yet unforeseen uses, i.e. the “ambitious innovation” scenario).

Moderate evolution scenario

In the moderate evolution scenario we forecast likely changes in demand based on evolutions of existing uses and applications of broadband. This approach bases forecasts on existing usage, by application, device, or user. It makes assumptions on how existing uses will evolve over time. As noted above, this necessarily has limitations. New and innovative devices and applications may not be adequately reflected in demand forecasts. Similarly this approach may erroneously extrapolate recent trends. For example early forecasts of mobile broadband tended to emphasise the importance of laptops in driving demand for mobile data and did not foresee the demand that would be derived from smartphones.

Nonetheless, basing forecasts on existing uses is likely to lead to more accurate forecasts in the medium term. Therefore we expect that in the short run the moderate evolution scenario might be relatively accurate. However, in the medium and longer term it is much more uncertain, and there may be a bias to under forecasting (i.e. there may be a greater risk that the moderate evolution scenario could under forecast, than over forecast) since by definition new innovative uses of broadband networks are excluded. Though, even in this scenario an over forecast cannot be ruled out: improvements in compression technology or an absence of demand for very high definition audio visual services could lead to an over-estimate of demand.[20]

Ambitious innovation scenario

The historical analysis of development of mobile, broadband and PC markets[21] revealed that when making longer term forecasts it was not possible to envisage all the use cases for which fixed and mobile networks were used. While it was well understood that broadband networks could be used to support the distribution of audio visual content, the rise of social networks as a driver of demand for broadband was perhaps less foreseeable.

[20] See Annex A, Annex B, and Annex C.

[21] See Annex A, Annex B, and Annex C.

In the ambitious innovation scenario we attempt to account for the inherent uncertainty in forecasting future use cases over a thirty year period by including innovative applications which could be a driver of significantly increased demand. These necessarily rely on more innovative technological and service developments.

Based on the research conducted in each sector we have posited assumptions on how more innovative services might develop. These are deliberately grounded on assumptions on demand and technology that are reasonable, albeit not near term evolutions of current demand. The objective is to consider how demand will evolve in a way that could plausibly come to pass, but which are not delivered given existing demand and technologies. The ambitious innovation forecasts are necessarily more uncertain, but such uncertain forecasts, are to a degree, inherent in longer range predictions. Previous longer forecasts considered in this report have acknowledged that future uses cannot fully be forecast. For example in the Federal Communications Commission (FCC) in the USA in 1988 noted in relation to demand for fibre to the home that:

> *"As with many new technological advances, broadband networks will lead to applications and services unknown before increased speed and capacity make those services possible. Increased capacity and new functionality often have been criticised as having no clear specific applications. But new technologies and services such as direct dial long distance, communications satellites, and interchange fiber have all stimulated demand and creative new applications unforeseen before the technologies development"*

It is not possible to say, a priori, whether the assumptions in the ambitious innovation scenario are biased to "over" or "under" estimate forecast demand over the coming thirty years.

Technology requirements to support each use case

A degree of judgement is required to identify the likely broadband capabilities that will be needed to support each use case. The ambitious innovation scenario imagines innovative applications which require the use of broadband over the next thirty years; whereas moderate assumptions assume that use of broadband will reflect more marginal, iterative improvements over existing uses.

The analysis considered the required capabilities of broadband networks which are necessary to deliver the service in terms of:

- bandwidth necessary to deliver the use case (both upload and download);
- other characteristics such as:
  - reliability (whether consistency of bandwidth or incidence of faults); or
  - latency;
  - coverage by geotype[22].

[22] The analysis segments households into "geotypes" by the degree of premises density (from most urban to most rural).

In practice, over a thirty year period the quality and characteristics of the different use cases will change and evolve over time. It thus requires us to make a number of simplifying assumptions. For example the “standard” technology to deliver AR/VR will evolve, or the typical resolution to watch “premium” TV services will change.

In order to make the modelling tractable, in the case of technologies such as AR/VR or display resolutions we assume that in a given year the required bandwidth depends on assumptions on how technologies are gradually taken up (which increases bandwidth demand over time as more sophisticated versions are taken up over time), and on assumptions on data compression technology which can reduce bandwidth demand over time.[23]

3.2.3 Assess potential demand up to 2050

Based on the research undertaken the analysis makes projections of future demand for each use case. The demand forecasts explicitly model demand for services which rely on UFBA and are incremental to uses that are that could rely on existing broadband networks. However, as we note below there is likely to be a degree of substitution of demand for “premium” services using UFBA networks and services which could use existing networks (such that where networks limitations constrain demand of use cases studied we assume a degree of substitution to services using lower capability broadband networks).

The projections assume demand is unconstrained by network capability (and hence includes any potential endogenous demand). Forecasts are based on the following assumptions which are specific to each use case and set out in full in the Annex F:

- Total potential adoption / take up in the long run.
- The rate of take up
- Assumptions on the Average Revenue (or cost saved) Per User (ARPU) associated with each use case.

Long run adoption

In order to estimate total impacts (over the 30 year period) it is necessary to make an assumptions around maximum household adoption for the given use case in the long run. In some cases it is assumed that the use cases will be mass market, in others they will be niche or targeted at specific market segments.

Informed by our historical analysis, we assume that ‘maximum’ adoption is reached 15 years after a launch year.[24] However the assumed launch year and maximum adoption are specific to each use and discussed below.

The assumption on maximum long run take up for a specific use case is made with reference to penetration of analogous use cases based on current technologies (for example VR/AR devices are made with reference to current

23 Set out in full in Annex F.

24 This is consistent with adoption of mobile phones, PCs and broadband as evidenced by the Historical analysis described in section **Error! Reference source not found.**.

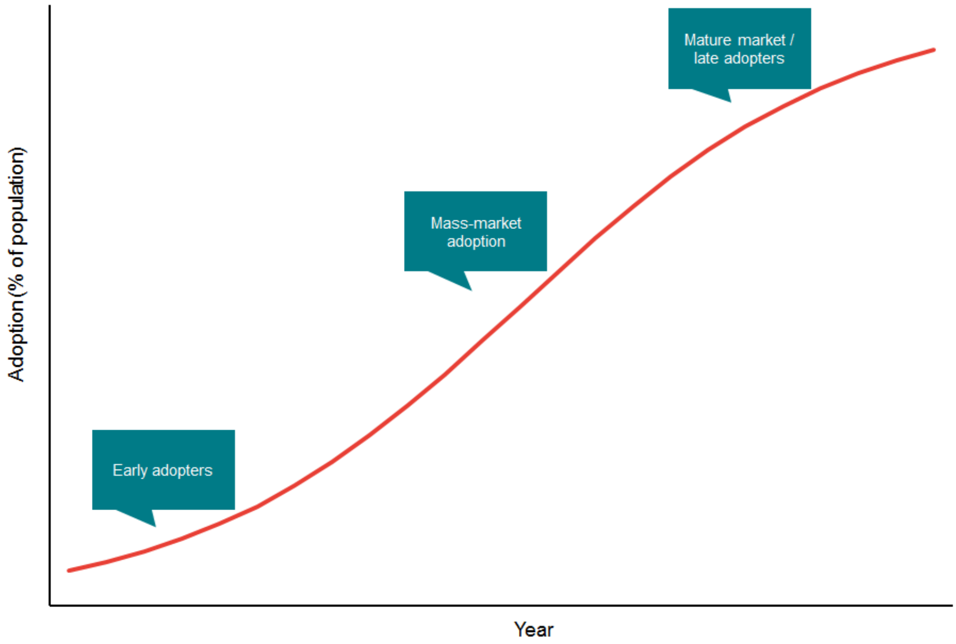
adoption of current generation gaming devices, take up of online graduate learning is made with reference to current take up of distance learning students in tertiary education).

It is assumed that demand is uniformly distributed across all households in the UK rather than concentrated in certain geotypes. Where relevant we consider the implications of relaxing this assumption. For example in the case of the provision of healthcare, users in rural locations may have higher value for telehealth services where there are fewer alternatives than users in urban locations.

Rate of take up

We assume across all use cases that the path of adoption will follow an 'S-shaped' adoption curve after launch (i.e. a logistic curve). Such adoption curve sees an initial exponential growth with the rate of growth speeding up as applications enter the 'mass-market' phase, before rates of growth fall as only late adopters remain. This pattern has widely occurred in the adoption of new applications.[25]

Exhibit 1. Illustration of S-curve adoption



Source: Frontier

Economic output related to the use case

For each use case we model total consumer demand, by estimating typical demand per user, then grossing up for the total market.

[25] See for example "Diffusion of Innovations", 5th Edition Paperback – 17 Nov 2003 by Everett M. Rogers

We forecast the consumer revenues associated with each use case. This is the average (incremental) expenditure per year per household that uses the application (not the consumer revenue related to the broadband service).[26]

In many use cases we assume consumer revenues, on a per user basis, may differ in the ambitious innovation and moderate evolution use cases. This is because ambitious innovation may include greater use of devices (for example multiple VR/AR devices in each household), or more technically advanced devices or services (for example 3D audio-visual displays rather than 2D displays) than the moderate evolution use case. Therefore the combination of more advanced technology and services and higher take up would lead to increased spend on each use case in the ambitious innovation scenario compared to the moderate evolution use case.

Cost saved

In some cases (such as the provision of telehealth/telecare or the costs of rolling out a 5G network) we assume that take up of advanced use cases do not lead to incremental demand for health or care overall. Rather, the use case can substitute for alternative more expensive services, or can more effectively deliver existing services. For example telehealth or telecare can be used to provide more cost effective care:

- consultations with medical staff can take place remotely saving travel costs, accommodation costs related to patients' physical presence or reducing costs of missed appointments; and,
- post-intervention monitoring can be done remotely in the home rather than in medical facilities which reduces accommodation costs.

3.2.4 Consider the impact on forecast demand for use cases of technical constraints of broadband networks

The analysis considers how demand for use cases might vary depending on choices of broadband technology roll out.

We assess the relative economic benefits enabled by the five technology scenarios that have been determined by the NIC as part of the parallel cost study.[27]

Coverage and roll out

The five technology scenarios are described in Figure 13:

[26] Conceptually the ARPU represents the sum of annual payments on devices to support the use case, subscriptions payments for content or services. The cost of one off irregular expenditure (such as costs of devices which are specific to the use case) are amortised over the device life.

[27] Prism study for NIC on costs of network upgrade.

Figure 13 Network roll out scenarios

Scenario	Description
1. 100% FTTP with new infrastructure	Fully pervasive rollout of FTTP to 100% of UK premises. New infrastructure throughout
2. 100% FTTP with infrastructure re-use	Fully pervasive rollout of FTTP to 100% of UK premises. Re-use of Openreach infrastructure enables faster roll out than scenario 1
3. Mixed fibre to 5G and FTTP	Fibre to 5G to 63% of premises (in the most urban geotypes). FTTP 37% of premises (with new infrastructure in the most rural geotypes) Same roll out profile as scenario 1.
4. FTTP with FWA/LRVDSL	Rollout of FTTP to c.90% of UK premises (as in scenario 1). Rollout of FWA/LRVDSL to c.10% of UK premises in very rural areas
5. G.Fast/DOCSIS with FWA/LRVDSL	Mix of G.Fast, DOCSIS and FWA/LRVDSL For premises with cable: 50%, G.Fast and 50% DOCSIS up to 300m from the Node and 100% DOCSIS beyond 300m Where only copper infrastructure exists: 100% G.Fast utilisation up to 300m from the Node and 100% FWA or LRVDSL Overall c.90% of premises have G.Fast or DOCSIS and c.10% of premises have FWA or LRVDSL

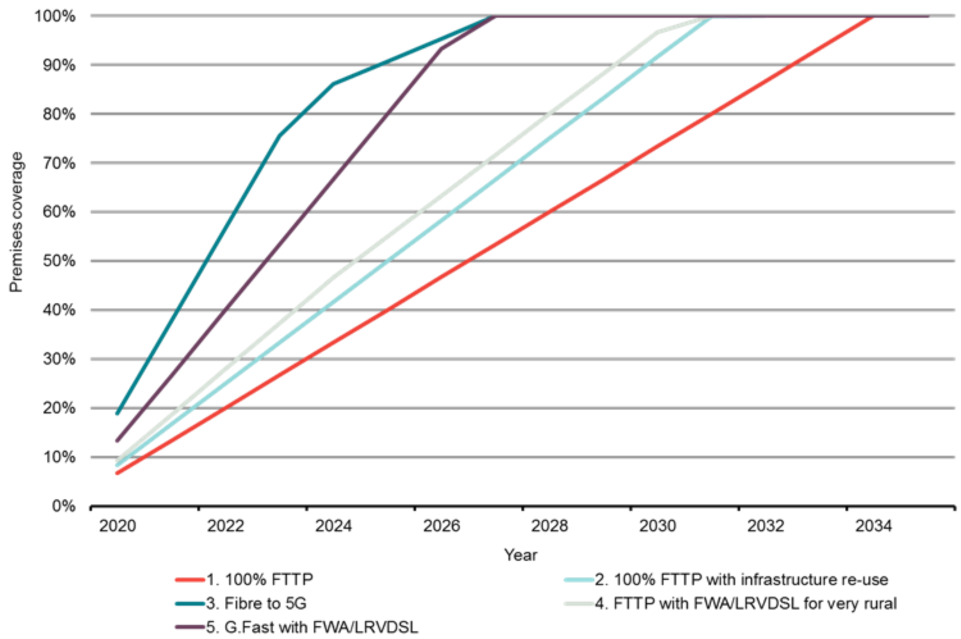
Source: Frontier

Notes: FTTP : Fibre To The Premises; FWA: Fixed Wireless Access to the local area; LRVDSL : Long Run Virtual DSL. Characteristics of FTTP assume fully pervasive rollout of FTTP to 100% of UK premises assumes and GPON at 32 or 16 way splitting for urban and rural as economically determined; Point to Point capability for symmetrical business services. In the assumption of FTTP with infrastructure reuse it is assumed re-use of Openreach duct under PIA etc; shared use of other utility ducts and poles (power, water etc); and shared/ open use of local authority/ public sector assets (CCTV, Urban Traffic Control, District Heating and Power, street furniture, etc).

Roll out profiles

Roll out profiles is specific to each technology. Technologies which involve more significant civil works have a longer roll out profile. Where technologies are able to roll out sooner, then this implies that the benefits of the technology can be enabled sooner (to those areas where the technology has rolled out) as illustrated in the figure below.

Figure 14 Assumed roll-out path in each technology scenario



Source: Prism

Technical characteristics

Upload and download

In each technology the design rules are such that the network is dimensioned in a way to ensure the peak capabilities with respect to upload and download speed (as described in Figure 15).

Figure 15 Broadband Technology Options

	Download Speed	Upload Speed	Latency
FTTC	80 Mbps	20 Mbps	15ms
DOCSIS3.0	300 Mbps	60 Mbps	18ms
G.Fast	300 Mbps	60Mbps	30ms
5G	500 Mbps	100Mbps	4ms
FWA/LRVDSL	100 Mbps	20 Mbps	99ms
FTTP	1 Gb/s	200 Mbps	20ms

Source: Frontier and Prism assumptions

Note: many FTTC lines do not receive 80 Mbps as they are located a long distance from a cabinet. Latency describes peak time latency. In the baseline scenario we assume that 90% of households have access to 70 Mbps and the remaining 10% have 10 Mbps.

In relation to latency we note that different technologies have different latencies. Where relevant we qualitatively consider the impact of latency on demand for each use case, though the majority of use cases are not affected by latency. G.Fast has a higher latency to FTTC as it can have higher number of active elements in the access network which can increase latency.

Reliability

Reliability can have a number of dimensions.

- First, it can relate to consistency of service across different geographic areas. Currently, on ADSL and VDSL networks line length can affect the bandwidth capacity of broadband services. Our analysis assumes that the 10% most rural households will only receive 10 Mbps service, which partly reflects the slower service in areas where households typically have longer line length.
- Second, reliability can relate to consistency of service by time of day. This reflects the phenomenon on some networks whereby the quality of service slows down at peak time as more users, who share network capacity, simultaneously use the network. Such contention issues are common to all broadband technologies modelled in this analysis where users share network capacity in the access network (and are discussed in the subsection below).
- Third, reliability can relate to the propensity of different networks to fault (for example due to aging infrastructure or susceptibility to weather related faults). Given that different network technologies have different propensity to faults, we consider below the extent to which use case demand will be affected by reliability.

We assume that FTTH has a higher level of reliability than copper based solutions such as G.Fast. For example broadband fault outages on copper based FTTC access technologies are currently affect 10% of lines per year.[28] Based on this the probability of a line having a fault at a given time is 0.005% in our modelling[29].

FTTP technologies are less prone to faults for a number of reasons:

- Fibre cables are naturally more robust than copper cables as they are largely unaffected by water and because they are non-conductive they are less prone to damage by lightning;
- There are fewer active (powered) elements in a fibre networks than a FTTC network covering a similar area; and
- Being newly installed, new fibre cables will have a longer operating lifetime than existing copper cables which are in many cases near the end of their working life, at which point fault rates tend to increase.

For this reason FTTP networks exhibit lower costs of maintenance.

However, in practice we note that in the use cases studied it is difficult to estimate the impact of faults on demand. This is because household broadband faults can occur for reasons other than the access network. For example these faults may be due to problems with customer-premises equipment (CPE). These can include problems with internal wiring, interference with or limitations of Wi-Fi routers.

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28 Current average fault levels in range of 8-11% of lines per year. Fault rates quoted are 2012/13 and 2011/12 figures from CSMG in a report prepared for Ofcom. They are calculated as the percentage of lines that experienced a fault in the given year. Products included in the analysis are Metallic Path Facilities (MPF), Wholesale Line Rental (WLR) and Shared Metallic Path Facility through Wholesale Line Rental (SMPF + WLR) (https://www.ofcom.org.uk/__data/assets/pdf_file/0027/79650/annex10.pdf).

29 Assuming on average a two day repair.

Therefore while faults related to the access network might be marginally lower for FTTP networks than G.Fast networks, faults related to internal CPE will be similar across different access technologies.

This means that applications which are very sensitive to faults (for example remote tele-surgery) may not be suitable for home use (given any combination of network or CPE fault could have a significant impact). Furthermore it is difficult to quantify the difference in fault levels that exist between different broadband technologies or their impact on demand.

Nonetheless we qualitatively consider where the incremental improvement in reliability could affect demand for different use cases.

Maximum or average network performance

We assume that network planners do not build-in artificial constraints which limit the performance of the network at peak times above the design rules set out above, for example by under-dimensioning backhaul leading to a high contention rate. A higher contention ratio implies that more end users are sharing the same data capacity.

Where a higher contention ratio is used, at peak times (when many users share the capacity) end users may be unable to access their maximum speeds. In practice network planners may invest to reduce contention ratios in response to increasing demand for bandwidth, up to the technology's maximum potential.

However, for the purposes of assessing demand enabled by different broadband technologies we assume that all investments are made to offer maximum performance (as described in Figure 15), i.e. that lack of investment in backhaul is not the binding constraint.

Assessing demand for use cases given different technologies

For each use case we consider whether the technical capabilities of different broadband infrastructures would be sufficient to support the service, or whether the service could not be provided with a given technology. For each use case we estimate the bandwidth and other technical requirements. Different use cases will require different capabilities which could include download and upload bandwidth; latency; and reliability. These assumptions are specific to the ambitious innovation scenario and moderate evolution assumptions.

Where the technology is not sufficient to fully deliver the use case we consider the impact on demand. The presence of technical network capability constraints (such as bandwidth limits) on a given use case are unlikely to mean that the use case cannot be delivered at all leading to binary "buy / do not buy" decisions. In practice, if a network's capabilities constrain the use case it is instead likely to *moderate* demand with some end users consuming less, or willing to pay less for the use case since it is offered at reduced quality.

The analysis makes assumptions for each use case about the degree to which demand is moderated when the full network requirements are not met based on judgements of the Frontier team following discussions with experts and review of the available literature and other studies.

In assessing the direct economic benefits that could be enabled by different technologies we assume that the use case is used in isolation, i.e. we estimate each use case assumptions without taking account of any combinatorial effects. We recognise that this assumption does not necessarily reflect actual household consumption (where a number of different services may be used in combination at any one time) and certain use cases may be complementary.

In section 5 we consider the implications of simultaneous demand for multiple uses of use case technologies.

3.2.5 Quantitative assessment of the difference in economic output as a result of broadband technology choice

Based on the analysis above, which estimates the incremental impact on economic output for each use case which is enabled by each broadband technology

We have not estimated macro-economic impacts such as overall productivity impacts that can result from greater coverage or take up of faster broadband. Instead we look at a micro-approach considering services and use-cases that will rely on broadband infrastructure, and specifically how choice of broadband technology can affect the potential demand in the vertical sectors studied. However, we note that the magnitude of economy wide productivity impacts is likely to relate to the degree to which the broadband networks are used. Therefore, the difference in the direct economic impacts realised in the different technology scenarios will reflect the difference in the wider economy wide productivity effects. For example, where the direct economic impact enabled by different broadband network technologies is similar then it is likely that wider economic productivity impacts will not vary across the different broadband network technologies.

Impact on economic output

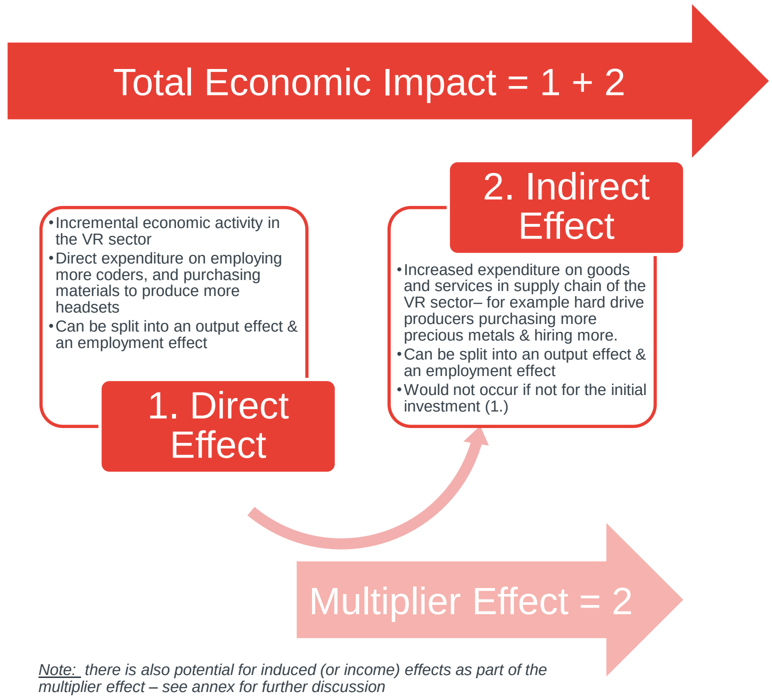
The **total economic impact** of additional economic activity in one sector comprises of two effects; the **direct effect**, and the **multiplier effect**.

The **direct effect** is an increase in output in the economy as a result of a change in final demand in a sector – additional activity in an industry such as VR will lead to an increase in output in the economy through expenditure on wages for more coders, material purchases for headsets etc.

As noted above, for some use cases we estimate the *cost saved* that are enabled by the use case, as an alternative to the incremental demand for the use case. For example in the case of telehealth, we assume that it will not lead to incremental use of healthcare, but instead will lead to cost savings for provision of healthcare. As noted above, telehealth and telecare has the potential to improve health outcomes as well as reduce costs. However, this analysis focuses on the relative differences in costs savings that can be achieved with different choices of network technology.

The **multiplier effect** captures the additional effect generated indirectly from additional activity. This relates to the additional flows of expenditure in the economy outside of the sector, following the additional activity within the sector. Those in the upward supply chain will purchase more goods & services– leading to an additional increase in output & employment in the economy that would not occur if not for the initial increase in activity in the sector. In addition, in theory there is potential for further induced effects which result from the income effect of hiring more workers in the sector to meet an increase in final demand. However, these induced effects are difficult to measure[30] and explicitly not estimated by the ONS; therefore this study focuses on indirect effects.

Exhibit 2. Total Economic Impact – an example in the VR sector



Source: Frontier

In any forward-look cost or benefit analysis it is important to reflect that benefits and costs occur in different periods and that people generally prefer to consumer goods and services today, rather than tomorrow. Future expenditure is therefore discounted using the social time preference discount rate of 3.5% per annum[31] over the period to 2050. We note that the direct impact will be felt partly by producers who supply the use cases. However, we do not consider it appropriate to use a discount rate of suppliers in the given use cases as our analysis is not intended to reflect a private investment decision of the suppliers. And instead reflects the present value (to society) of the difference in economic output enabled in each of the use cases as a result of different investments in broadband.

[30] The induced multiplier effect is not calculated by the ONS. To produce an estimate, they would have to assume that consumers do not change their final consumption patterns in response to changes in income. See Annex [●] for more discussion on the Induced effect.

[31] See "Discount rates and net present value" by the Cabinet Office.

Consumer benefits

Based on simple assumptions about the demand curve we estimate the consumer surplus enabled by the use case. Data on the nature and shape of demand curves are unlikely to be readily available. In this analysis we make a number of simplifying assumptions about the nature of the demand curve which are described in section E.2.

Externalities

An **externality** is defined as a cost or a benefit that applies to a party who did not choose to engage in the economic activity. Where relevant we consider whether there are likely to be externalities.

For example Online Classrooms and Tele-Health/Telecare, which fall into the education and health sectors, may potentially, lead to externalities for the economy. Examples of externalities arising from education can relate to spillover effects in worker productivity *(knowledge sharing of new skills)* and reduced risks from crime reduction. In relation to health, the externalities can include avoidance of contagious diseases whilst at the GP/hospital settings, “herd effects” (as one person’s health improves, their peers health improves due to the contagious nature of many common illnesses), and better health improves the rate of return to education for children or increases the productive capacity of the economy.

Externalities are difficult to quantitatively estimate, though where we would expect them to be significant we comment on their impact on the results of our analysis.

4 DETAILED ASSESSMENTS OF USE CASES

4.1 Introduction

This section sets out the use cases we use to assess the benefits generated by the different roll out assumptions as set out in section 2. Each section describes how the use case could develop, and the degree to which these developments will be dependent on developments to broadband networks by:

- setting out the assumptions used to forecast potential demand under each of the moderate evolution and ambitious innovation scenarios;
- describing the technical network capabilities required for the use case to function (and considers foregone demand if there are network constraints);
- reporting the resulting potential increase in economic output if broadband networks are able to deliver the forecast demand.

The Annex F sets out detailed assumptions on each use case.

We consider in turn:

- Premium audio visual display
- Virtual and augmented reality devices and services
- SOHO applications
- Smarthome applications
- Telehealth and telecare
- Online learning
- 5G cost savings

Our results are clearly dependant on a set of assumptions that are based off of research, but are subject to challenge. We have sensitivity tested what we think are the key assumptions in our analysis for each use case, and will discuss the key sensitivities from below for each use case.

- Maximum addressable market at maturity;
- Speed of adoption;
- Roll-out speeds;
- Counterfactual demand;
- And compression sensitivity.

A detailed study of the above sensitivities can be found in Annex D.

4.2 Premium audio visual display

4.2.1 Overview

The development of television (TV) over time has seen improving screen resolution and quality. In analogue television this involved the introduction of colour television and an increased resolution. High definition' (HD) screens and content first arrived in the UK in 2006[32] and is now the 'standard' for TV, video, and gaming, with around 77% of UK households now having a main TV that is HD-ready.[33]

The next generation of screen resolution is 'Ultra HD', or '4K' and '8K' TV[34]. 4K was first launched in the UK in 2017 and 8K is expected to arrive within the next three years.[35] A parallel development has been a shift in television and video viewing from broadcast platforms and physical media (e.g. DVDs) to delivery over IP based broadband networks (IPTV). Increases in the speed and capacity of broadband networks has allowed delivery of video content at a similar quality to traditional platforms, with the advantage that a large library of content is available 'on demand'.

Video streaming at higher resolutions requires proportionately more bandwidth, meaning that 4K and 8K streams will require significantly more bandwidth than the 720p and 1080p HD streams more commonly used today. As well as improving resolution, other advances such as wider colour gamut and higher-frequency screen refresh rates are also likely to further improve picture quality, but increase bandwidth demand.[36]

There are no immediate engineering constraints preventing resolution increasing indefinitely (e.g. 16K or 32K) pushing up the bandwidth requirement further still. However limitations of human eyesight (e.g. in the number of pixels the humans eye can effectively can differentiate) suggests that an end point will be reached, as consumers would not be able to notice any discernible difference from further improvements.[37] For example one commentator we engaged with noted that it would require an almost floor-to-ceiling display covering almost all the visual field in order to perceive the difference between a 4K resolution and an 8K resolution.

Therefore given that content producers incur significant costs in upgrading equipment and filming to a higher resolution, further upgrades are likely only to happen where there is significant consumer benefit.

While increases in screen resolution beyond 8K may not bring any significant benefits, other technology developments might increase the bandwidth required to deliver audio visual content. Current 3D TV services require double the bandwidth as a separate image is sent to each user's left and right eyes

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32 http://news.bbc.co.uk/1/hi/technology/6142998.stm accessed on 22nd September 2017

33 https://www.statista.com/statistics/387729/market-share-of-hdtv-and-hd-ready-tv-sets-in-the-uk/

34 '4K' and '8K' refers to the number of pixels on the television screen.

35 http://www.techradar.com/news/8k-tv-everything-you-need-to-know-about-the-futuristic-resolution

36 http://www.vodafone.com/content/dam/group/policy/downloads/Vodafone_Group_Call_for_the_Gigabit_SocietyFV.pdf

37 http://www.swift.ac.uk/about/files/vision.pdf

("stereoscopic") displays. However these have not proved popular with users with existing equipment and content being withdrawn, despite at launch being heavily promoted by content platforms and equipment manufacturers.

Future generations of audio visual technology could include "light-field cameras". Light field cameras use many microscopic lenses to identify individual light rays, which can be used to create a create a 3D resolution of the scene it has captured.[38, 39] These can be used to create more "immersive" 3D screens where users could "peer around the side" of objects which are projected from 3D screens in a way that is not possible with current stereoscopic 3D display techniques. Although not yet close to being widely available, this is a realistic possibility at some point within the scope of this study.[40] The bandwidth requirement for this sort of experience could be very high (upwards of 1Gbps)[41].

4.2.2 Forecast demand assumptions

Adoption forecast

We assume that in the long run all current TV households will migrate to a 4K or 8K TV, i.e. 95% of households by 2032 delivered via IPTV.[42] This assumption is based on current ownership of TVs (around 95% of households[43], and high take-up of HD equipment in the 10 years since its launch (77% of households).[44] Though we note that currently the majority of TV content is watched using standard definition, even though the majority of users have HD displays[45].

In common with other forecasters (see below) our assumption is that 4K sales will increase quickly over the next few years, as prices continue to fall and the 'mass adoption' period is entered. Once 8K displays come to market (generally expected to be around 2020-2022[46]) they may replace the 4K TVs in people's homes and become the new 'standard' over time.

38 http://lightfield-forum.com/what-is-the-lightfield/ (accessed on 6th October 2017).

39 http://spie.org/newsroom/6623-high-resolution-3d-light-field-display?SSO=1

40 Indeed Apple recently filing for a patent entitled "Light Field Capture" http://lightfield-forum.com/tag/camera-array/ (accessed on 6th October 2017).

41 See Annex F.3.

42 https://www.ons.gov.uk/aboutus/transparencyandgovernance/freedomofinformationfoi/householdsintheuk https://www.statista.com/statistics/269969/number-of-tv-households-in-the-uk;

43 http://www.barb.co.uk/resources/tv-ownership/

44 https://www.statista.com/statistics/387729/market-share-of-hdtv-and-hd-ready-tv-sets-in-the-uk/ accessed on 25th September 2017

45 For example Ofcom note that 83% of viewing of the five main PSBs is on Standard Definition. Ofcom Connected Nations 2016.

46 http://www.techradar.com/news/television/why-8k-televisions-will-go-mainstream-by-2020-according-to-analysts-1326567 accessed on 18th September 2017

PREMIUM AUDIO VISUAL DISPLAY FORECASTS

Intelsat report states that:

- 85% of professionals responsible for implementing 4K UHDTV technology believe that 4K UHDTV will be the norm in 10 years' time.[47]

ABI research[48] report forecasts that:

- HDR (High Dynamic Range)TV shipments will reach 245 global million units in 2022
- 8K TV sets will not have wide global adoption by 2020, and in the medium term will only be used globally in small quantities and in countries such as Japan where broadcasters are working toward 8K broadcast.

Grand View Research [49]estimates that, globally, the 4K TV Market size will be worth $380.9 billion by 2025

Broadband UK[50] estimates that by 2023 4K TV penetration will be 19% in the UK in their base case (requiring 30 Mbps download speed) and 40% in their aggressive case (requiring 40 Mbps).

Figure 16 Premium audio visual – demand assumptions

	Assumption	Source/explanation
Launch year	2017	Launch of 4K TVs in the UK
Maximum adoption	95% of households use next-generation screens	TV penetration in the UK today
Maximum adoption year	2032	15 years after launch year (fixed assumption across use cases)
Adoption	S-curve adoption	Fixed assumption across use cases

If network constraints are insufficient to deliver premium display our assumption is that incremental demand would fall by 25%, given that the different between a premium display and the standard display (which would be HD in early years and possible 4K in later period) may not be significant, i.e. the premium in consumer expenditure that could be captured through higher quality is limited.

Bandwidth and technical network requirements

In our "moderate evolution" scenario we assume that typical bandwidth demand for premium displays increase slowly reflecting a gradual adoption of 4K then a 8K TV. In the "ambitious innovation" we assume that 8K is adopted more quickly and newer technologies such as lightfield display are also adopted from 2040. This growing bandwidth (explained in more detail in Annex F.3) are a function of:

- Migration from lower resolution (4K) to higher resolution displays (8K) which increases a typical household's bandwidth demand.

[47] http://www.intelsat.com/wp-content/uploads/2014/09/4K_Ultra_High_Definition_TV_Adoption_and_Business_Models.pdf

[48] https://www.abiresearch.com/press/abi-research-forecasts-hdr-sets-will-surpass-4k-te/ accessed 5th October 2017

[49] http://www.grandviewresearch.com/press-release/global-4k-tv-market accessed 5th October 2017

[50] http://www.broadbanduk.org/wp-content/uploads/2013/11/BSG-Domestic-demand-for-bandwidth.pdf accessed 5th October 2017

- Assumptions on the bandwidth required for each type of display (44Mbps for a 4K display and 88Mbps for an 8K display up to 1Gbps for a Light–field display). This is the bandwidth required to deliver sports content (i.e. fast moving complex images). Bandwidth required to deliver other content would be lower.
- Increases in compression technology which we assume will reduce bandwidth demand at approximately 20% every ten years.

Figure 17 Bandwidth requirements for premium audio visual display

Scenario	2020	2025	2030	2035	2040	2045	2050
"Moderate evolution"	44	48	50	51	52	52	47
"Ambitious innovation"	88	99	125	195	235	319	384

The importance of reliability

As noted in section 2, FTTP networks are likely to be more reliable than copper based networks. An access line in a copper based access network might experience a fault once every ten years, whereas a fibre based network would experience faults less frequently. Of course households will experience other types of faults (not related to the access line) such as faults with their internal equipment, wiring or interference with the signal from their Wi-Fi router.

Nonetheless, at the margin, lower propensity of the access network to fault may at the margin increase the value for audio-visual content supplied on a FTTP network compared to a copper based G.Fast network. The importance of reliability could be more significant where end users rely on the network for audio-visual content (for example because they do not have access to alternative terrestrial or satellite TV services).

However, in practice the importance of a marginal difference in reliability is difficult to assess since the likelihood of a fault on a line at any point in time relatively small across all technologies (we estimate that at any one time the likelihood of a fault is 0.05%[51]). Furthermore other technologies (such as mobile) could be available to stream content (albeit potentially at lower resolution). Therefore we assume that reliability will not significantly affect differences in economic output between different broadband technologies (though recognise a degree of uncertainty).

Consumer demand

The table below sets out the assumption on forecast consumer demand associated with premium display.

This reflects incremental expenditure on premium display devices and services (i.e. incremental spend on premium technology and services over "standard" versions).

[51] Assuming one fault per line each ten years, with two days to repair on average.

Figure 18 Premium audio visual display – ARPU assumptions

Description	Assumption	Rationale
ARPU (2018) – "moderate evolution"	£138 per year	Based on 1 device (at £300), and 1 subscription per year (at £90[52])
ARPU (2018) – "ambitious innovation"	£217 per year	Based on 2 devices (at £400 each), and 1 subscriptions per year (at £90)
Inflation assumption (real)	-1% p/a	Technology efficiencies will decrease the cost of technology each year

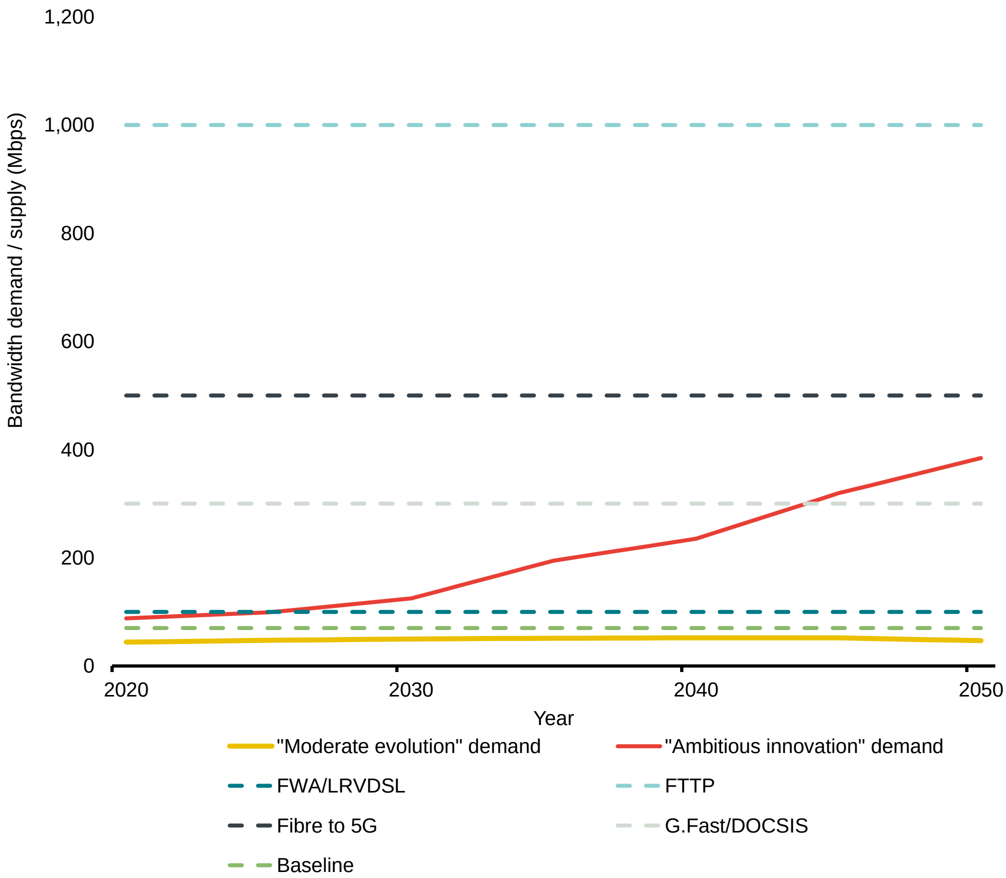
4.2.3 Result of demand analysis

Figure 19 below shows premium display download per household bandwidth demand from 2020 – 2050, as well as the available bandwidth under each broadband technology:

- FTTP is able to deliver the "moderate evolution" and "ambitious innovation" scenario in all years;
- Fibre to 5G is able to deliver "moderate evolution" and "ambitious innovation" in all years;
- G.Fast/DOCSIS is able to deliver "moderate evolution" in all years and "ambitious innovation" up to 2044;
- FWA/LRVDSL is able to deliver "moderate evolution" in all years and "ambitious innovation" up to 2025; and
- "FTTC" baseline (c.90% or premises) can deliver "moderate evolution" in all years, but not "ambitious innovation" in any year.

[52] Based on average price of a Netflix subscription per year (see https://www.netflix.com/gb/#this-is-netflix accessed on 4th October 2017).

Figure 19 per household premium audio visual display bandwidth capacity requirements and network supply constraints



Source: Frontier

Incremental demand for premium display devices and content under each technology scenario

Figure 20 below shows estimated incremental demand (relative to the baseline of current network capabilities) in the "moderate evolution" and "ambitious innovation" scenarios under each broadband technology.

"Moderate evolution" scenario

Each of the broadband technologies is able to deliver the "moderate evolution" bandwidth scenario in all years, meaning that incremental demand under all scenarios is broadly similar (with small differences based on assumed roll-out speeds). We estimate that each scenario generates less than £1 billion in incremental demand over the 30 year period.

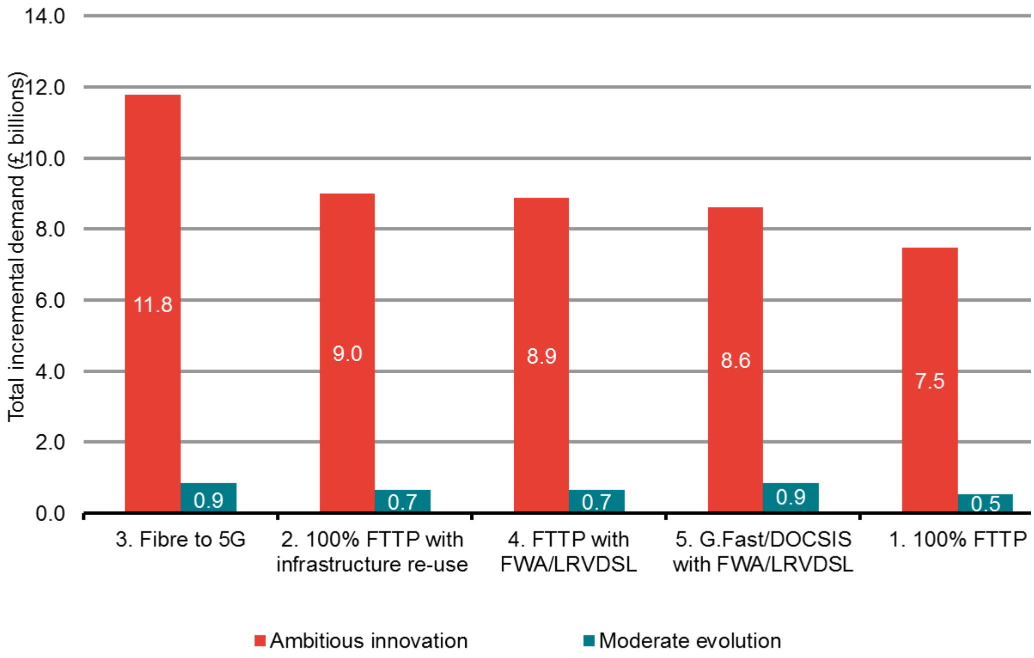
"Ambitious innovation" scenario

The key driver for benefits in the ambitious innovation scenario is the speed of network roll out. Fibre to 5G rolls out relatively quickly and so realises most benefits.

We estimate that:

- (Scenario 3.) Fibre to 5G would generate an additional £11.8 billion in demand over the 30 year period;
- (2.) FTTP with infrastructure re-use an additional £9 billion;
- (4.) FTTP with FWA/LRVSL an additional £8.9 billion;
- (5.) G.Fast/DOCSIS with FWA/LRVDSL and additional £8.6 billion; and
- (1.) FTTP with new infrastructure an additional £7.5 billion.

Figure 20 Premium audio visual display – total incremental demand under each bandwidth and technology scenario



Source: Frontier

4.2.4 Sensitivity testing

As discussed previously, incremental demand forecasts are dependent on many assumptions, which we discuss in detail in Annex D. However, for the premium audio visual use the results are particularly sensitive to some of the assumptions.

The key sensitivities that affect the incremental demand in the moderate evolution scenario are data efficiency compression improvements and in both scenarios, the roll-out speed of technologies.

In the moderate evolution scenario, if the analysis assumes 50% compression efficiency improvement every 10 years (in comparison to the baseline of 20% every 10 years) then much lower incremental demand benefits in our higher bandwidth technologies like 100% FTTP are forecast. This is because the existing FTTC technology will be able to achieve much more of the use case bandwidth requirements. As such 100% FTTP will have 92% lower incremental demand benefits with 50% compression every 10 years relative to our baseline assumption of 20% compression every 10 years.

In both scenarios, roll-out speed sensitivities have a relatively large impact on the results. Technology scenarios involving FTTP roll out (scenarios 1, 2 and 4) are particularly sensitive to roll-out speed assumptions since these scenarios are have slow roll-out profiles compared with 5G or G.Fast. In the moderate evolution scenario, the incremental demand benefits of scenario 2 (FTTP with infrastructure re-use) are 69% lower where roll out is 50% slower than in the baseline. Similarly, for scenario 2 (FTTP with infrastructure re-use) in the ambitious innovation scenario 50% slower roll-out leads to 60% lower incremental demand benefits, which is to be expected as this scenario is highly dependent on large bandwidth requirements for the premium audio visual use case.

Since maximum adoption is already at 95% in our base case, the 50% higher maximum addressable market sensitivity is not particularly informative in either of our scenarios, as maximum adoption is capped at 100%.

4.3 Virtual and augmented reality devices and services

4.3.1 Overview

Virtual Reality

Virtual reality (VR) is a technology that uses headset mounted displays to create an immersive audio-visual experience. The aim is to simulate the user's presence in a virtual environment using images and sounds.

The simplest VR headsets use a headmount for existing smartphones, where the smartphone's video image is made to feel more immersive.[53] More sophisticated VR devices have an integrated high resolution video display and headphones, and use sensors to detect the user's position or movement and adjust the video and audio stream accordingly.[54]

VR has many potential uses across the workplace and leisure activities. However, probably the most likely use in the near term is to support gaming applications. The gaming sector has driven sales of VR headsets to date, and is expected to continue to do so - a report by Nielsen stating that "*high demand for VR headsets by mobile and console gamers will fuel demand for VR content*".[55]

VR gaming devices and services are currently relatively niche compared to the overall gaming market. Traditional games consoles are currently much more popular than VR headsets (Sony sold 915 thousand VR headsets globally in the

[53] Google's "*Google Cardboard"* is an example (https://vr.google.com/cardboard/ accessed 14th September 2017

[54] The "*Oculus Rift"* is an example of a dedicated VR device (https://www.oculus.com/ accessed 14th September 2017).

[55] http://uk.businessinsider.com/nielsen-highlights-consumer-appetite-for-vr-2016-9 accessed on 14th September 2017

6 months after launch date, compared to 53.4 million PlayStation 4s in the 3 years after its release).[56]

VR also has a range of other potential applications. Entertainment providers could supply certain of their content as “immersive experiences”. The BBC for example has been trialling various immersive experiences, such as VR tours of Edinburgh festival[57] and Rome's historical landmarks[58] and of using real stories of refugees as the basis for an animated virtual experience.[59] BT has trialled this with sports matches, showing the 2017 UEFA Champions League final in VR.[60] However, it is unlikely to fully replace 2D displays, as the format for TV services, as the VR features would not sit easily with the editorial techniques of existing TV formats (long and short form films, documentaries, news).

There are also various workplace applications. For example in medicine, VR could aid surgical training or allow students access to virtual labs to get hands-on experience at a lower cost.[61] One factor which may determine whether VR becomes ‘mass market’ is likely to be the extent to which workplace applications become prevalent.[62] For example, one of the drivers of wide take up of PCs was that they had wide adoption in workplaces which increased demand from home users.

Augmented Reality

In contrast to the fully immersive virtual experience of VR, Augmented reality (AR) blends real life and virtual, with virtual elements overlaid in the user’s physical environment to create value for the user.

The potential applications of AR are very broad. Arguably more so than VR, as there are likely to be more limited scenarios where the user wants full immersion than some useful augmentation of their physical environment (where they can still see their surroundings and communicate with others). In future consumers could visualise new furniture by ‘placing’ it in their home, conduct a holographic call/videoconference, or answer emails without the need for a screen or keyboard. Similarly to VR, workplace AR applications could be key to driving success, with early AR releases appearing keen to tap in to this market.[63]

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56 https://www.ft.com/content/f7e231ee-fc84-11e6-96f8-3700c5664d30; http://www.wired.co.uk/article/sony-playstation-vr-near-1m-units accessed on 29th August 2017

57 https://www.bbc.co.uk/events/egvgfx/play/p059stdl accessed on 21st September 2017

58 http://www.bbc.co.uk/taster/projects/romes-invisible-city-vr accessed on 21st September 2017.

59 http://www.bbc.co.uk/rd/blog/2016-06-the-bbc-and-virtual-reality accessed on 21st September 2017

60 http://home.bt.com/tech-gadgets/phones-tablets/bt-sport-to-give-away-virtual-reality-headsets-for-free-ahead-of-uefa-champions-league-final-11364181144704 accessed on 21st September 2017

61 https://www.wareable.com/vr/virtual-reality-vs-augmented-reality-which-is-the-future accessed on 29th August 2017

62 Workplace applications was a key factor in driving mass adoption of PCs in the home as consumers got accustomed to using them at work and the benefits revealed themselves (see Annex C).

63 The re-launch of “Google Glass” is an example of a workplace focus. Advertising for the Microsoft Hololens focuses around workplace applications, such as for surgeons, car manufacturers and developers (see https://www.microsoft.com/en-gb/hololens accessed on 2nd October 2017).

Pokémon Go is a recent successful AR application.[64] Mobile app 'Snapchat' offers another popular AR application; with users able to augment their faces in photos using Snapchat's various 'filters'. Both of these examples are offered via apps on users' mobile phones. Similarly to VR, specific AR devices offer greater possibilities and are more interesting in relation to UFBA as they could require significant incremental bandwidth and potentially very low latency connections.[65]

To date however there have been no compelling AR devices that have achieved mass market success. Google launched "Google Glass" as an AR device, but the device struggled to gain traction from app developers and consumers, and was withdrawn after concerns about privacy and safety were raised.[66] However in January 2017 Google announced a new "Enterprise Edition", targeted at helping manual workers do their jobs.[67] Microsoft has also released its own AR headset, the "HoloLens*",* which the company describes as *the "first self-contained holographic computer*".[68]

4.3.2 Demand assumptions

Adoption forecast

Based on the evidence to date, gaming is likely to be an initial driver of demand and willingness to pay for VR (and to a lesser extent AR). It is it therefore conceivable that VR and AR gaming could become as popular as video game consoles, which today are present in around 8 million households.[69] Video entertainment is could also be a key VR/AR application in future.

Given the breadth of potential non-gaming applications, it is possible that VR and AR could in fact end up reaching many more households. Although, as noted above, there is still uncertainty around which applications could be key in driving adoption beyond keen gaming. Therefore we anchor the forecasts to the projected number of gaming users, recognising that the technology may have much wider application.

Our 'maximum' take-up assumption therefore represents a slight uplift from the 8 million households who own a game console today, at 33% of households (c.10 million). The remainder of households would use lower resolution screens (initially a continuing mix of SD and HD, but gradually migrating to HD). We also assume a 2016 launch year,[70] meaning maximum adoption is reached in 2031.

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[64] The game broke various records in its first month after launch (see: http://www.guinnessworldrecords.com/news/2016/8/pokemon-go-catches-five-world-records-439327 accessed on 29th August 2017.)

[65] Qualcomm "*VR and AR pushing connectivity limit"* (May 2017) (https://www.qualcomm.com/media/.../files/vr-and-ar-pushing-connectivity-limits.pdf).

[66] http://www.bbc.co.uk/news/technology-30831128 accessed on 14th September 2017.

[67] https://www.x.company/glass/ accessed on 29th August 2017.

[68] https://www.microsoft.com/en-gb/hololens accessed on 1st October 2017.

[69] http://www.barb.co.uk/tv-landscape-reports/tracker-games-consoles/ accessed 30th August 2017.

[70] This is around the release time of various popular VR headsets, such as the Oculus Rift and Samsung Gear VR.

We assume that demand for VR will increase more quickly, with AR growing more slowly[71], but potentially eventually proving more popular.

We assume that demand activity would fall by 50% if networks constrained household use of the VR AR. This would be a mix of users taking lower quality and less expensive AR or VR services, or simply choosing not to consume.

VR AND AR FORECASTS

- Greenlight Insights forecasts that by 2021 :
  - 24.2% of all revenue in VR will come from Enterprise
  - Location based VR will grow globally to a significant part of the industry, to revenues of $1.2billion
  - Overall revenues globally will be close to $75 billion[72]
- BOM (Noord-Brabant Development Agency) report[73] states that globally:
  - The global market for hardware (for example headsets) will increase 20 fold by 2021, with shipments doubling from 2020-21 to give 82.5 million headsets shipped in 2021.
  - By 2050 headset shipments are projected to be 240 million units
  - Global software revenues will increase from $1.1 billion in 2016 to $24.3 billion in 2020 (conditional on the take-up of the hardware being as predicted)
  - About 12% of Sony Playstation VR users indicated the technology made them feel sick. This could relate to poor game design or latency issues where user's movements are not synchronous with changes in the visual display.
- Goldman Sachs report[74] on VR and AR states that:
  - In 2025 global hardware sales in their base case will be $45billion, and software sales will be $35billion (with $11.6 billion of these software sales attributable to video games).
  - Only $9billion of the above software sales are predicted to be from AR, as technology matures for enterprise use cases slower.
  - $4.1 billion revenue, and 95 million users are estimated in 2025 base case for Live VR Events.

[71] Mark Zuckeberg, for example, noted that it "*won't be until 2022 until really takes off as the technology is simply not there*"

[72] http://variety.com/2017/digital/news/virtual-reality-industry-revenue-2017-1202027920/ (accessed 5th October 2017)

[73] http://cdn.instantmagazine.com/upload/4666/bom_vrar_2017reportpdf.68ec9bc00f1c.pdf (accessed 5th October 2017)

[74] http://www.goldmansachs.com/our-thinking/pages/technology-driving-innovation-folder/virtual-and-augmented-reality/report.pdf (accessed 5th October 2017)

Figure 21 VR and AR - adoption assumptions

	Assumption	Source/explanation
Launch year	2017	The release date of a number of popular VR headsets, such as the Oculus Rift, Samsung Gear, and Sony PlayStation VR[75]
Maximum adoption	33% of households use VR *or* AR	Slight uplift from number of households who today own a games console[76]
Maximum adoption year	2032	15 years after launch year (fixed assumption across use cases)
Adoption	S-curve adoption	Fixed assumption across use cases

Bandwidth and technical network requirements

Bandwidth requirements are potentially large for VR, since it is necessary to deliver the visual display directly in the centre of the user's field of vision, but also potentially across the users' entire potential field of vision. This is so that when user's turn their head or otherwise moves, the accompanying video display immediately changes.

Given the importance of low latency this may mean streaming far more information to the home than is actually being displayed at any time to allow the point of view to adjust instantaneously. A more efficient alternative would be to transmit lower resolution content which is beyond the user's current field of view, and only very high resolution content in the user's current field of view. This would create a lag where the resolution of content dipped each time a user moved its field of view. Our analysis assumes that the premium "AR VR" experience would offer a full higher resolution service.

The download bandwidth (described in more detail in Annex F.2) required to support VR / AR is a function of:

1. Resolution and type of device (we assume basic devices offer HD quality display and advanced devices offer 3D UHD quality display);
2. No of devices;

Video compression assumptions.

Figure 22 Bandwidth requirements for AR/VR (Mbps)

Scenario	2020	2025	2030	2035	2040	2045	2050
"Moderate evolution"	38	34	79	114	142	162	146
"Ambitious innovation"	75	174	253	314	361	1,011	1,528

Source: Frontier

As with audio visual content the reliability of different broadband technologies might affect demand, though this is difficult to assess. Furthermore other technologies (such as mobile) could be available to stream VR / AR content

[75] See http://www.independent.co.uk/life-style/gadgets-and-tech/news/oculus-rift-launch-first-vr-headsets-delivered-to-customers-a6956276.html; http://www.wired.co.uk/article/gear-vr-uk-launch (accessed on 27th September 2017); and http://www.independent.co.uk/life-style/gadgets-and-tech/news/playstation-vr-ps-sony-release-date-virtual-reality-headset-ps4-batman-a7359201.html (accessed on 2nd October 2017).

[76] http://www.barb.co.uk/tv-landscape-reports/games-console-retreat/ accessed on 27th September 2017.

(albeit potentially at lower resolution). Therefore we assume that reliability will not significantly affect differences in economic output between different broadband technologies.

Consumer demand

The table below sets out the ARPU assumption for VR and AR. This reflects expenditure on VR/AR devices and services, and an assumed inflation rate based on technology efficiencies over time.

Given that the technology is in its infancy, these revenues can be considered fully incremental, i.e. the base is close to zero. However, network constraints will reduce (not eliminate) demand since users will switch to lower quality services.

Figure 23 VR and AR - ARPU assumptions

Description	Assumption	Rationale
ARPU (2018) – "moderate evolution"	£193 per year	Based on 1 device (at £200), and 3 subscriptions or downloads per year (at £500 each)
ARPU (2018) – "ambitious innovation"	£279 per year	Based on 2 devices (at £300 each), and 3 subscriptions or downloads per year (at £50 each)
Inflation assumption (real)	-1% p/a	Technology efficiencies will increase the cost of technology each year

Source: Frontier

Notes: We assume that each device is kept for 5 years, and amortize cost of this period to get 'average' annual expenditure. Assume that each subscription/download priced at £50.

4.3.3 Results of demand analysis

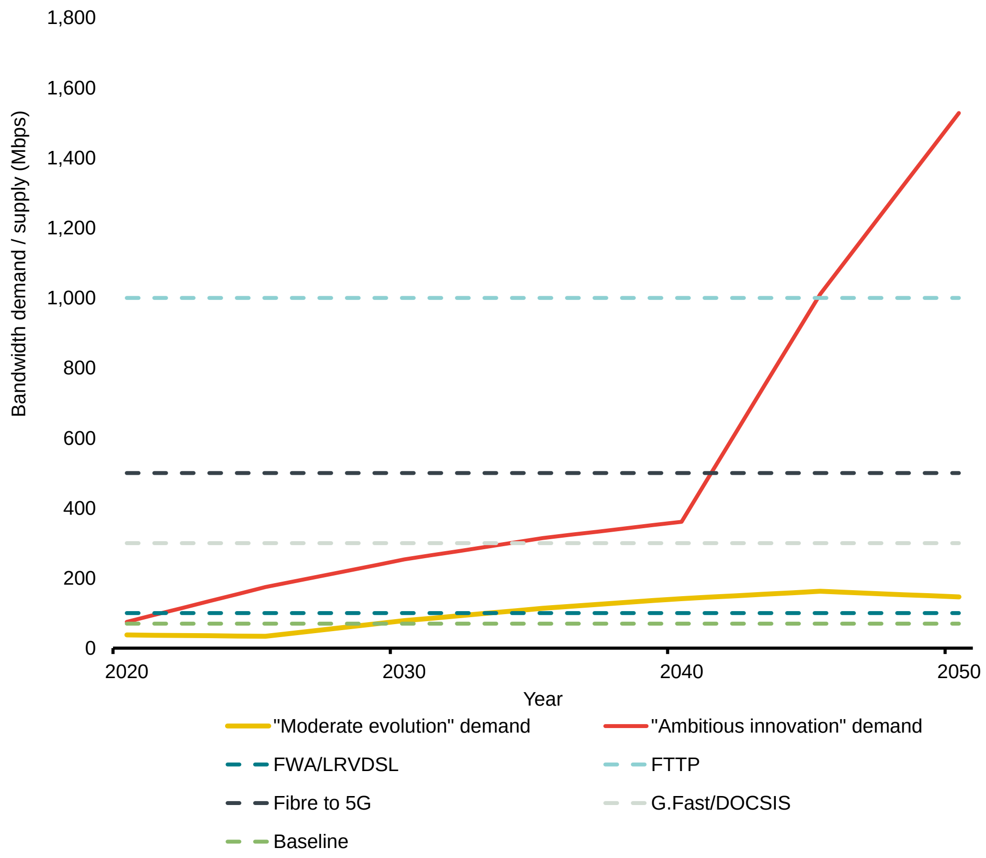
Figure 24 below shows VR and AR download bandwidth demand per household from 2020 – 2050, as well as the available bandwidth per household under each broadband technology. The significant increase in household demand from 2040 in the ambitious innovation scenario is a result of increased up take of very high resolution, 3D VR/AR devices which require significant bandwidth.

FTTP is able to deliver the "moderate evolution" scenario in all years and "ambitious innovation" up to 2045;

- Fibre to 5G is able to deliver "moderate evolution" scenario in all years and "ambitious innovation" up to 2041;
- G.Fast/DOCSIS is able to deliver "moderate evolution" in all years and "ambitious innovation" up to 2033
- FWA/LRVDSL is able to deliver "moderate evolution" up to 2033 and "ambitious innovation" up to 2021

- "FTTC" baseline (c.90% or premises) can deliver "moderate evolution" up to 2029, but not "ambitious innovation" in any year.[77]

Figure 24 per household VR and AR bandwidth capacity requirements and network supply constraints



Source: Frontier analysis

Incremental demand under each technology scenario

Figure 25 below displays estimated incremental demand (relative to the baseline) in the "moderate evolution" and "ambitious innovation" scenarios under each broadband technology

"Moderate evolution" scenario

Each of the broadband technologies is broadly able to deliver the "moderate evolution" bandwidth scenario in all years, with the only exception being the c.5% of households with FWA/LRVDSL segments having insufficient bandwidth in later years. Hence there is little difference in benefits of different broadband technologies studied in this report, with each generating around an additional £8-9 billion.

"Ambitious innovation" scenario

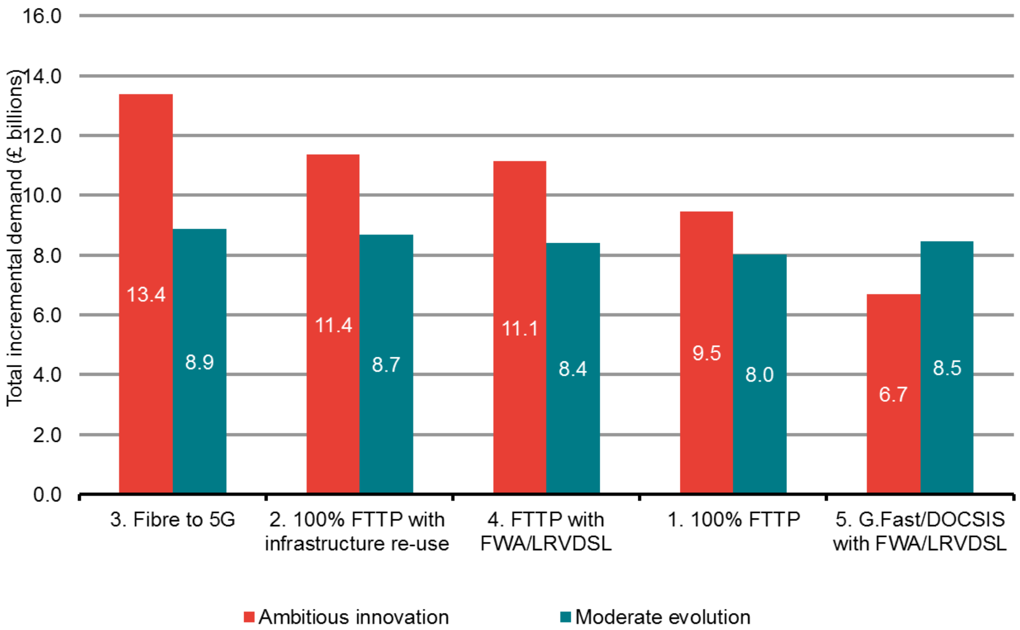
[77] For information on 'baseline' broadband speeds/coverage, see https://www.ofcom.org.uk/__data/assets/pdf_file/0035/95876/CN-Report-2016.pdf

The variation in incremental demand is more significant due to each technology constraining demand in a different number of years. FTTP is able to deliver the scenario in the most years though takes much longer to rollout. Whereas fibre to 5G is not sufficient from around 2040 when we assume use of more sophisticated CR / AR headsets drives network demand.

We estimate that:

- (3.) Fibre to 5G would generate an additional £13.4 billion in demand over the 30 year period
- (2.) FTTP with infrastructure re-use an additional £11.4 billion;
- (4). FTTP with FWA/LRVSL an additional £11.1 billion;
- (1). FTTP with new infrastructure an additional £9.5 billion; and
- (5.) G.Fast/DOCSIS with FWA/LRVDSL an additional £6.7 billion.

Figure 25 VR and AR – total incremental demand under each bandwidth and technology scenario



Source: Frontier analysis

Wider benefits of VR AR adoption

There are potentially wider benefits associated with VR AR adoption in the home which are not captured in this analysis. These could relate to its use in workplaces. As noted above VR AR technology could have many workplace applications. By enabling widespread residential use, the technologies could be more likely to be taken up on workplace (and vice versa with wide spread workplace use being a catalyst for increasing residential use). The Historical analysis illustrated how widespread adoption of workplace technologies such as PCs led to their rapid adoption in home.

Similarly, we also note that this residential technology which is envisaged for gaming applications might have other innovative applications which are not considered as part of this analysis. The Historical use case assessment noted that the wide installed base of PCs in the home (initially as gaming or home office tools) led to the rapid adoption of the internet which in turn realised economy wide economic gains.

The incremental economic impact of linked home and workplace demand, and the potential for VR / AR to have wider applications are difficult to quantify but are potentially non-trivial. Furthermore the extent to which access to very high capacity (as opposed to current capabilities of broadband) could constrain any wider benefits is also uncertain.

4.3.4 Sensitivity testing

As discussed previously, our incremental demand is clearly dependant on many assumptions, which we discuss in detail in Annex D. However, the VR/AR use case is particularly sensitive to certain assumptions due to its high bandwidth requirements in the ambitious innovation scenario.

The key sensitivities that affect the incremental demand in the ambitious innovation scenario are compression assumptions, and roll-out speeds in both scenarios.

In the ambitious innovation scenario, a more efficient video compression efficiency assumption of 50% compression every 10 years (in comparison to our baseline of 20% every 10 years) results in much higher incremental demand benefits in our higher bandwidth technologies like scenario 1 (100% FTTP) since more demand is able to be satisfied. Improved compression (compared to the base case has the most improvement to the scenario 5 (G.Fast) since it realises significantly more demand (81% higher incremental demand) than the base case.

In both scenarios, roll-out speed sensitivities have a significant impact on our results with the impact being strongest in the 50% slower roll-out speed assumption than in the 50% higher roll-out speed assumption. Technology scenarios involving FTTP (scenarios 1, 2 and 4) are particularly sensitive to slower roll-out speed assumptions since the base case assumes a relatively slow to roll-out. In the moderate evolution scenario, the incremental economic output in scenario 1. (100% FTTP) are 78% lower in a situation with 50% slower roll-out than in the baseline. Similarly, for scenario 2. 100% FTTP with technology re-use) in the ambitious innovation scenario 50% slower roll-out leads to 62% lower incremental demand benefits, which is to be expected as this scenario is highly dependent on large bandwidth requirements for the premium audio visual use case.

In terms of speed of adoption, in the ambitious innovation scenario scenario 3 (Fibre to 5G) and scenario 5 (G.Fast / DOCSIS) technology scenarios are impacted the most by a faster speed of adoption, with 10 years faster adoption resulting in 18% and 11% greater incremental demand relative to the baseline assumptions respectively. This is to be expected, as both scenarios have relatively fast roll out so can satisfy a faster growth in demand.

4.4 Small Office Home Office (SOHO) applications

4.4.1 Overview

Home working has become an increasing part of working life. In 2014 a record number of people in employment were home workers (defined as those who usually spend at least half their working time at home), with 5% (over 1.5 million)[78] of the workforce working within their home, and 8.9% using their home as a base whilst also working from other locations such as offices, or client premises. These numbers do not take into account the rise in “flexi-working”, where individuals use their home as an office on an infrequent but regular basis – around 1/3 of the workforce is estimated to work remotely at least some of the time[79].

By 2020 forecasts predict that over 70% of the workforce will have adopted some form of mobile working as the norm[80], and we can therefore expect a large proportion of worker be using their homes as offices in the future, at least some of the time. Similarly, research reveals that more than 60 percent of UK employees are willing to work remotely, at least occasionally, while 14 percent said they want to work from home every day[81].

Adequate communications technologies are an essential input for many of these workers. Home workers need to be able to communicate in calls, video conferences, share work, access large files etc. For the vast majority of home workers, existing broadband services are sufficient to facilitate everyday home working tasks such as emails, web browsing etc.

However, a sub-set of workers are likely to require higher levels of connectivity in order to facilitate their work. This could be working on live large datasets (for example trends towards IoT will see the collection, decimation of “big data”), or video editing. Therefore some users may require technologies and bandwidth above and beyond that which are used for personal use. This subcategory of workers is the basis for the SOHO use case.

Whilst overall number of home office workers is important, to estimate the impact of broadband investment we focus on individuals working from home in a career that requires high amounts of data as discussed above. We use the number of employees who are high bandwidth users (whose job involves the manipulation of large files – such as video, statistical software) which is estimated at 3% of the total of the total UK workforce[82]. The total number of relevant SOHO high bandwidth users can therefore be estimated to be around 320,000[83] currently.

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78 As above

79 https://www.citrix.com/content/dam/citrix/en_us/documents/oth/working-anywhere-a-winning-formula-for-good-work.pdf

80 https://app.croneri.co.uk/feature-articles/rise-mobile-and-flexible-working?product=8

81 https://www.advemix.co.uk/blog/remote-office-workers-in-the-uk-what-are-the-trends/

82 http://www.broadbanduk.org/wp-content/uploads/2013/01/Small-Business-Connectivity-Requirements.pdf

83 32m in employment*1/3 work from home some of the time* 3%high bandwidth employment =320,000 relevant.

4.4.2 Framework for assessing the benefits of SOHO

Teleworking is claimed to have a number of potential benefits to employees, employers and the wider economy, including:

- Cost savings for the employer;
- Productivity improvements in employees;
- Environmental externalities such as those from reducing commuting; and
- General improvements to the well-being of users as a result of improved work life balance.

The evidence available exploring the costs and benefits of telecommuting for both the employer and employee level is limited. Although there are a number of quantitative studies on the effect of tele-working on productivity, much of this analysis was conducted in very sector-specific cases – such as call centres, and for employers such as BT which may have less relevance to the use case studied.

Furthermore it is difficult to empirically measure some impacts of teleworking (such as the impact on knowledge and human capital spillovers).

Martin et al (2012)[84] conducted a meta-analysis of 32 existing papers exploring whether telework is effective for organizations, and found that telework does indeed have a small but positive correlation with improvements of productivity, commitment, retention, and performance. The authors cautioned on extrapolating these results, for example as many of the studies have discrepancies over what actually constitutes as a telework arrangement.

Similarly, many of the other studies included in our literature review involve self-reporting to surveys and are potentially affected by subjectivity and bias of self-selection into tele-commuting.

Shafizadeh et al (2000)[85] argue that although travel time savings from telecommuting may occur, it is difficult to compute if these are considered “work time” or “leisure time”, and thus the benefits may accrue to the employer or employee.

We must thus interpret the results from the literature with caution, understanding that they apply to very specific industries and are subject to individuals own bias, and that there are likely to be many other impacts on cost savings, work-life balance and environmental externalities that the literature is unable to explore fully.

In practice it would be difficult to accurately estimate the impact of teleworking on employer outcomes (in terms of greater productivity), or employee outcomes (in terms of the value of enhanced well-being), or on the magnitude environmental externalities.

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[84] Brittany Harker Martin, Rhiannon MacDonnell, (2012) "Is telework effective for organizations?: A meta-analysis of empirical research on perceptions of telework and organizational outcomes", Management Research Review, Vol. 35 Issue: 7, pp.602-616

[85] Kevan R. Shafizadeh, Particia L. Mokhtarian, Debbie A. Niemeier, Alan Salomon, (2000) “The costs and benefits of home based telecommuting”, California PATH Research Report

Therefore in estimating the impact that different broadband technologies would have on use of teleworking we simply estimate the volume of incremental equipment and services used to facilitate teleworking. These additional costs are likely to at least equal potential benefits for employers or employees (since if they did not it would be rational not to adopt teleworking. However, this estimate is not intended to represent the net cost or benefit of teleworking (which may include a number of other costs or savings such as travel or accommodation costs).

4.4.3 Demand forecasts

Adoption Forecast

As noted above the total number of relevant SOHO high bandwidth users can therefore be estimated to be around 320,000[86] *currently*. Furthermore approximately 3% of employees could be described as High Media users. We assume three separate effects will increase the use of SOHO applications; a structural change toward more employment in high media/data jobs, a number of occupations shifting towards being more data heavy over time, and an increase in the prevalence of working from home. We therefore estimate that percentage of High Media workers will increase from 3% of the population to 5% of the population in 2032 will therefore use SOHO applications.

Figure 26 Adoption Assumptions

	Assumptions	Source/explanation
Start Year	2017	320,000 estimated High Media already are remote workers currently[87]
Maximum adoption	5% of employees are high media remote workers	Slight uplift on the number of High Media jobs, as well
Maximum adoption year	2032	15 years after launch year (fixed assumption across use cases)
Adoption	Adoption increases as UFBA networks become available	We assume lack of UFBA broadband may currently constrain workers

Economic impact per user

As noted above there are a number of channels through which economic impacts of greater use of SOHO applications could be felt.

- Greater productivity as a result of time saved waiting for files to up load or download. The time that an individual must wait to upload files will not be entirely “lost” time. However, it represents an “inconvenience factor”. This is very difficult to quantify without qualitative evidence of consumers expectations of upload speeds.

[86] 32m in employment*1/3 work from home some of the time* 3%high bandwidth employment =320,000 relevant.

[87] Ibid.

- Firm wide productivity benefits as a result of lower churn and lower recruitment costs which are derived from being able to offer roles with enhanced work-life balance.
- Firm (or individual) cost saving as a result of lower travel costs and travel time where greater connectivity enables individuals to work away from the work place.
- Consumer welfare impacts as a result of enhanced work life balance.

Though, there may also be incremental costs incurred as a result of SOHO applications. For example increased costs of equipment or computing services. Furthermore in some occupations an increase in teleworking might be less efficient if it lowers scope for knowledge sharing.

Bandwidth and technological requirements

The majority of individuals engaging in a SOHO do not have bandwidth requirements above the normal level (except those already addressed in our Communications section of our smart home use case note, for video conferencing etc.). However, a small number of relevant SOHO’s handling large data every day in their work will be affected by bandwidth capacities, as they will be subject to “bursts” throughout their working day when uploading large data files. While high quality communications is obviously an important aspect of home working we note that this is captured in the Smarthome use case (in section 4.5).

To illustrate the impact that different technologies could have on SOHO workers Figure 27 shows the time to upload a 1GB file using different network technologies.

Figure 27 Time to upload a 1GB file on different broadband technologies

Broadband Technologies	Peak Upload Constraints (Mbps)	Time Waited[88]
FTTP	200	0 min 42 secs
Fibre to 5G	100	1 min 30 secs
G.FAST	60	2 min 23 secs
Superfast on FWA/LRVDSL	20	7 min 9 secs

Notes: Actual transfer speeds will likely be a bit slower than the above table shows, due to overheads.

To illustrate the impact that different broadband technologies could have on propensity to adopt SOHO applications we make assumptions about the requirements of high capability SOHO applications in the moderate evolution and ambitious innovation scenarios (Figure 28). We assume that SOHO users will be required to regularly upload large files and will have an upper limit on their willingness to wait.

Of course, in fact these simplistic assumptions do not reflect outcomes in a number of ways. First there will be a continuum of SOHO users with different needs and requirements. Second, it is not possible to model how changing expectations will affect SOHO user’s requirements. Increasing expectations will

[88] https://www.expedient.com/file-transfer-time-calculator/

mean users are likely to be more sensitive to delays. Third it is not possible to know the size of files that would be uploaded. Potentially SOHO users could be required to upload much larger files that cannot be foreseen currently.

Figure 28 Low and High bandwidth scenarios

	Low Scenario	High Scenario
Job Cases	9 x 120MB audio clips e.g./ one advert *Or* 9 x 120MB edited photos	1 x 13GB video required in *Or* 2 x 6GB photo portfolio.
Willingness To Wait	High – 15 minutes	Low – 10 minutes
Bandwidth Requirement	**10 Mbps**	**200 Mbps**

Source: http://greenlimepie.com/how-long-does-it-take-videos-to-process-on-youtube/
https://www.quora.com/How-many-GB-MB-are-in-a-3-to-4-min-video-HD

In relation to reliability we note that FTTH networks might offer greater reliability than copper based networks. Furthermore given that this use case relates to work rather than leisure uses of broadband, SOHO end users might attach greater importance to marginal differences in reliability. This in turn might mean that demand for more reliable networks (such as FTTH) is slightly higher and demand for (relatively) less reliable networks (such as copper based G.Fast) is slightly lower.

4.4.4 Results of the demand analysis

As noted above there are a number of potential benefits that can accrue to employers, or employees as a result of home working. For employers, home working can improve productivity (via improved recruitment and retention) or potentially home working could reduce costs (travel, or accommodation) or increase costs (increased investment in equipment to support home working). Employees could see benefits in terms of greater well-being (as a result of lower travel time and improved work-life balance). In turn, improved well-being could lead to positive externalities such as improved health and lower healthcare costs). Home working could lead to negative externalities such as lower human capital formation and human capital spillovers as a result of less knowledge sharing in the workplace.

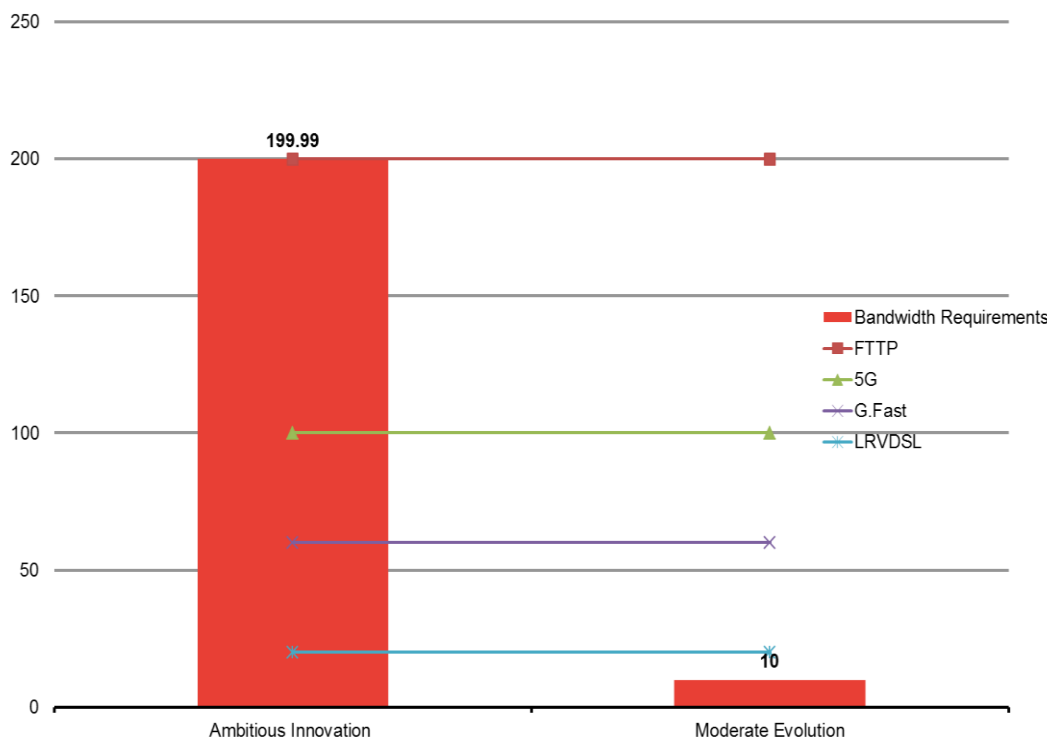
As noted above, this analysis has not attempted to quantify these impacts which are beyond the scope of this study. Instead we have attempted to assess the *magnitude* of home working enabled by different broadband technologies (to understand how choice of broadband networks affects the scale of home working). We do this by estimating the incremental investment in technology that would be required to support home working under our assumptions set out above.

Network constraints under different broadband technologies

Figure 4. below shows *upload* bandwidth demand per SOHO household from 2020 – 2050, as well as the available bandwidth under each broadband technology:

- FTTP is able to deliver the “moderate evolution” scenario in all years and “ambitious innovation” from 2020;
- 5G is able to deliver “moderate evolution” scenario in all years,
- G.Fast/DOCSIS is able to deliver “moderate evolution” in all years;
- FWA/LRVDSL is able to deliver “moderate evolution” in all years and
- “FTTC” baseline (c.90% or premises) can deliver “moderate evolution” in all years,

Figure 4. per SOHO household – bandwidth upload capacity requirements and constraints



Source: Frontier

Incremental demand under each technology scenario

“Moderate evolution” scenario

Under the moderate evolution scenario existing broadband technologies can deliver most conceivable SOHO applications such as video calling, messaging, email upload and download of documents. Therefore all potential High Media SOHO workers would be able to adopt teleworking patterns.

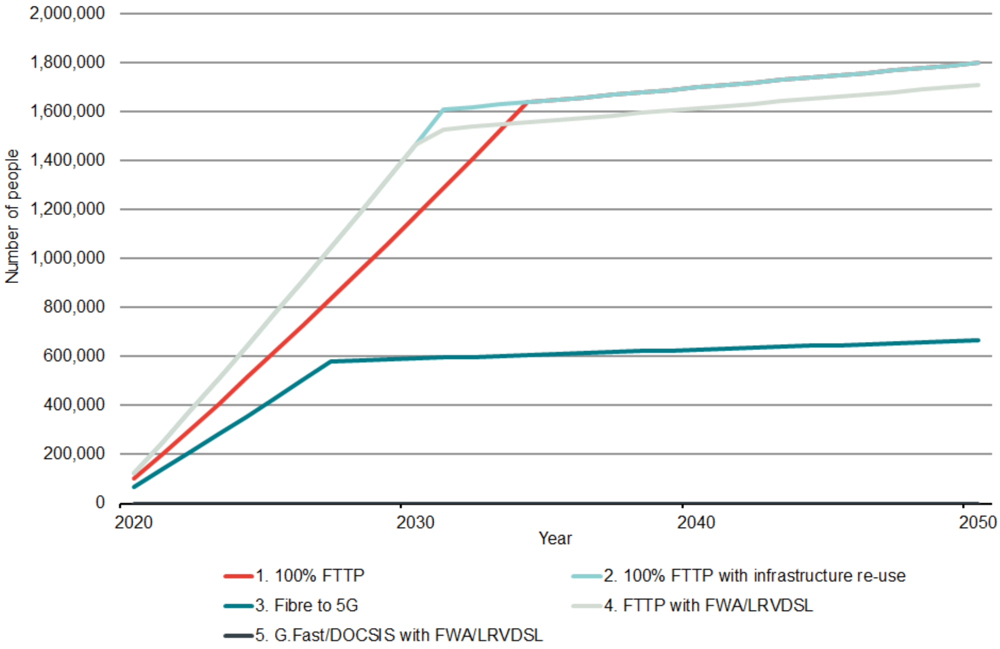
“Ambitious innovation” scenario

In the ambitious innovation scenario where home workers have to regularly upload large files, work with live datasets, analyse large “big data” data sets, then clearly investments in UFBA will benefit this sub-set of workers.

As noted above existing broadband infrastructure is sufficient for most purposes. Therefore investments in broadband which enabled home working will benefit the subset of users who require access to very high bandwidth. This could be those professions that edit video, or use very large datasets.

However, some of the technologies will constrain the number of workers that would be able to adopt teleworking practices. In particular those worker in rural areas where FWA or LRVDSL is deployed.

Figure 29 Number of worker that could benefit from SOHO under different technologies – Ambitious Innovation



Source: Frontier

Furthermore, it is possible therefore that the benefits of investments in broadband would be concentrated in rural areas where longer travel times necessitate a degree of teleworking. Investments in these areas could increase labour force participation in these areas (which could be as a result of an absolute increase in labour force participation, and transfers of workers from urban to rural areas). This in turn could have wider public policy benefits associated with reduced level of urban / rural inequalities.

4.5 Smart home

4.5.1 Overview

"Smart home" technology is defined broadly as technology which equips a household with the ability to automate and control various appliances around the home, from a central hub (e.g. smartphone or computer). The ability to control these appliances wirelessly requires that each device will be connected to the same network, which in most households would be their fixed broadband network via WiFi connected to the fixed network.

Many "smart home" technologies will only require a minimal amount of bandwidth to function, such as lightbulbs, thermostats and hub devices around the home where the data transmitted is very low and infrequent[89]. However, some specific technologies, such as video surveillance systems would potentially require significant additional bandwidth to function reliably, without hampering the households other use of the network. Home security is also the largest revenue producing area in the smart home technology realm, with over 61% of all US smart home revenues being attributable to network connected cameras in the 12 months ending June 2016[90].

Uploading surveillance feeds require significant upload bandwidth, particularly as the quality of the cameras improves. Similarly, smart communications products such as wireless webcams / videocalling cameras around the home may also require high bandwidth levels - particularly if the video is HD or if the webcams use a Lightfield Camera & Display for 3D display[91] in the more distant future.

Reliability of the network will also be important to both of these two use cases of smart home products. Losing surveillance footage can be costly to consumers, who will therefore put value on having a reliable network.

The role that broadband has to play in the smart home sector is therefore an essential one; without a reliable, consistent broadband connection consumers are less likely to invest in expensive smart home technologies[92] such a surveillance systems, and more likely to be disappointed by their products[93].

Figure 30 below sets out potential Smarthome uses.

Figure 30 Potential smart home uses

Potential smart home Uses:		Cost Level	Energy Saving?	Bandwidth Requirement
Thermostat/ Smart Meter		Low	Yes	Low <500kb/s

[89] Many devices may in future be smart and wirelessly controlled from a central hub via apps on smartphones or other devices.

[90] http://www.twice.com/news/statistics/61-smart-home-revenue-came-security-cameras-last-year/62470

[91] Discussion with R&D (Immersive and Interactive) team at BBC - Lightfield Camera & display would require 1GB upload & download speed

[92] Poor internet connection is the second largest barrier to adopting smart home technology → 25% https://www.gfk.com/fileadmin/user_upload/dyna_content/Global/documents/Reports/GfK-smart-home-teaserdeck-global.pdf

[93] PWC connected home report – of the 10% of smart home users who are dissatisfied most blame internet connectivity issues.

Lighting		Low	Yes	Low <500kb/s
Hub Technologies (e.g. Amazon Echo)		Medium	No	Low <500kb/s
Domestic Aids (e.g. Fridge, Vacuum, Electrical Outlet)		Mixed	No	Low <500kb/s
Communications (e.g. HD smart webcams)		Low	No	High 35 Mbps+
Security /Home Surveillance		High	No	High 50 Mbps+

Source: Frontier

4.5.2 Demand assumptions

Adoption forecast

smart home technologies have the potential for a gradual permeation into every home, in varying degrees of intensity depending on the consumer's interest in the technology. Whilst some of the existing smart technologies (such as smart meters) are commonly seen in homes[94], new more advanced technologies are being produced and permeating into homes. The total number of smart home

[94] We note that many smart meters do not rely on fixed networks and instead use GSM technologies.

devices is expected to reach 193 million units in the UK by 2020[95], with some estimates putting the average home at having 500 smart home products each by 2022[96].

Home security and smart lighting[97] are cited as key drivers of demand[98]. Similarly, 75% of consumers stated they would be willing to pay more on that smart surveillance technology in order to have additional safety features. There may be significant demand for high quality image recording, as consumers see safety as worth spending additional money on. Currently 3% of UK households have home surveillance security systems[99], but in the next 4 years penetration is expected to be at 17.4%[100].

Premium communications services such as UHD videocalling may become common[101] and can be integrated with existing smart home devices, such as Amazon's "Hello" device[102] which integrates both video call and smart home features. In 2015, 37% of established internet users stated they used Facetime/Skype at least weekly[103] whilst statistics from 2013 state that over 33%[104] of 25-34 year olds used these services at least quarterly.

Given the above two trends in Home Security and Home Communications, we assume that 50% of the population will adopt these smart home technologies, given that over time the costs of both technology hardware and cloud storage prices fall[105] and there are wide applications for the above equipment across a number of sectors.

Consumer demand

The table below sets out the ARPU assumption for smart home technologies, based off of predicted expenditure on products by households. We assume a central case where households engage with both smart home technologies that require higher bandwidth usage.

In our "moderate evolution case", it is assumed that households purchase one surveillance camera, one device with an integrated 4K camera for videocalling, and one subscription to cloud storage to store uploaded data. In our "ambitious innovation" case it is assumed that each household purchases of two of each.

[95] http://uk.businessinsider.com/internet-of-things-smart-home-automation-2016-8?cm_mc_uid=33947355901715059028102&cm_mc_sid_50200000=1505902810&cm_mc_sid_52640000=1505902810

[96] http://www.gartner.com/newsroom/id/2839717

[97] Lighting that can be controlled remotely via an app.

[98] PWC consumer report – 58% listed video surveillance as a priority.

[99] https://www.locksmithservice.co.uk/news/the-rise-of-smart-software-in-security/

[100] https://www.statista.com/statistics/528103/smart-home-penetration-uk-digital-market-outlook-by-segment/

[101] http://www.theaustralian.com.au/business/technology/review-logitechs-new-4k-webcam-gets-up-close-and-oh-so-personal/news-story/af040ccc69c461b74cc58fece7a0ca30

[102] https://www.digitaltrends.com/home/hello-videoconference/

[103] https://www.statista.com/statistics/322168/online-activities-of-established-internet-users-in-the-uk/

[104] https://www.statista.com/statistics/301662/online-video-calling-quarterly-by-age-uk/

[105] http://www.computerweekly.com/news/4500270463/Public-cloud-competition-results-in-66-drop-in-prices-since-2013-research-reveals

We consider that the impact of the multiple very low bandwidth smart home products that all homes will be likely to use are only likely to add a negligible bandwidth load.

Figure 31 Smart home - ARPU Assumption

Description	Assumption	Rationale
ARPU (2018) – "moderate evolution"	**£162 per year**	1 x Surveillance camera + 1 x cloud storage subscription +1 x 4K HD ready VC camera
ARPU (2018) – "ambitious innovation"	**£323 per year**	2 x Surveillance camera + 2 x cloud storage subscription +2 x 4K HD ready VC camera
Inflation assumption (real)	-1% p/a	Technology efficiencies will decrease the cost of technology each year

Notes: Full details of the assumptions used are set out in Annex F.4

Bandwidth and technical network requirement

Many smart home technologies will use minimal broadband, but even the most basic smart home surveillance products (or home communications webcams) could require a significant bandwidth to function at its peak capabilities, particularly as more than one camera could be required.

However, surveillance equipment could automatically switch to lower (but still sufficient) resolution if there were upload capacity constraints or could cache information locally until bandwidth became available.

For the purpose of modelling the difference in benefits that could be enabled by different broadband technologies we focus on upload constraints as use cases either require symmetric bandwidth, such as video calling, or upload dominates, such as home security. Given the asymmetry in upload and download network capabilities it is likely upload requirements will constrain use rather than download requirements.

The upload bandwidth required to support these smart home camera technologies is a function of:

1. resolution of recordings/streaming;
2. number of devices in the home; and
3. the frequency of use.

Resolution of recordings/streaming

We assume a "moderate evolution" scenario whereby standard definition cameras are suitable for the average household's home security, and high definition cameras are used for Home communications. This requires around 1.2 Mbps for the home surveillance at 1080p[106], and 10 mbps for HD home communications streaming[107]. In our "ambitious innovation" scenario however, 8K

[106] https://www.howtogeek.com/291176/how-to-change-the-video-quality-of-your-nest-cam/

[107] https://help.livestream.com/hc/en-us/articles/212062598-What-Kind-of-Internet-Connection-Do-I-Need-in-Order-to-Stream-

is expected for both home surveillance and home communications, requiring 50Mbps[108] for each 8K device to upload effectively at peak.

In both scenarios, other smart home devices (such as meters, or hubs) have a negligible impact on the bandwidth speeds required (<500kbps download speed)[109].

Number of devices

We have assumed that in "moderate evolution" scenario, two home surveillance cameras will be required. Similarly we have assumed two smart webcams will be required, potentially one fixed in living room whilst one could be used in an office or bedroom.

In the "ambitious innovation" scenario, we have assumed two high resolution home surveillance cameras are necessary.

Table 32 Bandwidth requirements at Peak hour usage[110]

	"Moderate evolution" scenario	"Ambitious innovation" scenario
Description	2 x Surveillance Camera in 1080p resolution *And* 2 x integrated HD videocalling cameras *Plus* 20x smart home devices requiring marginal bandwidth such as lightbulbs, hubs etc	2 x Surveillance Camera in 4K resolution *And* 2 x integrated 4K videocalling cameras *Plus* 50x smart home devices requiring marginal bandwidth such as lightbulbs, hubs etc
Bandwidth	2x 1.2Mbps upload speed for SD surveillance camera + 2 x 8 Mbps upload speed for HD webcam = **18.4 Mbps upload speed**	2 x 44Mbps upload speed for 4K surveillance camera + 2 x 44Mbps upload speed for 4K webcam = **176 Mbps upload speed**

In relation to reliability we note that FTTH networks might offer greater reliability than copper based networks. Given that some aspects of this use case relate to home security, it is possible that end users might attach some weight to marginal differences in network reliability.

108 *https://www.ispreview.co.uk/index.php/2015/06/youtube-tests-8k-video-streams-demands-50mbps-uk-broadband-speed.html*

109 https://www.libertyglobal.com/pdf/public-policy/Liberty-Global-Policy-Series-Connectivity-for-the-Gigabit-Society.pdf - smart meters only require 9.6kb/s. Accessed 5th October 2017

110 https://www.engadget.com/2015/07/17/bt-sport-ultra-hd-pricing/

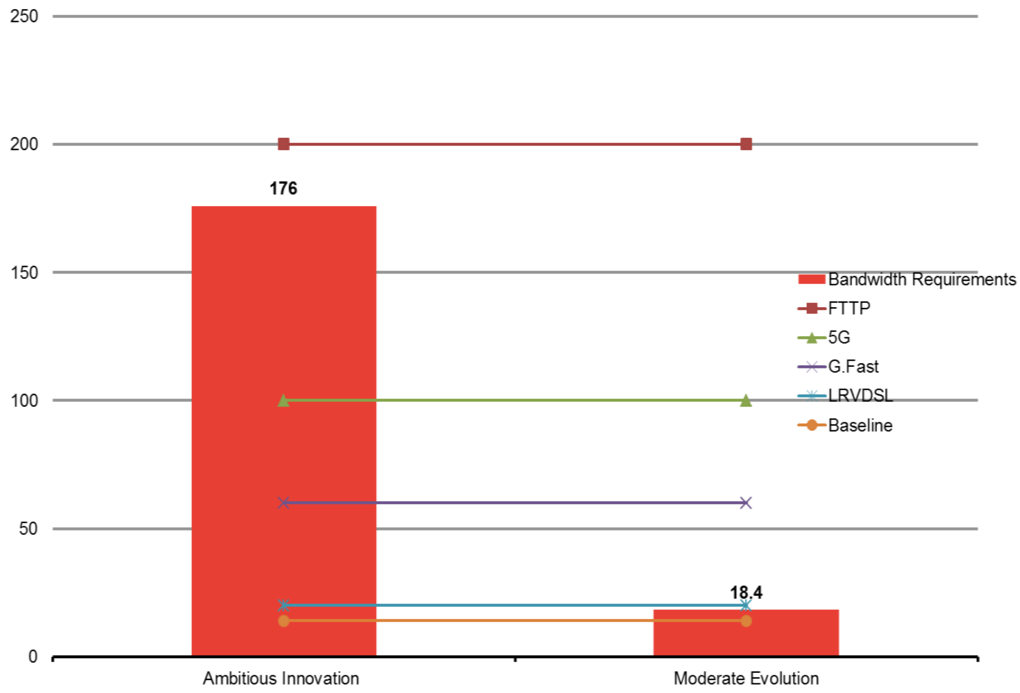
4.5.3 Results of the demand analysis

Network constraints under different broadband technologies

Figure 2 below shows upload bandwidth demand per Smarthome household from 2020 – 2050, as well as the available bandwidth under each broadband technology:

- FTTP is able to deliver the “moderate evolution” scenario and “ambitious innovation” in all years:
- all other technologies are able to delivered “moderate evolution” in all years, but not able to deliver “ambitious innovation” in any year; and
- the baseline is not able to deliver either scenario in any year.

Figure 2. per household smart home upload bandwidth capacity requirements and network supply constraints

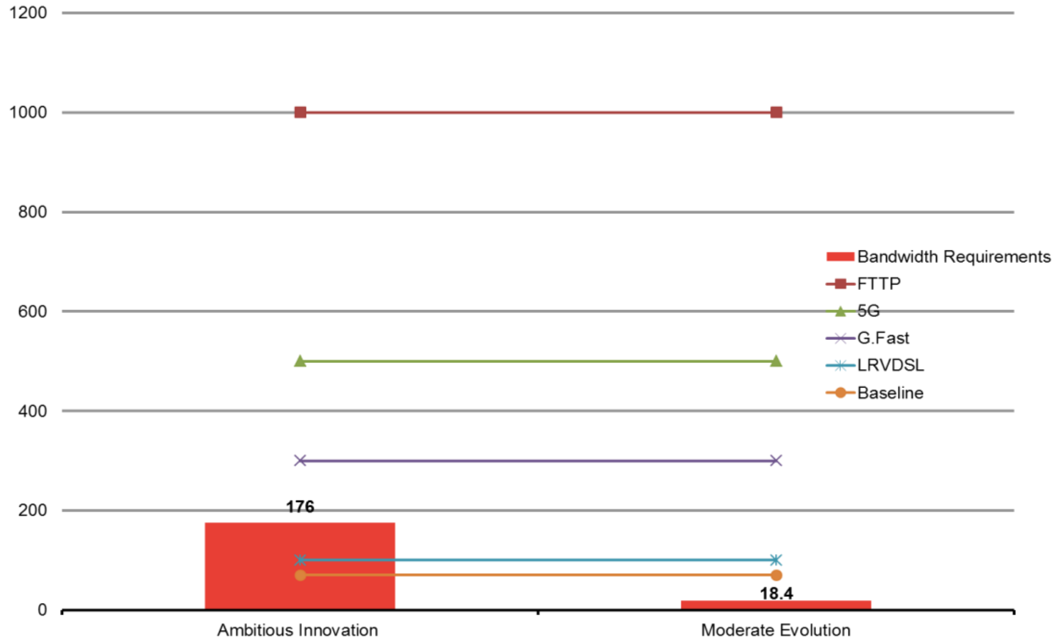


Source: Frontier

Figure 3 below shows download bandwidth demand per Smarthome household from 2020 – 2050, as well as the available bandwidth under each broadband technology:

- FTTP, 5G and G.Fast are all able to deliver the “moderate evolution” scenario and “ambitious innovation” in all years:
- all other technologies are able to delivered “moderate evolution” in all years, but not able to deliver “ambitious innovation” in any year (including the baseline).

Figure 3 per household smart home download bandwidth capacity requirements and network supply constraints



Source: Frontier

Incremental demand under each technology scenario

Figures 4 & 5 below displays estimated incremental demand (relative to the baseline) in the "moderate evolution" and "ambitious innovation" scenarios under each broadband technology

"Moderate evolution" scenario

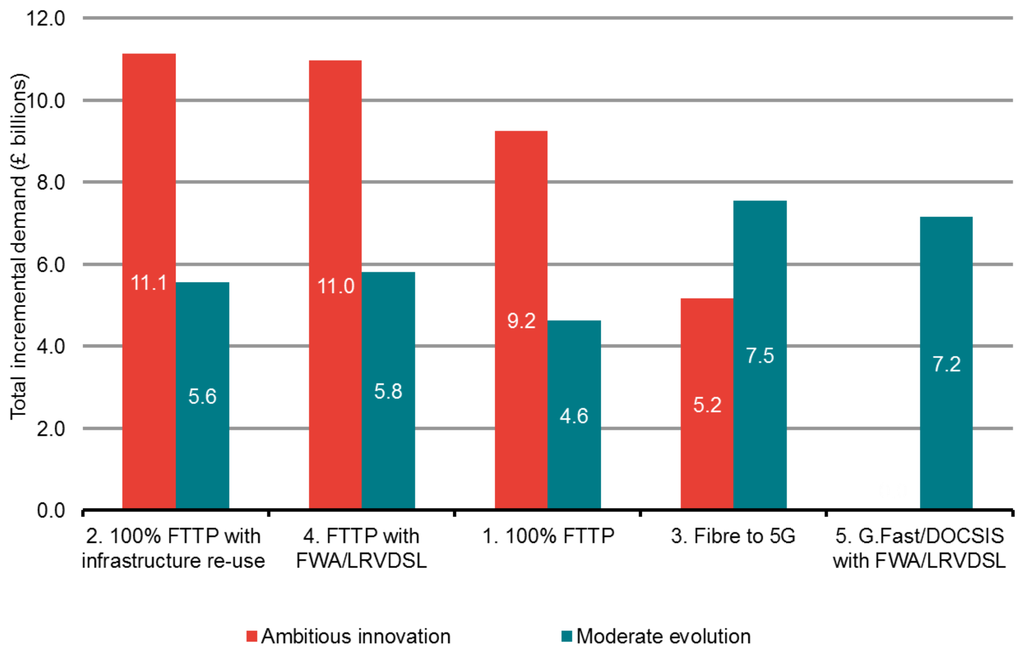
Each of the broadband technologies is broadly able to deliver the "moderate evolution" bandwidth scenario in all years, meaning incremental demand estimates are similar in all technology scenarios (ranging between £4.6 and £7.5 billion).

"Ambitious innovation" scenario

The variation in incremental demand is more significant due to each network technology being insufficient to upload surveillance camera content except FTTP constraining demand in all years. We estimate that:

- (2.) FTTP with infrastructure re-use would generate an additional £11.1 billion;
- (4.) FTTP with FWA/LRVDSL an additional £11 billion;
- (2.) FTTP with new infrastructure an additional £9.2 billion;
- (3.) Fibre to 5G an additional £5.2 billion; and
- (5.) G.Fast/DOCSIS with FWA/LRVDSL would generate no additional demand.

Figure 4. Smart home – incremental demand under each technology and demand scenario



Source: Frontier

4.5.4 Sensitivity testing

As discussed previously, our forecast economic output is clearly dependant on many assumptions, which we discuss in detail in Annex D. The smart home use case is however impacted most by the assumption on counterfactual demand (i.e. whether a reasonable "lower quality" substitute (with lower bandwidth requirements) is available, in both scenarios. In the base case we assume that the availability of reasonable substitutes at lower bandwidth means that where broadband network capabilities constrain the performance of the use case then demand is reduced to 75% of base case demand.

In the ambitious innovation scenario, if the forecast assumes counterfactual demand is 38% (i.e. half of the base case) then the investments in UFBA networks result in much higher incremental economic output relative to the baseline for all technologies other than scenario 5 (G.Fast). This is because (5.)G.Fast is unable to support VR/AR in the ambitious innovation use case, just like the baseline, and thus the incremental economic output still remains at zero.

4.6 Telehealth

4.6.1 Overview

Telehealth is defined as the use of digital communication technologies to deliver medical care, health education, and public health services at a distance. It relies on connecting and allowing data exchange between patients and their doctors in separate locations.[111] Telehealth includes telemedicine as well as other services, such as remote monitoring, assessment, communications, prevention and education.

There are many different potential forms of telehealth or telecare. These could include:

- Remote consultations with healthcare professionals;
- Vital signs monitoring;
- Activities of daily living monitoring;
- Home monitoring;
- Social networking, supporting online communities.

Telehealth is claimed to have a number of potential benefits (compared with healthcare in existing settings). These include:

- cost savings;
- improved health outcomes;
- improving the geographic, and demographic reach of health services;
- general improvements to the well-being of users.

Evidence on the effectiveness of telehealth

A 2011 study in the UK[112] modelled the impact of telehealth and telecare. It involved 6191 patients, 238 GP practices across three sites, Newham, Kent and Cornwall. It was a large scale, randomised trial, so its results were robust. The project focused on three long term conditions: diabetes, COPD and coronary heart disease. The programme provided a clear evidence base to support investment decisions in telehealth and telecare. However, given the costs of the interventions, the cost effectiveness of the telehealth programme was not proven. For example one study found that the "*probability of cost effectiveness was 11%... [the] results suggest that the QALY[113] gain by people using telehealth in addition to standard support and treatment was similar to those receiving usual care, and that total costs for the telehealth group were higher than for the usual care group*."[114] A study examining the effectiveness (though not cost effectiveness) of telecare concluded that "*telecare did not significantly alter rates of health or social care service use or mortality among a population with social care needs over 12 months*"[115].

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[111] https://www.healthit.gov/playbook/pdf/telehealth-startup-and-resource-guide.pdf

[112] Department of Health (2011) Whole System Demonstrator Programme Headline Findings https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/215264/dh_131689.pdf

[113] A QALY is a quality adjused life year and is used to measure change in outcomes for a given interntion.

[114] Henderson Catherine, Knapp Martin, Fernández José-Luis, Beecham Jennifer, Hirani Shashivadan P, Cartwright Martin et al. Cost effectiveness of telehealth for patients with long term conditions (Whole Systems Demonstrator telehealth questionnaire study): nested economic evaluation in a pragmatic, cluster randomised controlled trial BMJ 2013; 346 :f1035

[115] Adam Steventon, Martin Bardsley, John Billings, Jennifer Dixon, Helen Doll, Michelle Beynon, Shashi Hirani, Martin Cartwright, Lorna Rixon, Martin Knapp, Catherine Henderson, Anne Rogers, Jane Hendy, Ray Fitzpatrick, Stanton Newman; Effect of telecare on use of health and social care services: findings from

We also examined four “meta-analyses” of existing literature on the effectiveness of telehealth. We note that necessarily these meta-analyses draw information from previous older studies from different jurisdictions and therefore caution should be taken in interpreting the results where changing technologies and demand could affect the relevance of results. Care should be taken in extrapolating conclusions regarding tele-health from existing studies, as each original study is often specific to an individual health condition; the healthcare system; and the type of telehealth intervention.

Furthermore, the meta analysis noted below found that the robustness of results some original studies are weakened by study design or small sample size. We note that although there are potential benefits in health outcomes and cost savings from tele health, the evidence supporting this is mixed.

Pope et al (2011)[116] examined 16 meta-reviews, themselves covering 662 studies. Mostly these papers focus on health care outcomes, noting that there is a variability in effectiveness for some healthcare interventions and conditions for example with larger positive effects found for studies on mental health conditions, as opposed to physical health conditions. Seven of the eleven meta-analysis included urged caution regarding weak research design in the original 245 papers they cover, and thus concrete conclusions are difficult to draw from this meta-analysis.

Dario et al (2017)[117] examined 11 studies, specifically on the topic of chronic lower back pain and how telehealth interventions could affect health outcomes. The authors argue that telehealth interventions are *“not more effective than minimal interventions”*, as measured by various health care outcomes such as reducing pain.

Wade et al (2011)[118] examined 36 studies, specifically on the topic of how real time video communication technology can be used in a telehealth setting. The most useful conclusions drawn by Wade were in regards to the evidence on cost savings: 61% of the studies found telehealth to be less costly than the alternative. For applications such as home care, such telehealth technologies are cost effective, but interestingly for rural service delivery showed mixed results.

Totten et al (A recent meta review of 58 peer reviewed studies of potential benefits of telehealth found that of the studies that reported cost saving[119] *“four reviews (13%) concluded telehealth provides benefit in terms of reduced costs or utilization, 11 (34%) potential benefit, 10 (31%) were inconclusive, and 7 (22%) found no benefit or increases in cost or utilization”.* Furthermore, the meta-review noted that the quality of analysis underlying the conclusions on potential for cost

the Whole Systems Demonstrator cluster randomised trial, Age and Ageing, Volume 42, Issue 4, 1 July 2013, Pages 501–508, https://doi.org/10.1093/ageing/aft008

[116] Pope C, Rowsell A, O'Cathain A et al. For want of evidence: a meta-review of home-based telehealth for the management of long-term conditions. 2011.

[117] Dario A, Cabral A, et al. Effectiveness of telehealth-based interventions in the management if non-specific low back pain: a systematic review with meta-analysis 2017

[118] Wade. V et al A systematic review of economic analyses of telehealth services using real time video communication 2010

[119] Out of 58 included reviews, 32 contained some cost/utilization outcomes and of these focused on these outcomes exclusively. In the remaining 25 reviews, clinical outcomes and cost or utilization were included. See Telehealth: Mapping the Evidence for Patient Outcomes From Systematic Reviews Totten AM, Womack DM, Eden KB, et al. Rockville (MD): Agency for Healthcare Research and Quality

saving, meant that caution should be used in interpreting the results of the studies. *"Most of these finding are not the result of complex, sophisticated, or even comprehensive analyses. A few meta-analyses on utilization such as hospital admissions and emergency department visits were available. Furthermore, very few studies considered the overall cost-impact or cost-effectiveness of an intervention; rather they documented individual costs or resource use measures taken in isolation. Comprehensive cost-analyses are needed to understand the full implications of telehealth in various situations. Several of the authors of the reviews underscored that cost information was incomplete or inconsistently reported."*[120]

In relation to outcomes the study noted that in relation to telehealth applied to chronic disease or older patients that of the 31 studies, 13 (42%) reported benefits in primary or most outcomes, 11 reported potential benefits, 4 found no benefit, and 3 stated that the impact was unclear. In relation to remote patient monitoring of the 22 reviews that synthesized studies of monitoring, 10 concluded telehealth lead to positive benefits, 6 concluded benefits were possible, 2 were inconclusive, and 4 reported no benefit from telehealth.

4.6.2 Demand assumptions

Adoption forecast

Telehealth and Telecare have the potential to grow quickly in the next few years. In England, by 2010 roughly 1.7 million people were using some form of Telecare.[121] These were predominantly basic initial screening and assessment tools, including for example pendant alarms and other sensor based systems.

Numbers were lower for telehealth, with only 5,000 people in England using telehealth services in 2010.[122]

Since then, the number of patients adopting telehealth services has increased. A study by the European Commission estimates that in the UK, 9% of GPs offer virtual consultations to patients and 8% are equipped to monitor patients remotely.[123] Out of this sample, 1.5% of patients uses the consultation services occasionally and 5.4% routinely; 3.2% take advantage of remote monitoring occasionally, while 1.4% routinely.[124] These estimates would suggest that roughly 7.6m people in the UK used telehealth services.

One report states that in 2025 we could expect 3.4 million global users of VR/AR technology in healthcare, producing revenue of $5.1billion, for example in use for projecting MRI scans, or treating PTSD using VR controlled environments.[125] However, this is unlikely to drive residential broadband.

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120 ibid

121 https://www.kingsfund.org.uk/sites/default/files/Sustaining-innovation-telehealth-telecare-wsdan-mike-clark-nick-goodwin-october-2010.pdf, page 7. Accessed on 8 September 2017.

122 Ibid.

123 Benchmarking Deployment of eHealth among General Practitioners (2013), Annex II, Country Profile United Kingdom, page 11.

124 Ibid.

125 http://www.goldmansachs.com/our-thinking/pages/technology-driving-innovation-folder/virtual-and-augmented-reality/report.pdf

Given existing levels of take-up of forms of telehealth services we assume that adoption will continue to increase. A study by European Commission argues that penetration for Telecare services for people in the age range of 65 years and above will range between 3% and 15% of by 2030.[126] Penetration rates for telehealth is less certain, but it is estimated that roughly 25% of the population in the age range 50 to 80 years old would benefit from telehealth service; this percentage increases to 60% for the 80+ population.[127]

Given the mixed evidence on the cost effectiveness of telehealth we make reasonably cautious assumptions on the potential cost savings of telehealth. For example recent large scale randomised UK studies (set out above) concluded that telehealth was not cost effective. Nonetheless, there are a number drivers for further adoption: lower costs of devices, smaller devices (with smaller more power batteries) and a move to a decentralised provision of healthcare closer to users homes.

We therefore assume that adoption of more sophisticated video and monitoring telehealth applications will be as set out in Figure 33. We assume that the proportion of net cost savings (net of incremental costs incurred in providing telehealth / telecare for this proportion of activity is set out in Figure 35).

Figure 33 Assumptions on take up

	Assumption	Rationale
Launch	2020	Given households already take up forms of telehealth it is conceivable that more sophisticated video based or monitoring applications could arise at the start of the assessment period.
Maximum adoption	Primary care	We assume maximum adoption of 10% for remote primary care services, or equivalently roughly 6 to 7 million users over and above current users.
	Outpatient	We assume maximum adoption of 2% for outpatient services. Only a small number of outpatient services are substitutable by telehealth, for example collection of x-ray scans and other tests or mental healthcare services. For other services, for example blood transfusions and other laboratory tests, patients will still need visit the hospital.
	Inpatient	We assume maximum adoption of 5% for inpatient secondary care. This relates to a lower number of total bed days, whereby patients are discharged sooner and are monitored remotely via telehealth applications, and lower A&E admissions, similarly prevented by a higher patients monitoring rate.
	Social care	We assume maximum adoption of 5% for telecare services. We envisage more patients using video based monitoring application both for initial screening as well as for regular check-ups. For the elderly, telecare services have the potential of lengthening their ability to live alone in a self-sufficient way.

Source: Frontier Economics

[126] European Study on Users, Markets and Technologies, Directorate General for Information Society and Media European Commission, 2010.

[127] http://ec.europa.eu/employment_social/social_situation/docs/lot7_ict_finalreport_en.pdf

Notes: Adoption assumptions refer to the maximum percentage of incremental telehealth interventions in each area compared to the case now.

Network technology requirements

To successfully deliver video based and sophisticated monitoring telehealth and telecare services, networks must have a combination of technology requirements. In this section, we consider, in turn:

- bandwidth requirements;
- network reliability;

Bandwidth

Traditional telehealth services can be delivered via live video conferencing, for example to offer patients consultations. While data volumes transmitted from an individual household can to be relatively low,[128] we assume a HD communication in the moderate case and 4K in the ambitious innovation case. In addition we assume additional bandwidth required for remote physiological monitoring.

Since it is an important requirement for the provider of the service, we assume that this bandwidth requirement is symmetrically required for both download and upload. Also, given the focus on video, we make the same compression assumption (20%) as in our “virtual and augmented reality” and “premium audio-visual display” use cases.

Figure 34 Bandwidth requirements for telehealth[129]

Scenario	Communications	Monitoring	Total
"Moderate evolution"	5Mbps	3Mbps	8Mbps
"Ambitious innovation"	45Mbps	5Mbps	50Mbps

It is reasonable to assume that basic telehealth and telecare services are broadly deliverable on today’s networks. While some more complex applications of telehealth, such as remote surgery, would benefit from higher bandwidth requirements[130], these applications fall outside the scope of this report given that they are unlikely to occur in the home.

Reliability

Another dimension of technological requirements is network reliability. Having a reliable network is particularly important for remote patient monitoring services, in particular when monitoring is used as an emergency tool.

For other applications, such as remote doctor’s appointments, high network reliability is less problematic as the alternative is for patients to visit the GP’s practice or hospital. Poor reliability of broadband technology and high propensity of faulty connections might nonetheless have a significant downward impact on take-up. In this context, a G.Fast network, with higher propensity for faults than

[128] For example one report states that a teleconsultation could be carried out with bandwidth as low as 32 kbps (http://www.who.int/ehealth/resources/compendium_ehealth2013_7.pdf?ua=1).

[129] We note that for communications a large amount of bandwidth is required for shorter periods of time, whilst for monitoring the bandwidth requirement are less in both of our scenarios.

[130] For example, a surgeon operating remotely needs multiple HD video screens and highly reliable internet connection

fibre based approaches, could limit overall demand for telehealth services. However, even in the context of a slightly higher incidence of faults, (for example currently approximately 1 in 10 lines will incur a fault at some point in the year), this does not imply that video telehealth appointments or telehealth remote monitoring would not occur, since if a fault arose, there would be alternative options for the patient and medical team.

Cost savings

In this section, we consider the potential cost savings from adoption of telehealth services. While recent UK based studies have not found that telehealth and telecare is cost effective there is mixed evidence with some studies reporting positive savings. Therefore given the mixed evidence on the cost effectiveness of telehealth we make cautious assumptions on the potential for cost savings relating to the adoption of more sophisticated video and monitoring telehealth applications will be as set out in Figure 33.

We assume that the proportion of net cost savings (net of incremental costs incurred in providing telehealth / telecare) for the proportion of activity that can benefit from telehealth or telecare is set out in Figure 35[131].

Figure 35 Assumptions on maximum potential cost savings

	Assumption	Rationale
Primary care	10% cost reduction	We assume that the main sources of cost saving are accommodation costs and reduced number of cancelled appointments.
Outpatient	10% cost reduction	As with primary care, we assume cost savings to come from reduced accommodations costs and reduced number of missed hospital appointments.
Inpatient	5% cost reduction	Applying telehealth to inpatient appointments is likely to reduce the number of bed days for patients, whom are instead monitored remotely via new technology. More frequent patient monitoring is also likely to reduce emergency A&E admissions. We estimate the net cost saving to be positive and leading to a 5% overall cost reduction.
Social care	8% cost reduction	With telecare, the expectation is that more people will be able to live autonomously for longer, alleviating congestion problems for social homes and reducing day-care costs.

Source: Frontier Economics

Notes: Cost reductions refer to the percentage reduction in costs for the sub-set of interventions to which telehealth is applied.

[131] The total cost saving is the sum of total spend in each health sector covered multiplied by the proportion of activity that can benefit from telehealth telecare (Figure 33 at maximum adoption), multiplied by percentage of costs saved (Figure 35).

Figure 35 summarises our assumption on total cost savings.

Counterfactual

The cost savings identified in the previous section assume no technological constraint on telehealth and telecare adoption. In this section we discuss the counterfactual scenario: we identify what would be the cost savings in a world where the telecom network doesn't support telehealth.

As discussed above, the network technology might impose some limit on telehealth adoption. While we envisage that basic telehealth and telecare services are broadly deliverable on today's network, lower quality, such as lower video quality may affect the experience. This in turn might affect the experience of patients, with a few of them switching away from telehealth.

While most telehealth and telecare services would still be delivered reliability to affect take up to a degree. Under the counterfactual assumption, we assume that cost savings will be reduced by 25% if a network is unable to support the application (though the majority of users could use telecare but with lower bandwidth (SD consultations instead of HD or 4K).

4.6.3 Results and conclusion

While there are potential benefits to telehealth and telecare, these functions can largely be delivered over existing networks. Therefore the incremental benefits relate to improving provision of access to telecare in the most rural areas where broadband is not currently sufficient to support the use case.

Reliability could be a factor in determining the value of telehealth / telecare. However, we consider it unlikely that networks with a marginally greater likely of reliability would offer significant incremental benefits. This is because:

- telehealth would not be used in cases where reliability was critical (given the potential impact of failure of the communications network or of the Customer Premises Equipment); and,
- in most other cases in the event of a fault a user could have recourse to alternative healthcare facilities.

Our analysis has estimated the potential *cost savings* that could arise if telehealth and telecare is able to substitute for existing forms of healthcare delivery. However, we also note that telehealth and telecare have potential to increase the health (i.e. in some cases could be a more effective way to treat patients). To the extent that telehealth and telecare could increase levels of health, then this in turn could lead to externalities (though we have not quantified these).

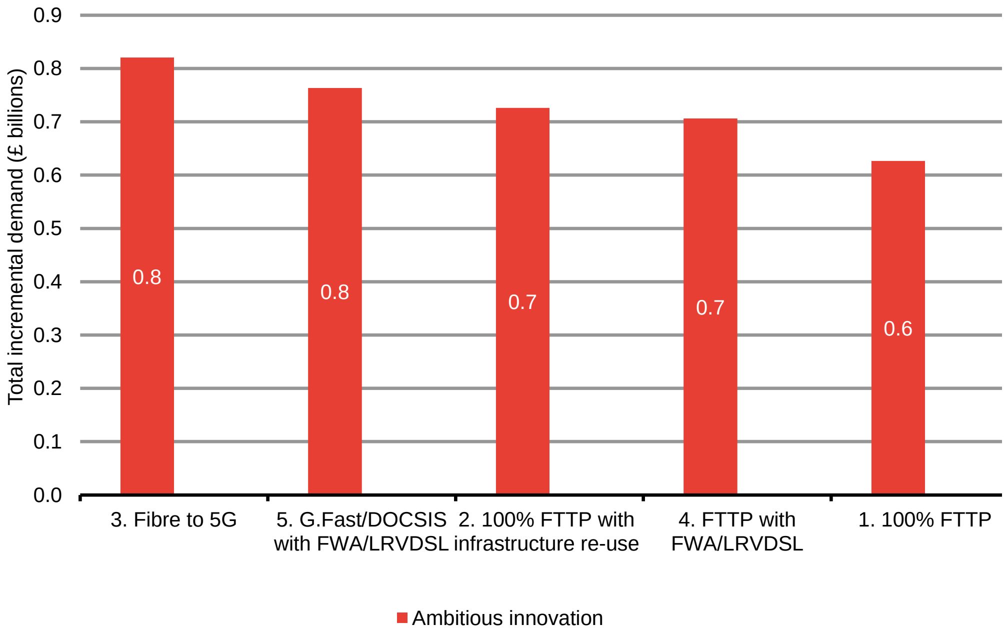
While precise estimate of the potential benefits of telehealth is difficult to assess. Some studies have noted that telehealth / telecare does not affect costs, and some that it can increase costs.

Therefore we make assumptions on the potential for telehealth to reduce costs of healthcare provision. We note that there are number of regulatory, privacy and cultural constraints on the take up of telehealth which might impede its use.

Figure 35 summarises our results. We estimate that:

- in the "ambitious innovation" scenario each broadband technology scenario could generate around an additional £600-£800 million in cost savings over the 30 year period; and
- in the "moderate evolution" scenario the effect is close to zero.

Figure 36 Telehealth – cost saving in ambitious innovation scenario



Source: Frontier analysis

4.7 Online learning

4.7.1 Overview

Digital technology has evolved and broadened the way in which teaching and training can be delivered - both in the classroom/work place and for distance learning. UFBA could potentially facilitate distance learning by improving current delivery methods and opening up new possibilities for learning.

Distance education technologies are divided into two modes of delivery: synchronous learning and asynchronous learning:

- In asynchronous learning, participants access course materials flexibly to fit their own schedules (this is the highly successful model operated by The Open University, the UK's largest academic institution).[132] Generally today's models entail flexible downloading and emailing, and can be accessed with "*little bandwidth and low-end computers*".[133]

[132] http://www.openuniversity.edu/ accessed on 3rd October 2017

[133] http://what-when-how.com/distance-learning/asynchronous-vs-synchronous-interaction-distance-learning/ accessed on 2nd October 2017.

- Synchronous learning is where all students are 'present' at the same time (e.g. by web conferencing), Synchronous distance learning is arguably more relevant in relation to UFBA, as this entails "real-time" video streaming. This type of distance learning is not yet mainstream, although online lectures are being trialled by some institutions in advanced countries and 'Massive Open Online Courses (or "MOOCs") – where a large number of geographically dispersed students simultaneously stream are quickly gaining in popularity.[134]

Given that synchronous distance learning is still in its infancy, the extent to which education and training will drive household demand for bandwidth is uncertain.[135] The two key unknowns are: (a) eventual take-up; and (b) the extent to which high bandwidth technologies such as ultra HD, AR and VR will feature. Current solutions tend to be fairly low quality video streams, but future developments spoken about include much higher bandwidth options, such as virtual field trips and holographic telepresence (where 3D cameras and AR devices are used to create the illusion of "presence" in a different location).[136] [137] One report [138] states that in 2025 an estimated 15 million users will utilize VR or AR technology for use in education, such as for "virtual field trips".

These new technologies could also have a role in asynchronous learning, For example, the student could download a virtual school trip to "attend" at their leisure.

There are number of VR education and training applications available, but are currently very niche, meaning eventual take-up is very uncertain. However the value of "transporting" yourself elsewhere is likely to be of significant value to distance learners (who may be time or financially constrained), suggesting many could take it up if it becomes accessible.

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[134] Popular MOOCs attract followings of up to 100,000 students (see: AD Little for Vodafone Group "Creating a Gigabit Society" (2016) page 22)

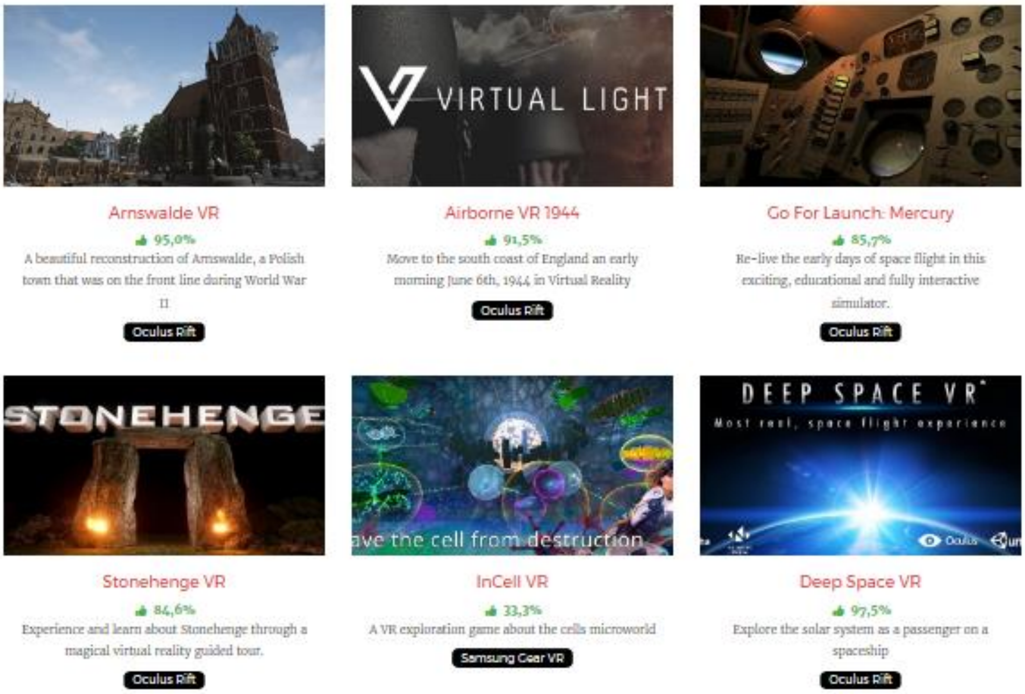
[135] Although households are the focus of this project for the NIC, current trends suggest that UFBA could also potentially play a role in the delivery of distance learning. Some institutions are currently considering options that will decrease their need for bandwidth (e.g. low quality video streams) because current networks are unable to fulfil their requirements (see AD Little for Vodafone Group "Creating a Gigabity Society" (2016) page 22).

[136] This is an augmentation of reality to create the impression that someone is "present" in a location where they are not. Microsoft's 3D capture technology, "Holoportation" provides this functionality when used in conjuction with its AR headset the "HoloLens" (see https://www.microsoft.com/en-us/research/project/holoportation-3/ accessed on 2nd October 2017).

[137] A.D Little "Creating a Gigabit Society" (2016); http://whatis.techtarget.com/definition/holographic-telepresence; and https://edu.google.com/expeditions/#how-it-works (accessed on 2nd October 2017).

[138] http://www.goldmansachs.com/our-thinking/pages/technology-driving-innovation-folder/virtual-and-augmented-reality/report.pdf (accessed 5th October 2017)

Exhibit 3. Online learning – examples of educational VR applications



Source: https://unimersiv.com/reviews/oculus-rift/

4.7.2 Demand forecast assumptions

Adoption forecast

We use the number of students at the Open University as the basis for our adoption forecast, and assume that the "addressable" market is around twice this number. This is based on the assumption that new technology will improve the distance learning experience, and attract some new students who would have otherwise previously chosen another education (or perhaps none at all).

This results in a total "addressable market" or "maximum adoption" of 350,000 students [139]. We also assume these are uniformly distributed across households at one student per household, and a 2012 "start year" - as this was when a number of MOOCs and synchronous distance learning programmes were launched in the UK and US[140].

139 The number of students at the Open University today is 174,739 (see http://www.open.ac.uk/about/main/strategy/facts-and-figures accessed on 3rd October 2017).

140 See for example See for example: http://www.telegraph.co.uk/education/educationopinion/9750392/Free-online-university-courses-are-Moocs-a-gamble.html; http://www.ed.ac.uk/news/2013/moocs-31011 http://www.nytimes.com/2012/11/04/education/edlife/massive-open-online-courses-are-multiplying-at-a-rapid-pace.html?mcubz=1; and https://www.futurelearn.com/about-futurelearn (accessed on 2nd October 2017).

Figure 37 Online learning – adoption assumptions

	Assumption	Rationale
Start year	2012	Year in which number of MOOCs were launched in UK and US
Maximum adoption	350,000 or 2% of households	A
Maximum adoption year	2027	15 years after launch (fixed assumption across use cases)
Adoption	S-curve adoption	Fixed assumption across use cases

Our assumption is that distance learning can still be delivered in a scenario where a given broadband technology constrains delivery using higher bandwidth methods. We also assume that this alternative would be a reasonably close substitute; in that the consumer would still be able to access broadly the same content (e.g. lower-resolution video can still be used), and get the same qualification. We therefore assume that demand is 25% lower in the “constrained” scenario than the “unconstrained” scenario.

Bandwidth and technical requirements

We assume that distance learning is delivered by a mix of premium display technologies which evolve over time.

Our “moderate evolution” scenario assumes the following market development:

- In 2020 100% of content uses HD video and by 2025 5% of content migrating to 4K video;
- “Basic” VR begins to enter the market from 2035, growing to 20% by the end of the period
- 4K grows to 80% by the end of the period, with HD video disappearing entirely.

In our “ambitious innovation” scenario we assume that:

- In 2020, 50% of content uses HD video and 50% use 4K video;
- By 2030, 4K grows to 75%, completely replacing HD;
- “Basic” VR enters in 2025;
- “Advanced” VR launches in 2035, growing to 40% by 2050.

This gives the implied average download bandwidth requirements shown in Figure 38. We note that there will also be some upload required for distance learning (e.g. two-way video conversations), however we do not expect this to be key to the experience or be constrained by any of the broadband technologies.

Figure 38 Bandwidth requirements for online learning

Scenario	2020	2025	2030	2035	2040	2045	2050
"Moderate evolution"	8	9	18	24	24	23	23
"Ambitious innovation"	26	31	34	48	58	66	72

Consumer demand

Residential broadband to support education could impact demand for education in three ways.

- It could be used as a complementary tool to support learning in the current formats (students using broadband to access learning, collaborate as a tool create and submit work).
- It could substitute for existing distance learning providing a more rewarding and interesting experience.
- It could increase demand for distance learning.

The technology used as a complement to traditional education will not increase revenue (students will still attend traditional institutions regardless of whether a distance learning option is offered complementing the course though they may derive greater consumer surplus). Therefore, our estimates of the potential incremental demand enabled by broadband networks will focus on the third instance (recognising that this may not be exhaustive).

There is necessarily a large difference in our consumer demand assumption in "moderate evolution" and "ambitious innovation", to reflect the uncertainty around how the distance learning market will develop.

Our "moderate evolution" scenario reflects the state of the market as it is today: synchronous and video-based methods are not a key part of distance learning methods (The Open University for example relies mainly on asynchronous methods); "MOOCs" are more niche and tend to be free, or very cheap, and frequently do not feed in to a formal degree or qualification.[141] "FutureLearn", for example, is a digital education platform owned by the Open University[142], which offers short self-contained, online courses, for free or at a very low cost.[143] We assume an incremental demand per users of £545 per year, which is around the price of a paid programme with FutureLearn[144].

Our "ambitious innovation" scenario reflects a world in which high-bandwidth distance learning methods are the norm, and make up a high share of all content. In this scenario students who study remotely are able to closely replicate the experience of being a "physically present" student, through high-quality interactive video, AR and VR. In this scenario it is reasonable to assume that a large part of the value students derive for distance learning is through these

141 https://www.thecompleteuniversityguide.co.uk/distance-learning/moocs-(massive-open-online-courses)/ (accessed on 3rd October 2017).

142 https://www.futurelearn.com/about-futurelearn (accessed on 3rd October 2017).

143 https://about.futurelearn.com/blog/upgrading-futurelearn-courses (accessed on 3rd October 2017).

144 https://www.theguardian.com/education/2016/may/26/moocs-earn-degree-credits-first-time-two-uk-universities

methods. Our ARPU assumption is therefore in line with the average fees paid to study at the Open University - which is £2,864 per year.[145]

The table below sets out the ARPU assumption for online education. This reflects incremental expenditure on online education that would be enabled by broadband services.

Figure 39 Online learning – ARPU assumptions

Description	Assumption	Rationale
ARPU (2018) – “moderate evolution”	£545 per year	Price per module on Future Learn
ARPU (2018) – “ambitious innovation”	£2,864 per year	Based on the average fees paid per year by Open University students
Inflation assumption (real)	0% p/a	We assume willingness to pay, and therefore price, for education remains constant over time

In relation to reliability we note that FTTH networks might offer greater reliability than copper based networks. However, it is unlikely that in many cases reliability could prove critical to this use case. This is because activities could be rescheduled, or alternative networks could be used. Therefore it is unlikely that reliability could be a critical factor which affected demand for the use case.

4.7.3 Results of demand analysis

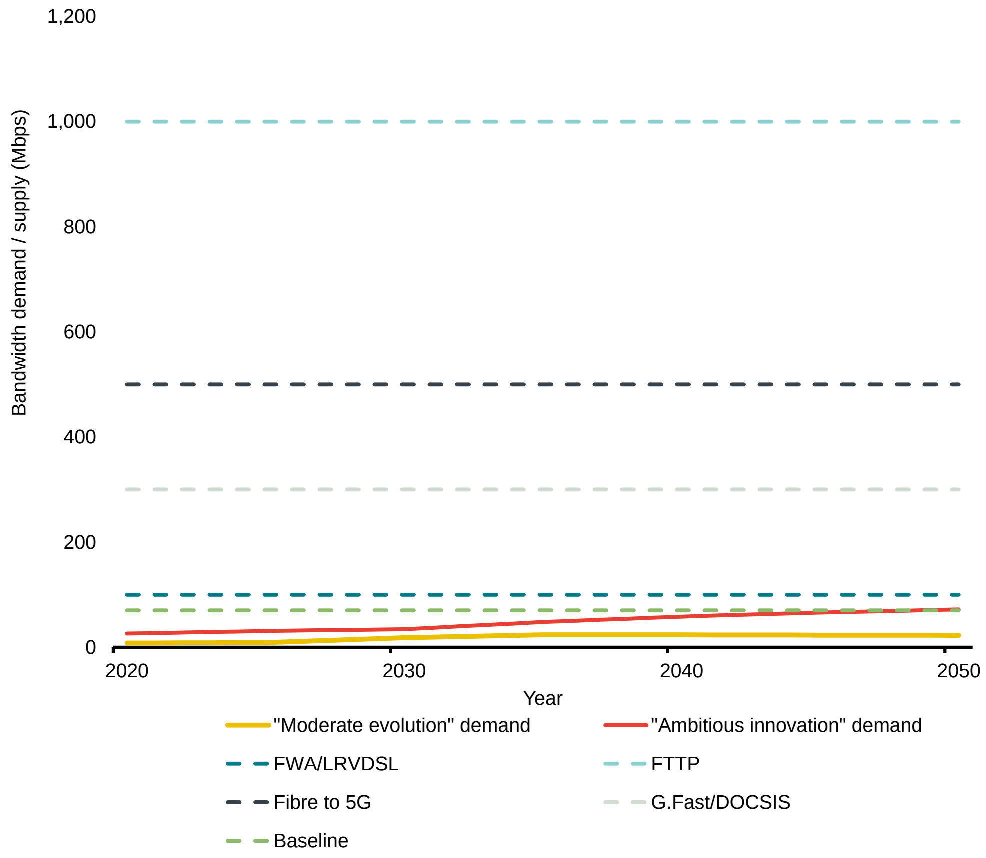
Figure 40 below shows distance learning download bandwidth demand per household from 2020–2050, as well as the available download bandwidth under each broadband technology.

Under our assumptions there is no constraint for our “moderate evolution” scenario in any of the roll out scenarios, but a slight download constraint in the baseline. However there is a more substantial baseline constraint in “ambitious innovation”, resulting in higher incremental demand.

We note there is likely to be some uploading required in distance learning (e.g. lecture seeing video of student) - however we assume that this will be less frequent and bandwidth intensive, and therefore not constrained by any of our technology scenarios.

[145] http://www.open.ac.uk/courses/fees-and-funding accessed on 3rd October 2017.

Figure 40 per household distance learning bandwidth capacity requirements and network supply constraints



Source: Frontier analysis

Figure 41 below shows the estimated incremental demand (relative to the baseline) in the “moderate evolution” and “ambitious innovation” scenarios under each broadband technology.

“Moderate evolution” scenario

Since all technologies and the baseline can broadly deliver education uses of broadband there is little incremental demand enabled by investments in broadband. However, consumers who would otherwise only be able to access slow speed broadband would obviously benefit from investments and be more able to access education.

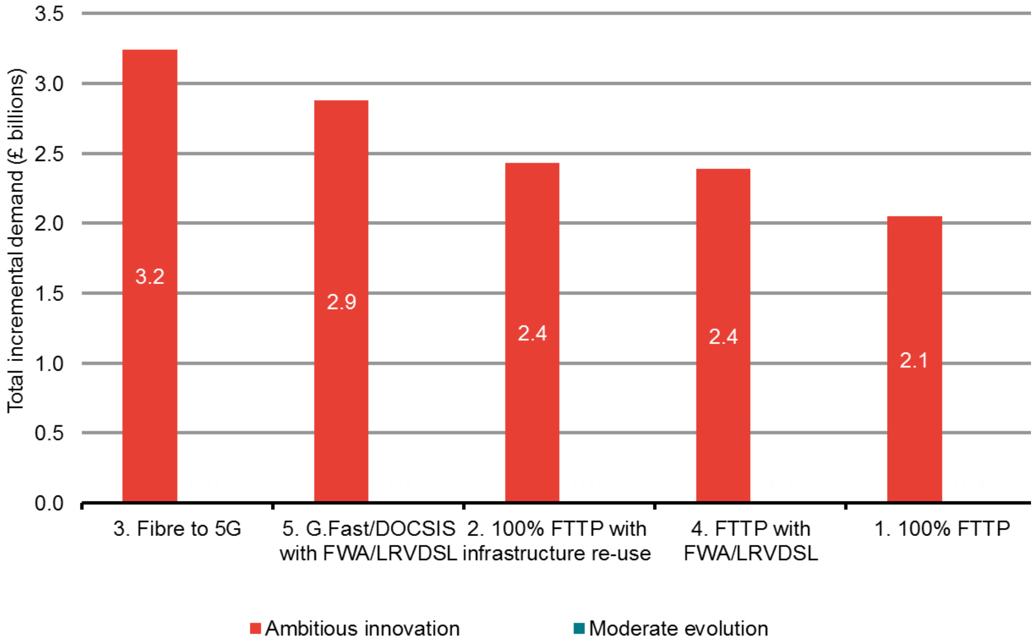
“Ambitious innovation” scenario

The variation in incremental demand is more significant due constraints in our baseline being “lifted” at different speeds in the broadband technology scenarios. We estimate that:

- (3.) Fibre to 5G would generate an additional £3.2 billion;
- (5.) G.Fast/DOCSIS with FWA/LRVDSL an additional £2.9 billion;

- (2.) FTTP with FWA/LRVDSL an additional £2.4 billion;
- (4.) FTTP with FWA/LRVDSL an additional £2.4 billion and;
- (1.) FTTP with new infrastructure an additional £2.1 billion.

Figure 41 Online learning – total incremental demand in ambitious innovation scenario



Source: Frontier Analysis

These estimates represent the incremental participation in education via distance learning as a result of further investments broadband. In practice broadband applications will also be used to lower costs of participation or to improve the delivery of education. The impact of broadband could have wider economic impacts improving educational outcomes or participation. Impacts of investment would particularly be felt where existing broadband speeds would otherwise remain at 10 Mbps.

Given the wide range of potential uses of broadband to support education the precise magnitude of potential incremental economic output enabled by investments in UFBA networks should be treated with caution.

However, as illustrated by the difference in the scenarios, existing broadband networks will support most education uses and it is only in innovative assumptions in how education will be delivered that investments in broadband realise significant benefits in this sector.

4.7.4 Sensitivity testing

As discussed previously, our forecasts of incremental economic output is clearly dependant on many assumptions, which we discuss in detail in Annex D.

However, for the our Online Learning use case only the ambitious innovation scenario is impacted by our sensitivity testing, since our baseline technology can achieve out moderate evolution bandwidth requirements in all years (so incremental economic output enabled by UFBA is zero).

In the ambitious innovation scenario, incremental demand is particularly sensitive to changes in roll-out speeds for our FTTP technology scenarios (which have relatively slow roll out in the base case), but not for scenario 3 (fibre to 5G) scenario. 50% faster roll-out of technology only results in a 7% increase in incremental demand relative to the baseline for scenario 3 (fibre to 5G), whereas 50% faster roll-out increases incremental economic output by 33% in scenario 1 (100% FTTP).

4.8 5G cost economies of scope

4.8.1 Overview

Fifth generation mobile technologies ('5G') which are planned to be introduced from 2020 onwards are intended to complement (rather than replace) existing 4G mobile networks (and their evolutions). 5G technologies are envisaged to enhance mobile networks in a number of key dimensions:

- providing access to far more machine to machine devices (Internet of Things) at low cost;
- providing much higher mobile broadband data rates than current 4G networks; and
- providing ultra-reliable, ultra-low latency networks for specific vertical applications.

IoT applications are likely to be supported by low frequency spectrum due to the need to provide ubiquitous coverage. As such, the existing infrastructure used to deliver services (using mobile spectrum already allocated for mobile use in the 800 and 900 MHz bands) can be re-used. However, the provision of higher data rates and lower latency is likely to require the use of large holdings of spectrum which are only available in higher frequency bands (such as 28 GHz)). Use of high frequency spectrum will require base stations to be sited nearer to user terminals than current mobile frequencies due to as the poorer physical propagation characteristics of high frequencies. This means that 5G networks will typically use a dense network of 'small cells' at street level to provide services.

When determining the economic benefits of economies of scope between roll out of fixed UFBA networks and mobile 5G networks we assume that 5G networks will be rolled out in urban areas from 2020 onwards. The rollout will be based on a network of small cells and will take place, independently of the roll out of 'fixed' broadband services. As such the demand, and hence consumer benefits derived, from 5G use cases would not be affected by the roll out of fixed broadband services[146].

[146] Potentially there could be some second order effects where 5G mobile is either a substitute for fixed broadband services, potentially lowering the benefits derived from fixed broadband upgrades or a complement to fixed services, potentially increasing the benefits derived from fixed broadband upgrades.

However, there are clear synergies or economies of scope between the co-ordinated roll out 5G networks and fixed broadband networks which would bring benefits in terms of reduced cost, compared to rolling out two networks on a standalone basis independent of one another':

- In the 5G to the lamp post fixed scenario, much of the infrastructure and equipment could be shared between the 'fixed'' and 'mobile' networks where the coverage of the two networks overlapped;
- In FTTH scenarios, the roll out of dense fibre networks to urban properties could provide backhaul for 5G operators at a lower cost than if fibre backhaul was rolled out under a counterfactual based on the existing FTTC/HFC networks (or alternatively the use of radio based backhaul was used in place of fibre).

We consider that the roll out of new technologies such as G.Fast or DOCSIS 3.1 on the current infrastructure will not reduce the cost of rolling out a 5G mobile network, compared to the status quo.

4.8.2 Methodology for estimating cost synergies

Our methodology aims to forecast the cost reductions that result from rolling out a 5G network where an existing "5G to the lamp post" or FTTH fixed scenario exists.

For assumptions on the scale of 5G roll out for both mobile and fixed broadband we rely on estimates from the reports commissioned by the NIC. We assume that the cost savings will be restricted to the "urban" and "suburban" geotypes:

- In "dense urban" geotypes, there are: fewer residential customers; existing dense fibre networks; and 5G sites at the street level may not be appropriate to deliver in-building broadband due to the high level of clutter;
- In rural geotypes, the level of demand is unlikely to be sufficient to justify the cost of roll out of a dense network of small cells using high frequencies.

We use the following estimates of the number of 5G base stations required to deliver an enhanced mobile broadband service from the LS Telcom report[147]

Figure 42 Number of base stations required for 5G mobile broadband coverage

Geotype	Number of base stations (thousand)
Urban	187
Suburban	309
Total	496

Source: LS Telcom report Table 22

Note: Based on a single shared multi-operator network

By way of comparison, approximately 75 thousand base stations would be required to deliver a 5G fixed broadband service[148].

However due to the uncertainties of forecasting fixed and mobile broadband on a standalone basis we do not consider it possible to determine the potential magnitude

[147] LS Telcom: FINAL REPORT 5G Infrastructure Requirements in the UK On behalf of the National Infrastructure Commission.

In terms of the number of base stations where there would be potential synergy savings to deliver a 5G fixed broadband service we assume that the 90% of 5G fixed broadband sites could be used for 5G mobile broadband (assuming that some sites cannot be co-located). Similarly we assume the 90% of 5G mobile broadband sites would be in areas served by FTTP and G.Fast networks in the case of a FTTP roll out in these geotypes (allowing for a small number of sites to be located in non-residential areas).

We use estimates on the costs associated with building and operating 5G base stations as shown below.

Figure 43 Input 5G base station costs (per base station)

Cost category	Capital expenditure (£thousand)	Annual operating expenditure (£thousand/year)	Asset life (years)
Fibre backhaul	12		25
Infrastructure (mast, buildings etc)	2	5	20
Base station equipment	4	0.2	10
Provisioning	1.5		10

Source: Prism for cost estimates. Frontier estimates of asset lives

Note: Annual operating costs for infrastructure covers costs of wayleaves,

In order to estimate the costs over 30 years, we convert capital expenditure to an annualised figure using an annuity calculation and then assume this annual cost is constant over 30 years from 2021 to 2050 which we then discount to a net present value. This gives the following costs per base station.

Figure Net present value per base station (2021-2050)

Cost category	Cost (£thousands)
Fibre connection	12.9
Infrastructure	71.2
Equipment	10.2
Provisioning	2.8
Total	97.2

Source: Frontier calculations

4.8.3 Analysis and results

Based on the assumptions set out above we estimate the cost savings of rolling out a 5G network where an existing "5G to the lamp post" or FTTH fixed scenario exists.

The potential cost savings assume the following.

- That a 5G mobile base station can use the same infrastructure and backhaul as a 5G fixed base station but that there will be no synergies on equipment or provisioning due to the different requirements of a fixed and mobile network;

[148] Source: Prism consulting for NIC.

- In the case of a FTTP or G.Fast roll out, that the cost of providing a fibre backhaul to a 5G base station in the roll out area will be 75% of the cost of providing a link in the counterfactual.

Combining these unit cost savings with the applicable number of 5G base stations gives the following results.

Figure 44 Estimated total cost synergies

	5G fixed scenario	FTTP and G.Fast scenarios
Savings per base station (£thousand)	84.1	9.7
Applicable 5G mobile base stations (thousand)	68	446
Total saving (£millions)	5,680	4,326

Source: Frontier Calculations

5 HOUSEHOLD COMBINATORIAL USAGE ANALYSIS

5.1 Introduction

Section 4 set out the benefits that broadband could enable across a number of different use cases, from a range of vertical sectors. This analysis was conducted independently for each use case, with the results combined. However, this analysis does not take full account of the interdependencies between use cases. In a given household there may be a number of users, each of whom will use a range of applications and services which rely on the household's broadband connection. An individual user may use multiple applications simultaneously, for example surfing the Internet while watching TV. Devices may generate traffic independently of users for example downloading software updates automatically, or uploading video surveillance.

This section considers the impact of the interdependencies between different users and use cases all using a single residential broadband connection. However, this is not a comprehensive forecasting exercise taking into account the representative nature of the use cases considered and the difficulty of forecasting how different use cases may combine over a single connection. Instead the aim of the analysis is to understand broadly the degree to which different technologies may constrain the combination of uses by a household, even if they do not constrain any single use.

5.2 Methodology

5.2.1 The peak hour

Generally, the relationship between network capacity and demand for a telecommunications network is assessed during the "peak hour" or "busy hour". The peak hour is the hour each month where the volume of data demanded by a household is at a maximum (given predictable variations in data download each day, week, and month). By dimensioning the network to deliver applications in the peak hour at a reasonable quality of service, the quality of service at other times should be at least as good.

For residential broadband the peak hour is generally in the evening, when people tend to be at home. The increasing consumption of video via broadband networks means that peak hour data traffic has been growing more rapidly than average traffic[149] as video consumption is concentrated in the evening.

[149] The Zettabyte Era: Trends and Analysis June 2017 https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html

5.2.2 Outline

Our analysis considers the potential typical household demand for bandwidth at peak busy hour. In doing so:

- We first consider a segmentation of UK households by their household characteristics (such as size) and use of technology.
- We then posit how each household type will use digital technology at the mid-point of our analysis (2030 – 2040). By this point, most use cases in this report will have rolled out. In this analysis we consider the typical use in the “moderate evolution” and “ambitious innovation” scenario.
- We finally consider different household segment’s consequent demand for bandwidth (at peak time), and compare this to the projected household capacity.

5.3 Household segmentation

There is likely to be significant heterogeneity in households’ attitudes to technology and hence their usage of broadband enabled services. These will reflect variation in a number of household factors which could include the following.

- The number occupants: the more people that live in a household, the higher their likely overall use of technology.
- The age of the occupants: younger users tend to use innovative technologies more than older users.
- Variation in the preferences of household occupants: individuals will vary in their use of technology.

In estimating typical household demand for bandwidth we make assumptions about the segmentation of households in the UK in their attitudes to technology from “always on” households to “seldom online” households taking into account both household size and the propensity to consume higher bandwidth services.

Using this segmentation we forecast the potential combinatorial use in terms of the peak bandwidth demand of highest users and of median (average) users. It is possible to examine the technological network constraints that might apply to individual segments.

To segment households we have used existing studies which segment *individuals* by their use of technology[150]. This analysis segments individuals in the following way.

- The majority of adults between 18 and 34 have the highest data consumption, and are identified as “always on”.
- Adults between 35 and 44 are equally split between “always on” and “fully connected” consumers.

[150] Source: http://www.personicx.co.uk/

- Digital consumption of adults between 45 and 54 is slightly lower and some users are identify within the "browser open" group.
- The majority of adults between 55 and 64 are "emerging users" (with some in the seldom online group).
- Most adults 65+ are identified within the "Seldom online" group.

By combining individual segmentation by attitudes technology, and analysis of household composition by size and age it is possible to segment UK households by their attitudes and take up of technology (using the same identifiers as individual segmentation). For example households with older children are assumed to be "always on", retired households are assumed to be "seldom online".

Figure 45 Household digital penetration

	Always on	Fully connected	Browsers open	Emerging users	Seldom online
Household penetration	35%	31%	16%	7%	10%

Source: Frontier Economics

We note that this approach cannot fully capture all the factors that affect household demand for bandwidth or the full heterogeneity of demand. However, it is a reasonable basis to estimate how differences in broadband technology could affect different households.

5.4 Assumptions on household usage

We assume that use cases described in this report are adopted, though households vary in their take up of different uses. Below we set out the assumptions that we make for household usage of broadband by digital segment around the middle of the assessment period (2030 - 2040) and the consequent bandwidth demand in each of the Ambitious Innovation and moderate evolution scenarios.

Moderate Evolution

For the *moderate evolution* scenario for each household segment we set out peak hour use of technology in Figure 46 below, assuming all of these devices/services are used simultaneously. Household segments with a greater number of members are assumed to use a greater number of applications simultaneously. We assume that the telehealth and educational use cases do not result in significant incremental bandwidth demand since these largely rely on video communications (which is included in the "Smarthome Comms" use case). To the degree that telehealth or educational use cases are active in the busy hour these may substitute other uses we have taken into account.

Figure 46 Peak hour use of technology: moderate evolution (peak hour per month 2030- 2040)

	Always on	Fully connected	Browsers open	Emerging users	Seldom online
VR / AR	2* headsets	1*headsets	1*headset	0*headset	0*headset
Display	1 * 8K display	1 * 4K display	1*4K display	1*HD display	1*SD display
Web-browsing	10MB per page (embedded instant HD video), 0.5 second delay	8MB per page (embedded HD instant video), 0.5 second delay	6MB per page (embedded HD instant video), 1 second delay	5MB per page, 1 second delay	5MB per page, 1 second delay
SOHO	10GB file uploads, 15 minute waiting time	1GB file uploads, 10 minute waiting time	1GB file uploads, 15 minute waiting time	100MB files, 5 minute waiting time	100MB files, 15 minute waiting time
Smarthome - surveillance	2*HD upload	2*SD upload	2*SD upload	1*SD upload	None
Smarthome - Comms	2*HD webcam	1*HD webcam	2*SD webcam	1*SD webcam	1*SD webcam
Telehealth	Limited telemonitoring	Limited telemonitoring	Limited telemonitoring	Limited telemonitoring	Limited telemonitoring
Distance learning	No incremental bandwidth requirement	No incremental bandwidth requirement	No incremental bandwidth requirement	No incremental bandwidth requirement	No incremental bandwidth requirement

Source: Frontier assumptions

Ambitious Innovation

For the *ambitious innovation* scenario we assume similar penetration of use cases but significantly higher bandwidth, as set out in Figure 47 below.

Figure 47 Peak use of technology ambitious innovation (peak hour per month 2030-2040)

	Always on	Fully connected	Browsers open	Emerging users	Seldom online
VR / AR	2* headsets	1*headsets	1*headset	0*headset	0*headset
Display	1 * 3D lightfield technology	1 * 8K display	1*4K display	1* 4K display	1*HD display
Web-browsing	10MB per page (embedded instant HD video), 0.5 second delay	8MB per page (embedded HD instant video) 0.5 second delay	6MB per page (embedded HD instant video) 1 second delay	5MB per page 1 second delay	5MB per page 1 second delay
SOHO	13GB file uploads, 10 minute waiting time	10GB file uploads, 15 minute waiting time	1GB file uploads, 15 minute waiting time	100MB files, 5 minute waiting time	100MB files, 15 minute waiting time
Smarthome - surveillance	2*4K upload	2*HD upload	2*HD upload	2*SD	None
Smarthome - Comms	2*4K webcam	2*HD webcam	1*HD webcam	1*HD webcam	1*SD webcam
Telehealth	Limited telemonitoring	Limited telemonitoring	Limited telemonitoring	Limited telemonitoring	Limited telemonitoring
Distance learning	No incremental bandwidth requirement	No incremental bandwidth requirement	No incremental bandwidth requirement	No incremental bandwidth requirement	No incremental bandwidth requirement

5.5 Results of the household combinatorial usage analysis

Based on the requirements of bandwidth for the use cases as set out in Figure 46 and Figure 47 we have estimated the bandwidth (download and upload) demand that could be required in combination in peak hour utilisation in the *moderate evolution* and *ambitious innovation* scenarios around 2030-2040.

Moderate Evolution

Figure 48 sets out the results of the combinatorial usage analysis, again it is worth noting that these "peak" constraints would only occur when all use cases were used simultaneously.

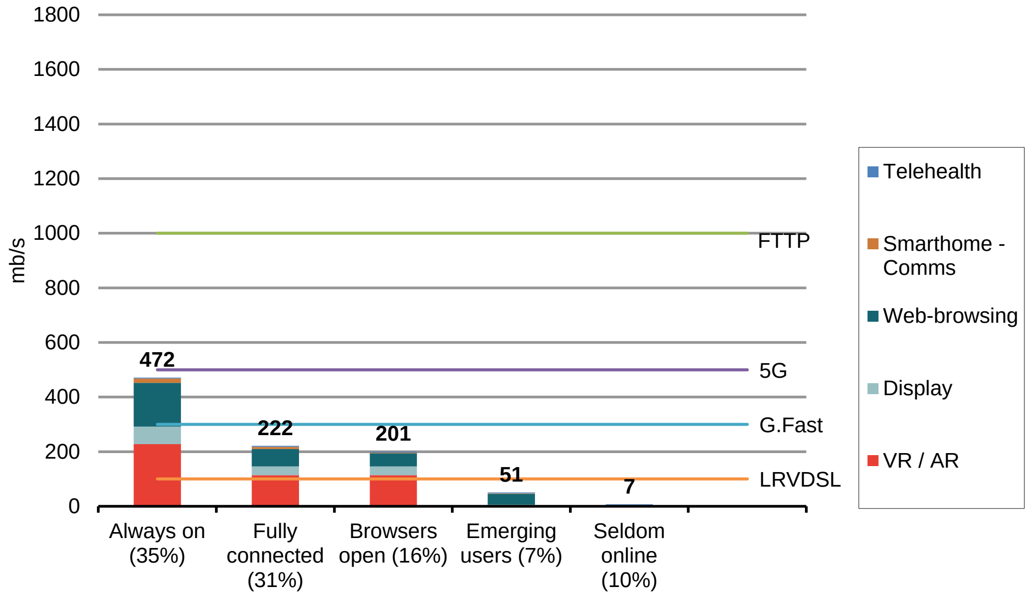
Figure 48 Bandwidth requirements by application (peak hour per month)

		Always on	Fully connected	Browsers open	Emerging users	Seldom online
VR / AR	Download	228Mbps	114Mbps	114Mbps	0Mbps	0Mbps
Display	Download	64Mbps	32Mbps	32Mbps	6Mbps	1Mbps
Web-browsing	Download	160Mbps	64Mbps	48Mbps	40Mbps	1Mbps
SOHO	Upload	98Mbps	14Mbps	10Mbps	2Mbps	1Mbps
Smarthome - surveillance	Download	16Mbps	3Mbps	3Mbps	2Mbps	0Mbps
Smarthome – Comms	Upload / download	16Mbps	8Mbps	3Mbps	2Mbps	2Mbps
Telehealth	Download	4Mbps	4Mbps	4Mbps	4Mbps	4Mbps
Total download		472Mbps	222Mbps	201Mbps	51Mbps	7Mbps
Total upload		134Mbps	29Mbps	20Mbps	8Mbps	6Mbps

Source: Frontier

Figure 49 sets out the stacked bandwidth peak download demand, alongside the capabilities of different broadband technologies assuming the moderate evolution scenario.

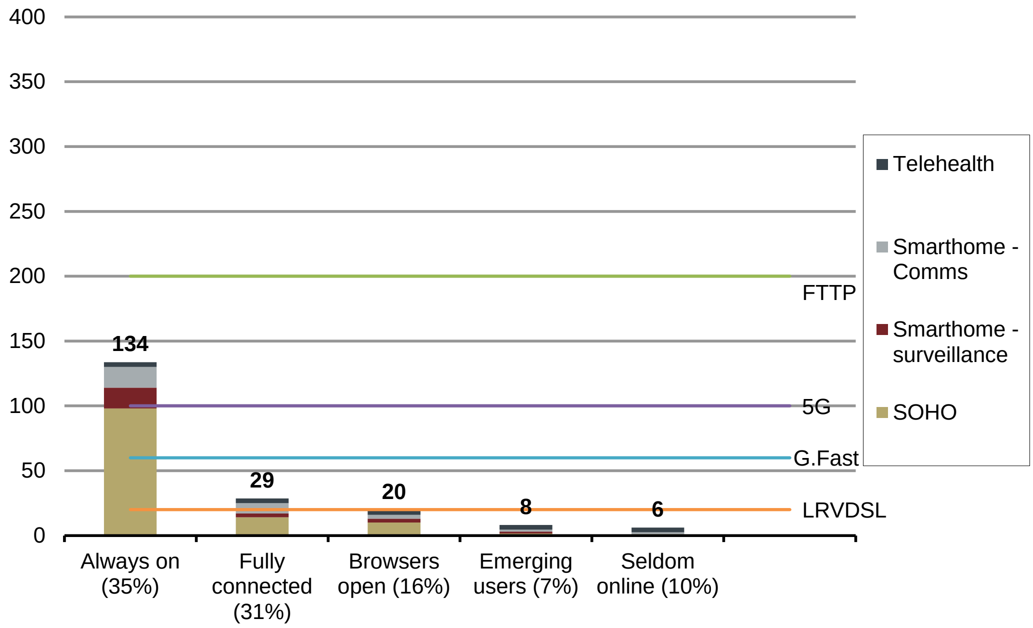
Figure 49 Household bandwidth *download* peak demand and network capability (moderate evolution 2040)



Source: Frontier

Figure 50 below sets out the household upload requirements in the moderate evolution scenario.

Figure 50 Household bandwidth *upload* peak demand and network capability (moderate evolution 2040)



Source: Frontier

In this analysis the "always on" household segment would face upload, but not download network constraints during peak hour when using all networks with the exception of FTTP. The G.Fast and 5G UFBA technologies would be sufficient in both the upload and download peak hour bandwidth requirements for the median household (located in the fully connected segment). Whilst FWA/LRVDSL would only be sufficient for the very least digitally engaged (emerging users and seldom online (17% of households)).

This analysis suggests that in the long run, using assumptions in the moderate evolution scenario, even where all technologies may be able to support individual use cases, a proportion of households may use applications in combination in such a way that only 5G or FTTP could meet the upload requirements.

Ambitious Innovation

Figure 51 sets out the results of the combinatorial usage analysis and considers the percentage of households that would face constraints at peak utilisation. It is worth noting, that these "peak" constraints would only occur when all use cases were used simultaneously, which may be infrequent. Furthermore, there may be mitigation strategies (such as communications or audio visual content could be made in lower definition, or page loads could be longer) for the duration of the constraint.

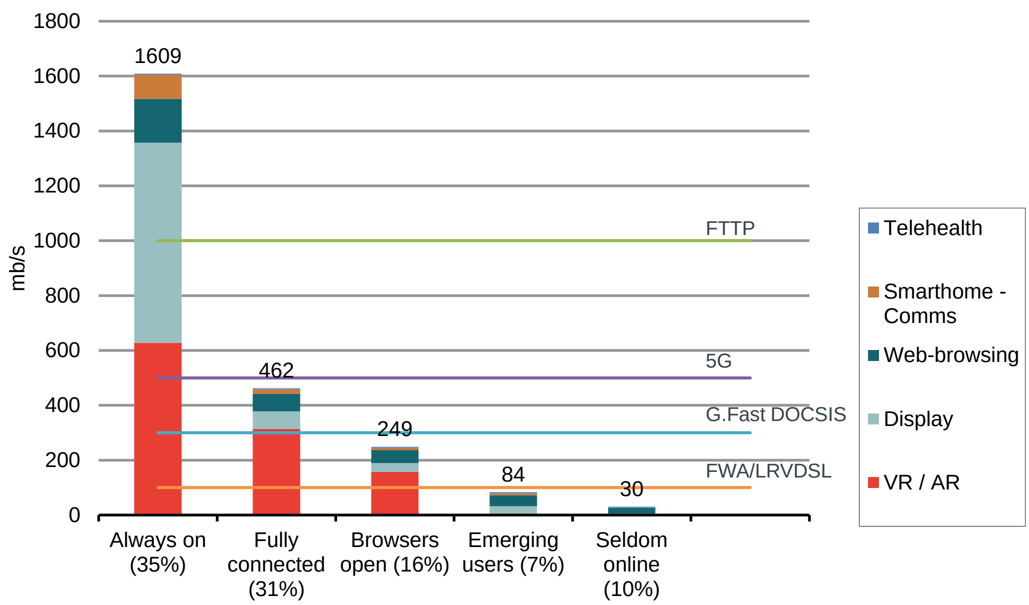
Figure 51 Bandwidth requirements by application (peak hour per month)

		Always on	Fully connected	Browsers open	Emerging users	Seldom online
VR / AR	Download	628Mbps	314Mbps	157Mbps	0Mbps	0Mbps
Display	Download	729Mbps	64Mbps	32Mbps	32Mbps	6Mbps
Web-browsing	Download	160Mbps	64Mbps	48Mbps	40Mbps	20Mbps
SOHO	Upload	191Mbps	98Mbps	10Mbps	3Mbps	1Mbps
Smarthome - surveillance	Download	88Mbps	16Mbps	16Mbps	2Mbps	0Mbps
Smarthome – Comms	Upload / download	88Mbps	16Mbps	8Mbps	8Mbps	1Mbps
Telehealth	Download	4Mbps	4Mbps	4Mbps	4Mbps	4Mbps
Total download		1609Mbps	462Mbps	249Mbps	84Mbps	30Mbps
Total upload		371Mbps	134Mbps	38Mbps	17Mbps	6Mbps

Source: Frontier assumptions

Figure 52 sets out the stacked bandwidth peak download demand, alongside the capabilities of different broadband technologies assuming the ambitious innovation scenario.

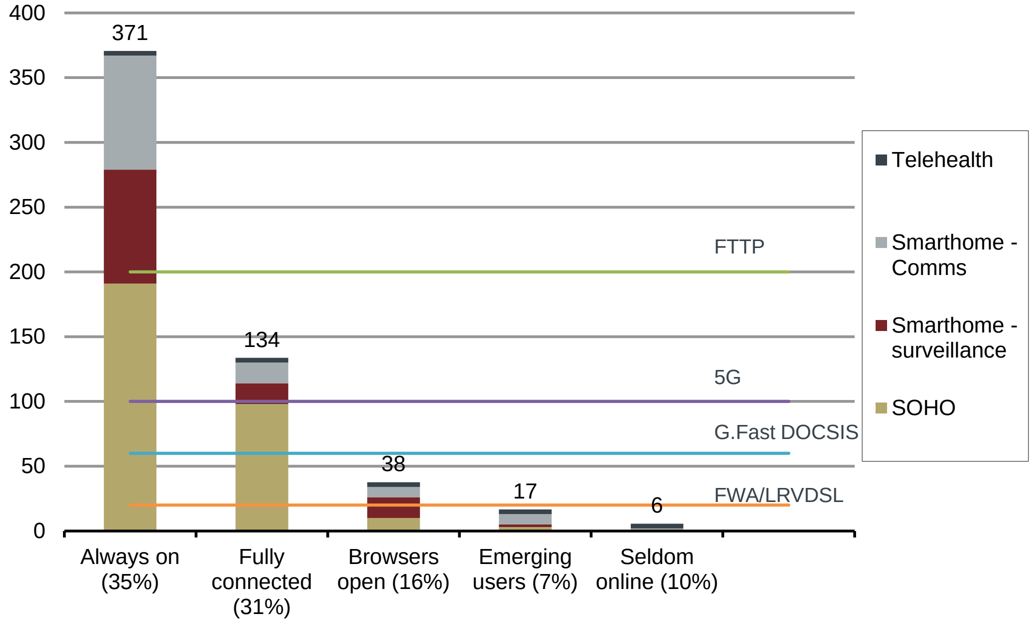
Figure 52 Household bandwidth *download* peak demand and network capability (2040)



Source: Frontier

Figure 53 sets out the household upload requirements in the ambitious innovation scenario.

Figure 53 Household bandwidth *upload* peak demand and network capability (2040)



Source: Frontier

In this analysis the "always on" household segment of households would face upload and download network constraints during peak hour even when using FTTP networks as dimensioned in this report (however by 2040 the capabilities of FTTP networks will be significantly enhanced). The median household (located in the Fully Connected Segment) would face constrained demand at peak times on all UFBA network technologies with the exception of FTTP.

G.Fast and DOCSIS would be sufficient for the less digitally engaged households (browsers open, emerging users and seldom online (33% of households)), but would impose upload and download network constraints on both always on and fully connected households (66% of households) during the peak hour.

This analysis suggest that in the long run, using assumptions in the ambitious innovation scenario even where all technologies may be able to support *individual* use cases, a proportion of households may use applications in combination in such a way that only FTTP will be support all applications at a high quality of service.

6 SUMMARY OF CONCLUSIONS

6.1 Introduction

We set out below the results of the analysis. We first summarise and draw conclusions from the analysis both in terms of key messages from the analysis, and the level of uncertainty around these messages. We then consider the implications of uncertainty on decision making.

6.2 Key messages

6.2.1 Overview of approach and its limitations

Our analysis has considered how investments in UFBA could realise incremental economic output (or in some cases cost savings) across a number of sectors. The analysis considers two scenarios for each of the sectors.

- a relatively moderate evolution of broadband technology demand; and
- a deliberately more ambitious, but plausible, view on how innovation will change how we use broadband networks over the coming 30 years, leading to significantly increased demand.

The analysis looks at the demand that could be created over and above that which can be delivered by current broadband technologies and infrastructure. It considers the degree to which this demand could be constrained by the network under different scenarios for the development of infrastructure and networks.

The results show that for some use cases current copper based infrastructure would be sufficient to support the broadband demand generated, even with ambitious assumptions on innovation. However, in other use cases, investments in full fibre networks would be necessary to support potential demand, particularly in the more ambitious demand scenario.

We note that caution should be adopted interpreting the quantitative results, in particular the level of the results, given that the measures used vary between use cases. In some cases the benefits relate to incremental consumer demand, whereas in other cases (telehealth and 5G) the benefits relate to cost savings, and in the case of SOHO relates a wider set of economic impacts enabled by homeworking (increased well-being, reduced travel costs, potential environmental impacts) for the cohort of workers unable to adopt homeworking with current broadband technologies. Furthermore, we note that the use cases selected are deliberately not exhaustive and therefore do not constitute estimates of total economy wide benefits. Finally, an analysis which considers outputs in specific user cases necessarily does not capture the potential spill over benefits of each use case. For example greater adoption of VR could facilitate wider adoption such in the workplace.

Nonetheless, the results illustrate the relativities of the impact of different broadband choices across the sectors studied.

6.2.2 Lessons from the historical analysis

In considering whether moderate evolution or ambitious innovation is the more likely outcome it is instructive to consider lessons from the historical use cases.

Forecasts are generally anchored in an assessment of current trends. This means that there can be a bias to under-forecast in markets where innovative applications and services are being developed as new applications can fundamentally change how consumers use technology. For example the growth in social networks underpinned much of the take up of broadband services for both fixed and mobile networks, but was not readily predictable prior to the roll out of these networks. In more mature markets, such as the delivery of television content, the scale and nature of growth in demand is better understood and therefore predictable. However, it is difficult to predict whether current broadband markets can be described as being in a mature phase, where further developments are refinements of existing use cases; or still in a phase of innovation where new innovations in residential use of broadband will be transformative and difficult to predict.

Video transmission is likely to be the key driver of network bandwidth across the use cases in both scenarios due to the high volumes of traffic generated by video applications compared to other types of information. Video transmission is central to the use of very high resolution displays; VR and AR technologies; some smart home applications (such as uploading surveillance video); telehealth and telecare (remote healthcare consultation); and remote education. Given that existing broadband networks already support video streaming (current networks allow the majority of homes to receive HD and UHD videostreams) then the incremental demand enabled by network investment may depend to a large extent on how demand for video transmission will evolve to require even greater resolution and/or the download and upload of multiple video stream. If over the coming decades consumers take up innovative 3D TV services (which may support a number of the use cases) this is consistent with the ambitious innovation scenario. Whereas, if is based on iterative improvements in display technology then the moderate evolution scenario is more likely.

There were a number of factors which tended to drive demand for network capacity, which were not fully forecast and were potentially “endogenous” (in that the development of networks with advanced capabilities enabled new innovative services). There are a number of examples of such innovations which were enabled as a result of developments within the wider ecosystem of related markets.

Furthermore, the Historical analysis revealed that non-technology barriers to adoption in some markets can delay take up even where potential use cases can be foreseen. For example, the use of residential broadband networks to support health and education applications has been posited for many years. However, in practice there have been a number of cultural and regulatory barriers to adoption even where the technology has been in place.

6.2.3 Results

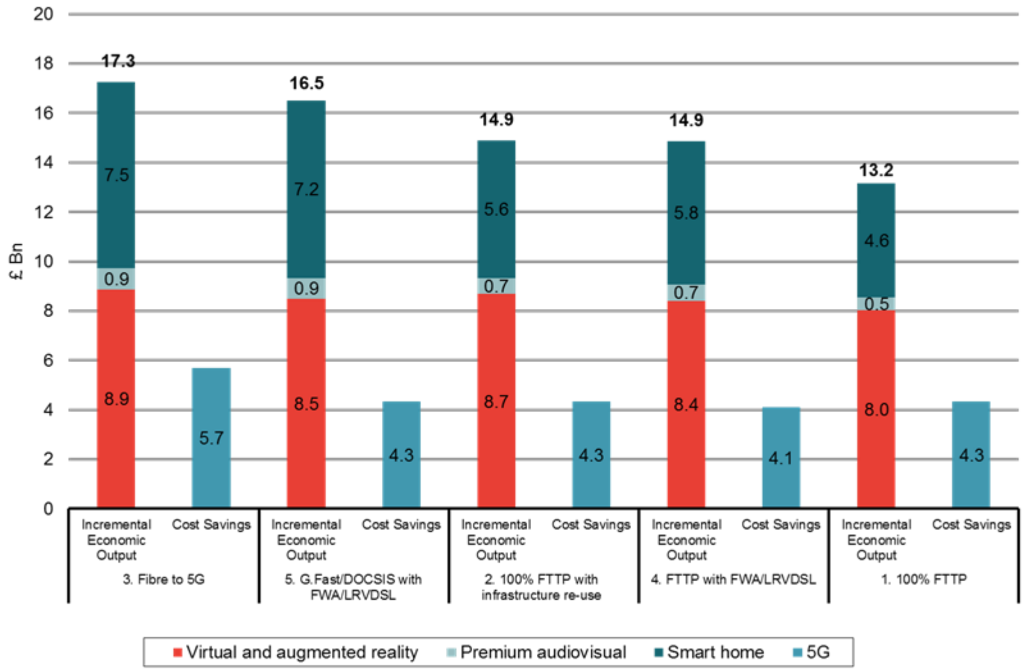
Moderate innovation scenario

In the moderate innovation scenario, further investment in broadband will enable a number of use cases (AR/VR, smart home and "premium display"). Similarly incremental broadband investments could facilitate greater teleworking for those workers that are required to work with large datasets for the small proportion of households that will only have a minimum 10 Mbps download service in the counterfactual but there would be little benefit to the majority of households that have access to up to 70 Mbps download bandwidth. In addition roll out of new fibre networks could lead to synergies and hence cost savings in the roll out of 5G networks. However, the existing baseline technology could largely deliver the use cases for online education, telehealth or SOHO teleworking and so investments in new network technologies would be unlikely to unlock additional benefits in these sectors. In the moderate evolution scenario, even forecasts advances in use of online education, telehealth or SOHO do not require further investment in UFBA.

In this scenario the benefits that would be enabled by UFBA investments are similar across all the potential technology deployment scenarios. To the extent that there are differences across different technology scenarios, these largely relate to the assumptions on the time taken to roll out networks. For example G.Fast (a technology upgrade of existing infrastructure) is assumed to roll out more quickly than FTTH, and therefore benefits of G.Fast are felt sooner (and the present value of near term benefits is therefore higher).

We estimate that direct incremental output enabled by improved broadband could amount to between £13.2bn and £17.3bn over 30 years. In addition it could lead to cost savings in the roll out 5G network infrastructure, compared to a standalone roll out of mobile 5G, of between £4.1bn and £5.7bn.

Figure 54 Present value of direct economic output across use sectors in the moderate evolution scenario to 2050 (£bn)



Source: Frontier

Extending the analysis to cover total direct incremental demand, potential multiplier effects, and consumer surplus benefits gives similar relativities as set out in *Figure 55.* The assumptions used to estimate multipliers and consumer surplus are set out in D.1. The estimates are made with a number of simplifying assumptions and should be interpreted accordingly.

As noted, these results relate only to the specific use cases so is deliberately not exhaustive and cannot directly be compared with costs of roll out of UFBA networks.

Figure 55 Total impact (NPV £bn)

Technology scenario	Impact on economic output		Cost Savings	Consumer Benefits
	Direct Impact	Indirect Impact		
1. 100% FTTP	13.2	8.0	4.3	3.3
2. 100% FTTP with infrastructure re-use	14.9	8.9	4.3	3.7
3. Fibre to 5G	17.3	9.8	5.7	4.3
4. FTTP with FWA/LRVDSL	14.9	8.8	4.1	3.7
5. G.Fast/DOCSIS with FWA/LRVDSL	16.5	9.4	4.3	4.1

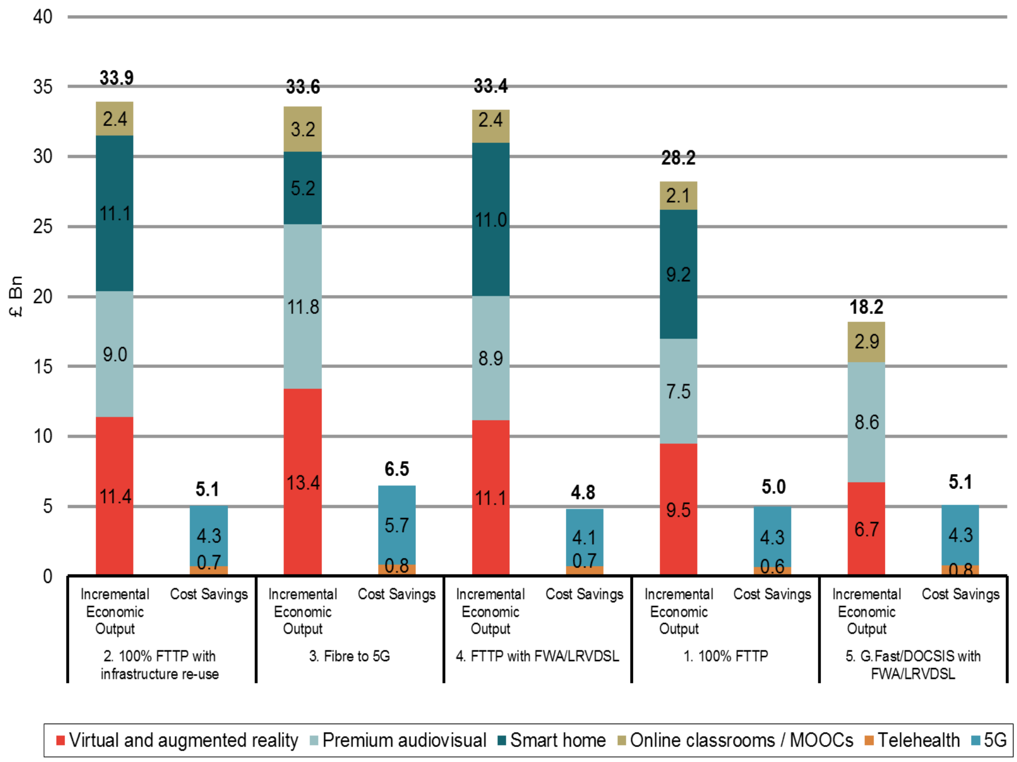
Source: Frontier

Ambitious innovation scenario

In the ambitious innovation scenario there is a significant differential between the different UFBA technology scenarios, as well as greater overall economic impacts. This reflects that in the ambitious innovation scenario some use cases require higher bandwidth than can be delivered using incremental technology upgrades of the existing copper infrastructure (e.g. G.Fast).

In this scenario the economic impacts for the scenario with highest benefit (FTTP with infrastructure re-use) are almost double those for the G.Fast scenario. The use cases driving these differentials are premium displays, VR AR services, and smart home (e.g. remote video monitoring). In addition in the ambitious innovation we assume that demand for healthcare (remote diagnosis with very high resolution 3D images) or teleworking that require high bandwidth may develop. In this case investments in UFBA networks would deliver cost savings in healthcare provision and support a greater degree of home working.

Figure 56 Present value of direct economic output across use sectors in the ambitious innovation scenario to 2050 (£bn)



Source: Frontier

Again, based on the assumptions on our total direct incremental demand, potential multiplier effects, and consumer benefits the relativities as set out in Figure 57, the relativities are similar when considering the broader impact.

Figure 57 Present value of total economic impacts (NPV £bn)

Technology scenario	Impact on economic output		Cost Savings	Consumer Benefits
	Direct Impact	Indirect Impact		
1. 100% FTTP	28.2	17.1	5	7.2
2. 100% FTTP with infrastructure re-use	33.9	20.5	5.1	8.7
3. Fibre to 5G	33.6	22.0	6.5	8.6
4. FTTP with FWA/LRVDSL	33.4	20.2	4.8	8.5
5. G.Fast/DOCSIS with FWA/LRVDSL	18.2	12.4	5.1	4.7

Sensitivity analysis

We have sensitivity tested the results to changes in the key assumptions (see Annex D). There are a number of uncertainties that affect the results which we explore in the sensitivity testing.

First, critical assumptions are the capabilities of network technologies and the technical requirements (principally bandwidth) of the use cases. If advances in technology such as compression mean that use cases can be delivered using lower bandwidth, then UFBA technologies with lower capabilities (such as G.Fast) may support a wider range of use cases than we forecast. However, if advances in technology mean that use cases can be delivered using existing networks then ultimately the value of further investment in any of the UFBA network scenarios will be diminished.

Second, the time to roll out new UFBA networks has a significant impact on when benefits are realised and hence the overall level of future benefits. Networks that roll out faster (such as G.Fast and the 5G network[151]) realise benefits sooner than FTTP networks, which we assume roll out over a longer time period. This can offset the increased benefits offered by full fibre networks in the long run.

Third, the rate at which innovation leads to changes in demand affects the benefits. We assume that for all use cases take up evolves gradually reaching market maturity after 15 years. However, faster increases in take up will increase the economic impact of broadband investments and slower increases in take up will reduce the economic impact of broadband.

Fourth assessing how constraints on usage due to network limitations (principally bandwidth) negatively affect demand for the use cases is important. We assume that if a technology is unable to fully support a use case, an alternative "lower quality" service will be consumed instead. Hence, in the presence of bandwidth

[151] In scenario 3 5G is rolled out to 63% of premises.

constraints, demand for a use case is *reduced* but not eliminated. However, it is not possible to predict whether the perceived differences between the use case delivered over high bandwidth networks and low bandwidth networks will significantly affect demand. If end users perceive such great differences that they choose not to consume the service where bandwidth is below the optimal level, the impact of network bandwidth constraints will be greater than we assume in our base case.

Finally we note that fibre based broadband access technologies are intrinsically more reliable than copper based broadband access technologies. However, in practice, a household's experience of reliability depends on more factors than the access technology. For example, actual reliability may be affected by expenditure on operations and maintenance of the access network and a well maintained copper based network could have a very low level of faults. In addition, customers' perception of network reliability also depends on the household's equipment, Wi-Fi interference, the robustness of the core network, etc. Therefore we assume that access network reliability does not have a significant impact on difference in economic impact of different UFBA networks. However, we recognise that reliability of the access network might become more important if users rely on it to a greater degree (for example in rural areas where it enables access to services) and the rest of the end to end network stack is delivered with high reliability.

6.3 Sources of uncertainty

The quantitative analysis has identified a number of sensitivities in relation to how broadband services will be used over a thirty year period. Based on the results of the analysis and research conducted as part of this project, we explore further some of the key factors that could lead to differences in demand outcomes and hence the need for different technologies.

- How will consumer expectations of "reasonable" services evolve?
- Will differences in UFBA network latency or reliability affect demand?
- Will increases in network capability create "endogenous" demand?
- Is it reasonable to assume that bandwidth required to deliver video will plateau?
- Will "upload" applications will become increasingly important?

6.3.1 How will consumer expectations of "reasonable" services change?

Ultimately for many use cases, the speed of users' broadband connections can directly affect the objective quality of the use-case which uses the broadband connection. Capacity constrained connections may for example:

- reduce video resolution, or increase artefacts which degrade the viewing experience; or
- lead to customers having to wait to download or upload large files.

The extent to which this affects consumers' value of broadband services will partly depend on how consumer expectations evolve over time.

It is clear that consumer expectations tend to increase over time. What was considered reasonable in the past becomes unacceptable over time. For example just as screen resolution has increased so has the TV form factor evolved; buffering on content streamed over IP networks is now rarer on many connections as content providers have competed to ensure that their content is delivered over networks which minimise latency, packet loss, and jitter[152].

Likewise broadband speeds were often measured by the speed of downloads on a consumer's line. A broadband speed's line could iteratively be defined by the time take to download a typical single mp3 file, mp3 album, large photo, feature film, or application. Over time consumers' propensity to be prepared to wait for downloads will decline as they expect virtually instant access to content though streaming.

The volume of data downloaded by applications over the internet tends to increase and consumer expectations of what is a reasonable "delay" tends to decline. Therefore the speeds of broadband services considered "acceptable" tends to increase.

Furthermore, increasingly, internet based applications are rolled out globally and users communicate globally through Internet fora, meaning that end users could benchmark their service's performance against global benchmarks.[153] Forecasting the impact of consumer expectations on acceptable broadband speeds is difficult. First it is difficult to predict how consumers' expectation will change over time. In practice the impact of a longer delay could be considered minimal to the perspective of a 2017 broadband user. However, even small delays may be unacceptable to the 2050 user. Second, there are a number of offsetting strategies that content and application providers can adopt to mitigate the impact delays in downloading data.

- Application, content or web pages can begin to be used even before they are fully down loaded.
- Content can be cached locally in advance of use.
- Rather than moving large files to and from customer premises, the data can be kept in the cloud and only the display streamed (subject to the latency being low enough and the bandwidth high enough).

6.3.2 Whether differences in UFBA characteristics other than bandwidth will affect demand

While, the linkage between use cases and network capabilities in this study focused on potential bandwidth requirements, other factors such as latency or

[152] Content providers increasingly compete by offering enhanced performance. Some content providers invest in their own Content Delivery Networks (CDNs) to deliver their content using servers located in (or close to) customers ISP which offers superior performance than rivals.

[153] For example if LTE networks were unavailable in the UK (but available elsewhere) there would be a consumer response. Similarly when the Apple iPad compatible with 4G was launched there were concerns that its 4G functionality would not be available in the UK since at the time the UK did not have wide spread 4G networks.

reliability could lead to differences in the perceived effectiveness of broadband technologies. Our analysis of the use cases suggested that none of the use cases studies were significantly sensitive to reliability or latency.

Latency

The majority of use cases rely on upload or download of video. Latency has no significant impact on the quality of service of streaming video, which is typically buffered (i.e. content is displayed significantly after it is received to smooth our variations in bandwidth). As noted above, it is possible that lower latency could be important for certain gaming or AR / VR applications. However, the latency offered by FTTC, FTTP, 5G or G.Fast networks is similar and sufficient.

It is possible that in the future new residential applications could be developed with required ultra-low latency, or that it becomes critical for certain home working applications. However, our research did not reveal any obvious household examples where this is the case.

Reliability

There are likely to be differences in the reliability of different networks, with copper based networks intrinsically more prone to faults than fibre base networks for the reasons set out in section 2.

However, in practice we note that in the use cases studied it is difficult to estimate the impact of differences in fault rates on demand.

As noted above, network faults are a rare occurrence (currently around a 0.05% chance of a fault on a line in a day). While there are differences between the propensities of different broadband technologies to fault, this will simply make a rare occurrence even rarer, so that consumers may not be able to objectively perceive differences between the different technologies.

In addition, even in the best case faults will still occur on residential broadband services, due to external factors. As such it is unlikely that applications which rely on absolute guaranteed reliability would be used in home settings. Therefore it is likely that only applications that tolerate occasional faults would be used or alternative networks (e.g. mobile) would be required in any case.

Nonetheless, as more reliance is placed on broadband networks in the future (for example at the point where it becomes the key technology to deliver audiovisual / TV content), then it is possible that perceived differences in network reliability could become more important when consumers are making purchasing decision.

6.3.3 Consideration of “endogenous” demand

Both the moderate evolution and ambitious innovation scenarios are based forecasts of potential demand which are independent of network capacity (i.e. unconstrained). We then consider how different technologies may constrain this “exogeneous” demand.

However, it is argued that demand for network capacity is to a degree “endogenous”, i.e. greater capacity networks will stimulate increased demand even when existing networks do not constrain demand. For example, application developers could seek ways to exploit increased capacity in innovative ways.

The Historical analysis revealed that many forecasts of mobile or fixed broadband speeds or adoption under-forecast relative to outturns. This was understandable; forecasts are necessarily backwards looking and cannot predict the scale or speed of adoption of new innovations, and miss the inter-related nature of technology market development.

The Historical assessment of mobile and fixed broadband markets noted that there were a number of factors which were not fully forecast which tended to drive demand for network capacity, but which were potentially "endogenous", in that the development of networks with advanced capabilities enabled new services. Indeed one justification of the ambitious innovation is that we cannot predict how technological innovation will transform how households' use broadband technology given the complex interrelationships between device, application and network markets.

Examples of innovations which were not fully predicted could include:

- the adoption of peer-to-peer software to share content over broadband networks, and the subsequent development of legal streaming services satisfy demand for legal access to audio-visual content;
- the development of social networking initially designed as a tool to communicate became a key video sharing platform;
- the rapid adoption of the internet, given the existing installed base of PCs; and,
- the sharing of user generated content as a result of the simultaneous development of video sharing platforms, device innovations (high resolution cameras and high resolution screens on mobile handsets) and increasing capabilities of mobile networks.

While we recognise demand could be endogenous to network investment, our demand analysis does not explicitly model the scale of endogenous demand for a number of reasons.

First, the ambitious innovation scenario models demand which deliberately considers how broadband uses could evolve in a very ambitious way which would likely capture any innovations leading to "endogenous" demand.

Second, we note that the relationship between advances in network capabilities and development and take up of devices and services that fully use the networks is not determinative.

Finally, we note that explicitly introducing endogeneity could potentially distort the analysis, with an automatic assumption that higher bandwidths bring greater benefits, even if this is not supported by evidence.

6.3.4 Limits on human perception may mean demand for improvements in video resolution will plateau

In recent years the overall growth in the volume of data which travels across broadband networks is largely due to increases in the propensity to use broadband networks to watch audio-visual content coupled with increasingly high resolution services. Video streaming is expected to be a key driver of near term growth. This partly reflects a number of factors.

- Continued substitution from other technologies such as terrestrial TV transmission, satellite transmission or cable TV to use of broadband networks to watch audiovisual content. This has a disproportionate impact on network capacity as viewing is concentrated in peak hours.
- The increasing penetration of devices with higher resolutions that can access video content, including HD displays on smartphones and IP enabled UHD televisions.

Therefore the potential bandwidth requirements for audio-visual content will be critical for the assessment of future demand for broadband. While it is reasonable to assume that over the medium term most viewing will migrate to IP based platforms, the bandwidth requirements are more uncertain.

While the bandwidth requirements of audio visual content have increased gradually over time the extent to which such trends will continue or will level off if customers do not perceive benefits from higher resolutions is unclear.

On the one hand there may be a number of physical constraints which suggest that bandwidth requirements for video streams may not increase significantly:

- Ultimately household members are limited in the number of screens that they can view at any one time. While the number of devices connected to the internet is likely to increase, viewers can only concentrate on a single device at any one time.
- Recent trends (and near medium term projections) show increases in bandwidth driven by increases in screen resolution (itself partly a function of increases screen size). Screen resolution has improved in recent years, from SD, HD, UHD (4K / 8K); and screen size has increased so a 40” TVs are common. However, there are limits to the resolution that is perceptible by the human eye. For example one expert we spoke to as part of this project noted that a user would have to stand directly in front of a floor to ceiling display in order to perceive a difference between a 4K and 8K display.
- Content producers may be unwilling to invest the significant amounts required to upgrade to higher resolution production where this does not provide perceptible benefits to consumers.
- Furthermore, for the reasons set out in Annex D.6 we have assumed that the rate of improvements in data compression will slow from recent trends. Whereas if they continued at existing rates our assumptions on the bandwidth required to supply videostreams could be excessive.

On the other hand future innovation could increase demand for video bandwidth. As discussed in section 4.2, future innovations could increase the bandwidth required to deliver audio visual content. Lightfield cameras and displays are able to create 3D images which are superior to current generation of stereoscopic 3D TV displays. Were these technologies to become more widespread their adoption could dramatically increase the capacity required to deliver audiovisual content.

6.3.5 There is uncertainty on the extent to which upload capabilities will be required

To date residential broadband demand and supply has been strongly asymmetric with networks offering higher download speeds and a much greater quantity of traffic downloading.

Some of the future use cases could require significant upload capabilities. For example SOHO workers may need to regular upload large files, or Smarthome surveillance might continuously require constant upload of multiple high definition video streams. To the degree that such communication is machine to machine, the limitations related to the human ability to perceive (visual) data set out above will not apply.

However, there is uncertainty in the degree to which faster upload capabilities are required.

- Advanced techniques such as Artificial Intelligence used in servers in the cloud might be able to create significant value from processing large streams of sensor and visual data (whether to identify home security alerts, or to monitor road networks from sensors placed on cars, or monitor our health). In such circumstances the ability to rapidly, and frequently upload could become more important than is currently foreseen.
- However, there are ways that the volume of data uploaded could be reduced. For example smart video cameras could use intelligence to only upload surveillance camera content when it is critical.
- For user or machine generated content, the timeliness of some uploads may not be critical with data cached and uploaded at off peak times.
- Finally, depending on the development of cloud computing, over time users may rely less on uploading and downloading files which are processed and manipulated locally on users' devices. Instead all processing for large files may occur on the cloud, with devices acting as dumb terminals displaying the results of computations run in the cloud.

The evolution of these factors will determine the required capabilities of broadband networks.

6.4 Infrastructure policy decisions taking account of uncertainty

Based on the use cases in the *moderate evolution* scenario, there does not appear to be a strong demand side case to invest widely in FTTP infrastructure.

Indeed, assuming a moderate evolution of broadband applications and services it is conceivable that existing networks could support most (but not all) of the use cases described in this report. For use cases which are not supported on current networks the magnitude of benefits are related to the speed of UFBA roll out rather than the quality of the specific UFBA network. Therefore G.Fast applications (if widely available) would generate larger benefits than FTTH networks with longer rollout profiles.

However, demand forecasting is intrinsically uncertain over this timescale. The Historical use case analysis reveals how demand for technology can evolve in unexpected ways in much shorter time scales than we consider here. Reflecting this uncertainty, the assumptions in the ambitious innovation scenario deliberately consider how services and applications that use broadband might develop with currently unused or unknown use cases. These necessarily rely on more innovative technological and application developments. In this scenario, widespread investments in UFBA would lead to large benefits and the quality of the network would become critical, with FTTP infrastructure leading to significant incremental direct benefits (which may lead to indirect impacts elsewhere in the economy and welfare impacts for consumers).

The inherent uncertainty in how demand could evolve leads to significant risks related to either over-investment or under-investment. The risks of over- and under-investing are accentuated by high level of sunk costs (which increase the cost associated with making investment which lie underutilised) and the time required to roll out (which increases the costs of a wait and see approach).

However, these risks are not necessarily symmetric in nature or magnitude. Depending on the costs of infrastructure roll out, the deadweight loss due to inefficient investment may be smaller than the risk of foregone welfare if users cannot access applications that they value highly. Furthermore, given that broadband is part of a wider ecosystem of related network, device and application markets there could be wider impacts in related markets if there is under investment in networks. In particular the use case approach adopted in this report does not account for wider “spill over” benefits that may be abled by the adoption of the use cases set out in this report (or indeed other use cases not assessed in this report).

With significant demand uncertainty a “real options” view would indicate there could be value in waiting for more information, even if the central case suggested there were benefits in investing now. Similarly an iterative approach, investing first in geographic areas of lower cost (e.g. dense urban areas), or in areas where the wider benefits of better broadband are likely to be greater (e.g. rural areas) could be optimal. This is because a decision to invest ‘now’ foregoes the real option value of ‘wait and see’ or maintaining flexibility (i.e. not committing to a single project covering the whole of the UK).

To some degree the risks of the “wait and see” approach to upgrading networks may be mitigated by the time for innovative services to develop. The historical analysis illustrated that network improvements do not necessarily immediately lead to advances in applications, devices and services. Indeed it can take many years for such interdependent ecosystems to develop. For example the smartphone ecosystems, centred on Apple’s iOS and Android, developed a number of years after the launch of 3G mobile data networks. However, once these eco-systems develop, they can quickly lead to innovation and investment which generate new generations of applications, services and devices. If broadband network's capabilities were insufficient to support new generations of applications, services and devices, then the level of foregone economic welfare could be significant. Furthermore, iterative approaches to network upgrade could lead to differences in coverage of broadband services within the UK, which in turn could cause public policy concerns (i.e. a digital divide) as well as potential losses due to the inability to standardise services across the country.

Finally, it is necessary to take account of the global perspective. Applications, services and devices are increasingly developed to serve a global audience or are internationally standardised. This means that differences in network infrastructure compared to other developed countries could lead to risks that the UK lagged in the critical digital services that increasingly support all sectors of the economy.

ANNEX A HISTORICAL ANALYSIS OF MOBILE COMMUNICATIONS MARKET DEVELOPMENT

A.1 Introduction

The development of mobile communications is of interest for a number of reasons:

- Investments in mobile infrastructure have similar characteristics to those in fixed infrastructure. This requires relatively long term forecasts of demand in order to make decisions on technology standards and investment in infrastructure and equipment. However a shorter time period between ‘generations’ of technology means that we have more examples of the forecasts and out-turns in mobile than for fixed networks;
- Due to convergence there are complementarities between developments in the fixed and mobile network sector; and
- It is a good example of a sector with a complex ecosystem of devices, network equipment, applications and infrastructure.

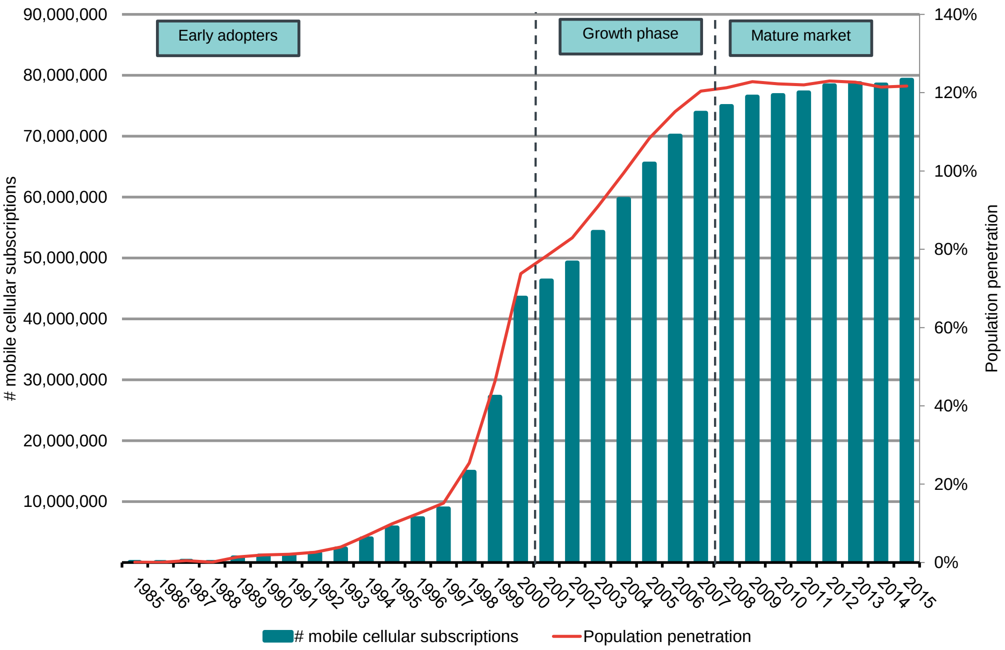
Mobile communications have become ubiquitous, with 1.2 subscriptions/devices per capita in UK. The evolution of the mobile market, from its initial introduction in the mid-1980s, to the near universal adoption today, offers interesting lessons on how technology markets develop. This section therefore reviews the evolution of the mobile market in the UK, and considers the implications on how the UFBA market may develop.

Figure 58 shows the growth path of adoption of mobile phones from 1985 (the launch of the first ‘1G’ networks) to 2015. Mobile take up has followed a typical ‘S-curve’ of technology diffusion. Initially high costs meant mobile phone use was limited to businesses and early adopters. This was followed by a phase of fast growth and mass adoption as prices fell, before levelling off as the market reached maturity.

Therefore, this section discusses the development of the sector during each of the three phases of growth reflecting changes in the applications and eco-system. For each phase we discuss the key market and economic features which affected development of the market.

1. **Period up to 2000:** early growth and network investment;
2. **Early 2000s:** feature phones, support for data, but limited consumer data demand; and,
3. **2007 - present:** smartphone revolution, high data demand from ‘over the top’ OTT applications.

Figure 58 UK mobile cellular subscriptions & population penetration, 1985 – 2015



Sources: World Bank; Oftel Annual Report 1994

A.2 Period up to 2000: early growth and network investment

During this phase of development take up of mobile services increased from zero up to 0.6 devices per capita. Mobile phones were limited to voice and text services and mobile data services were in their infancy.

A.2.1 Initial forecasts tended to severely underestimate future demand

Early mobile phone networks served a small number of customers with phones in cars, as equipment was not hand portable. In the early 1990s efforts were made at a European level to take advantage of technical developments to introduce a standard hand held mobile telephone that could be used across Europe. Initial estimates of demand, based on projecting forwards then current demand, severely under-estimated the potential for demand with estimated demand of around 200 thousand subscribers in the UK by the year

- Forecasts tended to underestimate potential demand There was Government support for sector via supply of spectrum and standardisation and support for market entry
- Projected mobile demand was assumed to iteratively develop existing applications
- There was a high degree of integration between network providers and service providers
- Growth was derived from reduction in device prices, increasing competition (e.g. free on-net and local calls), and spectrum release

2000[154]. There were also concerns raised that usage would be limited as people would not want to make telephone calls in the street.

While mobile phones have been an unequivocal global success, this tendency to under forecast was widespread as analysts failed to foresee the true level of demand. Figure 59 sets out some early to mid-1990s forecasts for mobile subscribers and subscriber growth rate. In the case of each forecast the actual subscriber numbers at the date were many multiples higher.

Figure 59 Early forecasts of mobile market growth

Source	Base	Forecast	Actual outcome
BIS Strategic Decision (1991-92)	GSM only	1.9m subscribers in Europe by 1995	7m by mid-1995
EMCI (1991-92)	All cellular	11.5m subscribers in Europe by 2000	
ETCO (1991-92)	All cellular	16m subscribers in Europe by 2000	252m in 2000
PA Consulting Group (1991-92)	All cellular	20m subscribers in Europe by 2000	
OECD (1995)	All cellular	33.8m-122.0m subscribers in OECD countries by 2000	447m in 2000
Economic Services (1991-92)	All cellular	15% per year growth worldwide	Between 1991 and 1995 worldwide compound annual growth was 61% per year
Motorola (1991-92)	All cellular	100m subscribers worldwide by 2000	1.0bn in 2000
Petrazzini (1996)	All cellular	250m-350m subscribers worldwide by 2000	

Sources: OECD (1995) "Mobile and PSTN communication services: competition or complementarity?; Ben Petrazinni (1996) "Global telecoms talks: a trillion dollar deal"; World Bank

There are a number of reasons why early forecasts of demand for mobile services were under estimated.

- It was clear that mobile phones had some utility for everyone so if the price fell enough there would be high penetration. However, analysts tended to assume that the then market conditions, where mobile phones were a niche premium product, would be maintained in the future meaning that economies of scale would be limited.
- Early forecasts may have under estimated the degree to which mobile services would be additional and complementary to fixed networks rather than instead of them, and expected developments in fixed technologies to limit demand for mobile.[155]

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[154] http://www.gsmhistory.com/the-beginnings/

[155] For example, in 1989 the UK Government warned against expecting that all fixed subscribers would adopt a mobile phone ("*Lest an impression is given that advances in mobile radio technology will lead in the future to all telephone subscribers being connected to the public telecommunications networks through Personal*

- The combination of spectrum release and the adoption of the GSM 2G standard meant that there were no real capacity constraints on networks once GSM was introduced, with new entrants having strong incentives to expand the customer base rather than compete for existing subscribers.
- One of the early barriers to adoption was high handset prices. However, 'silicon' economics rapidly reduced the cost and increased the value of handsets.

Below we set out some of the factors that drove this accelerated uptake of mobile.

A.2.2 There was Government support for the mobile sector via supply of spectrum and standardisation and support for market entry

This phase of market development was typified by a high degree of government and regulatory intervention in terms of spectrum licencing, technology standardisation and the development of competition. The first generation of network technology (1G) was developed in the late 1970s and rolled out in the UK from 1985 by Cellnet (a joint venture between BT and Securicor which later became O2) and Vodafone who were licensed at the same time (introducing competition in mobile before fixed services). This generation used analogue radio transmission and supported voice calls only. [156]

The second generation (2G – or GSM)[157] was launched in 1992 by Vodafone, followed in 1993 by Cellnet and Mercury One2One[158] and 1994 by Orange.[159] The European Commission supported standardisation of mobile services in terms of the 2G technology by requiring all mobile licensees to adopt the standard[160] and by specifying the spectrum bands that should be released by EU governments.

2G uses digital transmission, more efficiently transmitting calls and providing greater capacity. 2G was also significantly more secure than 1G; it supported SMS; and, (later on) narrowband data services. Furthermore, the standardisation enabled 'roaming' abroad. However, 2G was primarily designed for voice (before large scale adoption of the Internet) and offered a poor Internet browsing experience.

Communication Networks, one should add that technology is also advancing on other fronts. Fibre optic links to the home would have the potential to offer wider spread of services such as videolinks and represent another possible manifestation of technology and competition in the service of the user"). See: http://www.gsmhistory.com/wp-content/uploads/2013/01/6.-DTI-Phones-on-the-Move.pdf

[156] 1G used spectrum inefficiently and suffered from security issues. and the UK government took the decision to phase it out from the early 1990s. It was eventually switched off altogether in 2000 and 2001.

[157] 2G was developed by European Telecommunications Standards Institute (ETSI).

[158] One2One became T-Mobile when bought by Deutsche Telekom in 1999.

[159] The UK government initially licenced three new entrants in the 1800 MHz band with two of the licensees merging.

[160] For example in 1989 the Department of Trade and Industry noted that "The Department is likely to require any Personal Communication Networks to conform to a publicly available technical standard to increase competition between operators and between equipment suppliers in the interest of users." See: http://www.gsmhistory.com/wp-content/uploads/2013/01/6.-DTI-Phones-on-the-Move.pdf

A.2.3 Projected demand was assumed to iteratively develop existing applications

In its consultation anticipating the launch of 2G services (in 1989) the Government commented on potential future trends which might drive demand for mobile data services[161]. The report noted that predicting the future was difficult (for example it had "*no unique insight into the future*") but it described what it considered the key trends which could drive demand for data:

- a trend towards digital technology (away from analogue communication technologies);
- a move from mobile radio technology being a business service to a more mass market consumer service;
- mobile "office" communication facilitated by the take up of portable devices such as laptops, portable facsimile machines, calculators, dictation machines and electronic diaries; and,
- mobile networks would improve access to emergency services (particularly where there is no fixed connection).

A.2.4 Integration between network providers and service providers

Throughout the early period mobile phones were only used to provide mobile voice services which were directly provided by mobile network operators. There was very limited scope for users to use services and applications from other providers.

The high degree of vertical integration, where each of the four Mobile Network Operators (MNOs) were the only providers of services on their networks meant that there was a limited degree of innovation of services provided on the network. Some innovations by the MNOs included the introduction of pre-pay which was launched in 1996; and SMS which was launched in 1995.

A.2.5 Market growth was led by reduction in prices and increases in competition

The increasing penetration of mobile services was the result of economies of scale in network services and devices leading to falling costs and hence lower prices. A significant element was the reduction in handset prices. The economics of device manufacturing and standardisation (with much of the world adopting the GSM standard) meant that devices became smaller, cheaper and more reliable and resilient (with longer lasting batteries).

The cost of network services also fell rapidly due to reductions in the cost of network equipment, economies of scale as traffic increased and increased capacity as the Government issued more spectrum over time.

[161] Dti (1989) Phones on the Move, Personal Communications in the 1990s - a discussion document See: http://www.gsmhistory.com/wp-content/uploads/2013/01/6.-DTI-Phones-on-the-Move.pdf

The government ensured entry which intensified competition meaning that lowered costs were passed through to consumers and operators targeted all segments of the market. For example One2One entered the market in 1993 and differentiated itself out by offering free local and on-net calls. Orange entered the market the following year differentiating itself on coverage and the quality of its handsets (as opposed to price).

A.3 Early 2000s: Feature phones and support for mobile data but limited consumer demand

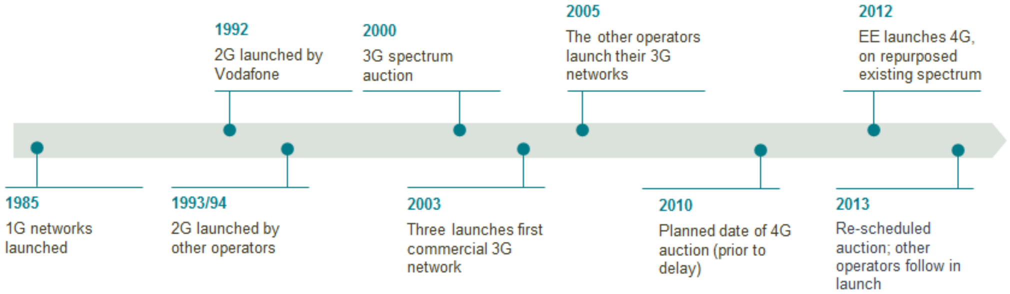
By 2000 adoption of mobile phones had significantly increased to around 43m subscriptions (74% population penetration). The UK Government was preparing to license a new operator, and to release new spectrum to support the next generation of "3G" network services. Device manufacturers competed to add features to their products.

- Projected mobile demand was assumed to iteratively develop existing applications
- There was strong government support for new services
- Network competition driven by differentiation
- Device technology evolved as "feature phones" became popular
- Network operators tried to maintain a degree of vertical integration between networks and services which prevented innovation and potentially restricted demand

A.3.1 Network competition driven by differentiation

Mobile operators have iteratively upgraded their networks to offer faster, more reliable services. However, there have been significant costs involved in upgrading their networks to each new generation of technology. This is primarily related to upgrading each mobile mast to install new equipment, acquiring spectrum to offer each new generation of technology, and upgrading the capacity of each provider's core and backhaul network to accommodate the consequent increase in data demand. Figure 60 below summarises the development of mobile networks.

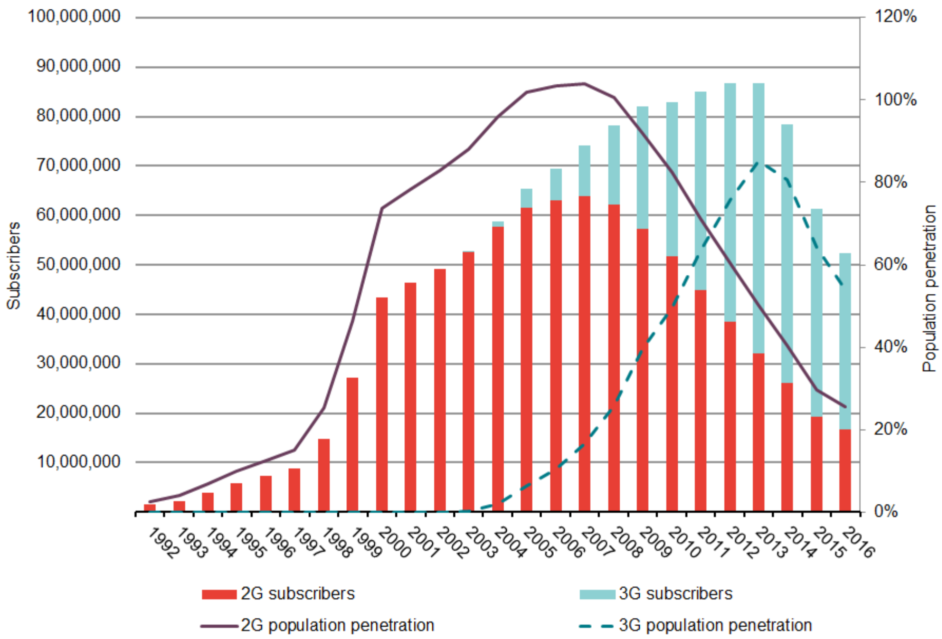
Figure 60 Timeline of key mobile network developments in UK



Source: Frontier

In the case of 3G, UK operators collectively invested £22.5bn[162] to acquire spectrum in 2000. Despite these investments it was not until 2003 that the first of these (Three) began to roll out their 3G network which was followed by other networks in 2004.

Figure 61 UK 2G and 3G subscribers and population penetration, 1992 – 2016



Source: TeleGeography

Notes: Population penetration is defined as the total number of 2G / 3G mobile subscriptions per head of the population

This delay was partly due to a lack of consumer demand for the new services rooted in a lack of compelling applications and a poor choice of handsets which were compatible with the 3G standard. In addition operators priced data services with high marginal costs to end users which discouraged take up. For these reasons both 3G roll out and take-up was gradual: it was not before 2008 that 3G even reached 20% population penetration.

A.3.2 There was strong government support for new services

During this period the UK government and the EU continued to support the sector by ensuring that spectrum was released and by taking a leading role in the adoption of a new set of standards for the next generation of “3G” services. The 3G standard was specifically designed to offer packet data services in addition to voice, using spectrum with much greater efficiency than 2G. This enabled faster (‘broadband’) data services.

The EU required that member states set aside spectrum specifically to launch 3G services alongside existing 2G services. The UK industry and government groups

[162] This was around four times the initial predictions. Klemperer, 2002

participated in a range of international stakeholder groups[163] to design the standards that would be used in 3G services.

A.3.3 Projected mobile demand was assumed to iteratively develop existing applications

The UK government had to project the potential future demand for mobile data services. In its 1997 consultation on its support for 3G services the UK Government described the potential use cases which would stimulate demand for the new technology. These were largely assumed to be a mix of services already provided on fixed networks to be provided on mobile networks, and new services such as video calling.

- *"High speed internet and intranet access and electronic mail,*
- *video telephony and conferencing,*
- *on-line banking and shopping,*
- *entertainment services, e.g. audio on demand, video games,*
- *direct instant access to home or office IT systems, regardless of location."*[164]

The prospect of combining mobile communications, which had to date been a fast growing and profitable business model, with Internet access, another fast growing and profitable business, led analysts to predict that 3G spectrum would be a 'licence to print money'.

In fact take up of "new" data services by 2007 was relatively low. 44% of households were aware that their mobile had internet access and this function was used by only 13% of mobile phone users; and 35% of users were aware that their handset had email access and only 8% of mobile phone users accessed email on their device[165]. Consumers instead tended to rely on embedded handset features rather than network data services; such as cameras (used by 41% of consumers), alarms (used by 38% of consumers) or games (used by 21% of consumers).

However, there were a number of factors which delayed the take up and profitability of mobile data services:

- The initial 'release' of 3G technology ('Release 99') offered limited bandwidth and capacity, with service speeds akin to 'dial up' fixed access when users were becoming accustomed to broadband speeds and applications at home;

[163] These included the ITU's 'International Mobile Telecommunications 2000' programme; the European Telecommunication Standards Institute (ETSI) which developed detailed and comprehensive specifications; the UMTS Forum established by the European Commission which is an association of telecommunications operators, manufacturers and regulators active both in Europe and other parts of the world which considered the regulatory framework and the harmonised Spectrum requirements.

[164] DTI (1997) MULTIMEDIA COMMUNICATIONS ON THE MOVE A CONSULTATION DOCUMENT FROM THE DEPARTMENT OF TRADE AND INDUSTRY

[165] Ofcom CMR 2007 figure 1.76. See: http://webarchive.nationalarchives.gov.uk/20160702162827/http://stakeholders.ofcom.org.uk/binaries/research/cmr/ccm.pdf

- There was a significant delay between licences being issued (with the timetable being set out by the European Commission) and 3G equipment and handsets becoming available;
- With low frequency spectrum being reserved for other applications (e.g. television broadcast) or GSM, the spectrum used for 3G required a high number of based stations (and hence significant investment) to achieve good coverage.

For 2G networks, Vodafone and O2 predominantly relied on 900 MHz spectrum which has better propagation characteristics than the 2100 MHz spectrum allocated for 3G use. This meant that the distance a signal could travel from a base station was greater for 2G than 3G and as such fewer base stations were need to provide 2G coverage as would be needed to provide equivalent 3G coverage. In the initial phase of 3G roll out, with limited demand, financial constraints as revenues stagnated and planning restrictions on new sites, operators chose to largely roll out 3G equipment on existing 2G sites, leaving ‘white spaces’ in 3G coverage in areas which could not be reached from existing base stations.

The need to roll out additional infrastructure resulted in changes to the industry structure:

- the two smallest operators, T-Mobile and Three joined forces in a network sharing agreement to build out the 3G network faster than they could individually;
- the merger of T-Mobile and Orange to form EE was in part motivated by the need to upgrade the network to offer data services; and
- O2 and Vodafone entered in the “Beacon” network sharing agreement combining their networks across the county.

A.3.4 Device technology evolved as “feature phones” became popular

During this period manufacturers competed to build more sophisticated handsets with more features. Mobile devices incorporated cameras, better screens, multiple screens, inbuilt radios, music players. Gradually mobile phones started to replace a number of distinct standalone devices. However, these features tended not to rely on mobile data, and indeed demand for mobile data was relatively low.

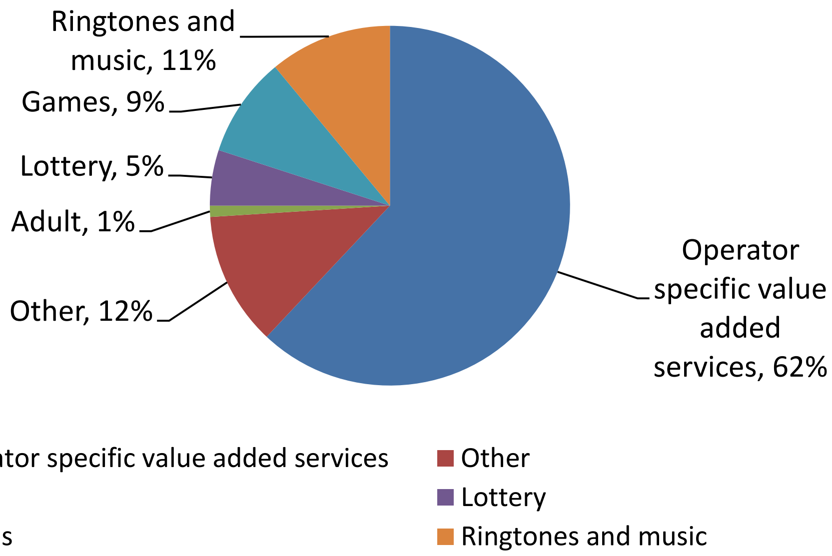
However, this period saw the increase in importance of mobile operating systems. Handset manufactures had previously each used their own proprietary software on their device. This meant that it could be difficult for mobile operators to sell all customers value added services and applications since new services may not be compatible with different mobile devices.

Symbian was one of the first “open” operating systems designed for mobile. Symbian was established in 1998 by Nokia, Ericsson, Motorola and Psion. Its aim was to create an operating system that could be used by a number of device manufacturers[166]. The software was shared with device manufacturers and software developers to make it much easier to create services that could reach large numbers of consumers[167].

A.3.5 Operators attempted to extend vertical integration into services which may have restricted demand

Mobile operators considered new applications ("value added services") as strategy to increase their revenues from selling their mobile services. According to a report quoted by Ofcom in 2003 retail revenues related to mobile Value Added Services accounted for £1.4bn. Operators collected approximately £0.9bn of revenue on these value added services in 2003.

Figure 62 Mobile value added service revenues, 2003



Source: Ofcom CMR 2004

This strong revenue stream for operators led them to attempt to disrupt access to some competing services, particularly those that competed with operators' core voice and text revenues (such as VoIP or messaging or calling).

Mobile operators controlled and approved the handsets that were available on their network and therefore could ensure that their customers only bought services from them (a "walled garden" such as Vodafone's Vodafone Live or T-Mobile's T-Zone). Therefore operators made incremental revenues by retailing services, applications, music and ring tones to their customers who were unable to switch to rival services[168].

Arguably this slowed development of the market as consumers were frustrated by the lack of choice and innovation of services and apps.

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166 The Symbian software was based on basic operating software in Psion's handheld computers adapted for mobile phones.

167 See: http://news.bbc.co.uk/1/hi/sci/tech/1948381.stm

168 For example in 2006 T-Mobile customers were unable to access email which was not approved by T-Mobile. (See: https://www.theregister.co.uk/2005/09/16/t-mobile_email/).

A.4 2007 - present: the smartphone revolution

2007 saw the launch of the iPhone, and the following year saw the launch of Google's Android mobile operating system. These new products, arguably, altered the competitive dynamics in the industry. It led to the gradual loosening of the mobile operator's control of the devices (and related services offered). Users now expect to be able to customise their handsets. In addition operators (partly as a result of pressure from Apple) altered their data pricing to reduce the marginal cost to users at the same time that new technologies (High Speed Packet Access – HSPA) dramatically increased the capacity of 3G networks.

- By 2007, the voice mobile market was saturated but there was scope for mobile data growth
- The smartphone model was a game changer
- The adoption of smartphones generated significant consumer demand for mobile services
- In the UK, the Government supported 4G but regulatory and institutional constraints restricted roll out of new standard
- Network competition (differentiation) gave networks incentives to invest

A.4.1 More recent forecasts of mobile growth underestimated demand

Mobile services are provided using scarce spectrum. Given the scarcity mobile operators, governments and international bodies have an interest in understanding demand for mobile spectrum to support voice, personal data and M2M. For this reason there are a number of forecasts of demand for mobile services. Mobile forecasts focus on the total data demanded.

We have considered in detail a number of forecasts.

Figure 63 Mobile demand forecasts studied

	Period of forecast	Key drivers of demand
UMTS forum – 2005	2010-2020	Business internet access (web, email, internal business systems) Customised “infotainment” Multimedia messaging Mobile internet access Location based
UMTS - 2011	2010-2020	HD (High Definition) Voice will challenge VoIP SMS, small traffic-consumer application Social networking Dongles and tablet in the data traffic explosion The dramatic growth of video traffic M2M
ITU 2011	2011-2015	New devices: smart phones, dongles, tablets Apps and app stores Video traffic Social networks M2M
ITU 2015	2020-2030	Video usage Device proliferation Increase screen resolution Cloud computing Apps and app stores Fixed to mobile substitution

Source: UMTS April 2005 REPORT NO 37 FROM THE UMTS FORUM MAGIC MOBILE FUTURE 2010-2020;UMTS January 2011 UMTS Forum Report 44 Mobile traffic forecasts 2010-2020 report; ITU (2011) ITU Report ITU-R M.2370-0(07/2015) IMT traffic estimates for the years 2020 to 2030; ITU (2015) Report ITU-R M.2370-0(07/2015)IMT traffic estimates for the years 2020 to 2030; Report ITU-R M.2243 (00/2011)Assessment of the global mobile broadband deployments and forecasts for International Mobile Telecommunications.

Typically the forecasts adopt a common methodology.

- They disaggregate demand for data services by application / and or device
- They consider how demand for each type of application will grow
- They may consider the relationship between average usage and peak usage.

A.4.2 Identification of applications

Given all methodologies base forecasts on trends in existing usage, in the near term there is a reasonable degree of accuracy on the applications and services use. However, over a longer time frame it is much harder to predict the applications that will drive demand.

For example a 2005 UMTS study forecast demand for broadband. The study was reasonably accurate in determining some trends that would affect demand.

The forecast correctly noted that geo-location apps and services would become a "new" source of demand as geo location potential was integrated into devices (GPS sensors). It noted that there was potential for resistance as a result of consumer concerns over privacy *"Consumer attitude and reluctance to be located may impede some development in location-based services*".

The forecast identified that "internet access" would be a key driver of demand. However this was loosely defined ("*Mobile Internet access (consumer segment) and mobile Intranet/Extranet access (business segment) will benefit from higher frequency of use and larger file sizes."*)

All forecasts agree that access to entertainment content will drive data demand. *"The user will have the ability to view, hear, or interact with entertainment media wherever or whenever desired"*[169] In some ways the forecasts predicted elements of sharing content, clips and user generated content via platforms such as YouTube.. *"In addition, the user will increasingly have the ability to adapt and use media elements to create their own personalised entertainment experience."*[170]

Some technology trends correctly forecast drivers of mobile use. For example, a 2011 forecast by ITU[171] noted that a number of developments would increase demand for data including: multi-tasking (enabling mobile phones to complete more complex operations), the development and introduction of Graphic Processing Units (processing chips which are specific to graphics processing), and a greater use of cloud for mobile services. Equally, forecasts on the future technological capabilities of handsets have not been adopted. For example the same report note that future devices would enable users to compartmentalise devices into separate virtual devices.

However, some aspects of the application and device features that would drive demand were less accurately forecast. These were particularly so where it involved in making predictions about technology or cultural trends.

Health monitoring was repeatedly cited as a driver for mobile data demand. *"Technology for monitoring a person's vital signs (i.e., "physiological monitoring") will form part of a personal area network, with the mobile device as the hub. The local device will perform a first level of analysis, with more sophisticated analysis and long term data capture available through wireless transmission of the health information to a server maintained by individuals or their healthcare providers."* [172]

Forms of social networks, where individuals choose one-many, and or one-one communications have existed since the inception of the internet (initially via chat rooms or message boards). Early forecasts recognised the relevant of such networks as a way of sharing content. However, they did not appear to foresee the scale that social networks would have on data demand. In 2005 UMTS noted that "*New opportunities will arise from social behaviour which is unpredicted*." However, the form of social networks were not predicted. For example the 2005

[169] UMTS April 2005 REPORT NO 37 FROM THE UMTS FORUM MAGIC MOBILE FUTURE 2010-2020.

[170] UMTS April 2005 REPORT NO 37 FROM THE UMTS FORUM MAGIC MOBILE FUTURE 2010-2020.

[171] ITU (2011) ITU Report ITU-R M.2370-0(07/2015) IMT traffic estimates for the years 2020 to 2030.

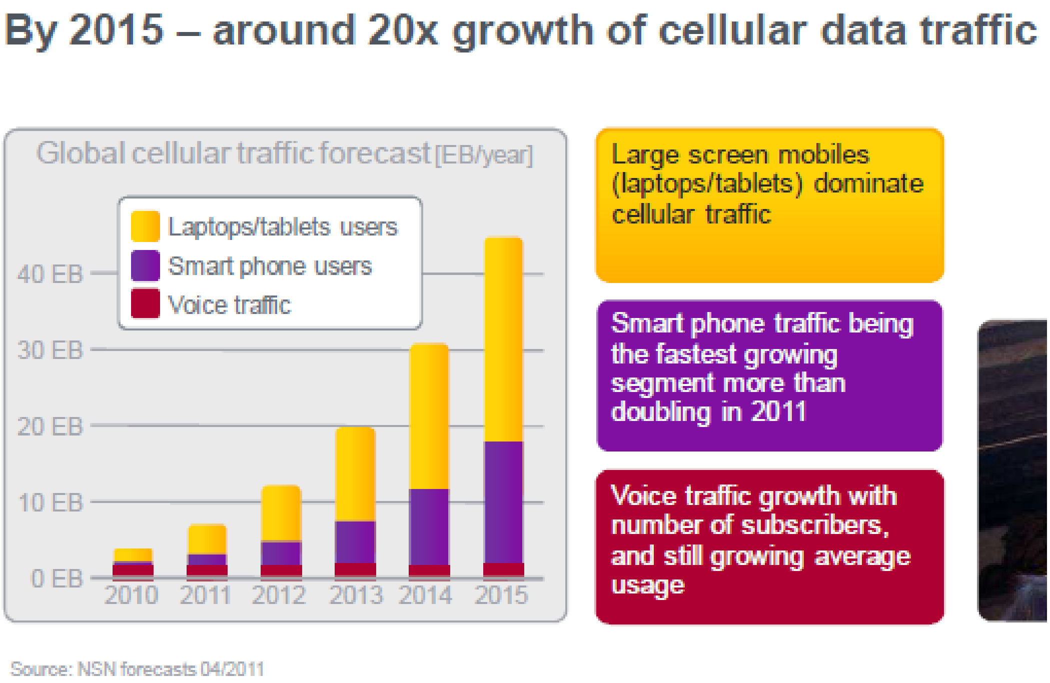
[172] UMTS April 2005 REPORT NO 37 FROM THE UMTS FORUM MAGIC MOBILE FUTURE 2010-2020.

study stated that photo sharing would be primarily via MMS: "*Relations between people will expand: P2P communications (such as MMS) traffic volumes will grow from 2012 to 2020 thanks to the migration from text based MMS to photo/video based MMS and thanks to the increasing number of M2M file transfers.*"[173]

Early (2005) forecasts of mobile services predicted that device innovation would drive demand for data. For example it noted that between 2010 and 2020 there would be a mass adoption of "retinal displays" akin to Google Glass ("*Retinal displays: a type of head-up display that "paints" a picture directly on the sensitive part of the user's retina. The image appears to be on a screen at the user's ideal viewing distance")* While increasing resolution of display has undoubtedly led to increases in demand for data, this form of technology innovation (while technically feasible) has not to date been adopted.

Later forecasts have considered increasing use of devices such as dongles as key to growth in demand. In the 2011 forecast the UMTS forum noted that dongles had been key to driving demand between 2005 and 2011. It noted that connected laptops and dongles would "dominate cellular traffic". In doing so it pointed to countries such as Finland, where in 2009 dongle and laptop connected traffic amounted to 90% of mobile data traffic. In fact use of smartphones has been the key driver of data traffic.[174] Similarly in 2011 the Nokia Siemens Networks forecast that data traffic from laptops and mobile would dominate cellular traffic (see Figure 64).

Figure 64 Traffic forecasts by device type



Source: Nokia Siemens Networks (2011) Radio Evolution Beyond LTE

173 UMTS April 2005 REPORT NO 37 FROM THE UMTS FORUM MAGIC MOBILE FUTURE 2010-2020.

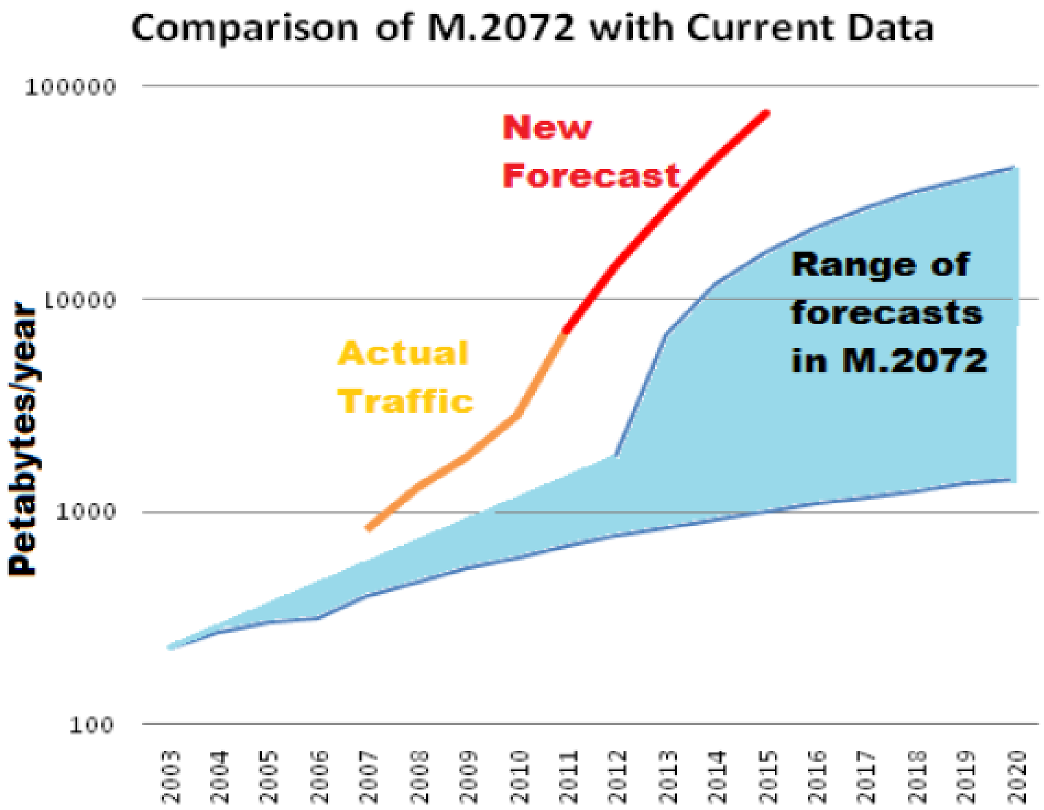
174 UMTS January 2011 UMTS Forum Report 44 Mobile traffic forecasts 2010-2020 report.

A.4.3 Accuracy of forecasts

Early forecasts underestimated the scope for consumer demand for data. For example, a forecast from 2005 noted that data traffic would overtake voice traffic in 2020. In fact data traffic grew much quicker, overtaking voice traffic by 2009.

The ITU reviewed the earlier forecasts that it made to forecast data traffic in 2005. It found that of the range of forecasts that it studied in 2005, the outturn exceeded even the higher estimates of this range.

Figure 65 Comparison of forecasts with outturn



Source: *Report ITU-R M.2243 (00/2011) Assessment of the global mobile broadband deployments and forecasts for International Mobile Telecommunications.*

A.4.4 By 2007 voice mobile market was saturated but there was scope for mobile data growth

In 2007 86%[175] of adults had a mobile phone (93%[176] by 2016). However, prior to 2007 users were slow to adopt the next generation technology (3G). By 2007 3G penetration was around 15% four years following the launch of the service.

The very high penetration of mobile presents both problems and opportunities for businesses in the mobile sector. The very high penetration means that options for growth through market expansion become more limited. However, this is mitigated to an extent by the fact that the rapid pace of technology change means consumers replace handset technology to ensure they have the latest

[175] Ofcom (2008) CMR paragraph 1.2.2.

[176] Ofcom CMR 2016.

features; and that changing technologies present opportunities to use mobile services and mobile infrastructure in new ways (for example using mobile networks for Machine to Machine services, or other mobile connected devices such as tablets).

However, the ubiquity of mobile services can present opportunities to exploit “network externalities”. New mobile applications can achieve faster growth as a result of the high penetration. Social networks, communication tools, mobile search or mapping and navigation for example all benefit from the fact that penetration of mobile is high, since the value of joining these services is higher where others already have access to the service.

A.4.5 Mobile phones have developed from communication tools to a converged multimedia device

This fast evolution of device technology was driven by significant consumer demand for mobile services, combined with high levels of competition in the handset market - meaning manufacturers have consistently looked to innovate, and be ‘first’ with the latest new feature. Improvements in network technology and changes in user preferences have also contributed towards the speed and direction of innovation. For example, the popularity of camera phones has meant that manufacturers have significantly improved the quality of the cameras; as ‘selfies’ have become more popular they have also added and improved front facing cameras.

Figure 66 illustrates the evolution of mobile technology with four devices.

Figure 66 Evolution of the mobile phone

Year of release	1994	1998	2007	2017
Display			3.5"	5.8"
Screen resolution	4 x 13 characters	5 lines	163 ppi	570 ppi
CPU			Single core 412 MHz	Octa-core (4x2.3 GHz & 4x1.7 GHz)
Storage	Phonebook: SIM card + 125 entries Call records: 10 dialed, 10 received, 10 missed calls	Phonebook: SIM only Call records: 8 dialled, 5 received, 5 missed calls	Up to 16 GB	Up to 256GB card slot + 64GB internal
Features	SMS	SMS, clock, alarm, 3 games (Snake, Memory, Logic), 28 languages, interchangeable fascias	Accelerator, proximity, SMS (threaded view), email, HTML, Google Maps, audio/video player, TV-out, organizer, document viewer, photo viewer, predictive text input	Iris scanner, fingerprint, accelerometer, gyro, proximity, compass, barometer, heart rate, SpO2, SMS, MMS, email, push mail, IM, HTML5, fast battery charging, wireless charging, natural language commands and dictation, MP4/MP3 player, photo/video editor, document editor
Operating system			iOS (upgradable to iOS 3.1.3)	Android 7.0 (Nougat)

Sources: www.gsmarena.com; Apple; Samsung

As well as the clear changes in aesthetics, a stark contrast between the early phones and today's is their functionality.

Phones evolved to be much more than just communication tools, and are now able to perform tasks for which consumers previously relied on multiple devices - such as take photos, play music and send/receive email. Greatly improved storage, screen resolutions and processing ability have enhanced the user experience across this range of activities. Mobile phones now have embedded range of wireless connectivity options: support for 2G, 3G, 4G, Bluetooth, WiFi, Near Field Communications.

A.4.6 A key enabler of demand was open app stores

Apple's iPhone launch in 2007, and Android's launch the following year, appears to be associated with a shift in market dynamics. It enabled users to customise their handsets, and app developers to design and market apps which use the device functionality.

As mobile phones have become more sophisticated, the operating system (OS) on which they run has become increasingly important. Before smartphones each handset manufacturer tended to use its own proprietary and closed OS. This would offer a limited number of services which were designed and offered by the manufacturer. Crucially the OS allows any app developers to provide apps and services which use and integrate the devices features.

Although data-based activities were technically possible in the 1990s there was limited take up. There were limited sites which offered content. In some cases manufacturers tried to control access to content whereby users could only access limited content provided by them directly ("a walled garden" of content). For example in the 2000s, Nokia attempted to impose high controls on the underlying software and relationships, with developers creating Nokia-specific content and branding it in this way. The rationale for this approach was to give Nokia a critical position in whichever way mobile applications evolved over time and thereby ensure continued demand for its handsets.[177] This model however led to very limited content that was slow to evolve.

Strong device and mobile Operating System (OS) providers used different business models. For example Blackberry targeted its proprietary data services at business users; Apple integrated its device design and manufacturing and OS; Google developed the Android mobile OS which could be licenced for free bundled with Google's search and other apps. However, this shift opened up the closed walled gardens adopted by some mobile operators.

Apple launched its app store in 2008[178] and Google in 2012.[179] These are both open-access marketplaces, where app developers are free to innovate and design a huge range of apps, publish them for free and directly sell these to consumers, and offer on-line advertising alongside their app. This model has led to intense competition between app developers and huge choice for consumers between apps, which are often free or very cheap.[180,181]

The market for the supply of OS is very concentrated, for example, in the UK the combined Android and iOS share of smartphones stood at nearly 98% in March 2017 (57.2% Android; 40.4% iOS).[182] The concentrated nature of the operating system market is for a number of reasons:

- First, operating systems exhibit strong network effects[183]. The value app developers derive from publishing their content to a particular OS/app store increases as more consumers also sign up (since they are potential customers). Therefore developers have a strong preference to publish in a larger OS, which in turn benefits the consumer through increased competition, greater choice and quality of apps. This means that new smaller entrant OS can struggle to enter and expand.
- OS can exploit "lock-in" mechanisms. Google and Apple exploit the convenience to consumers of keeping the same OS as they upgrade handset. Both companies allow users to easily transfer content or view on another

177 WhatsApp today has over 1 billion users worldwide (https://www
.quora.com/How-many-users-does-WhatsApp-have-worldwide)

179 https://www.theverge.com/2012/3/6/2848223/google-play-store-rebranded-android-market

180 Rakestraw, Eunni and Kasuganti (2013) "The mobile apps industry: A case study"

181 However, as discussed above, this kind of platform (bringing together app developers and consumers) can lead to network effects which means it is very difficult for new app stores to enter the market.

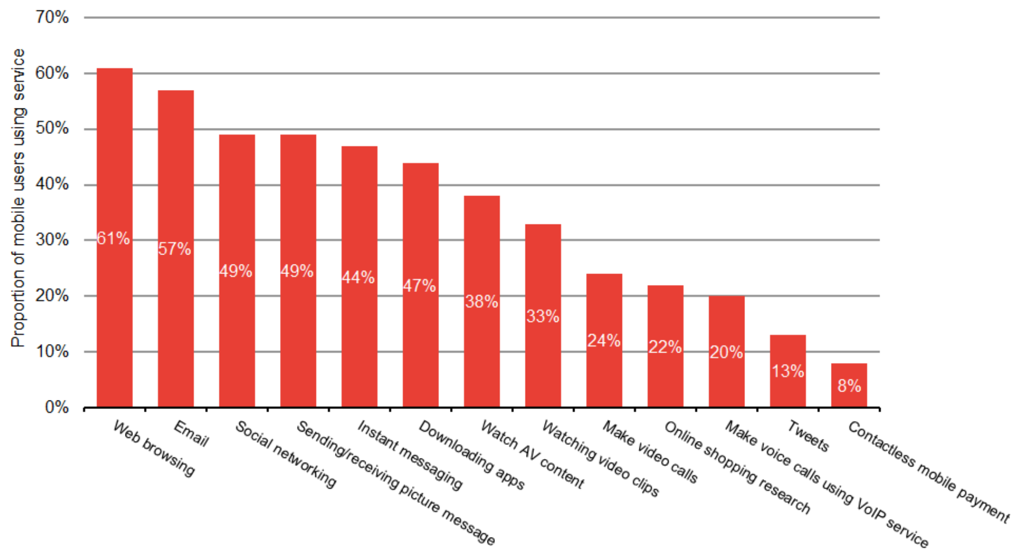
182 Kantar Worldpanel (https://www.kantarworldpanel.com/global/smartphone-os-market-share/)

183 Network effects occur for products or services which increase in value for a consumer as more other people begin to use the product or service as well.

compatible device. Apple, for example, achieved this by automatically saving content to the user's iCloud or Apple ID.[184]

Figure 67 shows usage rates of some of the most popular mobile data services for UK mobile users in 2016. Most of these applications were foreseen when 3G standards were being set in the 1990s (with social networking being the notable exception) with the main distinction being that it was expected that mobile networks and operators would provide and control many of these applications (such as video calling or exchanging digital images) rather than these being provided by 3rd party's 'over the top' of networks.

Figure 67 Use of mobile data services among UK mobile users, 2016



Source: Ofcom Communications Market Report 2016

A.4.7 In UK regulatory and institutional constraints delayed roll out of 4G

Roll out of 4G networks in the UK was delayed initially due partly to challenges with the process designed to allocate spectrum, but once spectrum was available deployment was swift.

In 2009, Ofcom recommended that the 800MHz spectrum band should be auctioned together with 2.6GHz spectrum to support new 4G services. Ofcom proposed limiting the ability of the larger existing providers to buy spectrum. These limitations were disputed by the operators, and the ensuing consultation process on the auction rules, together with the 2010 UK election, caused a delay in the spectrum auction until 2013.

In 2012 Everything Everywhere (EE), which was created as a result of the merger between Orange and T-Mobile UK, announced it wished to launch 4G services. EE already had access to a sufficient quantity of spectrum to launch 4G

184 https://support.apple.com/explore/managing-apple-id; https://www.apple.com/uk/icloud/ .

services[185] as a result the merger, and so could launch prior to the planned 4G spectrum auction. EE had unused spectrum in the 1800MHz band which had been standardised internationally for 4G use. EE therefore asked Ofcom's permission to repurpose it for 4G before the auction and gain a significant head start in the market. After a consultation, Ofcom decided to grant this approval in October 2012.

The 4G spectrum auction was ultimately delayed until February 2013 (four years later than planned). Spectrum was won by the four MNOs as well as by BT. By that time, 4G networks were rolled out in most countries in Western Europe and 4G coverage in Germany reached 75%. By the time that 4G launched in the UK demand for data grew quickly.

A.5 Implications for UFBA

In assessing the scope for future demand for UFBA there are a number of features of the development of the mobile network that are relevant.

- The market for fixed broadband is also a function of the supply (and demand) for other complementary services, applications and devices that use the network. Given the complex interdependencies between the different complementary markets, a supply shock in the network (such as an increase in the capacity or capability of the network as facilitated by UFBA) will only lead to increases in demand in related markets as they gradually respond to consumer demand. But likewise, demand for UFBA will depend on the development of services, apps and devices which use the network.
- Medium term forecasts of future demand for network services necessarily are generally based on iterative improvements to existing services. However, this can mean that forecasting is uncertain if uptake of new applications drives significant demand growth in the longer term. Forecasts of mobile demand such as those made in the early 1990s, severely underestimated future demand because they underestimated the rate at which mobile phones would become a mainstream technology rather than a luxury good. Conversely forecasts made when 3G spectrum was licenced under-estimated the time required to build the eco-system necessary to migrate Internet based services to mobile devices and so under estimated take up.
- The potential for the UFBA in the coming thirty years may be analogous to the mobile sector in the early 2000s. There is high penetration of broadband services. However, demand from most customers for the incremental benefits of UFBA services is uncertain, though development of apps, devices and services which could use the high capacity UFBA networks could stimulate demand as was the case for mobile following the launch of 4G services.
- The mobile industry structure has evolved over the period moving from four vertically integrated operators delivering end to end services to a structure with multiple providers of applications over the top, multiple mobile virtual

185 However, it required an approval of 1800MHz 'liberalisation' (lifting the requirement that 1800MHz can only be used for 2G) by Ofcom. However, it required an approval of 1800MHz 'liberalisation' (lifting the requirement that 1800MHz can only be used for 2G) by Ofcom.

network operators serving retail customers and the four networks partnering in two infrastructure sharing arrangements.

Competition in mobile networks and applications has led to innovation and investment even with increasing concentration in the underlying infrastructure. The evolution of the industry structure may differ for UFBA where for most areas of the country there are at best two competing network infrastructures at present.

ANNEX B HISTORICAL ANALYSIS OF BROADBAND MARKET DEVELOPMENT

B.1 Introduction

Broadband is defined as a high-speed Internet access using wide bandwidth data transmission.

Broadband was first launched in the UK in 2000 and has since become an essential part of modern life for both residential and business users. It has transformed how we communicate, shop and consume audio-visual content. Broadband along with other ICT have created efficient markets via online platforms, reduced barriers to entry in a variety of markets, lowered shopping costs, and created vast amounts of data which can be used to create value for providers and consumers. Broadband has also transformed how some services, including government services, are supplied, and in so doing improves the ability to realise social and public policy objectives.

To date, the UK has largely chosen the path of upgrading existing networks. FTTP access is relatively rare and instead the incumbent has chosen a strategy of iteratively upgrading the copper network to offer incremental improvements in quality (DSL; to ADSL; ADSL2+; FTTC and now G.Fast). This approach has delivered broadband to the majority of household which is sufficient to deliver to the majority of users.

As was noted in the 1995 study on demand for broadband: *"provision of infrastructure too far ahead of consumer demand for the increased bandwidth will represent poor investment"* i.e. there is little support for the 'build it and they will come' view of investment. For example, Japan, which was a global leader in fibre deployment, generates less consumer Internet traffic per capita on fixed consumer networks than the UK, with minimal fibre roll out[186]. However if in the long run broadband infrastructure does not keep pace with customer demand, the choking off of demand could lead to significant loss in economic welfare.

Given the uncertainties in forecasting demand for incremental improvements to broadband, such a strategy can be considered commercially sensible. Most use cases imagined have been delivered using a combination of iterative upgrades of existing infrastructure and technologies to improve the efficiency and effectiveness of data transmission and storage.

However, it can be argued that broadband (and incremental increases in broadband speeds), can be regarded as "experience goods". These are goods where it is difficult for consumers to ascertain the value of the good prior to using it. This characteristic can be a barrier to consumers upgrading their service and

186 Cisco VNI assumes 17.6 GB per capita per month of data on consumer networks for Japan in 2015 while for the UK in 2016 the equivalent figure was 40.7 GB of consumer data per capita per month on fixed networks. Source: https://www.cisco.com/c/dam/m/en_us/solutions/service-provider/vni-forecast-widget/forecast-widget/advanced.html

therefore a barrier for network operators to invest in their networks. "Experience good" characteristics can also provide a public policy justification for intervention to stimulate demand for faster broadband to mitigate the information asymmetry that consumers face when valuing faster broadband speeds.

In this section we draw out some of the factors that led to the growth in popularity of broadband services and hence what led telecommunication operators to make investments in broadband networks. In particular we note that:

- **There is limited infrastructure competition in the UK.** In some areas, broadband infrastructure providers compete in a duopoly (BT and Virgin Media's cable are both present) and in other areas there is a monopoly where only BT is present.
- **Regulatory policy focused initially on increasing competition among broadband providers over BT's access infrastructure**. This was successful at increasing take up and demand, though has not led to conditions where providers have been incentivised to invest in new competing infrastructure.
- **Superfast broadband was initially offered by incumbents making relatively low cost upgrades to existing access cable and telecommunication networks**. The competition between the BT and cable networks appears to have spurred each to upgrade the speeds offered over their infrastructure. However, despite the significant increase in demand for broadband, potential entrants have not been incentivised to invest in competing infrastructure as standalone costs of building new infrastructure are an order of magnitude greater than the cost of upgrading existing networks.
- **Government intervention has been focused on improving provision in rural areas** where existing operators have not had the incentive to roll out higher speed broadband.
- **Demand for broadband was fuelled by demand for the plethora of services that use the internet and the step change in the user experience compared to previous narrowband services (i.e. dial up).** However, demand for broadband is an "experience good" whose true value can only be discerned by users after consuming it. This may be a barrier to further investment in the network if the perceived benefits are limited.
- **Average speeds have increased over time and complaints have gone down, suggesting good outcomes for UK subscribers in general**. However, there remain some subscribers who have a poor customer experience in terms of speed and reliability.

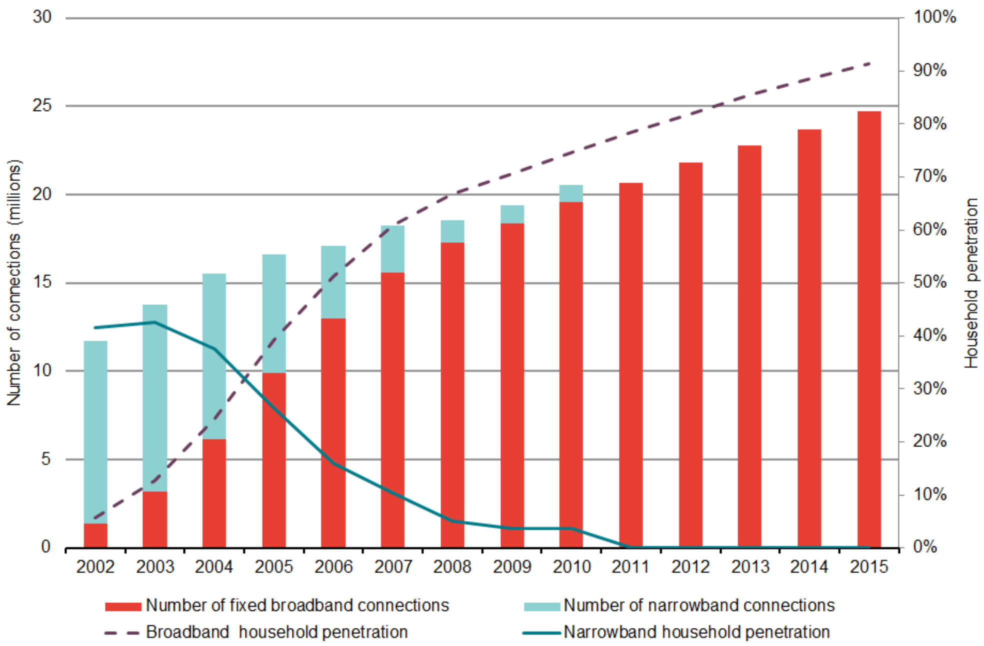
B.2 Take up and coverage of broadband has grown, however, coverage of UFBA is low

Broadband penetration in the UK is now almost ubiquitous with a household penetration approaching 90% (Figure 68). Broadband has replaced narrowband “dial up as the means to connect to the Internet[187]. Dial up offered internet access, albeit at far lower speeds than broadband, using existing telephone lines allowing households to connect a PC to the internet with a modem.

- Broadband penetration in the UK is now almost ubiquitous
- Initially the UK lagged behind other countries in the take up of broadband
- Current coverage of UFBA networks in the UK lags behind many other peer countries.

Broadband has been delivered as an overlay over existing copper based networks requiring incremental investment in order to facilitate high speed data transfer.

Figure 68 Fixed broadband and narrowband connections in UK, 2002 - 2015



Source: *Ofcom Communications Market Report 2004-2016; ONS*

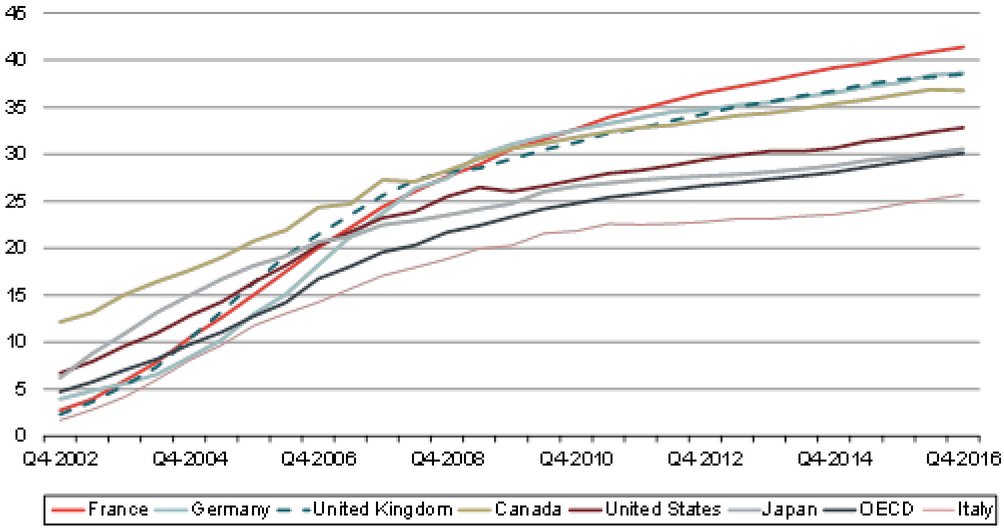
Note: *Household penetration is defined as the number of broadband connections divided by the number of households*

However, take up of broadband in the UK was initially lower than in similar countries. For example, Figure 69 shows that in 2002 the UK had one of the lowest penetration rates of broadband compared to comparator countries. This reflected limited investment and high pricing by BT and the cable operators. Ofcom’s “2005 Strategic Review of Telecommunications” opened up BT’s infrastructure to competing providers such as TalkTalk and Sky through local

[187] A dial up modem provides speeds up to 56Kbps whereas average broadband speeds today are 36.2Mbps with even the first broadband services typically offering speeds an order of magnitude faster than dial up As well as being significantly faster, broadband improved upon narrowband by its ‘always on’ nature. Narrow band used the same frequencies as audio analogue voice meaning that to connect to the internet the user had to disconnect their landline first. Instead Broadband uses a higher and wider set of frequencies than analogue voice.

loop unbundling. By 2016, the broadband penetration rate in the UK it was one of the highest amongst similar countries partly driven by strong competition among providers and the consequent reduction in prices.

Figure 69 Fixed broadband penetration (broadband connections per 100 households), G7 countries



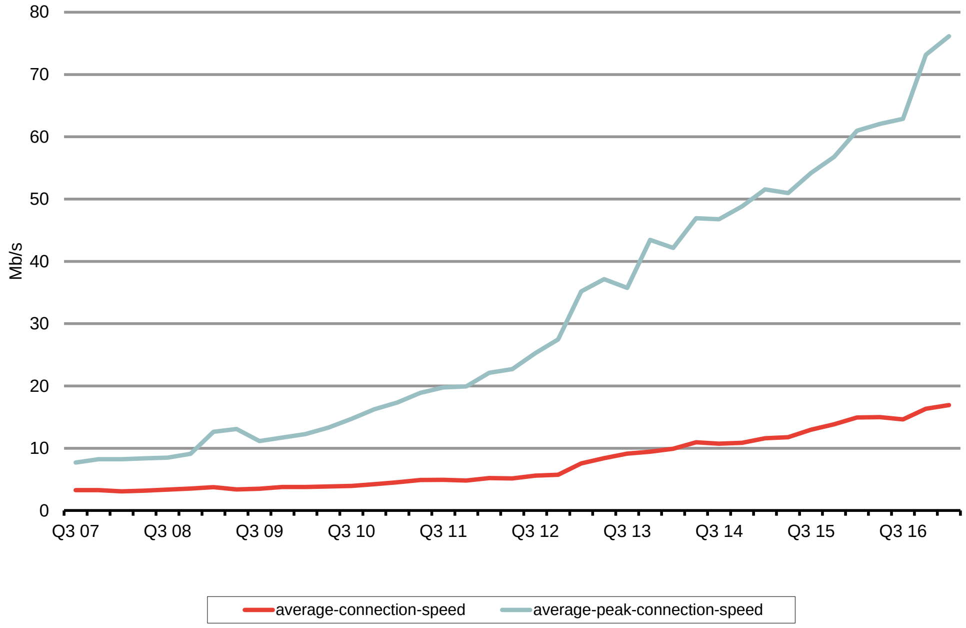
Source: OECD

Note: http://www.oecd.org/sti/broadband/1.7-BBPenetrationHistorical-G7-2016-12.xls

Competition also spurred increases in broadband speed as competitors sought to differentiate their services. Initially this could be achieved through improvements in equipment alone (i.e. ADSL2+) but since 2009 has required increased investment in infrastructure, e.g. roll out of fibre to the cabinet (FTTC). However both BT and Virgin Media still rely on copper infrastructure for the final connection to the home.

There is a significant gap between the average speed taken by customers, and the potential speeds that their lines could support. However, this is likely to reflect the fact that users do not require peak access speeds on a sustained basis, with operators dimensioning their backhaul and core networks to offer lower capacity than could be served through the access networks.

Figure 70 Broadband speeds



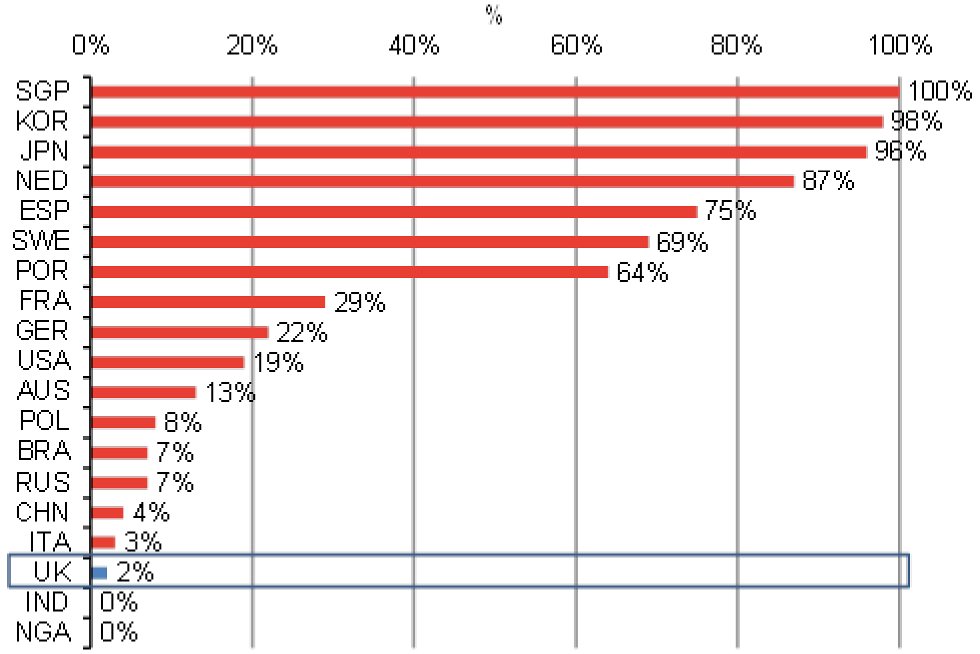
Source: Akamai State of the Internet

Note: Average peak connectivity describes the maximum potential speed of customer's infrastructure

While take up of broadband is high in the UK, coverage of UFBA networks in the UK is low compared to many comparator countries. According to Ofcom, the UK performs poorly compared to the majority of our global peers[188], for example those countries where investments in full fibre infrastructure have been made.

[188] Ofcom (2016) Making communications work for everyone Initial conclusions from the Strategic Review of Digital Communications paragraph 4.2.

Figure 71 Percentage of households in areas served by ultrafast broadband products (with advertised speeds of 300Mbps or more) (September 2016)



Source: Ofcom iCMR 2016 Figure 3.34.

B.3 There are only two significant access infrastructure providers in the UK and only one in half the country

Broadband was initially offered by cable and telecommunications incumbents making relatively low cost upgrades to their existing access networks. With limited exceptions, the access infrastructure can be described as a duopoly in areas where cable competes with BT's network. Outside cable areas, BT is generally the monopoly provider. The high fixed costs of rolling out a fixed telecommunications network has meant that there was little incentive to roll out a new competing network where BT already offers broadband with a small incremental expenditure to upgrade its existing network.

> “
> - There is currently limited infrastructure based competition in fixed broadband in the UK: half the country have duopoly provision, and the other half face a monopolist.
> - Nonetheless, network competition did provide a degree of incentive to innovate with their existing copper or cable networks.
> - However, the limited network competition has not incentivised operators to roll out a new fibre network.

BT first rolled out ADSL in 2000[189] over its copper access network and BT as well as access seekers have since launched various upgrades to the ADSL standard leading to faster speeds.

[189] BT

Cable operators began offering broadband in 2000. In the 1980s and 1990s cable companies were licensed to provide cable TV and phone services in distinct geographic areas ('franchises'). BT was prevented from supplying broadcast TV services via its national network. During the 1990s and early 2000s the cable companies gradually consolidated eventually becoming Virgin Media which included almost all cable areas in the UK, and covered 53%[190] of households in the UK[191].

The high fixed costs of rolling out a fixed telecoms network means that there have been limited examples of alternative infrastructure competition[192]. A number of small providers targeting specific geographic areas have installed fibre based access networks. These include Cityfibre who operate in Bournemouth, and in collaboration with TalkTalk in York, and are investing in other cities; or Gigaclear who operate in in a number of small developments in more rural areas.

However, competition between the two different networks has generated a degree of competition at an infrastructure level (access based competition on the BT network offers a further level of competition). The different capabilities of the network have become a key point of differentiation between the operators (as illustrated by marketing material of Virgin Media in Figure 72) with Virgin Media seeking to position itself as a premium provider. This in turn has incentivised BT to upgrade its network to Fibre to the Cabinet (FTTC) technologies. FTTC upgrades copper from the exchange to a street cabinet with fibre, but the copper network is used from the cabinet to the premises. FTTC improves broadband speeds, over copper based ADSL technologies, but given the last element of the connection relies on a copper line, the potential speed declines rapidly with line length.

Figure 72 Example of Virgin Media marketing

Source: https://my.virginmedia.com/customer-news/articles/better-broadband/speed-upgrade.html

The role that network competition played in incentivising operators to upgrade their networks was noted by Ofcom:

> *"The degree of end-to-end competition from cable networks appears to play a role in encouraging incumbents to deploy*

[190] 14.4m homes passed in Q1 2017. http://www.virginmedia.com/content/dam/virginmedia/dotcom/documents/corporate/factsheet_may_2017_edit.pdf

[191] Other cable franchises which are not part of Virgin Media include WightFibre on the Isle of Wight.

[192] In some areas operators were licensed to provide a Fixed Wireless to the Locale service.

> *faster broadband. In particular, as cable networks upgraded their networks to DOCSIS 3.0 to begin to offer superfast broadband, incumbents came under more pressure to offer FTTP or FTTC broadband. Near-universal cable availability in the US and Canada has driven investment in fibre networks from incumbent operators."*

However, competition from cable has not led BT to make significant investments in FTTP technologies to date. Although BT has invested in providing coverage to 500,000 premises with a combination of FTTP and G.Fast[193].

[193] As at June 2017. See: http://www.btplc.com/Sharesandperformance/Quarterlyresults/Investormeetingpack.pdf

THERE ARE A NUMBER OF DIFFERENT BROADBAND TECHNOLOGIES

As noted above, broadband is a term which encompasses various different technologies including:

- **Asymmetric Digital Service Line (ADSL)** is a technology which transmits digital data over traditional copper-based telephone lines from the exchange. In the UK the incumbent telecoms operator BT owns this network[194]. BT first rolled out ADSL in 2000. ADSL is the predominant broadband technology with about 54%[195] of subscribers on this type of connection and coverage of 99.9%. Initially ADSL offered speeds of 8 Mbps. Iterative advances in ADSL technology have improved speeds for consumers. ISPs could differentiate their offering by investing in the next generation of ADSL technology or using VoIP to lower costs. The current generation of ADSL2+ offers maximum speeds of around 24 Mbps.[196]

- **Fibre to the Cabinet (FTTC).** The speeds achievable by ADSL are limited as speeds decline as the copper loop distance increases. In order to offer faster speeds the operators' equipment needs to be moved closer to the end user, e.g. in cabinets, with fibre connected back from this equipment (hence fibre to the cabinet) BT launched FTTC using VDSL2 in 2009, offering speeds of up to 76 Mbps[197]. In March 2017, BT begun conducting pilots for its ultra-fast G.Fast technology, which could be capable of data speeds of up to 330Mbps.

- **Cable** networks use fibre optic and coaxial cables (hybrid fibre coax – HFC) to deliver superfast broadband services in addition to the TV and phone services for which the networks were initially rolled out in the 1990s. Broadband was first launched in 2000 by Telewest (which had acquired roughly half of the cable television franchises by this point), and NTL (who owned most remaining franchises) followed shortly afterwards. NTL and Telewest merged forming Virgin Media which now owns all of the cable networks in the UK. Virgin Media has continued to invest substantially to update the network, the most recent example of which is DOCSIS 3.0 - which offers speeds of up to 300Mbps. Early trials have begun on full-duplex DOCSIS 3.1 which will potentially be able to offer speeds of up to 10 Gbps. Today around 20% of broadband connections are cable and coverage is around 53%[198].

- **Fibre to the home** broadband is delivered via clusters of fibre optic cables. Fibre-to-the-home/premises (FTTP/H) broadband, where fibre optic cables running directly to the home, can produce speeds of up to 1 Gb/s, but currently coverage is low and constitutes a small minority of connections.[199] BT had initially intended to roll out FTTP services to up to 25% of the households in its area[200]. However, it subsequently revised its plan and now has only relatively low proportion of residential FTTP connections. FTTP is available to 1.7% of households or 498k households. This includes BT, 137k premises passed by KCom[201], 100k premises passed by Hyperoptic, 14k (to be extended to 40k) premises passed by TalkTalk, and Virgin Media which plans to roll out some FTTP[202]).

- **Other broadband technologies include:** satellite broadband, fixed wireless access, or fixed broadband using mobile technologies (such as 4G and 5G).

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194 Except in Kingston upon Hull

195 As at Q4 2016. Source Ofcom. See: https://www.ofcom.org.uk/research-and-data/telecoms-research/data-updates/telecommunications-market-data-update-q4-2016

196 https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/advice/broadband-basics

197 https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/advice/broadband-basics

B.4 Government intervention has focused on providing better quality broadband to rural areas

Coverage of broadband of any speed is now almost ubiquitous. However, faster connections are concentrated in more urban areas due to a combination of shorter loop lengths and lower cost of rolling out FTTC and hybrid fibre-co-axial[203] (HFC) networks. This means that there are significant parts of the country (typically rural areas) where faster broadband connections are unavailable. Figure 73 sets out the coverage and take up of broadband by speed.

- While coverage of broadband networks is high there is significant geographic variation in quality.
- Rural areas have broadband with much slower connections.
- Government intervention has focused on improving coverage in rural areas by providing public subsidies (£1.7bn) for broadband provisions.

Figure 73 Coverage and take up of broadband (2016)

	Coverage	Take up
Any broadband	100%	78%
0 – 2 Mbps	1%	
0 – 10 Mbps	5%	8%
> 10 Mbps	95%	92%
> 30 Mbps	89%	31%
> 300 Mbps	2%	0.01%

Source: Ofcom (2016) Connected Nations

There is significant variation in the coverage, availability and take up of broadband between rural and urban areas. For example, while 2% of urban households are unable to receive a broadband connection of greater than 10Mbps, this increases to 25% in rural areas (see Figure 74). Similarly, average download speeds[204] are slower in rural areas than in urban areas. The average download speed in 2016 was 37Mbps in the UK whereas this was 21Mbps in rural areas (though rural download speeds were even lower in 2015 at 13Mbps).

198 14.4m homes passed Q1 2007, out of a total of 27m homes in the UK. See: http://www.virginmedia.com/content/dam/virginmedia/dotcom/documents/corporate/factsheet_may_2017_edit.pdf

199 https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/advice/broadband-basics

200 Source: BT 2009/10 Q4 and Full Year Results. See for example: https://www.btplc.com/Sharesandperformance/downloads/PDFdownloads/q410transcript.pdf

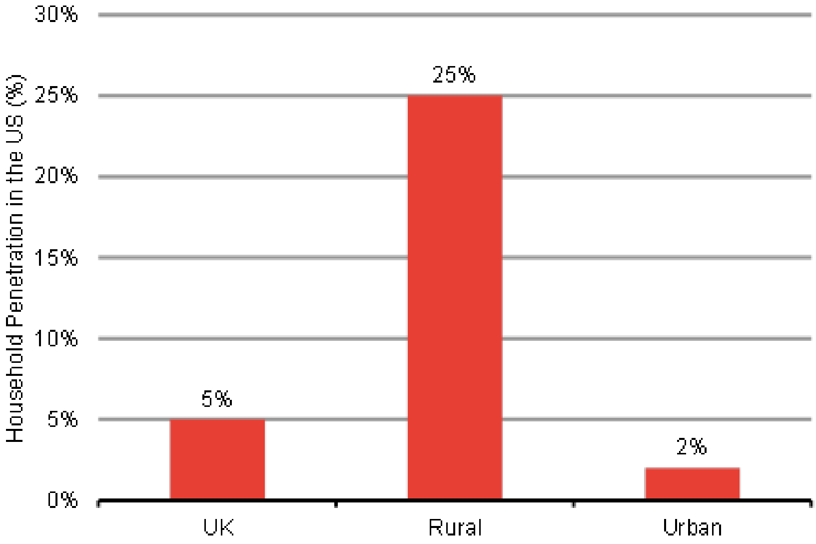
201 See: http://www.kcomplc.com/media/1623/preliminary-presentation-2016-2017-v2.pdf

202 See: https://www.ofcom.org.uk/__data/assets/pdf_file/0008/101051/duct-pole-access-remedies-consultation.pdf paragraph 3.10.

203 HFC networks are used to deliver TV and broadband over cable TV networks using “DOCSIS” networks standards.

204 Note that average download speeds are a function of the available broadband speed as well as the package chosen by consumers.

Figure 74 % of premises with download speed less than 10Mbps



Source: Ofcom (2016) Connected Nations

IT IS MORE COSTLY TO DELIVER HIGH QUALITY BROADBAND IN RURAL AREAS

It is more costly and less profitable to roll out broadband services in rural areas. This is for a number of reasons. First, houses in rural areas are located further from the exchange, therefore there can be more civil works required to install longer cable. Second there are fewer households per exchange, and there can be lower economies of scale to upgrade an exchange area. Third, the delivery of broadband using existing copper networks (either ADSL or FTTC) in rural areas results in slower connections which reduces demand for broadband. This is because the quality of connection degrades as the distance between the household and the exchange increases. At very long lengths of copper line the service degrades significantly.

Government intervention has focused on improving coverage in rural areas. ‘Broadband Delivery UK’ (BDUK), part of the Department of Culture, Media and Sport has led the policy on increasing coverage and has assisted in the distribution of £1.7bn public funding to support superfast broadband[205]. BDUK’s objective has been to support investment in “superfast” (i.e. at least 30 Mbps) in more rural areas. It initially targeted those areas that it believed would otherwise not receive FTTC broadband (by increasing coverage from 66% to 90% of households) by early 2016. Then in a second wave it aimed to increase coverage of “superfast” broadband to 95% of households by 2017.

More recently, the Government implemented a USO which imposed a legally binding requirement to provide a download speed of at least 10Mbps.

[205] See: https://www.gov.uk/government/news/additional-129-million-boost-for-nationwide-broadband-rollout

B.5 Regulatory intervention initially focused on improving competition on BT's network

Since 2004 Ofcom's regulatory objective has largely been to increase competition over BT's copper network. When implementing regulation, Ofcom has to balance a number of often competing objectives: it wants to encourage high take up of services (and low prices), but it also wants to preserve incentives to invest and innovate, and where possible to ensure a degree of competition. Different regulatory tools can be used to achieve different outcomes. Low wholesale prices for BT's network services will lead to higher access and take up increased. Furthermore, the relative attractiveness of different regulated services will incentivise entrants to invest in infrastructure in different ways.

In its 2002 Access Directive the European Commission mandated that national regulatory authorities should impose conditions to ensure that operators found to have SMP on a set of defined markets provide non-discriminatory access to their network such that competitors are able to provide equivalent services to end users.[206]

In the UK, Ofcom has implemented this framework, with the approach evolving over time, reflecting the evolving market developments. The key elements of regulation are set out below.

> - Since 2004 Ofcom's regulatory objective has largely been to increase competition over BT's copper network.
> - Regulation which provided wholesale access to a broadband service (WBA) and access to the copper loop between the exchange and end users' households allowed entry and encouraged service based competition.
> - Competition lowered prices which increased uptake and in turn lowered costs (and lowered prices further).
> - However, the degree of innovation and differentiation that is possible with LLU based competition is ultimately limited.
> - As consumers have switched to FTTC products (which use fibre to a street cabinet then copper lines from the cabinet to the house) BT's market share has increased. BT has around two thirds of retail share of fibre connections.

[206] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32002L0019

KEY REGULATORY INTERVENTIONS IN THE UK

2002 - Ofcom mandates Wholesale Broadband Access (WBA) to BT's ADSL network

In 2002, Ofcom mandated that BT offer 'bitstream' access to its ADSL network. BT introduced its wholesale 'Datastream' product. This was a product for wholesale customers to purchase connectivity from BT[207] to resell to customers. This was a wholesale broadband service offered by BT, but it allowed its customers to choose certain parameters of the service such as contention (which would affect speeds at peak times) or quality of service (such as response to faults).[208] Operators such as Thus and Tiscali were quick to respond and launch services using BT's Datastream product[209]. Today a number of operators still offer broadband services on this basis. However, the WBA wholesale product was a wholesale service controlled by BT and largely replicated BT's retail offer. It meant that alternative operators had limited opportunity to innovate in terms of price or product.

2002 - Local loop unbundling (LLU) supports greater investment and innovation

In 2002 Ofcom mandated Local Loop Unbundling (LLU) whereby BT was required to allow service competitors access to its local copper network at wholesale prices (i.e. the copper "local loop" between the exchange and the house was unbundled). The objective behind this was to make this "last mile" of network available to other service providers at a fair cost to allow competitors to offer their own active equipment and thereby open up competition in the broadband market.[210] Lack of clarity around the regulatory regime and high prices for LLU meant that take-up was initially slow.

2005 - Structural separation of BT helps to prevent discrimination

In September 2005 BT agreed with Ofcom to create a separate division called OpenReach (in lieu of a market investigation reference). The rationale for structural separation was to prevent BT from discriminating in favour of its own services, so entrants can compete.[211]

As the same time Ofcom lowered the LLU price and improved the process for roll out of LLU by BT's competitors. From 2005, LLU take-up and coverage began to grow quickly, reaching 67% coverage by 2006 and 94% by 2014. Notable LLU broadband providers include Sky and TalkTalk, who have 5.7m and 3.9m broadband subscribers respectively.[212][213]

2010 - BT required to offer its wholesale FTTC service to customers

As BT rolled out a FTTC infrastructure from 2009 Ofcom set out regulations which allowed operators to compete in the retail provision of the new FTTC broadband service. BT was required to offer a wholesale service "Virtual Unbundled Local Access (VULA). Initially Ofcom did not set the price of VULA (noting that the price would be constrained to a degree by the price of copper based services), but imposing the requirement that it should be "fair and reasonable". However as the technology matured in 2014, Ofcom imposed a price regulation using a margin test methodology (which gave BT flexibility to set the retail price).

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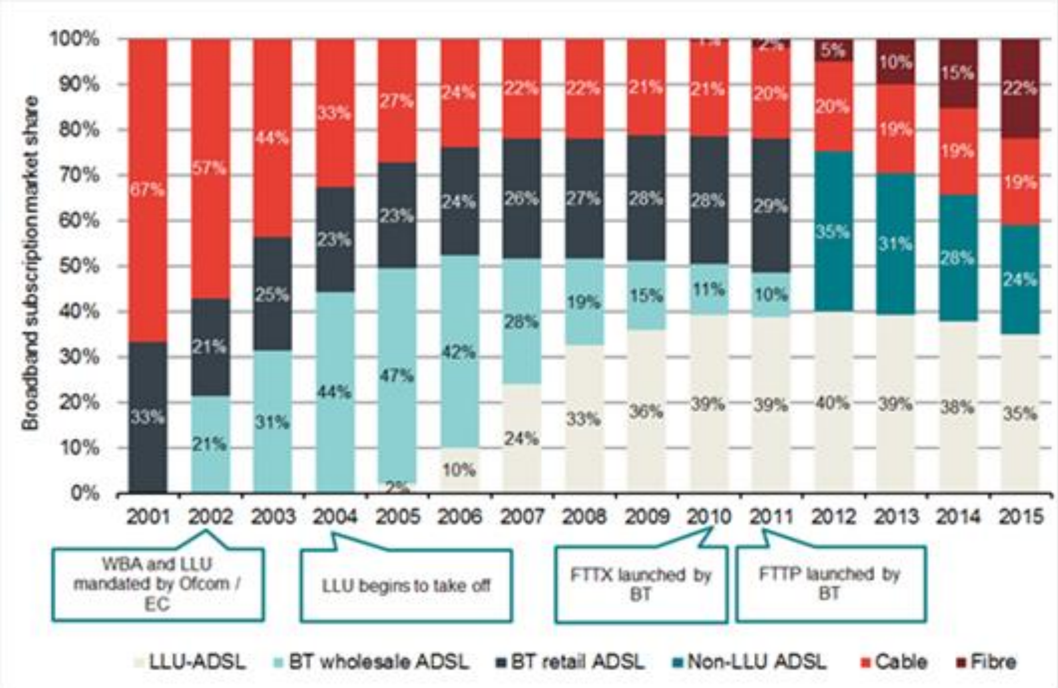
[207] https://www.ofcom.org.uk/__data/assets/pdf_file/0028/58438/tcoms_annexs.pdf

The evolution of different broadband technologies can be seen in Figure 75.

- Initially retailers of broadband using BT's wholesale broadband service captured market share in the nascent market. By 2005 these accounted for 47% of broadband subscribers.
- LLU quickly took off from 2004 as new operators offered services. With LLU based competition from competitors to BT increasing market share to 40% in 2010.
- However, increasingly users are migrating to FTTC which is provided to users using the VULA remedy.

Figure 75 Broadband connection type market shares, 2001 - 2015



Source: Ofcom Communications Market Reports 2006 - 2016

Note: *BT wholesale and retail Non-LLU ADSL are combined from 2012 onwards as Ofcom stopped reporting them separately from this year*

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[208] https://www.ofcom.org.uk/__data/assets/pdf_file/0026/23939/dsl.pdf; https://www.thinkbroadband.com/news/1241-thus-launches-another-datastream-variant

[209] https://www.thinkbroadband.com/news/1241-thus-launches-another-datastream-variant

[210] Ofcom Communications Market Report 2005.

[211] https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2017/bt-agrees-to-legal-separation-of-openreach

[212] Telegeography.

[213] In its 2010 review Ofcom also put forward a remedy of Virtual Unbundled Local Access ("VULA") specifically designed for Fibre-to-the-Cabinet (FTTC) superfast broadband services. This differed from BT's existing physical LLU on copper networks in that Physical LLU allowed rivals to install their own hardware at the telephone exchange and to even take full control of a telephone line, whereas under VULA BT still effectively retains control over the physical line. The benefit of this remedy is that it gives rivals much more freedom in their management of the connection (Ofcom Review of the wholesale local access market 2010)

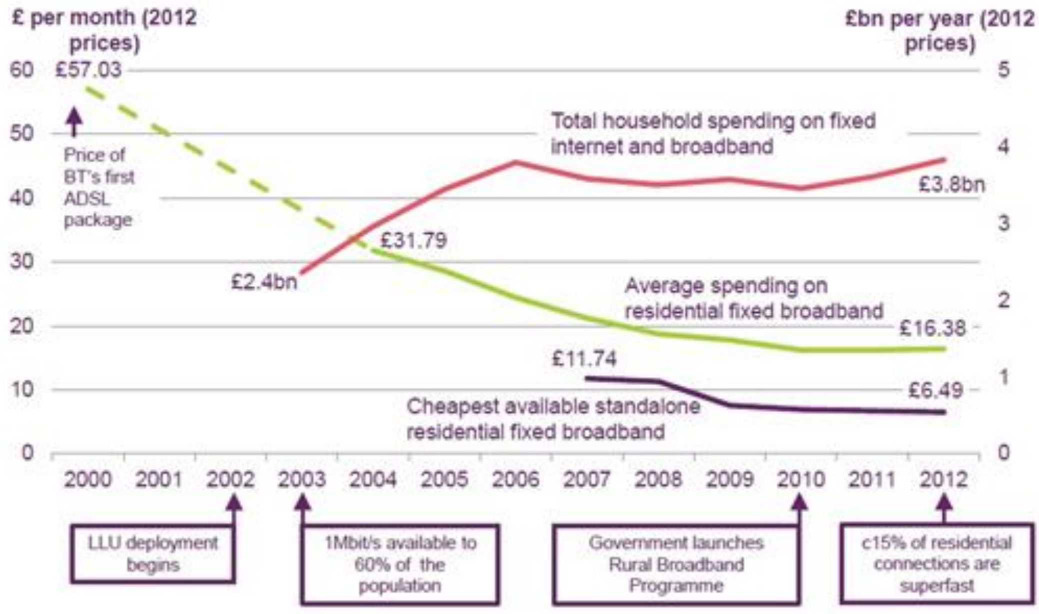
New entrants and increased competition have pushed down prices over time

These remedies have been successful in increasing competition. As Figure 75 shows, WBA and LLU has resulted in a number of new entrants providing LLU-ADSL or through wholesale access to BT's network, with the relative share of these two types of broadband growing significantly. Ofcom highlighted the benefits of competition where suppliers invest in their own equipment in 2007 when it noted that:

> *"[a] major driver of recent falls in the cost of telecoms services has been the accelerated rate of exchange unbundling. […] unbundling exchanges gives operators control over more of the value chain and access to economies of scale not available when using BT wholesale tariffs. … LLU has opened up the retail market by allowing operators to offer differentiated services by installing their own equipment in exchanges".*[214]

Broadband prices have also fallen also substantially over time which is likely to have been driven largely by increased competition (Figure 76). The fall in prices was partly attributable to economies of scale whereby investments made by operators within each exchange to facilitate broadband investments exhibited economies of scale as more households took up broadband. This in turn enable operators to lower prices, and hence increased demand for broadband.

Figure 76 UK retail broadband prices, 2000 - 2012



Source: Ofcom

[214] Ofcom

There were limits to LLU based competition

Regulatory interventions to promote LLU based competition initially promoted a degree of competition over the quality of the product offered. LLU providers were able to differentiate by offering more advanced forms of ADSL technology. Providers progressively upgraded their infrastructure from ADSL to the ADSL2+ standard. This meant that providers could offer faster speeds (up to 24 Mbps for ADSL2+ compared with up to 10Mbps). However, further upgrades were not possible as the technical limits of using ADSL with an LLU approach were reached.

However, when BT launched its FTTC based service other operators were less able to differentiate their service compared with BT's since the VULA wholesale product offered fewer opportunities to innovate or differentiate[215].

BT's retail market share has grown

Despite significant regulatory intervention to enable competition BT's retail share of fixed broadband connections has increased over the period. It increased from 24% in 2006 to 37% in 2017 (see Figure 77). This is primarily driven by increased retail market share for BT for FTTC connections, where operators such as Sky and TalkTalk have less control over the costs and functionality of the access connection and so cannot differentiate themselves to the same degree as they could with ADSL based services.

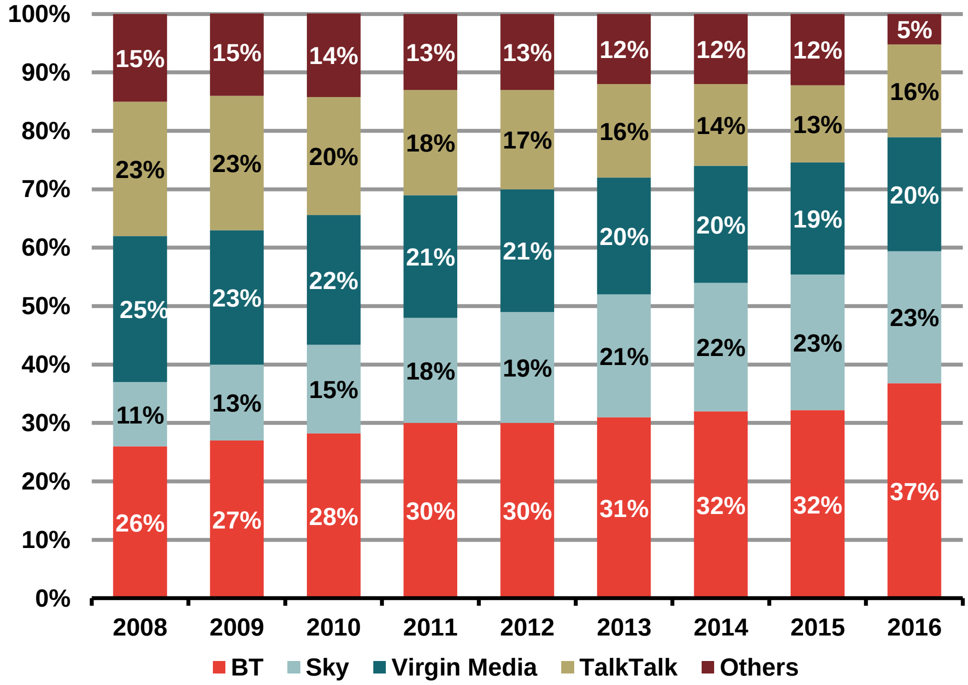
In 2015, 54% of retail superfast broadband connections were provided using VULA (with the remainder largely using cable). Of these, approximately two thirds of FTTC were offered by BT Retail[216]. For Q3 2015/16, new VULA based broadband customers are split broadly 50:50 between BT Retail and other communications providers.[217]

[215] See Ofcom (2016) Making communications work for everyone Initial conclusions from the Strategic Review of Digital Communications paragraph 4.8. https://www.ofcom.org.uk/__data/assets/pdf_file/0016/50416/dcr-statement.pdf

[216] Of all retail superfast broadband connections 54% were using VULA. 37% of retail superfast broadband connections were VULA offered by BT Retail and 17% of tail superfast broadband connections were VULA offered by other communications providers.

[217] See Ofcom (2016) Making communications work for everyone Initial conclusions from the Strategic Review of Digital Communications paragraph 4.9. https://www.ofcom.org.uk/__data/assets/pdf_file/0016/50416/dcr-statement.pdf

Figure 77 Broadband retail market shares, 2004 – 2017



Source: Frontier analysis, Ofcom CMR 2016, 2014, Telegeography

B.6 New applications, devices and services have driven demand

Demand for broadband connectivity is derived demand based on the applications consumers use it for. Key to broadband's success therefore is the internet's open protocol, and Wi-Fi's open protocol which allows any type of device to connect to the internet, meaning that a wide variety of broadband applications and devices have become available to consumers.

In the early years of broadband, the predominant use was internet browsing on desktop and laptop computers. The internet's model enabled anyone to publish and consume content. This has led to huge demand and supply, and today there are over 1 billion websites on the World Wide Web.[218] The intense competition means that much content is free at the point of access (supported by a number of business models such as advertising sponsorship or ancillary services).

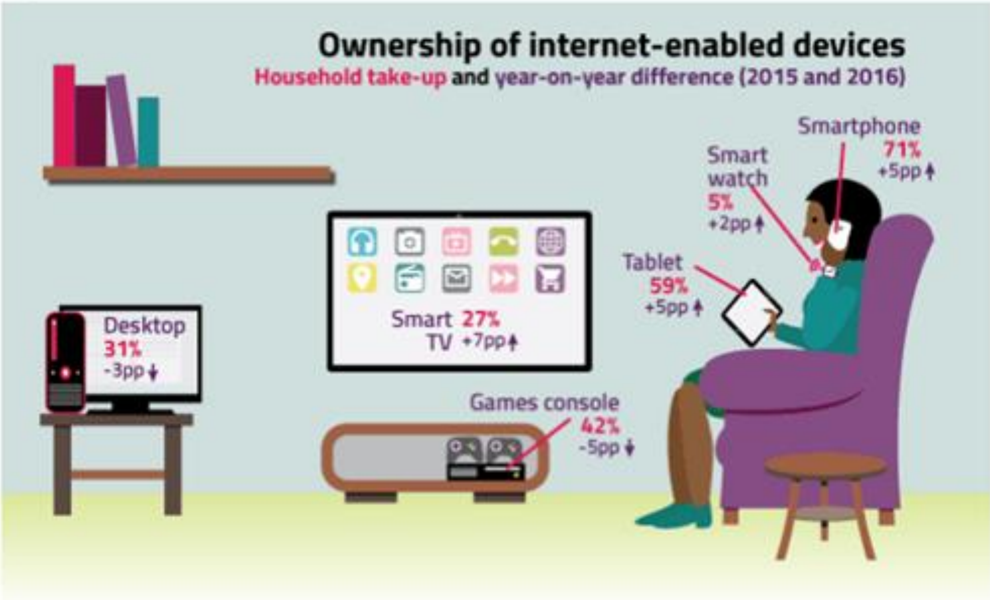
- Demand for broadband was fuelled by the growth in applications and services offered on the internet. Technical hardware innovations (such as Wi-Fi and Bluetooth) have increased the value that consumers have for their broadband connections.
- The difficulties of forecasting demand for broadband are not new. Early studies encountered similar difficulties but were reasonably accurate in the potential uses for broadband.
- It is possible that broadband is an experience good, such that end users cannot foresee ex ante the value that they would have for upgraded broadband services.

In recent years there has been a trend towards greater usage of internet-enabled portable devices in the home connected to broadband via Wi-Fi. Wi-Fi uses short range wireless transmission to connect a home's router with a number of devices.[219] Nowadays a home could have, for example, a desktop PC, multiple mobile phones, tablets a smart TV, and a games console all connected wirelessly to the same fixed broadband connection. The increase in the number of internet-enabled devices has led to higher demand and further increased the breadth of broadband applications. Figure 78 illustrates the variety and growing popularity of these internet-enabled devices.

[218] http://www.internetlivestats.com/total-number-of-websites/

[219] http://www.telegraph.co.uk/technology/2016/11/01/mobile-web-usage-overtakes-desktop-for-first-time/

Figure 78 Ownership of internet-enabled devices, 2015 and 2016



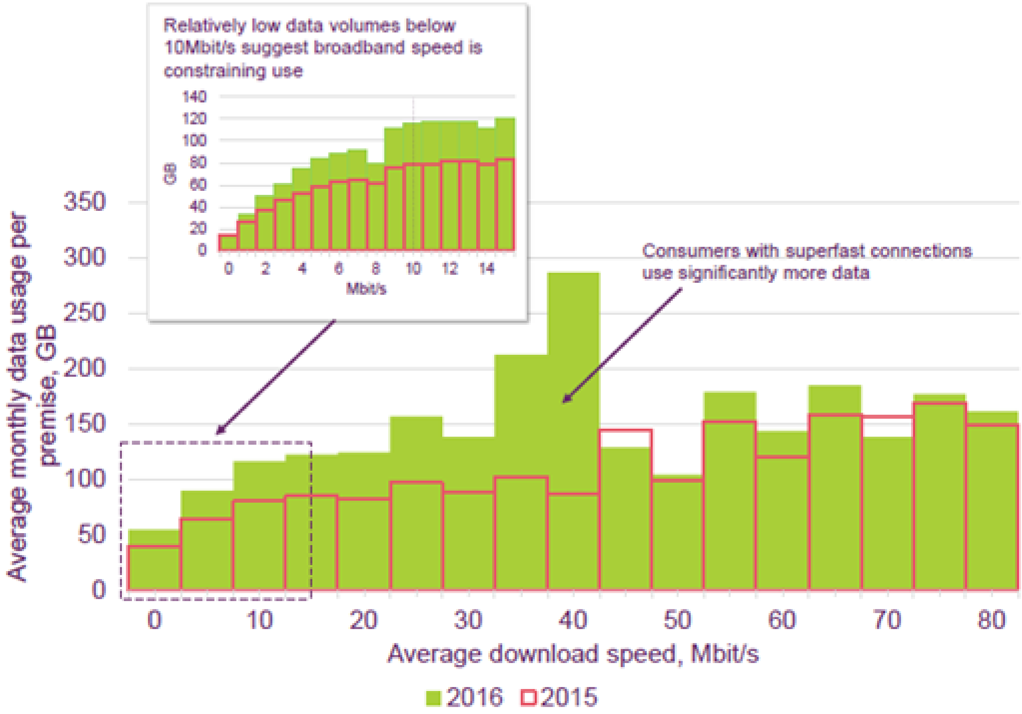
Source: Ofcom CMR 2017 Figure 5.7

As noted above, the average speeds of broadband networks have increased. However, the evidence that increased network speeds lead to increased data consumption is mixed. While it is difficult to make strong inferences based on the correlation of download speed and data consumption[220] an analysis of data on consumption and average broadband speed reveals the following.

- At slow speeds (less than 10 Mbps) there is a strong correlation between speed and consumption.
- As average connection download speeds increase to 40 Mbps consumption increases.
- However, for higher download speeds (between 40 Mbps and 85 Mbps) there does not appear to be a strong relationship between line speeds and consumption.

[220] It can be difficult to make strong inferences from the correlation between consumption and line speed for a number of reasons. First it is unknown whether users choose a low broadband speed as they do not consume data or vice versa. Second even though a low speed might indicate low consumption, the quality of the data connection is likely to much lower for slower speeds. Therefore a low speed connection is likely to be of less value to consumers who require high bandwidth applications.

Figure 79 Relationship between total data consumption and broadband speed



Source: Ofcom Connected Nations 2016

B.7 Qualitative forecasts of the demand for broadband were reasonably accurate

A number of public bodies and commentators during the 1990s forecast the potential uses of broadband services. These were inevitably based on existing uses and the uncertainties in making such forecasts were well recognised.

The purpose of forecasts of fixed broadband use is necessarily different to forecasts of mobile broadband use. In the case of mobile broadband, it is necessary to understand not just whether users require a mobile access connection in a binary “yes/no” sense, but what would be the resulting average peak demand used by average mobile access devices sharing the Radio Access Network. This is so spectrum planners and mobile network operators can consider the likely demand for mobile spectrum and network assets. Therefore, often forecasts of mobile services are often more detailed than for fixed networks, in terms of estimating the volume of data required, and hence the volume of spectrum required to supply services.

Planners of fixed networks face a different set of objectives when considering demand for fixed networks. They consider whether customers have demand for a data access service, and if so what the applications that use each household’s connection are. Hence, the objective of forecasts for fixed broadband is to determine whether specific technologies are sufficient to provide households with bandwidth. For these reasons, forecasts of demand for fixed networks in residential areas often focus on the demand from individual households, and whether telecoms network infrastructure is sufficient to support household demand.

For example a 1995 UK Parliamentary report noted that while there was a degree of common understanding of the potential uses for broadband technologies there were disagreements.

> *"Advocates of a sophisticated NII [National Information Infrastructure] see society at the threshold of an "information age" which will replace the industrial age we now inhabit. They see business productivity restrained by the absence of an effective information infrastructure and a huge unmet latent public demand for a variety of services. On the other hand, there are those who see visions of an information superhighway as hype based on poor assumptions about consumer demand and over-estimates of the ability of service providers to deliver goods to use even a fraction of the communications capacity technically possible."*[221]

In many ways the debate over the future demand for broadband has not changed. In 1995, a number of different research papers reviewed the potential uses of future broadband networks.

221 Parliamentary Office of Science & Technology (May 1995) Information Superhighways: The UK National Information Infrastructure Paperback Page 27

Figure 80 Potential applications for future broadband infrastructure

Parliamentary Office of Science & Technology	Trade and Industry Select Committee	Bangermann Report	US NII Agenda for Action	BT
Academia (supporting collaboration) **Education** (distance learning, adult education) **Services in the home** (home shopping, finance management, estate agent, video calling, video on demand, games, email) **Healthcare** (databases, remote diagnosis, remote monitoring of patients, improved teaching, remote surgery) **Publishing** (newspapers, articles, journals, books) **Public service delivery** (public access to information	**Video on Demand** **Interactive television** **Access to databases in multimedia format** **Interactive education and training / distance learning** **Home shopping, including product display and measuring, fitting and ordering** **Home financial services** **Remote burglar alarms** **Video phones** **Remote medical diagnosis** **Advice and alert facilities** **Remote utility meter reading**	**Teleworking** **Distance learning** **University research** **Telematic services for SMEs** **Road traffic management** **Air traffic control** **Healthcare networks** **Electronic tendering**	**Economic productivity benefits,** **Healthcare**, (Telemedicine, Unified Electronic Claims, Personal Health Information, Patient records) **Civic Networking** (Community access networks, Dissemination of Government services, Universal access) **Research** ("solving grand challenges", remote access to scientific collaboration) **Lifelong learning,** **Delivery of government services**	**Home shopping and banking** **Estate agent** (video clips for house hunting) **Travel agents** (selection and ordering of holidays and hotels) **Market research** (polling) **Healthcare** (consultation with and between doctors) **Care in the community** **Security** **Consultancy** (access to specialised services) **Public information** **Electronic libraries** **Video on demand** **Interactive games** **Video meetings, special interest groups** **Video calls, and conferencing** **Email** **Teleworking**

Source: Parliamentary Office of Science & Technology (May 1995) Information Superhighways: The UK National Information Infrastructure Paperback Page 27

What is striking about this list (22 years on) is that many of these use cases also feature on more recent forecasts of the potential uses for broadband infrastructure (entertainment, telehealth, mass online education), or that the forecasts were reasonably accurate at predicting how the new technology would be used (travel booking, estate agent, video on demand, home shopping).

Similarly an earlier report from (1988) in the US considered what household demand for applications that might use fibre based broadband connections would look like. The report noted that while provision of HD TV services was an obvious application that could use fibre based broadband connections, there were few other obvious uses for broadband at the time. It noted that not even the local telecoms providers were able to "identify new non-video broadband applications"[222]. The report concluded that *"entertainment video will be the only residential service requiring true broadband capacity at any time soon"*. This was because other data services ("*telemetry, meter reading, videotext, and other existing and new information services proposed by carriers and information service providers*" could be delivered using existing copper networks.

The report did acknowledge the potential for what would become the internet as we understand it: *"Future services requiring large bandwidth and high transmission rates are likely to develop. … New personal computers that will permit browsing video databases combining live action video, sound, graphics and computer power are predicted to be on the market within five years and will require higher speed networks that are available today to most residences."* [223]

Furthermore the report noted that new networks would themselves stimulate demand for new services and applications that were not yet knowable.

> *"As with many new technological advances, broadband networks will lead to applications and services unknown before increased speed and capacity make those services possible. Increased capacity and new functionality often have been criticised as having no clear specific applications. But new technologies and services such as direct dial long distance, communications satellites, and interchange fiber have all stimulated demand and creative new applications unforeseen before the technologies development"*

Some commentators questioned the willingness of customers to pay for the significant investments that would be required to upgrade networks. For example an Arthur D Little comment article from 1994 noted that: "*Pessimistic forecasts currently project that only 20 million U.S. homes will be hooked up to some version of the information superhighway by the year 2000. If our analysis is correct, less than half that number will be fully activated, with additional roll-out slowing dramatically."* [224]

In fact 44 million households (42%) had internet access at home in 2000[225].

Therefore the debate today over whether the benefits of new potential use cases will justify private or public investments in networks; or indeed the scale of network investments necessary to facilitate new use cases, is similar to the debate from the mid-1990s.

> *"Some thus argue that many of the anticipated uses of the NII [National Information Infrastructure can be achieved with relatively modest enhancements to existing infrastructure, or even that the NII already exists because current networks in industrialised nations are capable of providing any informational service for which there is* ***known*** *demand. Others argue that an advanced network with the capacity to handle any potential future service is the only meaningful target, and see tinkering*

222 FCC (1988) Robert M Pepper Through the Looking Glass: Integrated Broadband Networks, Regulatory Policy and Institutional Change.

223 Ibid.

224 Arthur D Little (1994) Viewpoint Hitchhiking on the Information Superhighway David L. Fishman. See: http://www.adlittle.se/prism_se.html?&view=112

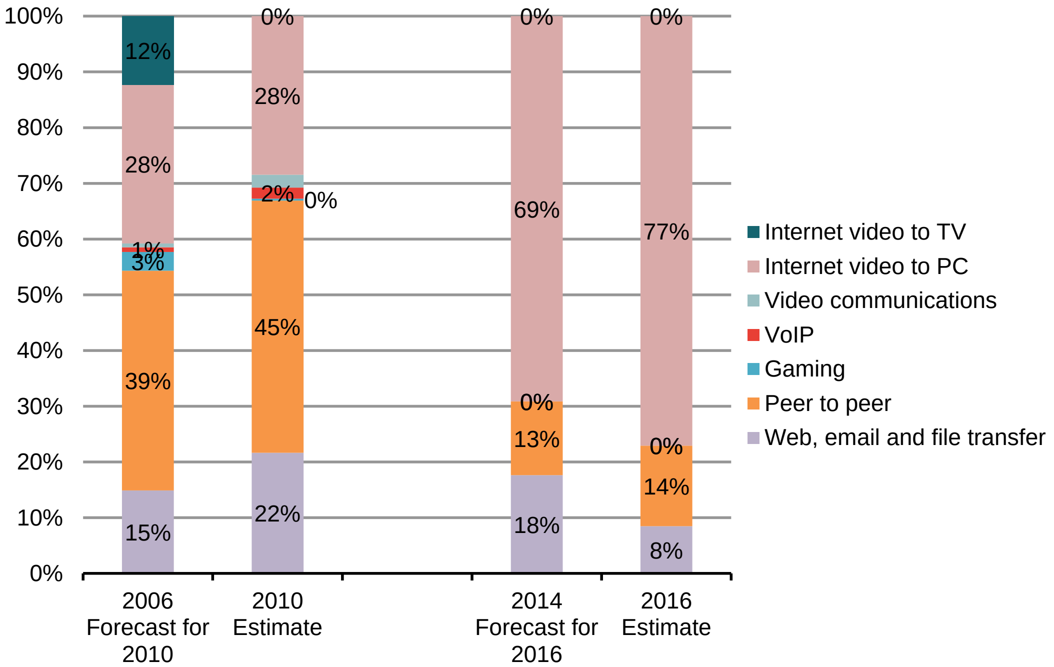
225 See: https://www.census.gov/prod/2001pubs/p23-207.pdf

with compression and other techniques as short term expedient getting in the way of the ultimate need to wire up all households workplaces, leisure and education facilities to a universal, globally standardised, and massively broadband, low cost networks."

Cisco annually makes short to medium term forecasts of fixed broadband use. Typically, Cisco starts with the current applications which drive demand for broadband and considers how they will evolve over a five year period.

For example Figure 81 sets out the share of data use by application for the years 2010 (based on the forecasts made in 2006 and 2010) and 2016 (based on forecasts made in 2014 and 2016). They demonstrate that even in the relative short term it can be difficult to accurately predict the share of data that different applications will use. For example the 2010 share taken by peer to peer traffic and web browsing traffic was higher than predicted in 2006. While IPTV services were virtually eliminated as a contributor to demand by 2010 this was in a way that was not predicted in 2006. Similarly even in the relatively short period between 2014 and 2016 the share of fixed data demand taken by internet video grew more quickly than was anticipated.

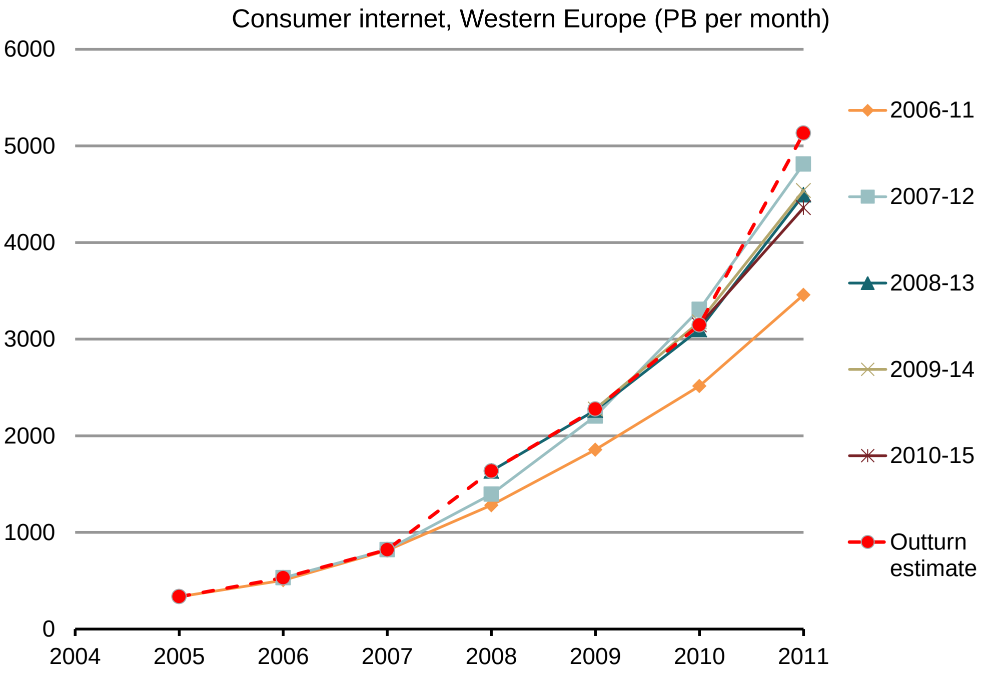
Figure 81 Forecast and outturn drivers of demand by application



Source: Frontier analysis of Cisco

It is possible to compare forecasts over time to understand the extent to which outturns are symmetrically over or under estimated, or whether there is a bias in the outturns. For example, comparing Cisco's annual forecasts with the outturns on a consistent basis forecasts are reasonably accurate over the short term. But in some years over the period studied there was an under-forecast; and in no year was there a material over-forecast.

Figure 82 Forecasts of fixed broadband compared to outturn

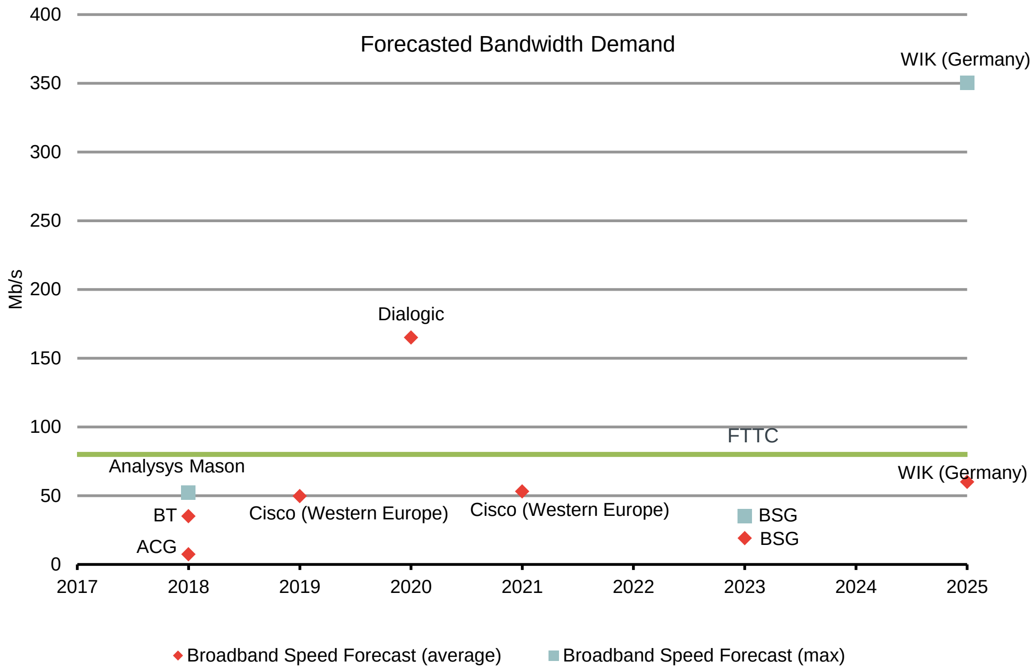


Source: Cisco

More recent forecasts have considered the likely data requirements required by typical households by summing the households' use of applications that could be required by typical households over reasonably foreseeable periods.

Some of these forecasts are summarised in Figure 83 below.

Figure 83 Forecast bandwidth demand



Source: ACG, Analysys Mason, BT, Cisco, Dialogic, Cisco, BSG, WIK

Note: Cisco relates to average usage in Western Europe

Typically, the forecasts are in the range of 5 to 15 years. Many of the studies segment users by the degree of intensity of their broadband use. These tend to consider a median or average user, and a high intensity user of broadband services.

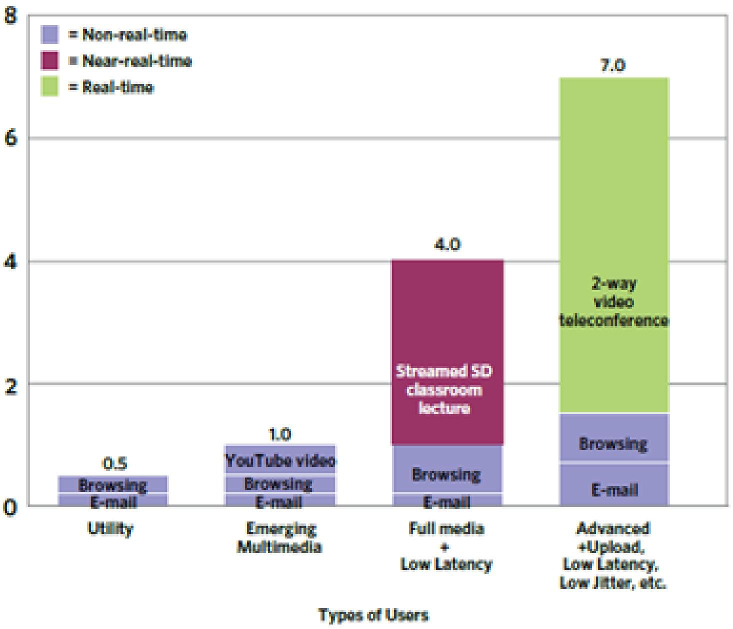
Similarly forecasts in the US segmented the household base by their intensity of use of broadband services.[226] For example a 2010 study forecasted four types of user:

- Advanced. These consumers use large amounts of data and tend to use the highest quality voice, video, and other cutting-edge applications.
- Full media. These consumers are moderately heavy users of broadband and mobile applications, seeking to access high-quality voice, data, graphics, and video communications but, typically not in the most cutting-edge forms.
- Emerging multimedia. These consumers utilize some video and graphical content but still see the Internet primarily as a way to communicate and access news and entertainment in a richer format than found in offline content.
- Utility. These consumers are largely content to access the Internet for basic news, communication, and basic entertainment.

The study considered the peak demand that typical households in each group would require. The forecasts then noted that the requirements of a "full media" household segment would be sufficient for most households in the subsequent years (up to approximately 2018). The report noted that for many households this would be in excess of what is required (since many households do not use their peak requirements), and that compression techniques might mean that actual demand might turn out to be lower than is required.

[226] FCC (2010) Broadband Performance OBI Technical Paper No. 4

Figure 84 Household segmentation - US



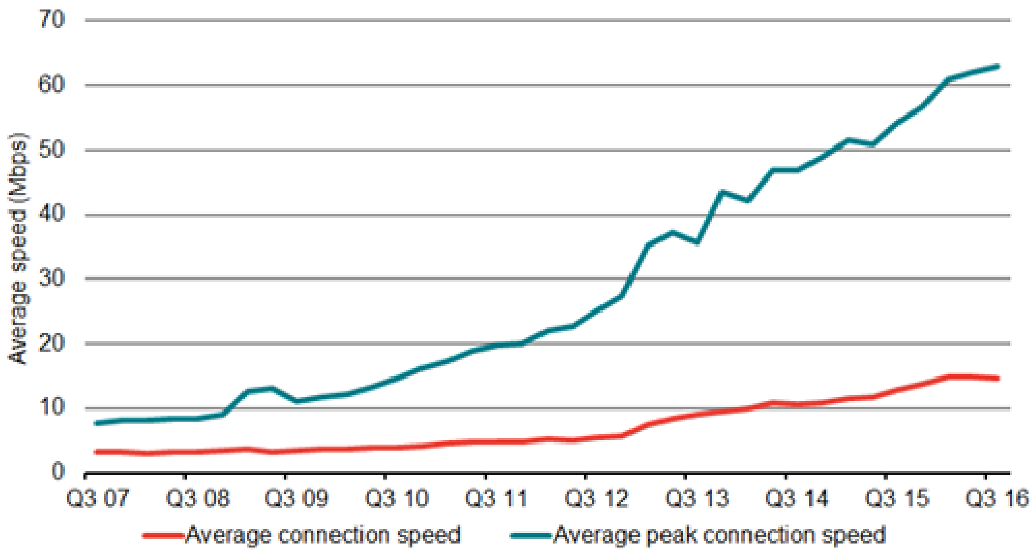
Source: FCC (2010) Broadband Performance OBI Technical Paper No. 4

B.8 Broadband service continues to improve both qualitatively and qualitatively

Over time, broadband has progressively improved in terms of technical standards (principally speed of connection) in response to consumer demand. “Bandwidth” determines the upload, download speed of a connection. Over time average speeds have increased quickly, from an average peak connection speed of less than 10 Mbps in 2007 to over 60 Mbps today (Figure 85). This has partly been driven by the roll out of faster fibre networks, but operators have also made significant investment in upgrading existing copper and infrastructure.[227] As well as faster speeds, network upgrades have also resulted in other improvements such as increased reliability and lower latency.

[227] For example in 2008 BT began to upgrade its copper exchanges to ADSL2+ which offered three times faster speeds (24 Mbps) than the limit at the time (8 Mbps) (https://www.theguardian.com/technology/2008/apr/17/telecoms.broadbandspeeds).

Figure 85 Average and peak broadband connection speed, 2007 - 2016



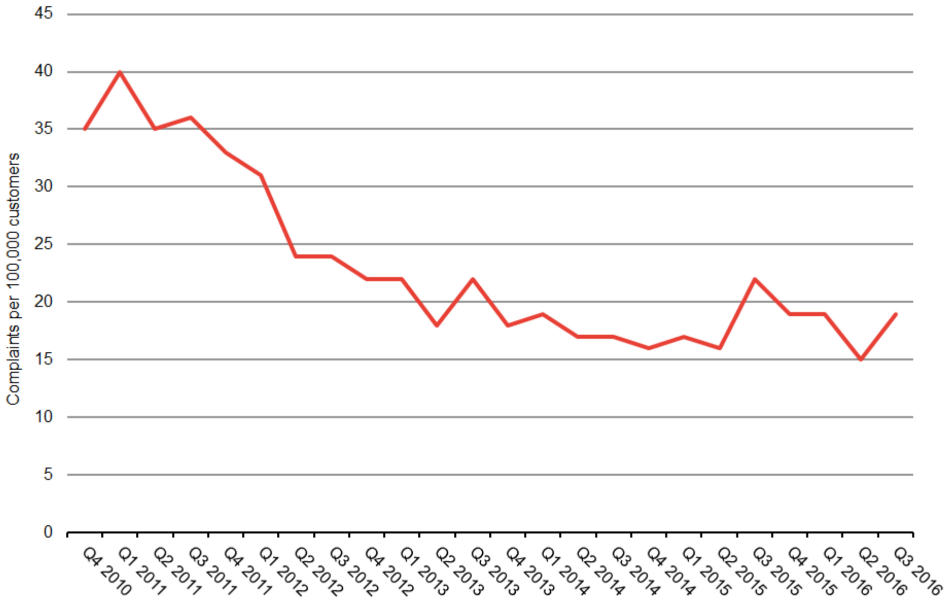
Source: Ofcom Source: Ofcom

Note: Prior to 2008 Ofcom only reported headline speed (and not actual average speed). For these years we assume that actual average speed was 50% of headline speed.

There is also evidence to suggest that consumer's experience of broadband has been improving with numbers of complaints made by customers falling over time (Figure 86). Interestingly the steepest fall coincided with BT commencing roll out its fibre network. The fact that people are spending more and more time on internet-enabled devices is further evidence of an improving experience and increased consumer value.[228]

[228] Average time spent online doubled between 2005 and 2015 (https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2015/time-spent-online-doubles-in-a-decade).

Figure 86 Number of complaints made about broadband per 100,000 customers, 2010 - 2016



Source: Ofcom

However, Ofcom has noted that there are potential causes for concern regarding service quality. For example consumer groups, industry bodies, communications providers and individuals reported their dissatisfaction with slow repairs and installations, missed appointments and poor customer service, among other issues. Ofcom noted that when services worked well they were sufficient to meet consumers' needs. However, when there was a problem the inconvenience to users was "acute". Given the reliance that consumers place on broadband and communications faults were analogous to a power cut or loss of water supply.[229]

Furthermore, given that the UK lags behind its peer countries in the availability of UFBA networks (in the same way that it lagged behind in terms of take up of broadband in the early 2000s), as demand for faster speeds grows, the UK will not be well placed to take advantage of opportunities of high capacity networks. While the future demand for broadband capacity cannot be known with certainty, a constraint on the network capabilities will in turn constrain demand for applications and services that rely on broadband connections. As was noted in the 1995 assessment of the need for broadband infrastructure:

> *"failure to provide infrastructure in phase with developing services and demand will create a critical stumbling block and pass the advantage to companies in countries where the infrastructure can support such services."*[230]

[229] See Ofcom (2016) Making communications work for everyone Initial conclusions from the Strategic Review of Digital Communications section 5. https://www.ofcom.org.uk/__data/assets/pdf_file/0016/50416/dcr-statement.pdf

[230] Parliamentary Office of Science & Technology (May 1995) Information Superhighways: The UK National Information Infrastructure Paperback Paragraph 4.3.1

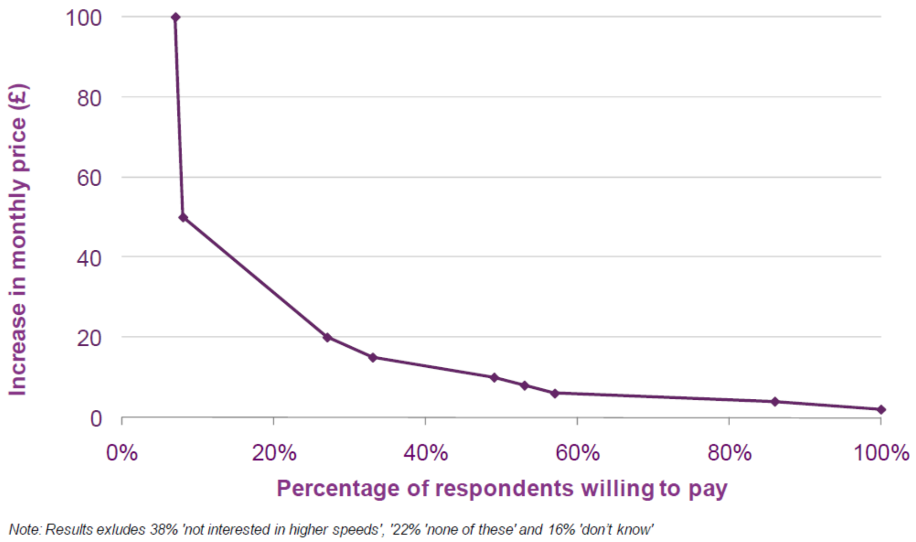
B.9 Evidence of willingness to pay for higher speeds and quality

B.9.1 There has been a consistent pricing premium on superfast broadband

Virgin Media ("Virgin") completed its network upgrade to DOCSIS 3.0 by July 2009, enabling it to offer speeds of up to 50 Mbps.[231] BT announced the roll-out of its FTTC infrastructure in May 2009, aiming to provide approximately 500,000 homes and businesses with access to speeds of up to 40Mbps by early 2010.[232]

At this early stage of superfast broadband ("SFBB") roll-out, Ofcom carried out consumer research on the use of fixed and mobile internet. This 2010 study found that about half of all fixed broadband subscribers said that they would be willing to pay an extra £10 per month to double their current broadband connection speed. This can be seen in Figure 87 below.

Figure 87 Willingness to pay to double current broadband speed



Source: Ofcom, 2010

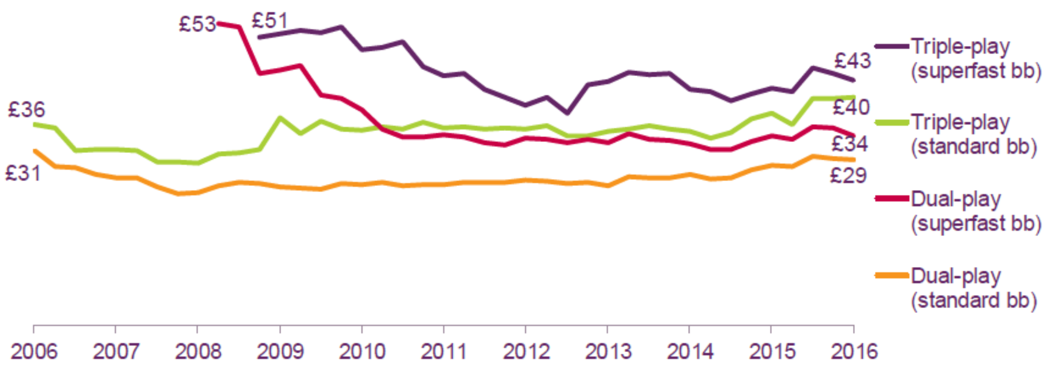
Note: https://www.ofcom.org.uk/__data/assets/pdf_file/0021/42915/consumer_research.pdf

SFBB has been priced at a premium to standard broadband since its roll-out, as can be seen in Figure 88. There appears to have been significant convergence in the pricing of the two generations of technology, especially between 2008 and 2010 in dual-play tariffs and in the last few years for triple play tariffs. However, SFBB does remain more expensive than standard broadband.

[231] Telegeography

[232] Ibid.

Figure 88 Cheapest available dual and triple-play monthly tariffs: 2006 to 2016

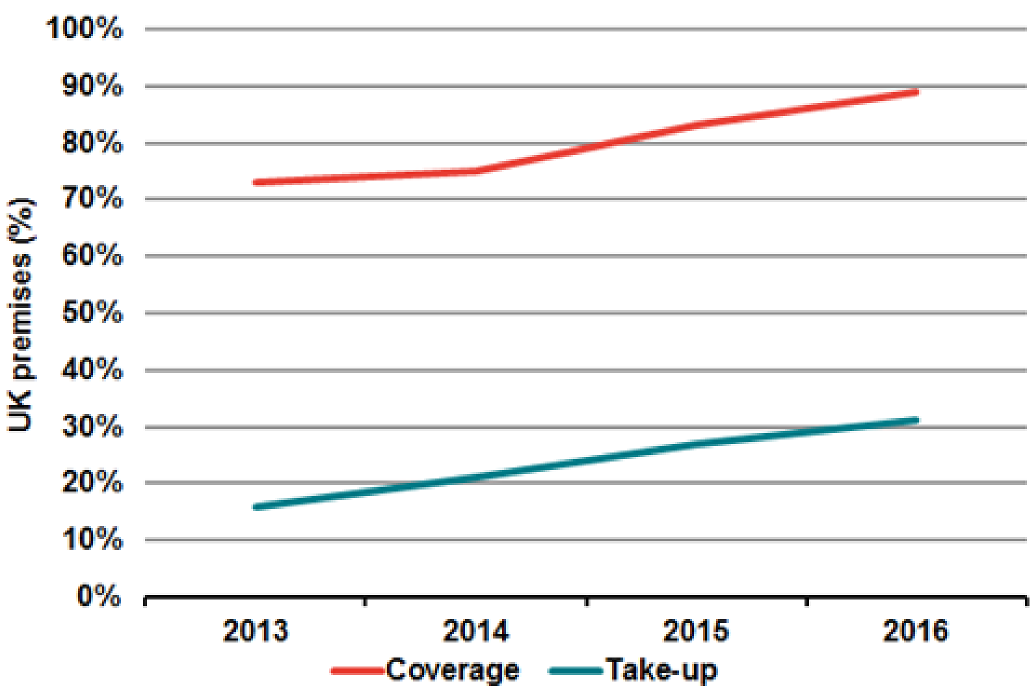


Source: Ofcom, 2017https://www.ofcom.org.uk/__data/assets/pdf_file/0028/98605/Pricing-report-2017.pdf

B.9.2 However, take-up of SFBB has continued to grow

As can be seen in Figure 89, take-up continues to grow, approximately doubling from 16% in 2013 to 31% in 2016. This is consistent with the finding that there was demand for SFBB, but for the majority of users only at a relatively low premium to standard broadband.

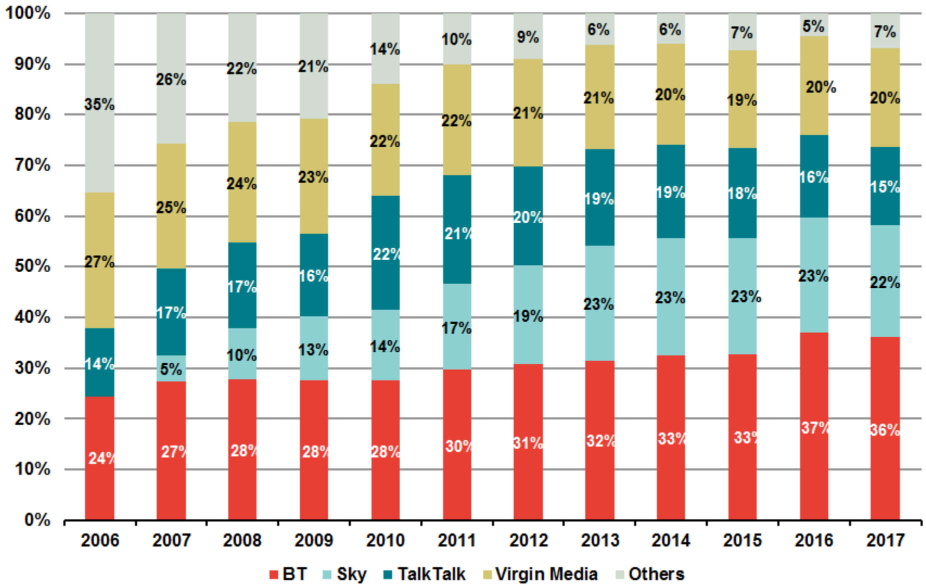
Figure 89 Coverage and take-up of SFBB



Source: Ofcom, 2016 https://www.ofcom.org.uk/__data/assets/pdf_file/0035/95876/CN-Report-2016.pdf

Indeed, Virgin's market share has remained largely stable since 2009 (declining slightly recently, which could be on account of competition from BT's fibre product). Given that it offers only SFBB and tends to market itself as a premium brand, its stable share could again suggest that there exists some willingness to pay for greater speeds for a significant segment of the market.[233]

Figure 90 Retail broadband market shares



Source: Telegeography

Note: Note that BT's share includes EE from 2016

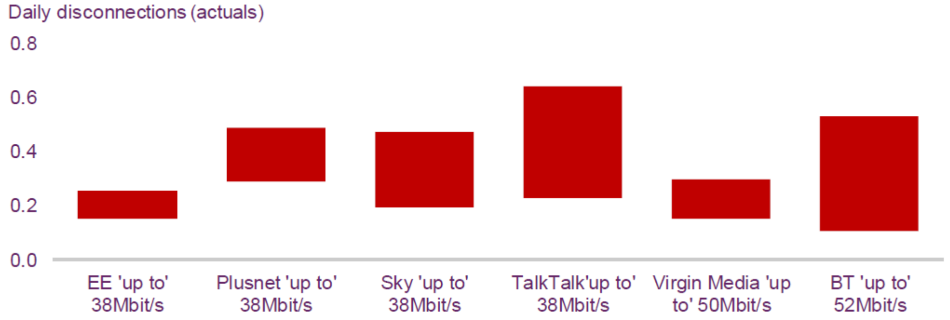
B.9.3 How customers value reliability is unclear

As mentioned above, Virgin has differentiated itself on speed and brand, and has been providing SFBB for a longer period than BT and other access seekers. Given that it has maintained its market share over this period, we may infer consumers' willingness to pay for reliability by considering the reliability offered by Virgin. So, if Virgin offers superior reliability compared to its competitors, it could be argued that consumers pay the premium for both speed and reliability. If, on the other hand, reliability is poorer than competitors, it could be inferred that consumers do not value reliability as much and are paying the premium primarily for speed.

As seen in Figure 91, Virgin had fewer daily disconnections on average compared to competitors that offered similar speeds.

233 A willingness to pay for higher speeds has also been found in mobile. For instance, a 2012 study by McKinsey found that existing smartphone users would agree to pay a premium of EUR 8-10 for a 4G plan. See "Seizing the 4G opportunity", 2012, McKinsey & Company, Inc.

Figure 91 Average daily disconnections of 30 seconds or longer to a 95% level of confidence, November 2016



Source: Ofcom, 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0015/100761/UK-home-broadband-performance,-November-2016-Technical-report.pdf

However, Virgin appears to perform worse on other measures of reliability such as speed of web page loading, latency, packet loss and jitter, especially in peak hours (Figure 92 to Figure 94).[234]

[234] This is because cable networks typically suffer from contention in the access network, which can affect performance in peak hours.

Figure 92 Average and peak-time loading of web pages to a 95% level of confidence, November 2016

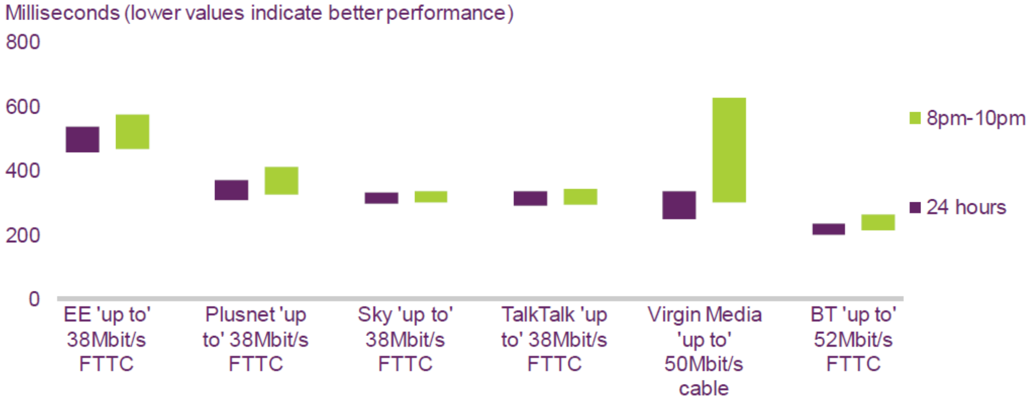


Figure 93 Average and peak-time loading of web pages to a 95% level of confidence, November 2016

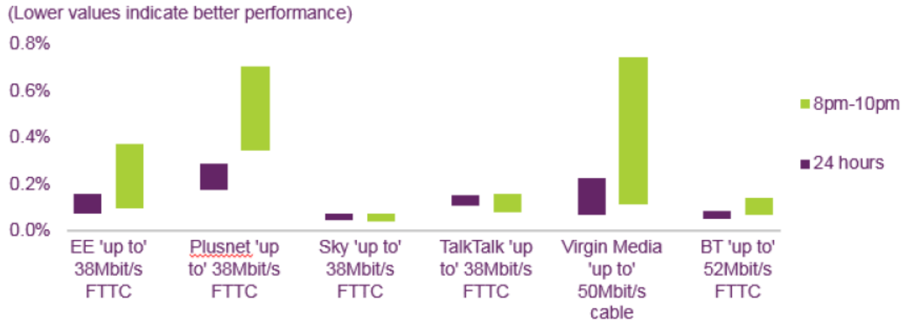
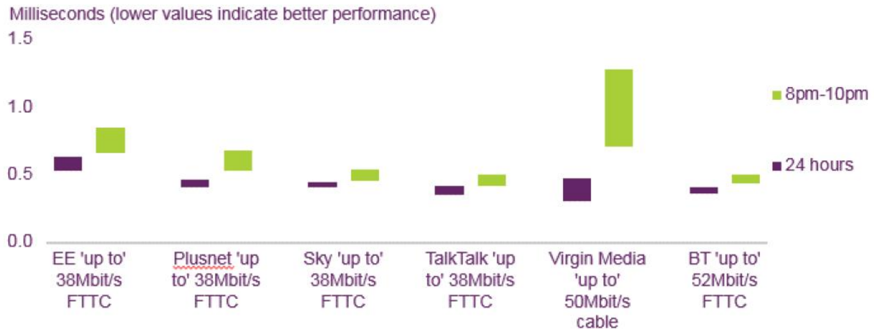


Figure 94 Average and peak-time downstream jitter to a 95% level of confidence, November 2016



Source: *Ofcom, 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0015/100761/UK-home-broadband-performance,-November-2016-Technical-report.pdf*

Given that consumers have been willing to pay for Virgin's product despite a poorer performance on these metrics, it appears that they assign greater value to speed than reliability.

B.9.4 So far, there appears to have been a willingness to pay for the newer technology

This evidence of revealed preference could suggest that consumers are willing to pay at least for greater speed, and perhaps also reliability.

However, it is also possible that a proportion of SFBB take-up may have been driven by conspicuous consumption.[235] It may be that SFBB in general, and Virgin's product in particular, is viewed as a "luxury good" because of the pricing (and branding, in the case of Virgin). It is therefore possible that some demand for Virgin/SFBB has been driven by this.

B.10 Implications for UFBA

That broadband has been a successful technological innovation is undisputed. Take up and coverage of basic services is high. There have been advances in terms of the speeds and capability of broadband services over time. The UK's low coverage of UFBA networks is potentially a concern.

There are a number of implications for the evolution of UFBA.

- Growth in broadband was triggered by a combination of increased coverage, falls in prices driven by competition, technology improvements and economies of scale and a rich range of services that required 'always on' broadband connectivity.
- Competition between cable and fixed in those areas where they competed did provide a degree of competitive incentive to develop and supply broadband. Virgin Media's cable consistently differentiates its service with reference to BT's. However, there are limits to the degree of competition when competition is limited to duopoly in half of areas with monopoly in the remainder. This may limit BT's incentive to upgrade infrastructure in areas where they face no current competition and little prospect of entry from alternative infrastructure operators.
- In the early 2000s, the UK lagged behind in the supply of broadband services at competitive prices compared to comparable countries. Supply and hence demand for broadband was fuelled by differentiation among providers using BT's network. This was facilitated by regulatory interventions which promoted access based competition. As consumers are moving to fibre broadband services, it appears that scope for competition has narrowed and in turn BT's market share is growing.
- The high costs of providing broadband in rural areas and the lack of competition mean that a degree of government intervention to support investment in these areas is necessary.

Average speeds have increased over time and complaints have gone down, suggesting good outcomes for the UK. However, given the evolving technologies, there is a risk that demand may again outstrip the capabilities of the network.

[235] Conspicuous consumption refers to expenditure on luxury goods as a display of wealth and such goods are often referred to as "Veblen goods".

ANNEX C HISTORICAL ANALYSIS OF PC MARKET DEVELOPMENT

C.1.1 Introduction

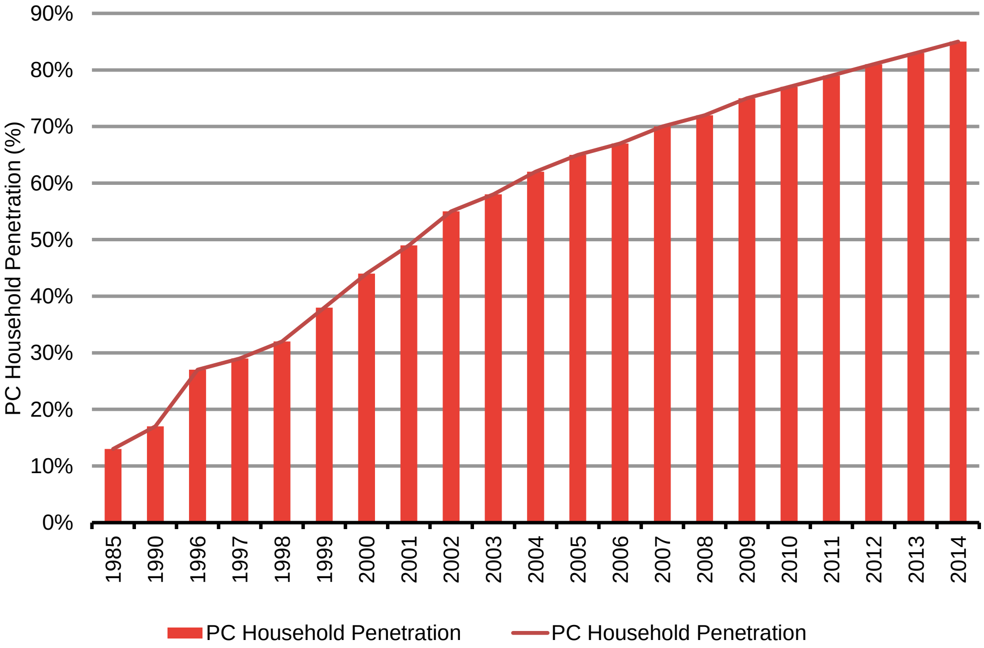
The development of Personal Computers (PCs) is of relevance to the development of UFBA for a number of reasons:

- Similarly to broadband, it a general purpose technology (GPT) which while providing no direct benefit in itself is a platform which can be used by households and businesses for a range of applications. This range of applications in aggregate drives demand for the GPT.
- Over time, PCs have increased significantly in terms of their capabilities, leading users to upgrade on a regular basis, in a similar way to users upgrading their broadband speed. However, in recent years the incremental improvements have not been perceived to add significant value, i.e. current capabilities are sufficient for many users, with developments being supply-side driven rather than to meet customer needs. This has led to a slowing of the upgrade cycle and reduction in PC shipments. If broadband usage were to reach a similar phase, where most users considered their current service to be sufficient, this could have significant implications for the need for continued investment in infrastructure.
- PCs were the device used by the majority of users to access the Internet but have now been supplanted by other devices as the primary method of Internet access at home. Given that uptake of innovative devices may be one driver of increased demand for bandwidth, this migration of usage between devices is of interest.

PCs are now almost ubiquitous a household object: in 2014 88% of UK households had a PC (see Figure 95). PCs can be described as electronic devices[236] which enable the processing of information, and offer flexibility and functionality by allowing users to connect peripheral devices (screens, keyboards etc) and allow users to customise devices by installing software programmes which have specific uses.

[236] A note on the terms and definitions used: the physical electronic devices which do the processing and computing are the “hardware”. This is distinguished from the computer programmes that run on the computers which provide the different uses and functionality for the device, which are “software”. The software which runs the computer’s basic functions and user interface is termed the “operating system” (“OS”). The OS is typically (but not always) embedded with the hardware when sold to consumers. Finally other devices can be attached to the computer in order to enhance its functionality; these can include monitors, keyboards, a mouse, memory expansion etc. These are termed “peripherals”.

Figure 95 UK Household Computer Penetration 1985 - 2014



Source: ONS

PC technology has rapidly evolved (see Figure 96). Each generation of devices enables more sophisticated applications to be offered to consumers.

Figure 96 The evolution of the personal computer

					
Model	Apple II	IBM PC (5150)	IBM Ambra	eMac G4/1.42	Dell Inspiron 24 3000
Year of Release	1977	1981	1995	2005	2017
Processor	1 MHz	4.77MHz	33MHz	1.42GHz	2.3 GHz
Memory (RAM)	48 KB	16KB	8MB	256 MB	8 GB
Computer Data Storage	Floppy Drive (optional)	Dual 160KB 5.25-inch disk drives	2x CD-ROM (1.3GB)	12X "Combo Drive" (80GB)	Cloud Data Storage

Source: Frontier

The story of the PC is in many ways a case study on the impact of network effects in technology markets. At successive points in the evolution of the market network effects have led to a supplier holding a significant market share.

- The PC value chain is not vertically integrated. The hardware, software, operating system, and peripheral devices are offered by distinct providers. Providers at different levels of the value chain quickly settled on a standard and innovated around that by focusing on specific levels of the value chain.
- This differed from the development of business computers (which pre-dated PCs) and early hobbyist machines where firms tended to be vertically integrated providers of hardware, peripherals, operating systems and software.
- IBM's decision not to adopt a vertically integrated model when it launched its PC (unlike rivals at the time) did two things. It provided the hardware standard which other manufacturers would use. And it meant Microsoft was able to provide the OS to IBM, and other "clones" which used similar and compatible components to produce similar hardware.
- Microsoft has had a predominant position in the PC Operating System (OS) market from the early 1990s to the current day. The role of the OS as a platform to bring together hardware manufacturers and software providers enabled Microsoft to leverage the network effects created by the platform.
- Microsoft used its position in the OS market to build market share in related markets (word processing software, internet browsers, and media players).
- Google quickly built up a strong position in PC search (which it extended to mobile and other activities).

In some cases, the creation of a privileged position in one market appears to provide advantages in other related markets. For example Microsoft used its position to dominate internet browsers, word processing and spreadsheet tools, or music player software applications. However, it is not always a given that a strong market position in one market leads to a strong market position in other markets.

- IBM had a very high market share in the market for business mainframe computers in the 1970s and 1980s, however this did not translate to an advantageous position in PC markets.
- Microsoft is the standard for PC OS, but has not built a significant position in mobile computing, or key internet applications (such as email, search or social networking).
- Intel was the standard for PC processing chips, but did not leverage this position into producing chips for mobile devices, which is now dominated by ARM.

Competition Authorities rightly scrutinise behaviour of dominant firms to prevent them from leveraging into related markets. However, the evolution of technology can mean that even entrenched market positions can be challenged.

We have described the development of the market for PCs as encompassing four phases.

- **Phase 1:** competition among a small "cottage industry" of integrated device / OS manufactures (1975-early 1980s);

- **Phase 2:** the hardware and software market is very competitive while the OS market "tips" to Microsoft (1985 - 2000);
- **Phase 3:** continued dominance in OS by Windows as the internet becomes a key driver of PC use (2000 – 2010);
- **Phase 4:** the PC market matures and the rise of mobile (2010 – present).

C.2 Phase 1 competition among integrated device / OS manufactures (1975-early 1980s)

Computers were developed in the 1960s and 1970s as business tools. They were expensive and physically large devices, which required a degree of technical knowledge to operate and were unaffordable for most households. Business computers tended to use a mainframe model, where computing power was provided by a centralised hub and a number of individual users had distributed terminals attached.

> - Personal computers were a niche product for early adopters – and there were many smaller manufacturers competing with each other.
> - Each manufacturer tended to use proprietary hardware and software, and no single standard dominated.

The early phase of the PC market was characterised by a number of small providers competing to offer personal computers to early adopter households. At this time PCs were a niche product for early adopters – and there were many smaller manufactures competing with each other.

In the mid to late 1970s, there were a number of manufacturers designing and manufacturing PCs that would be small and cheap enough for households to buy and with user friendly interfaces that could be used by users without technical training. These machines were typically bought by hobbyists or used to play games with some cross over into business use.

In the UK there were a number of suppliers of PCs which included US based firms such as IBM, Apple, Commodore, Atari. These competed in the UK with domestic based providers such as Acorn and Sinclair.

The firms competed by offering ever more advanced hardware (faster computing processors, bigger internal memory, better graphics and sound capabilities) and user friendly interfaces. For example, Commodore's Commodore 64 in 1982 offered colour screen. The Apple Macintosh in 1984 was the first PC with a mouse and used a graphical user interface (compared to the text based interfaces used on other devices).

In addition, software developers competed to provide products. For example, early spreadsheet programs included Lotus 1-2-3 and word processing programs included Word Perfect. These programs drove uptake of PCs by businesses in particular, spreadsheets which provided business users a flexible analysis tool which was truly innovative.

Manufacturers such as Apple, Commodore and Atari used their own proprietary operating systems. This meant that suppliers of peripheral devices or software would have to be licensed by the device manufacturer. This “closed” approach limited the availability of software and other peripheral devices. For example, Atari attempted to favour its own in-house software developers by keeping the details of its early computers secret to prevent external developers offering software that would compete with its own[237]. However, while this approach initially benefited Atari by softening competition for its software, it ultimately restricted the supply of software which ran on the devices and hence limited the device’s popularity.

C.3 Phase 2: the hardware and software market is very competitive while the OS market “tips” to Microsoft (1985 – 2000)

In this phase the PC went from being a device with niche demand to a mass market device. This growth was supported by its use as a tool to access the internet. Furthermore, strong competition in the market for hardware, peripheral devices and software meant consumers benefited from low prices and rapidly improving technical capabilities.

The rapid increases in processing power over time provided a number of clear benefits to consumers:

- Increased user friendliness with graphical user interfaces running multiple programs simultaneously (multi-tasking) supplanting single command line drive operating systems running a single program at a time;
- Increased multimedia capabilities allowing PCs to store, edit and replay audio, images and video; and
- The ability to play increasingly complex games.

> - The open standards of IBM’s PC created the standard which consumers, manufacturers and software developers focused on.
> - There was intense competition from PC manufacturers who produced cheap IBM PC “clones” with improved hardware at lower cost than IBM.
> - Microsoft Windows OS was a two sided platform selling to PC and device manufactures and software developers.
> - The two sided platform exhibited network effects: the more consumers that used the OS, the greater the incentive software developers had to focus on the Windows OS rather than alternative OS. In this way the market “tipped” to the Microsoft Windows OS.
> - Microsoft Windows further entrenched its position by bundling proprietary software with its OS.
> - However, these bundling practices attracted the attention of Competition Authorities.

The rapid development in applications meant that PCs quickly became obsolete, unable to run current programs, requiring upgrades every three to four years to ensure that consumers and business could enjoy the full benefits of PC ownership.

[237] In relation to the Atari 400 and 800. Source: https://arstechnica.com/features/2005/12/total-share/

However, in this phase of competition the market “tipped” to the Microsoft OS, initially provided with IBM’s PCs, which became a de facto standard for production of PCs.

IBM had been a significant provider of business computers in the late 1960s to the 1970s. In 1981 when it launched its PC IBM had a market share of 62% in the mainframe market according to one estimate[238]. It offered bundles of hardware and software, and therefore controlled the supply of all hardware and software to its business consumers. IBM attempted to leverage its knowledge and understanding in building business computers to create its first PC. However, this did not translate to equivalent position in the PC market.

This was because, in order to develop and launch its PC within a short space of time IBM adopted a strategy of outsourcing components and software[239]. This had three important impacts on the development of the market.

- First, other manufacturers were able (and in fact positively encouraged) to build peripheral devices and software that interacted with the PC. Users benefited from strong competition for the supply of peripherals and software.
- Second, Microsoft licensed the OS that it had designed for IBM in its first PC to other computer manufacturers.
- Third, the open hardware standards and “off the shelf components” used by IBM meant that alternative manufacturers could manufacture “clones” of IBM’s PC at lower cost and with greater technical capabilities. Initially, US manufacturers such as Compaq, then later Asian manufacturers produced such “clones”. The fact that there were many providers of PCs using the same OS meant that there was a constant stream of devices with ever more sophisticated hardware. By contrast, firms which integrated their OS and device hardware (such as Apple, Commodore, Atari etc) could only release new updated versions periodically in line with their internal R&D and production cycles.

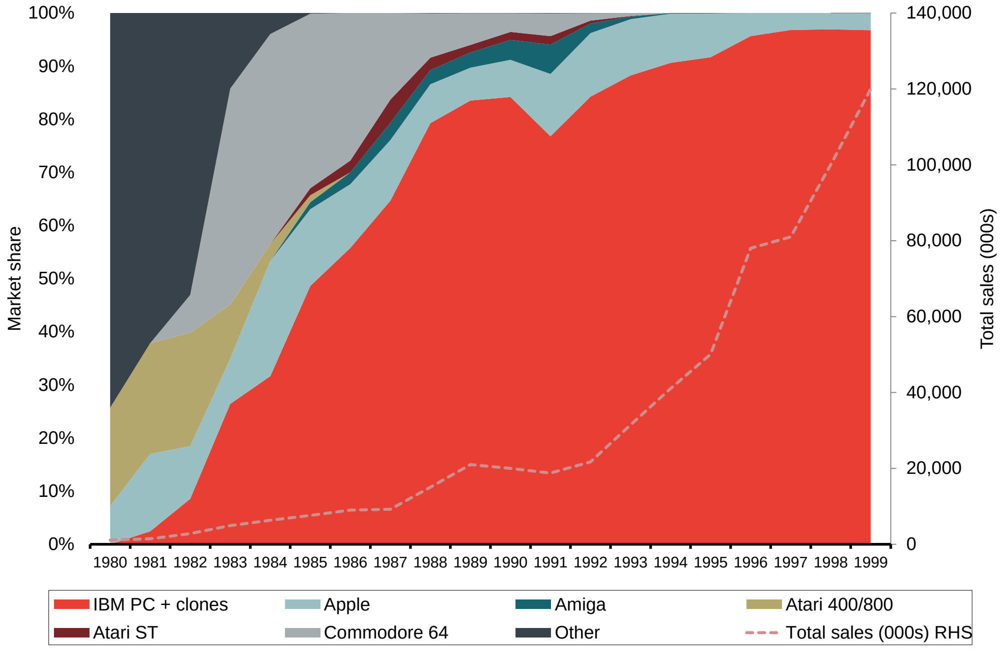
This meant that consumers benefited from low prices enabled by low cost manufacturers. At the point of upgrade consumers were able to keep existing peripheral devices and software, and consumers would know that their software was compatible with other IBM “clone” devices (for example at work and at home).

Application and software developers could realise economies of scale by creating products using the Microsoft OS reaching a wide proportion of customers. The market share of IBM and “clone” PCs using Microsoft’s OS grew quickly.

238 http://www.nytimes.com/1982/01/09/business/dominance-ended-ibm-fights-back.html

239 Goldman Sachs, December 7, 2012 Clash of the titans

Figure 97 Market share by PC type and total PC sales



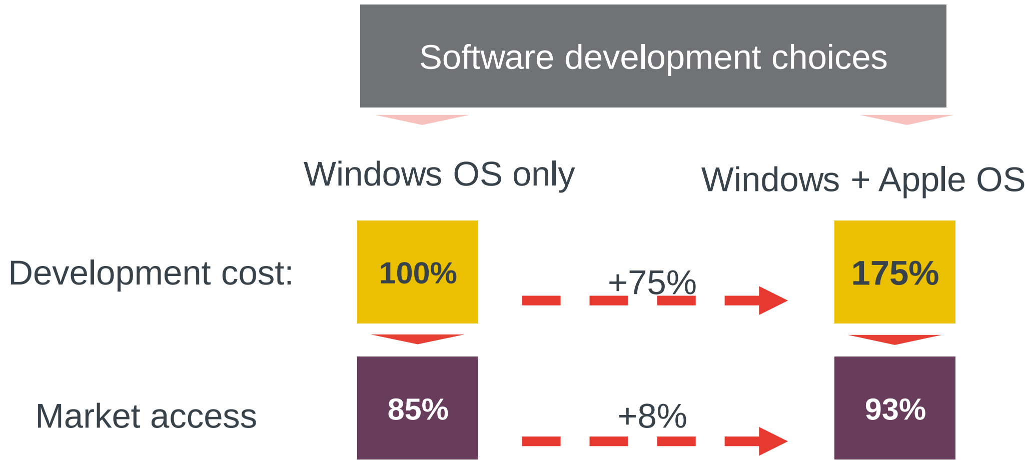
Source: *http://jeremyreimer.com/m-item.lsp?i=137*

IBM had created a standard around which almost all PCs were made. However, despite creating the standard which other manufacturers were able to use and therefore consumers were able to benefit from, IBM was not able to reap the benefits of the service. Instead, it was Microsoft, who supplied the operating system to the majority of PCs that was able to build a commanding market share. And Intel who supplied iterative generations with the processing chips that powered PCs benefited as these effectively became the "standard".

Intel maintained its market position by innovating in its core product and producing ever faster versions of the processing chips. Microsoft was able to benefit from network effects to build and maintain its market position. The reason was that the operating system was the "platform" by which application and software developers were able to access the vast majority of consumers. This encouraged application and software developers to focus on developing products for Microsoft's platform. For example, developing software for both Windows and Apple's OS could add 75% to the cost[240], compared to the cost of just developing software for Windows. However, it would only lead to an incremental gain in market share of 8%.

[240] Goldman Sachs, December 7, 2012 Clash of the titans

Figure 98 Software development costs on multiple platforms (1990)



Source: Adapted from Goldman Sachs December 7, 2012 Clash of the titans Exhibit 72

Microsoft's Windows platform was therefore a "two sided market" where it licensed its OS to both software developers and device manufacturers. One important economic feature of two sided markets is the presence of positive "**network externalities**" between the two sides of the market which increases demand. The network externality here describes how demand from consumers is positively correlated with demand from software developers. As more consumers buy PCs using the Microsoft OS, this in turn increases demand from software developers to create software for the Microsoft OS which in turn increases demand from consumers for the PCs using the Microsoft OS. As noted by Bill Gates:

> *"One of the most important lessons the computer industry learned is that a great deal of a computer's value to its user depends on the quality and variety of the application software available for it. All of us in the industry learned that lesson-some happily, some unhappily . . . . .A positive-feedback cycle began driving the PC market. Once it got going, thousands of software applications appeared, and untold numbers of companies began making add-in or accessory cards, which extended the hardware capabilities of the PC. The availability of software and hardware add-ons sold PCs at a far greater rate than IBM had anticipated-by a factor of millions.. . .The IBM standard became the platform everybody imitated.*[241]

Microsoft entrenched its position by bundling software applications within its operating system.

The fact that it developed the Operating System arguably meant that it had advantages in developing new applications. For example, it was argued that Microsoft application developers were able to incorporate new features before they were widely available[242].

- Microsoft developed Word and Excel as word processing and spreadsheet tools. The leading word processing program for PC in the 1980s was DOS-

[241] Gates et al. (1995), The Road Ahead. http://www-siepr.stanford.edu/papers/pdf/00-51.pdf

[242] See: htt://cs.stanford.edu/people/eroberts/cs201/projects/corporate-monopolies/development_microsoft.html

based WordPerfect. Microsoft Word for DOS, which had been released in 1983, had a significantly lower share. That situation changed dramatically with the introduction of Microsoft Word for Windows in 1989. By 1993, it was generating 50% of the word processing market revenue, and by 1997 it was up to 90%.[243]

- In this period internet browsers were launched to navigate the internet. The Netscape browser launched in 1995 and quickly became the most used browser. However, when Microsoft bundled its Internet Explorer with its Windows Operating system it rapidly grew market share. By the early 2000s Internet Explorer was by far the most used internet browser. However, this bundling practice attracted the attention of the Competition Authorities and Microsoft was required to "unbundle" the search engine in the EU in 2009[244].
- Microsoft offered a bundled "music player" with its Windows OS. However, following investigations by Competition Authorities in Europe [and the US?] Microsoft was required to "unbundle" the product in 2005[245].

C.4 Phase 3: continued dominance by Windows in the OS market as the internet becomes a key driver of PC use 2000 - 2010

By 2000 the PC had gone from being a device that was designed to support basic word processing and games applications to one that primarily offered access to the internet. This change brought the PC mass market appeal.

For example Figure 99 illustrates how the use of PCs evolved from its early incarnations to the early 2000s (based on US data). By 1997 44% of households with a PC were using it to access the internet. By the early 2000s around 90% of households with a PC used it to access the internet.

However, in the early period slow internet connections (initially narrowband then early broadband) meant that the PC was primarily the processor of computing tasks. PCs were shipped with ever more sophisticated hardware and software, and larger memory to perform more complex tasks, since cloud type computing services was not a viable option with poor internet speeds.

- The PC went from being a "home office tool" to a tool for accessing the internet.
- The PC was still used for processing data (rather than processing in the cloud)
- Microsoft's dominance in PC OS continued.
- New technology "platforms" grew on the internet, exploiting network effects. The market for search engines quickly "tipped" to Google.
- Microsoft's prominent market position in OS did not guarantee it high market share in all related markets.

[243] Source: http://www.computerhistory.org/atchm/microsoft-word-for-windows-1-1a-source-code/

[244] See: http://europa.eu/rapid/press-release_IP-09-1941_en.htm?locale=en

[245] See: http://europa.eu/rapid/press-release_IP-04-382_en.htm

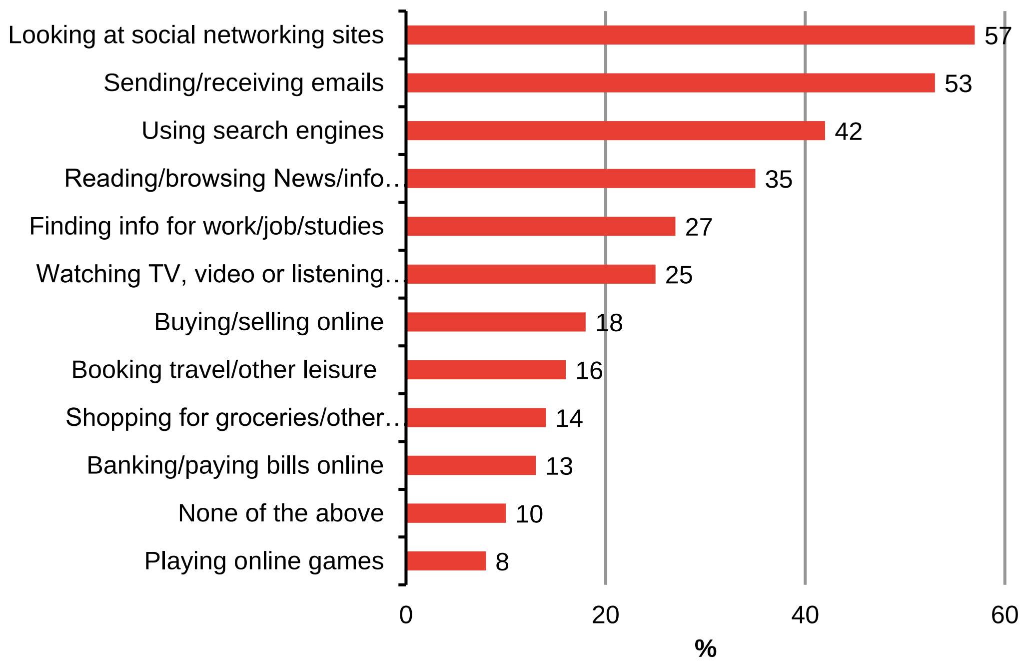
Figure 99 Use of PC at home for People 18 years or over (in US)

	Internet	E-mail	Spreadsheets	Word Processing	Manage household finances	Playing games
1984	0%	0%	0%	32%	0%	46%
1989	0%	5%	21%	61%	0%	44%
1997	44%	45%	29%	61%	44%	54%
2001	90%	84%	32%	58%	31%	56%
2003	89%	82%	33%	56%	33%	50%

Source: US Census Bureau

As can be seen in Figure 100 by the end of the decade in the UK PCs had a wide variety of uses but the most popular relied on accessing the internet.

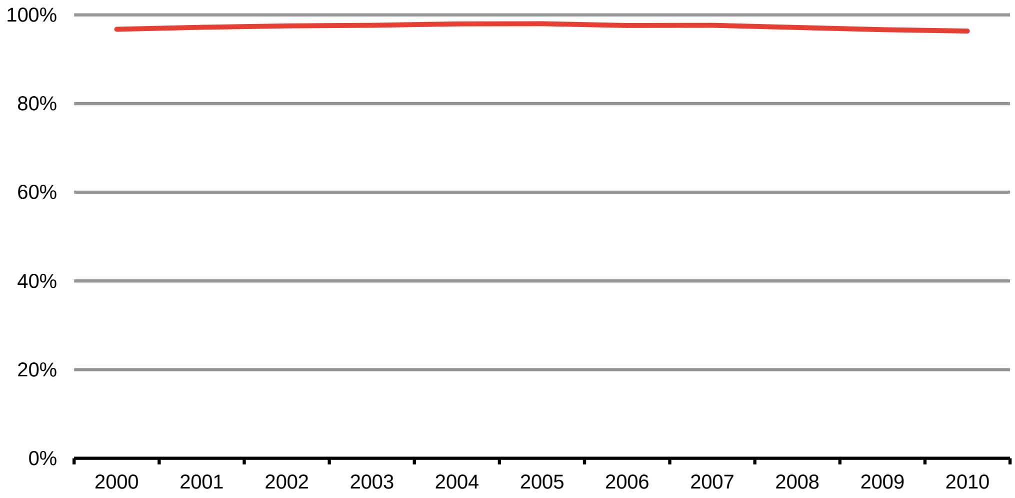
Figure 100 Use of the PC in 2010 (UK)



Source: Ofcom CMR 2011

Throughout the 2000s, Windows was the dominant operating system used by PCs (Figure 101). According to one estimate, its worldwide market share over the period remained above 95% (with the remainder captured by Apple and a number of other smaller manufacturers). The network effects created by Windows OS meant other platforms were unable to capture significant market share.

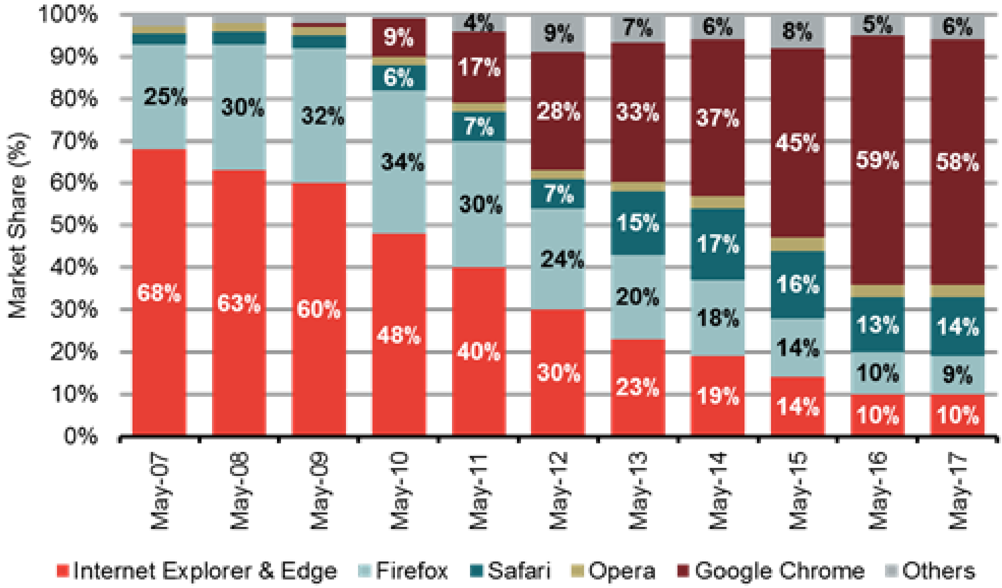
Figure 101 Microsoft Windows market share 2000 - 2010



Source: http://jeremyreimer.com/m-item.lsp?i=137

However, the internet offered new opportunities for entrants, which over time would challenge Microsoft's position. As the internet gained importance as a tool to share information and do business, so the search engine became the neceessary tool to navigate the internet. Google's search engine was founded in 1998. At the time, most search engines returned a list of Websites ranked by how often a search phrase appeared on them. Google's innovation was to incorporate into the search algorithm the number of *links to each web site* (websites with a greater number references to it were considered more useful, and hence were given greater prominence in search results). Google started selling advertisements with its keyword searches in 2000 therefore adopting a two sided market: providing search services for free and monetising its service by supplying advertising. The market for "search engines" exhibits network effects: the more consumers that use the service, the greater the degree of accuracy the search provider is able to offer (which increases the value to users of the search engines). Google quickly established itself as the predominant search provider. Google was able to entrench its position by diversifying into other related markets. For example it launched its email "Gmail" and Google Earth in 2004, and in 2008 it launched its own web browser "Chrome". Since its launch in 2008, Chrome has quickly built market share, displacing Microsoft's Internet Explorer as the most used browser (Figure 102).

Figure 102 Web Browser Market Share (2007 – 2017)



Source: W3Counter

The internet also began the process of buying sharing and storing audio visual data. In 1995 Bill Gates predicted the revolution in the way we store and use music. He noted that

> *"Record companies, or even individual recording artists, might choose to sell music a new way. You, the consumer, won't need compact discs, tapes, or any other kinds of physical apparatus. The music will be stored as bits of information on a server on the highway. "Buying" a song or album will really mean buying the right to access the appropriate bits. You will be able to listen at home, at work, or on vacation, without carrying around a collection of titles. Anyplace you go where there are audio speakers connected to the highway, you'll be able to identify yourself and take advantage of your rights.."*[246]

However, despite the prescience of the statements, it was not Microsoft that was able to build its market position in the supply of audio visual content. There were two key market developments that spurred the use of PCs to store and acquire audio-visual data.

First, Apple's iPod was a music player which continued advances in compression and storage technologies with a user friendly interface. The PC was a way to store and access music (and later videos) which could then be transferred to the music player.

The other factor was the rise of peer to peer sharing. Peer to peer sharing was a file sharing application which linked people who had files with those who requested them and was made possible by growing adoption of broadband services, and storing content digitally on PCs. Napster launched the music sharing application in 1999, but was shut down in 2001 since it infringed

[246] See: http://www.newsweek.com/road-ahead-181290

copyright laws. However, other peer to peer services quickly sprang up to illegally share copyrighted movies and games.

While peer to peer may not have been widespread, it was a catalyst which prompted content providers to supply platforms for using the internet to legally download and access music and video content.

C.5 Phase 4: the rise of mobile 2010 – present

The current phase of the PC could be described by the rise of mobile and the gradual decline of the PC.

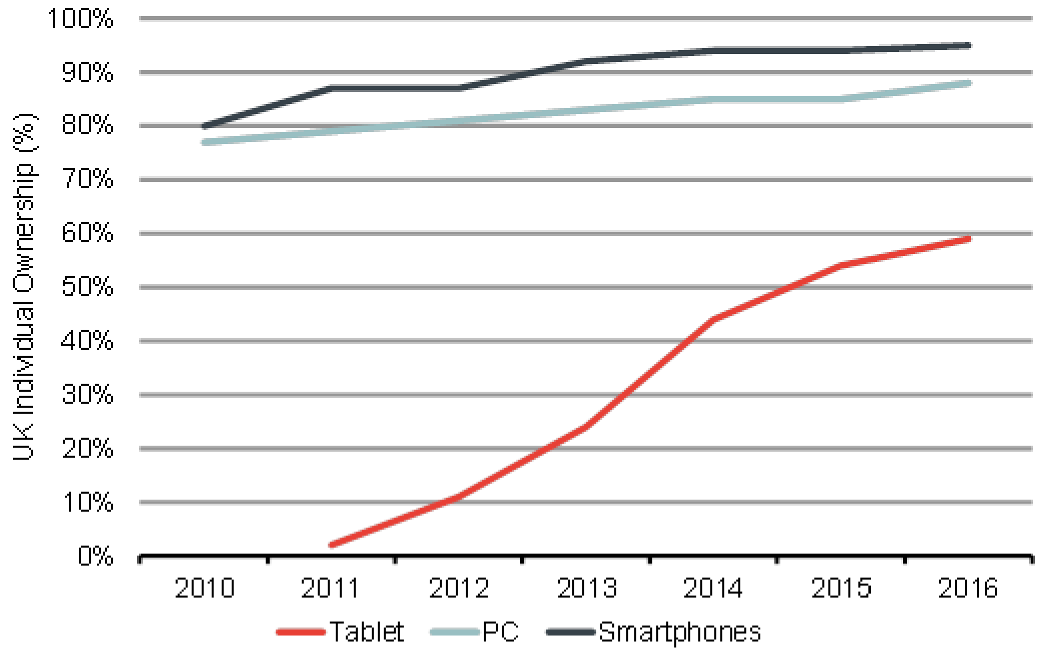
A number of factors have driven the relative decline of PCs:

- The rate of increase in processing power began to slow as physical constraints limited the ability to deliver more computing power at an affordable price
- PCs became 'good enough' for most applications for most users with only a few niche applications such as gaming or video editing requiring continuing upgrades;
- Increasingly faster broadband connections allow data and processing to be carried out in the "cloud" limiting the need to have local processing and storage;
- Other devices have supplanted PCs as the primary interface with cloud based applications.

> - The supply of a wide range of mobile devices with user friendly interfaces and high processing power has diminished the importance of the PC.
> - The faster broadband connections meant that simpler, cheaper, laptops which access to the internet and cloud could perform equivalently to more expensive, sophisticated PCs.
> - Google's Android OS is now the dominant OS on smartphones.

The rise of smartphones during the decade prefaced a change in how we interact with technology. Accessing content became mobile, personalised and cloud based. The cameras on smartphones meant that we could take photos and video and share them. Smartphone adoption is now higher than PCs and adoption of "tablet" computers grew from a standing start in 2011 to almost 60% in 2016 (Figure 103).

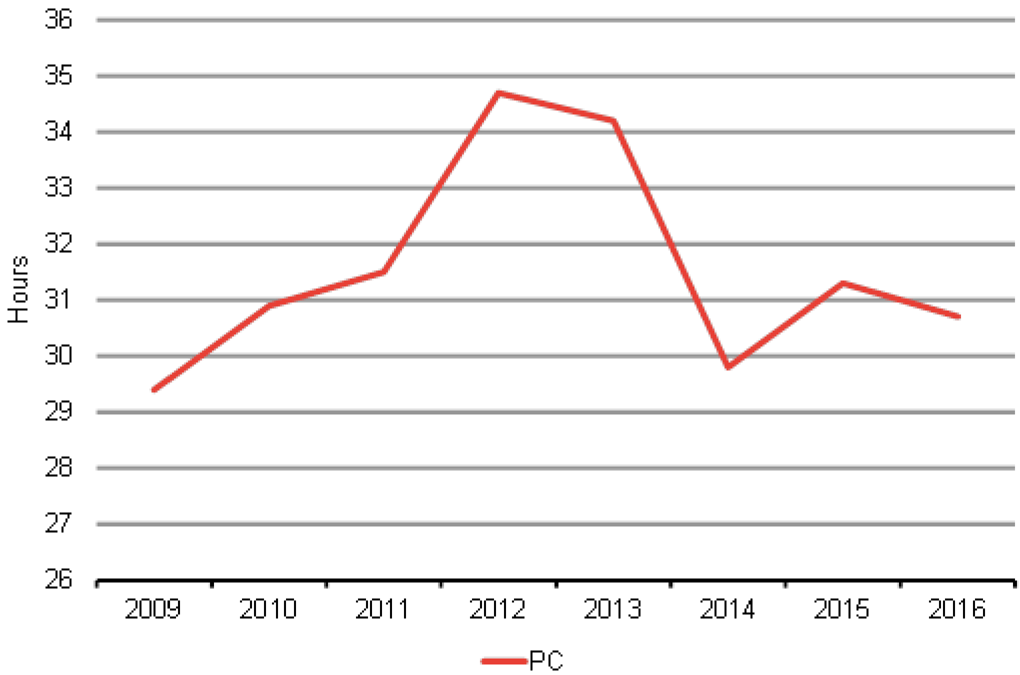
Figure 103 UK Individual Ownership of Tablets, Smartphones and PCs



Source: Ofcom Market Report 2016/ONS

These new devices have partially substituted for activities which were previously done on PCs. For example the average time spent online each week using a PC has declined from a peak of just under 35 hours per month in 2012 to 30.7 hours per month in 2016 (compared to 60 hours per month spent accessing the internet on a smart phone).

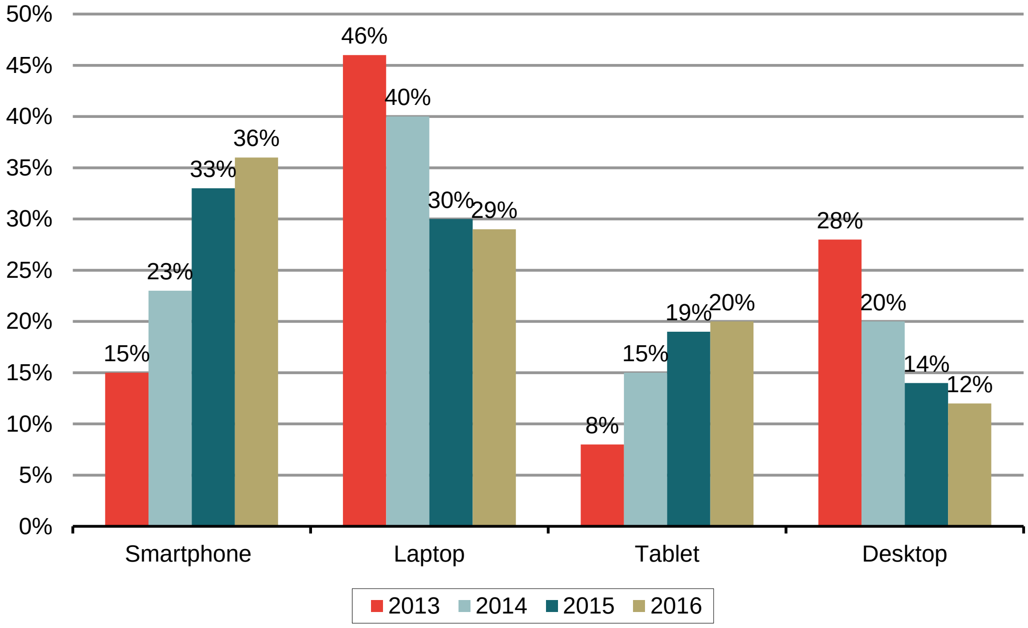
Figure 104 Average Time Spent Online Per Month on a PC



Source: Ofcom

When asked about the most important device for accessing the internet in 2015, the Smartphone displaced the laptop as the most important device for consumers (Figure 105).

Figure 105 Most important device for internet access (2013 – 2016)



Source: Ofcom CMR 2016 Figure 5.14

Google saw the potential for mobile and invested in its Android operating system which it licenses for free to smartphone manufacturers who in turn are required to offer Google's range of mobile tools. Android now has a 87% share in the smartphone OS market[247].

The migration from PC to mobile devices to access the internet has meant that manufacturers of the processing chips which were used as the "standard" in PCs have also seen their market position challenged. Since the market settled on the PC as a standard Intel had a strong market position producing the processing chips which powered each generation of PCs. However, as consumer demand is migrating to mobile, so the importance of manufacturers of processing chips for mobile devices has increased. Specifically, the company ARM produces the processing chips for Apple and a number of Android based devices and claims to have a 95% market share in smartphone processors[248].

C.5.1 Broadband has diminished the need for high end processing chips as we move to cloud architectures

Rapidly improving broadband connections has reduced the importance of the PC as a processing and storage device. The "cloud" can provide enhanced processing and storage capabilities and supply these in near real time via high quality broadband connections. Over time PCs may revert to being the "dumb

[247] http://www.idc.com/promo/smartphone-market-share/os

[248] https://www.arm.com/markets/mobile accessed 06/07/2017

terminals" similar to the mainframe architecture of business computing in the 1970s.

Software and content that was previously stored on devices can be more efficiently (with greater resilience) stored in datacentres accessed via the cloud.

PC manufacturers now offer cheaper and simpler devices which offer internet which access applications and store data on the cloud rather than on the device.

C.6 Implications for UFBA

In assessing the scope for future demand for UFBA there are a number of features of the development of the PC market that are relevant.

- The installed base of devices meant that the popularity of the internet (and related demand for connectivity) took off quickly.
- The Internet was first a driver for PCs and then as broadband became good enough, effectively undermined the PC for home use.
- The PC's popularity was partly driven by a common technology between business and home use (exploiting network effects). However, Android's market position in mobile may challenge the market position of the PC.
- PCs were successful because they were an open platform. There was a very competitive market for manufacturers of hardware, peripherals and software. The creation of a "standard" around which hardware and software manufacturers (as well as consumers) clustered created benefits for consumers. In contrast, iOS is a more closed platform where Apple is the only provider of devices that run iOS. While Android is open, in that Google licences its OS to any device manufacturers it imposes strong constraints on how the device is developed in order to protect the Google products which are embedded in the Android platform.
- Technology markets can "tip" especially where there are network effects. The presence of network effects provide benefits to consumers – the benefits of settling on a standard for the PC was beneficial to consumers which increased demand.

However, in tipped markets, dominant providers have the ability to extend dominance in related markets – which can potentially limit innovation. So competition authorities exercise vigilance over the markets in order to prevent anti-competitive conduct by dominant firms (e.g. anti-competitive bundling or discriminatory practices).

However, the introduction of broadband, and in particular mobile broadband, has changed the dynamics, diminishing the central role of the PC in content generation and consumption. PCs are increasingly used as another "dumb" terminal to access cloud based applications (including video streaming which is the biggest driver of bandwidth) which can be substituted for other devices, reducing the control exerted by those companies such as Microsoft and Intel that controlled the PC platform.

ANNEX D SENSITIVITY ANALYSIS

D.1 Introduction

Forecasting benefits over a 30 year period clearly involves significant uncertainty. This is particularly true given that our use cases are either relatively new or not yet available, and that the broadband technologies have either low coverage or have not yet been rolled-out.

While the use cases studied are based on existing uses of broadband, there is obvious uncertainty over many factors including:

- how technology developments will influence maximum potential demand;
- the speed at which demand for new services will be adopted;
- the degree to which existing services will be seen as reasonable substitutes for new advanced services;
- the speed of roll out of networks;
- the technology requirements of the new services.

We account for uncertainty in terms of bandwidth, price and intensity of household usage in our “moderate evolution” and “ambitious innovation” scenarios.

In this section we present sensitivity analysis which seeks to understand the impact of flexing various assumptions on results. In particular we wish to check whether variation in key assumptions have a material impact on the pattern of the results. However, we note that given the inherent uncertainty in long term forecasts, the out turns could be higher or lower than are assumed in our sensitivities. We have not exhaustively tested every input assumption, but have instead focused on those most relevant, and likely to affect results.

We consider in turn:

- the maximum addressable market at maturity;
- the speed of adoption;
- “counterfactual” demand (i.e. demand assuming technology constraints);
- technology roll-out;
- compression sensitivity

For each we set out the baseline assumptions, and sensitivities, compare the results of each sensitivity, *for each technology scenario, and each demand scenario*, with the base line, and comment on the results.

We finally present a table with the combined results.

D.2 Maximum addressable market at maturity

A key conclusion drawn from our historical analysis is that forecasting the speed and total adoption of new technologies is very difficult - with many forecasts falling a long way away from the eventual market outcome (e.g. mobile phones).

For all of our use cases, we assume a 'maximum' adoption which is reached 15 years after launch. The maximum adoption for a given use case is based on existing forecasts and/or adoption of comparator technologies, and the assumption of 15 years to reach market maturity reflects broadly what was observed for mobile PC and broadband technologies in the historical analysis. The majority of use cases are either still in the 'early adopter' phase or are yet to become available. It is possible that (like 3D TVs) some forecasts could prove overly optimistic despite bullish forecasts today; similarly some use cases could end up being much more successful than we have forecast, or be taken-up at a greater speed. Figure 106 summarises the baseline assumptions and sensitivities we test.

Figure 106 Sensitivity assumptions maximum addressable market at maturity

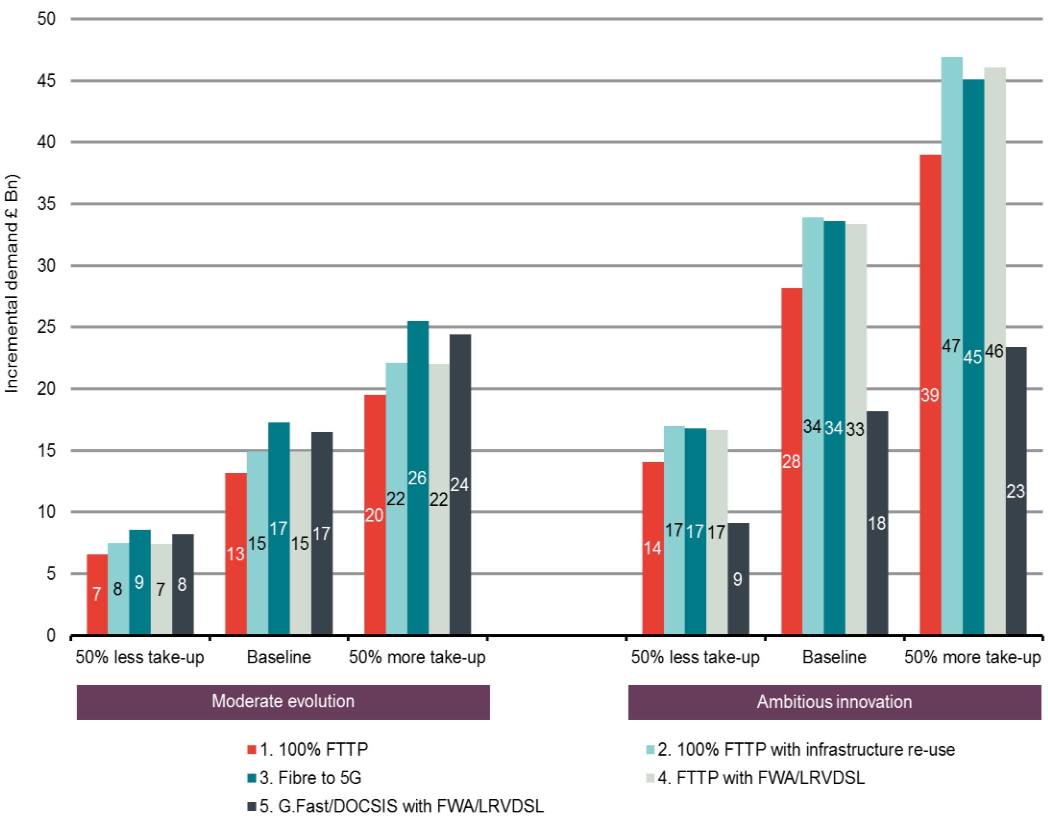
Sensitivity	Analysis Run		Sensitivity		
			Baseline	50% higher	50% lower
Maximum addressable market at maturity	50% lower and 50% higher take-up of our use case technologies. Where we already assumed high take-up at the baseline, we have bound take up at 100%.	VR & AR	33%	50%	17%
		Ultra HD Resolution	95%	100%	48%
		Smart Home	50%	75%	50%
		Telehealth	100%	100%	25%
		Online Classrooms	1%	2%	1%
		SOHO	2%	3%	1%

Source: Frontier

Figure 107 below shows the impact on incremental demand of a 50% lower and 50% higher (where possible)[249] household take-up in the moderate evolution and ambitious innovation scenarios. Varying the assumptions on the potential take up of the use case changes the magnitudes, but not relativities of the results.

[249] For use cases where we already assume high take-up, we bound the increase at 100% of households.

Figure 107 Maximum adoption sensitivities – incremental demand



Source: Frontier analysis

D.3 Speed of adoption

The chart below shows incremental demand in each technology and bandwidth scenario, in three different adoption sensitivities:

- 5 years to reach maximum adoption;
- 10 years to reach maximum adoption; and
- 20 years to reach maximum adoption.

Figure 108 summarises the baseline assumptions and sensitivities we test.

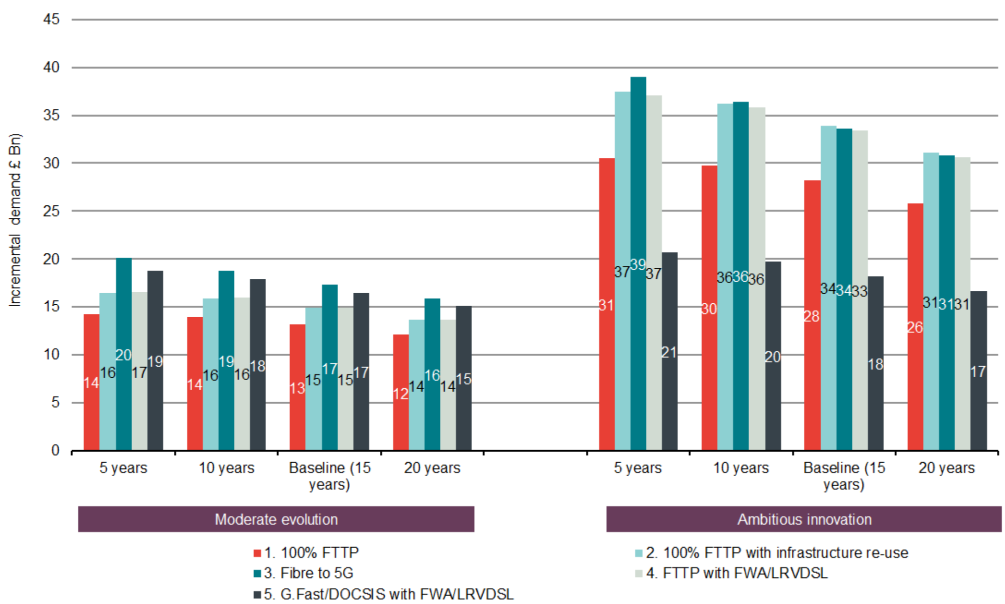
Figure 108 Sensitivity assumptions speed of adoption

			Baseline peak year	5 years take up (peak year)	10 years take up (peak year)	20 years take up (peak year)
Speed of adoption	Our baseline assumption is that it takes 15 years from out "start year" of the technology to reach peak adoption, so we run sensitivities that this peak adoption will be met in 5, 10 , and 20 years.	VR & AR	2032	2022	2027	2037
		Ultra HD Resolution	2032	2022	2027	2037
		Smart home	2032	2022	2027	2037
		Telehealth	2035	2025	2030	2040
		Online Classrooms	2027	2017	2022	2032
		SOHO	2032	2022	2027	2037

Source: Frontier

In both the moderate evolution and ambitious innovation scenarios, the impact of adoption speed on incremental demand is not particularly pronounced in the case of most network technologies. This is because for most technologies considered there is a significant lag in the time to roll out, so increasing the speed of potential adoption take up has limited impact on demand, since the broadband networks are unable to support the demand. In both cases the effect is most pronounced for Scenario (3.) Fibre to 5G, as the quicker roll-out profile means the greatest proportion of the earlier demand is able to be met.

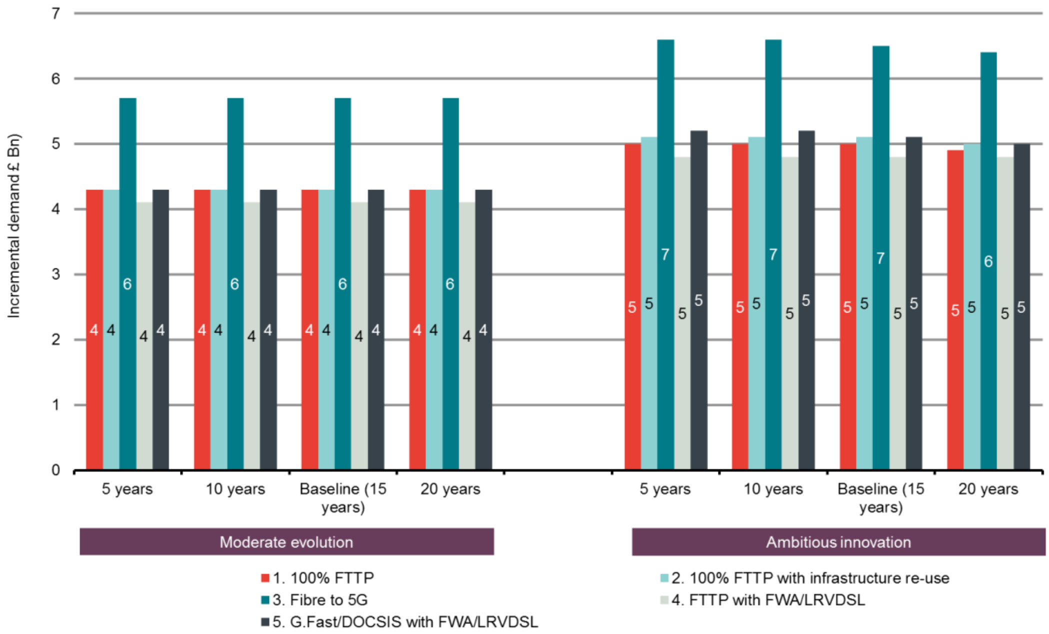
Figure 109 Adoption speed - incremental demand sensitivities



Source: Frontier analysis

In moderate evolution the impact of different adoption paths on cost savings is non-existent. This is because, in this scenario speed of adoption doesn't impact the 5G use-case or the Telehealth use cases as all technologies can achieve these use cases across all years. Similarly in the ambitious innovation scenario, the impact of adoption speed on cost savings is very small for the same reasons.

Figure 110 Adoption speed - cost savings sensitivities



Source: Frontier analysis

D.4 Counterfactual demand

In our baseline assessment, we make an assumption about demand in the counterfactual where a given broadband technology is unable to support the use case. This is because in most cases the presence of a network constraint does not lead to a binary “buy / do not buy” decision. Rather, a network constraint will *moderate* demand.

Figure 111 summarises the baseline assumptions and sensitivities we test.

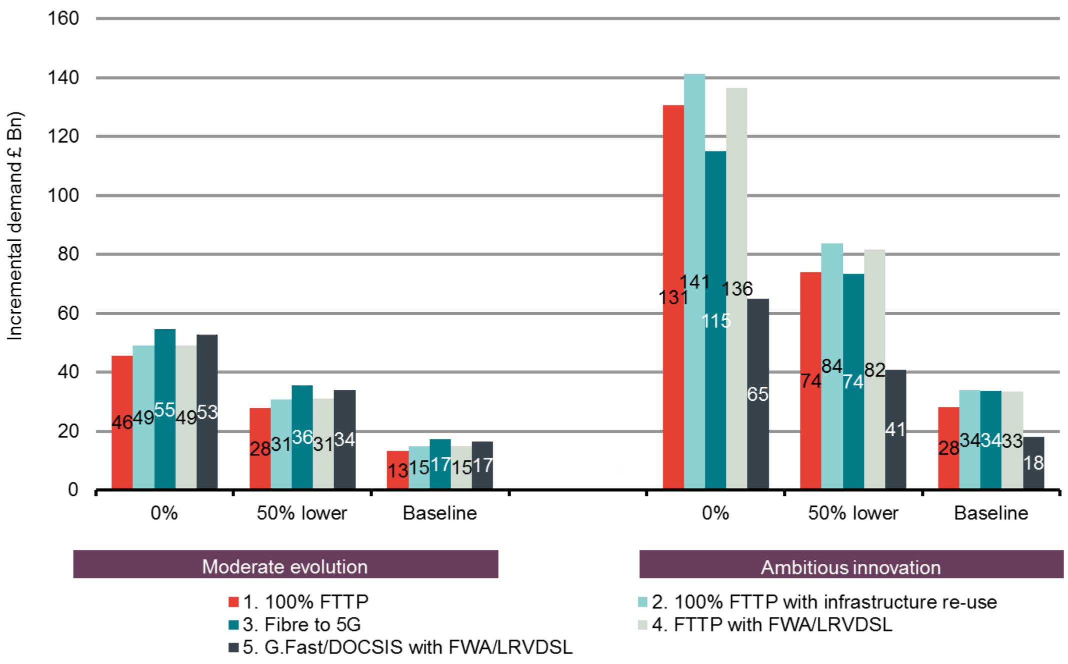
Figure 111 Sensitivity assumptions counterfactual demand

			Baseline CF demand (£)	50% lower CF demand (£)	Zero CF demand (£)
Counterfactual Demand	Our baseline a reasonable amount of demand achievable in the constrained scenario. We test sensitivities of 50% lower demand, and zero counterfactual demand which is possible given many of the uncertainties surrounding bandwidth requirements of our use cases.	VR & AR	50%	25%	0%
		Ultra HD Resolution	75%	38%	0%
		Smart Home	75%	38%	0%
		Telehealth	75%	38%	0%
		Online Classrooms	75%	38%	0%
		SOHO	50%	25%	0%

Source: Frontier

We test sensitivities of half the baseline assumption and 0% counterfactual demand (i.e. that all model demand is choked off in the presence of network constraints). Both of which could be possible considering the uncertainty in other variables such as bandwidth requirements that will impact demand in our constrained scenario. The results from these sensitivities on incremental demand are shown below in Figure 112.

Figure 112 Counterfactual demand – incremental demand sensitivities



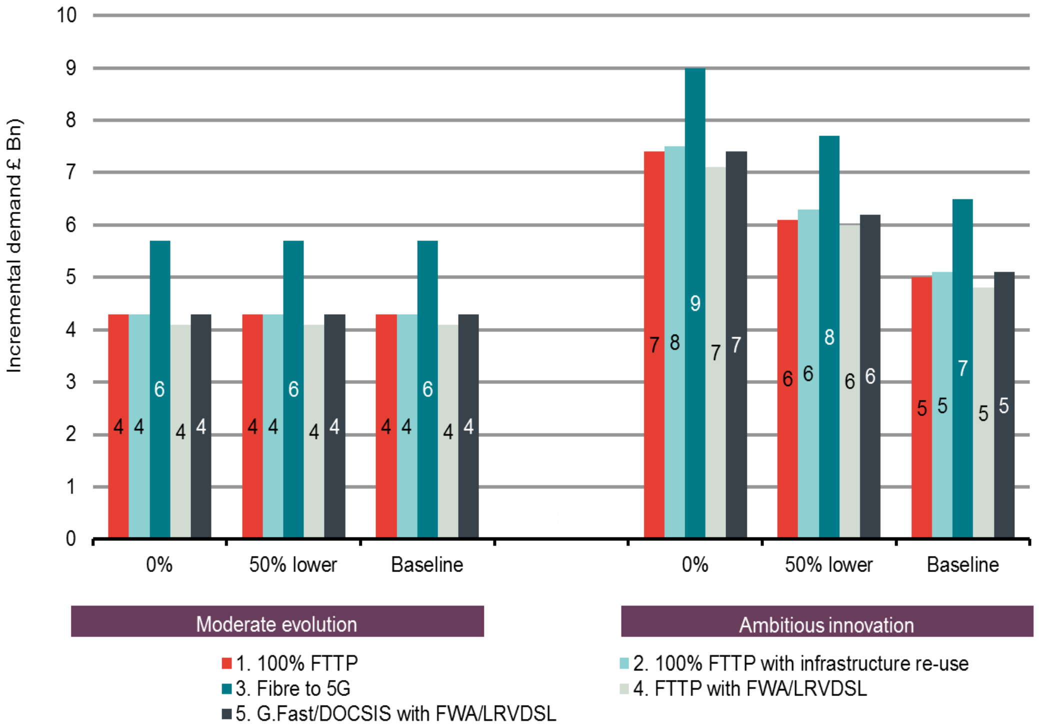
As can be seen in the charts, the results are sensitive to reductions in counterfactual demand in both the moderate evolution and ambitious innovation scenarios. With counterfactual demand at 0% (i.e. in the presence of network constraints consumers stop buying services), in the ambitious innovation scenario the two 100% FTTP technology scenarios (Scenarios 1 and 2) see incremental demand increase four-fold, whereas for our Fibre to 5G (Scenario 2) technology incremental demand increases by just over three-fold. A different pattern emerges in the moderate evolution scenario however, whereby all technology scenarios have a more similar magnitude of increase (incremental demand increases roughly three fold for each technology).

In the ambitious innovation scenario, with counterfactual demand at 0% for all technologies, cost savings increased by more than 48% for both of our 100% FTTP technology scenarios (Scenarios 1 and 2), whilst the effects on the other technologies are slightly lower such as Fibre to 5G (Scenario 3) where costs savings increased by 38%. These sensitivities in cost savings are solely attributable to the Telehealth use case, as 5G use case cost savings are not sensitive to the assumptions on counterfactual demand.

In the moderate evolution scenario, the impact of lower counterfactual demand on cost savings is non-existent, as our Telehealth use case is achievable under the baseline in moderate evolution and our 5G use case is unaffected by changed to counterfactual demand. Therefore, there is no impact of this sensitivity on cost savings.

The results from these counterfactual demand sensitivities on cost savings are shown below in Figure 113.

Figure 113 Counterfactual demand – cost savings sensitivities

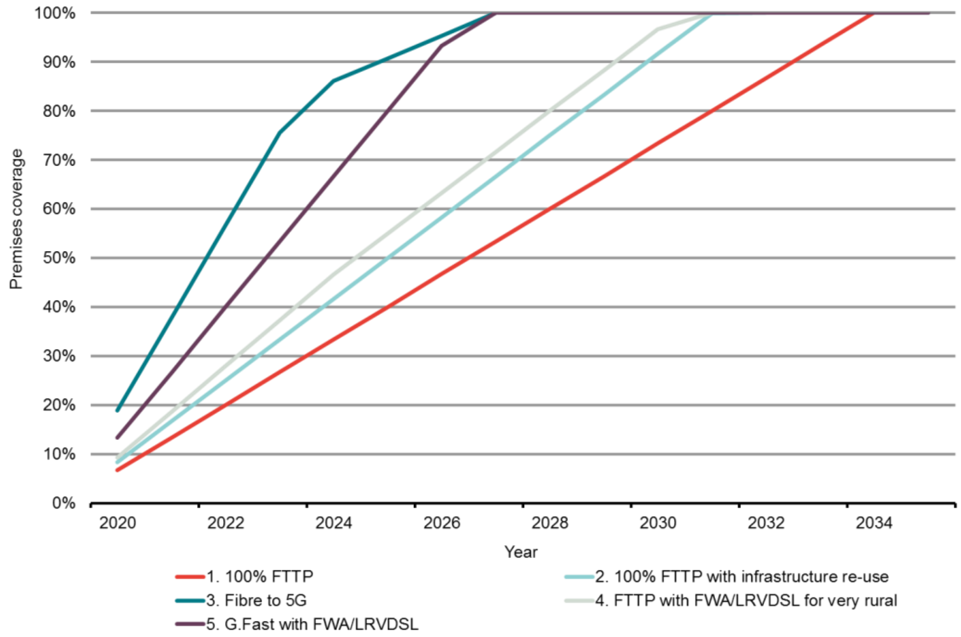


Source: Frontier analysis

D.5 Technology roll-out speed

Our baseline benefits assessment assumes a roll-out speed for each technology. This is illustrated in Figure 114. In reality it is difficult to forecast with great accuracy the speed of such large and complex infrastructure projects.

Figure 114 Roll-out profile in our baseline



Source: Frontier

In order to model this uncertainty we look at sensitivities where the roll-out speed is 50% slower and 50% quicker than for each technology in the baseline. Figure 115 summarises the baseline assumptions and sensitivities we test.

Figure 115 Sensitivity technology roll out

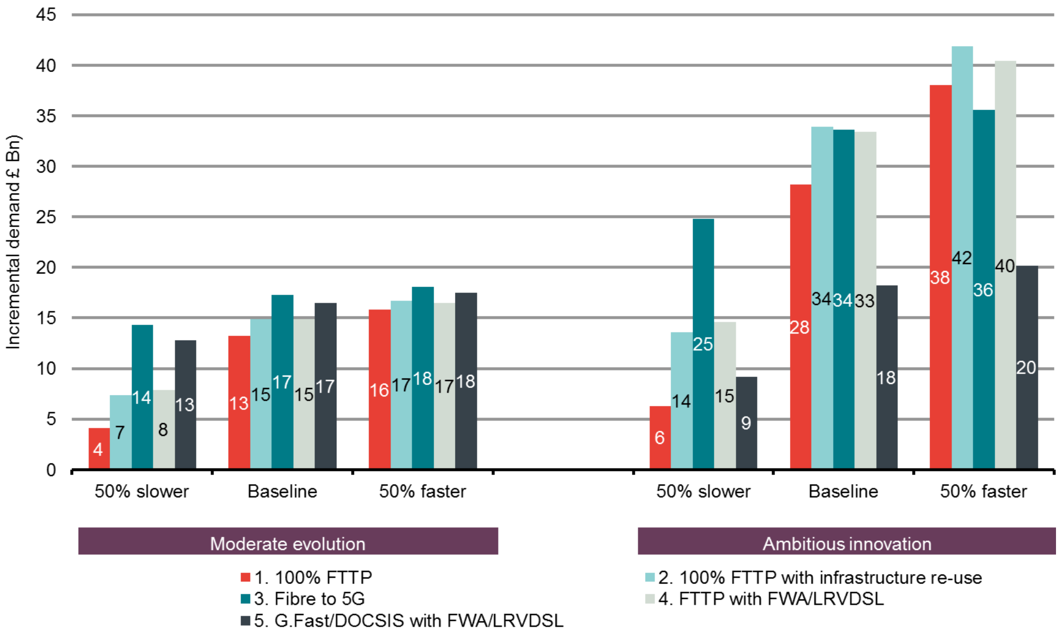
				Baseline roll-out speed (years)	50% faster roll out	50% slower roll out
Technology roll-out	We base our speed of technology roll-outs on estimates from PRISM. However, since roll out requires large infrastructure project there are inherent uncertainties in roll-out speed. We thus test sensitivities of 50% faster and 50% slower roll out speeds.	(1.) FTTP with new infrastructure		15 years	7.5 years	30 years
		(2.) FTTP with infrastructure re-use		12 years	6 years	24 years
		(3.) Fibre to 5G	5G	4.4 years	2.2 years	8.8 years
			FTTP	8 years	4 years	16 years
		(4.) FTTP with FWA/LRVDSL		11.4 years	5.7 years	22.8 years
		(5.) G.Fast/DOCSIS with FWA/LRVDSL		7.5 years	3.8 years	15 years

Source: Frontier

The results for these sensitivities on incremental demand are shown in **Error! Reference source not found.** below.

In both the moderate evolution scenario and ambitious innovation scenarios, as expected, faster roll-out increases total incremental direct economic output in each technology scenario and slower roll-out reduces total direct economic output. The impact of slower roll-out however is much greater in the ambitious innovation scenario.

Figure 116 Technology roll-out speed – incremental demand sensitivities



Source: Frontier analysis

In relation to 5G cost savings, faster rollout could help realise cost synergies of a rollout of the 5G networks. Since there are cost savings associated with telehealth the roll out speed has a limited impact on cost savings.

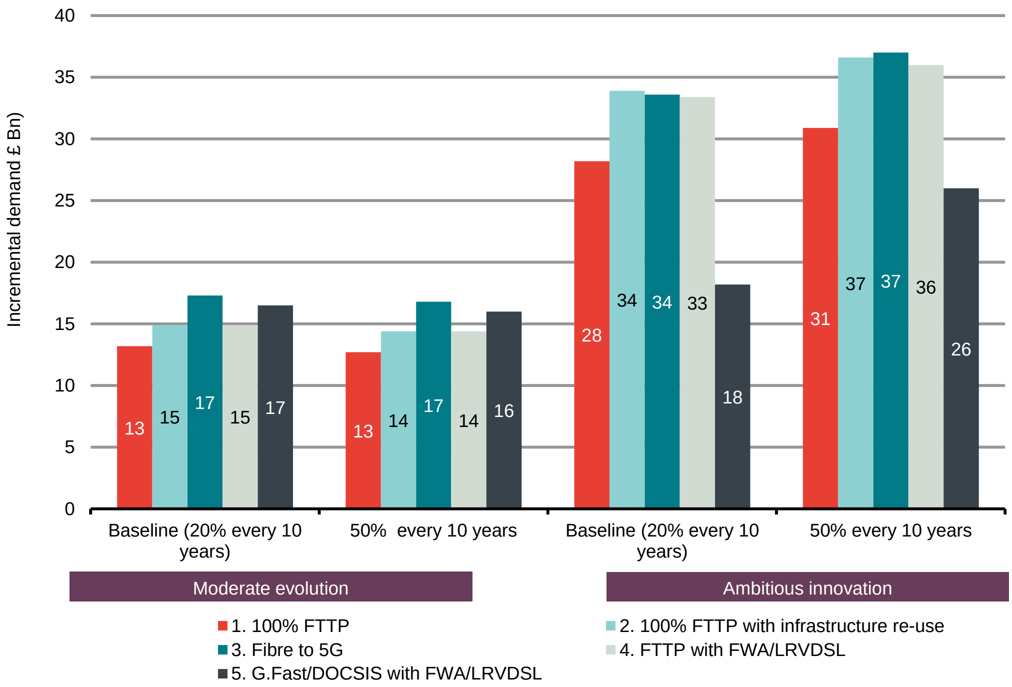
is no impact of faster roll-out in both the moderate evolution and ambitious innovation scenarios and, as 5G cost savings are constant, and the tele-health cost savings are also achievable under all our technologies thus the impact of faster roll-out is negligible.

D.6 Compression sensitivity

In our baseline assessment, we make an assumption about advances in video compression technology which tends to reduce to reduce the bandwidth required to deliver video to a given resolution. We assume compression efficiency will increase at a rate of 20% every 10 years. This is however, subject to many assumptions about technology improvements in the future, and a fairly conservative estimate. As such, we have run a sensitivity test whereby we set a more optimistic compression assumption of 50% every 10 years.

The results for this sensitivity on incremental demand are shown in Figure 117 below.

Figure 117 Compression – incremental demand sensitivities



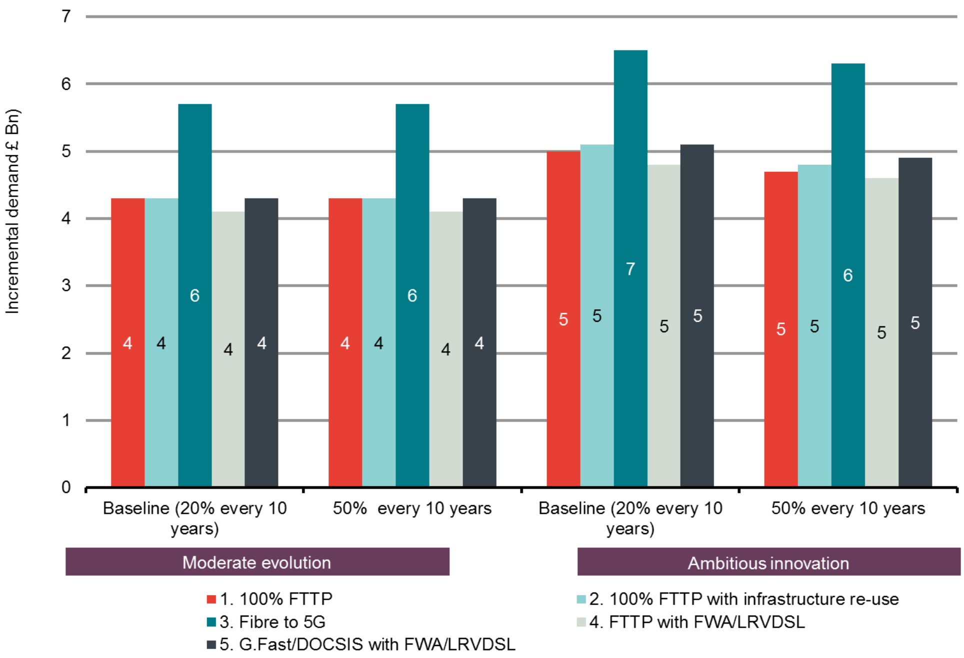
Source: Frontier

In the moderate evolution scenario and ambitious innovation scenario, the effect of compression is different. In the moderate evolution scenario, incremental demand is actually reduced for many of our technologies, as the baseline technology is able to meet more of the use case bandwidth demand assuming more efficient compression.

In the ambitious innovation scenario however, the G.Fast scenario has much greater incremental demand. This is to be expected, as now this technology too can meet much more projected demand relative to the baseline (which even with this 50% compression every 10 years still fails to meet some of the use case requirements in the years until 2050).

The results for this sensitivity on cost savings are shown in Figure 118 below.

Figure 118 Compression – cost savings sensitivities



Source: Frontier

The impact of greater compression on cost savings is fairly minor, as 5G cost savings are not affected by compression assumptions, and the Telehealth cost savings are only impacted under the ambitious innovation scenario. We see that our (3.) Fibre to 5G scenarios cost savings fall relative to the baseline, as the baseline will now be able to achieve more of the Telehealth use case.

D.7 Summary of overall sensitivity results

We conclude that the results are robust to the sensitivities. However, as noted in the report in assessing the results it is necessary to interpret with caution. This is because the use cases deliberately are not exhaustive, but rather are intended to be used to illustrate the impact that different choices on broadband networks can make to economic output across a range of different vertical sectors. The estimates do not represent the total investment return (which may be derived across a range of sectors which were not included within the scope of these forecasts. Finally, as with any long range forecasts, there is a significant degree of uncertainty.

The results are particularly sensitive to assumptions on counterfactual demand and technology roll out speeds.

- Under our baseline the model assumes that in the presence of network constraints consumers substitute to a lower capability technology. However, if we assume a lower counterfactual assumption (i.e. consumers stop consuming in the presence of network constraints) we have a greater divergence between the baseline and the UFBA demand. Lower counterfactual demand would be reasonable if there was a significant degree of product differentiation between high bandwidth services and low bandwidth services.

- The results are sensitive to assumptions on technology roll-out speed . This is because many of our UFBA technologies have a long roll-out profile. Thus, with a faster roll-out more incremental demand can be realised from an earlier date, thus the delta to the baseline is much larger. This is important to note, as technology roll-out speeds are difficult to predict exactly.

Figure 119 and Figure 120 set out the results of the sensitivity test on direct economic impacts.

Figure 119 Sensitivity table of incremental economic impact

		(1.) FTTP	(2.) FTTP with re use	(3.) Fibre to 5G	(4.) FTTP with FWA/LRVDSL	(5.) G.Fast/DOCSIS with FWA/LRVDSL
Maximum addressable market at maturity						
Ambitious Innovation	Baseline	28.2	33.9	33.6	33.4	18.2
	50% Higher	39.0	46.9	45.1	46.1	234
	50% Lower	14.1	17.0	16.8	16.7	9.1
Moderate Evolution	Baseline	13.2	14.9	17.3	14.9	16.5
	50% Higher	19.5	22.1	25.5	22.0	24.4
	50% Lower	6.6	7.5	8.6	7.4	8.2
Speed of adoption						
Ambitious Innovation	Baseline	28.2	33.9	33.6	33.4	18.2
	5 years	30.6	37.4	39.0	37.1	20.7
	10 years	29.8	36.3	36.4	35.8	19.7
	20 years	25.9	31.1	30.8	30.6	16.7
Moderate Evolution	Baseline	13.2	14.9	17.3	14.9	16.5
	5 years	14.3	16.5	20.1	16.5	18.8
	10 years	13.9	15.9	18.7	16.0	17.9
	20 years	12.1	13.7	15.9	13.7	15.1
Counterfactual Demand						
Ambitious Innovation	Baseline	28.2	33.9	33.6	33.4	18.2
	50% Lower	74.0	83.9	73.5	81.6	41.0
	Zero demand	130.7	141.3	115.0	136.4	65.0
Moderate Evolution	Baseline	13.2	14.9	17.3	14.9	16.5
	50% Lower	28.0	31.0	36.9	31.0	34.2
	Zero demand	45.7	49.2	56.0	49.2	52.8
Roll-out						
Ambitious Innovation	Baseline	28.2	33.9	33.6	33.4	18.2
	50% faster	38.0	41.9	35.6	40.4	20.2
	50% slower	6.3	13.6	24.8	14.6	9.2
Moderate Evolution	Baseline	13.2	14.9	17.3	14.9	16.5
	50% faster	15.8	16.7	18.1	16.5	17.5
	50% slower	4.1	7.4	14.3	7.9	12.8
Compression						
Ambitious Innovation	Baseline	28.2	33.9	33.6	33.4	18.2
	50% Compression over 10 years	30.9	36.6	37.0	36.0	26.0
Moderate Evolution	Baseline	13.2	14.9	17.3	14.9	16.5
	50% Compression over 10 years	12.7	14.4	16.8	14.4	16.0

Figure 120 Sensitivity table of incremental economic impact (+/- relative % to baseline)

		(1.) FTTP	(2.) FTTP with re use	(3.) Fibre to 5G	(4.) FTTP with FWA/LRVDSL	(5.) G.Fast/DOCSIS with FWA/LRVDSL
Maximum Addressable market at maturity						
Ambitious Innovation	50% Higher	38%	38%	34%	38%	29%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Moderate Evolution	50% Higher	48%	48%	47%	48%	48%
	50% Lower	-50%	-50%	-50%	-50%	-51%
Speed of adoption						
Ambitious Innovation	5 years	9%	10%	16%	11%	5%
	10 years	6%	7%	8%	7%	5%
	20 years	-8%	-8%	-8%	-8%	-15%
Moderate Evolution	5 years	8%	11%	16%	11%	14%
	10 years	5%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
Ambitious Innovation	50% Lower	162%	147%	119%	144%	125%
	Zero demand	363%	317%	242%	308%	257%
Moderate Evolution	50% Lower	112%	108%	113%	108%	107%
	Zero demand	246%	230%	224%	230%	220%
Roll-out speeds						
Ambitious Innovation	50% faster	35%	24%	6%	21%	11%
	50% slower	-78%	-60%	-26%	-56%	-49%
Moderate Evolution	50% faster	20%	12%	5%	11%	6%
	50% slower	-69%	-50%	-17%	-47%	-22%
Compression						
Ambitious Innovation	50% Compression over 10 years	10%	8%	10%	8%	43%
Moderate Evolution	50% Compression over 10 years	-4%	-3%	-3%	-3%	-3%

D.8 Use-case sensitivity results

This section contains tables and charts containing sensitivity analysis for each use-case individually, as opposed to holistically as above. This is important, as certain use- cases (such as premium audio visual, and VR/AR) are particularly impacted by assumptions such as compression that affect the total delta incremental demand in a more limited way.

D.8.1 Premium Audio Visual

The key sensitivities that affect the incremental demand in the moderate evolution scenario for our premium audio visual use case are data efficiency compression improvements and in both scenarios, the roll-out speed of technologies.

In the moderate evolution scenario, if the analysis assumes 50% compression efficiency improvement every 10 years (in comparison to the baseline of 20% every 10 years) then much lower incremental demand benefits in our higher bandwidth technologies like 100% FTTP are forecast. This is as the existing FTTC technology will be able to achieve much more of the use case bandwidth requirements. As such 100% FTTP will have 92% lower incremental demand benefits with 50% compression every 10 years relative to our baseline assumption of 20% compression every 10 years.

In both scenarios, roll-out speed sensitivities have a relatively large impact on the results. Technology scenarios involving FTTP roll out (scenarios 1, 2 and 4) are particularly sensitive to roll-out speed assumptions since these scenarios are have slow roll-out profiles compared with 5G or G.Fast. In the moderate evolution scenario, the incremental demand benefits of scenario 2 (FTTP with infrastructure re-use) are 69% lower where roll out is 50% slower than in the baseline. Similarly, for scenario 2 (FTTP with infrastructure re-use) in the ambitious innovation scenario 50% slower roll-out leads to 60% lower incremental demand benefits, which is to be expected as this scenario is highly dependent on large bandwidth requirements for the premium audio visual use case.

Since maximum adoption is already at 95% in our base case, the 50% higher maximum addressable market sensitivity is not particularly informative in either of our scenarios, as maximum adoption is capped at 100%.

Figure 121 Relative % change in incremental demand compared to baseline

		1. 100% FTTP	2. 100% FTTP with re-use	3. Fibre to 5G	4. FTTP with FWA/LRVDSL	5. G.Fast
Ambitious Innovation						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	74%	64%	51%	62%	57%
	Zero demand	152%	130%	101%	126%	114%
Roll-out speeds						
	50% faster	33%	21%	1%	18%	11%
	50% slower	-78%	-61%	-11%	-57%	-64%
Compression						
	50% Compression over 10 years	28%	23%	25%	23%	81%
Moderate Evolution						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	55%	51%	50%	50%	50%
	Zero demand	110%	101%	100%	100%	100%
Roll-out speeds						
	50% faster	10%	2%	0%	2%	1%
	50% slower	-62%	-43%	-1%	-39%	-10%
Compression						
	50% Compression over 10 years	0%	0%	0%	0%	0%

Source: Frontier

D.8.2 Visual Reality/ Augmented Reality

The VR/AR use case is particularly sensitive to certain assumptions due to its particularly high bandwidth requirements in the ambitious innovation scenario.

The key sensitivities that affect the incremental demand in the ambitious innovation scenario are compression assumptions, and roll-out speeds in both scenarios.

In the ambitious innovation scenario, a more efficient video compression efficiency assumption of 50% compression every 10 years (in comparison to our baseline of 20% every 10 years) results in much higher incremental demand benefits in our higher bandwidth technologies like scenario 1 (100% FTTP) since more demand is able to be satisfied. Improved compression (compared to the base case has the most improvement to the scenario 5 (G.Fast) since it realises significantly more demand (81% higher incremental demand) than the base case.

In both scenarios, roll-out speed sensitivities have a significant impact on our results with the impact being strongest in the 50% slower roll-out speed assumption than in the 50% higher roll-out speed assumption. Technology scenarios involving FTTP (scenarios 1, 2 and 4) are particularly sensitive to slower roll-out speed assumptions since the base case assumes a relatively slow to roll-out. In the moderate evolution scenario, the incremental economic output in scenario 1. (100% FTTP) are 78% lower in a situation with 50% slower roll-out than in the baseline. Similarly, for scenario 2. 100% FTTP with technology re-use) in the ambitious innovation scenario 50% slower roll-out leads to 62% lower incremental demand benefits, which is to be expected as this scenario is highly dependent on large bandwidth requirements for the premium audio visual use case.

In terms of speed of adoption, in the ambitious innovation scenario 3 (Fibre to 5G) and scenario 5 (G.Fast / DOCSIS) technology scenarios are impacted the most by a faster speed of adoption, with 10 years faster adoption resulting in 18% and 11% greater incremental demand relative to the baseline assumptions respectively. This is to be expected, as both scenarios have relatively fast roll out so can satisfy a faster growth in demand.

Figure 122 Relative % change in incremental demand compared to baseline

		1. 100% FTTP	2. 100% FTTP with re-use	3. Fibre to 5G	4. FTTP with FWA/LRVDSL	5. G.Fast
Ambitious Innovation						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	74%	64%	51%	62%	57%
	Zero demand	152%	130%	101%	126%	114%
Roll-out speeds						
	50% faster	33%	21%	1%	18%	11%
	50% slower	-78%	-61%	-11%	-57%	-64%
Compression						
	50% Compression over 10 years	28%	23%	25%	23%	81%
Moderate Evolution						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	55%	51%	50%	50%	50%
	Zero demand	110%	101%	100%	100%	100%
Roll-out speeds						
	50% faster	10%	2%	0%	2%	1%
	50% slower	-62%	-43%	-1%	-39%	-10%
Compression						
	50% Compression over 10 years	0%	0%	0%	0%	0%

Source: Frontier

D.8.3 Smart Home

The smart home use case is however impacted most by the assumption on counterfactual demand (i.e. whether a reasonable “lower quality” substitute (with lower bandwidth requirements) is available, in both scenarios. In the base case we assume that the availability of reasonable substitutes at lower bandwidth means that where broadband network capabilities constrain the performance of the use case then demand is reduced to 75% of base case demand.

In the ambitious innovation scenario, if the forecast assumes counterfactual demand is 38% (i.e. half of the base case) then the investments in UFBA networks result in much higher incremental economic output relative to the baseline for all technologies other than scenario 5 (G.Fast). This is because (5.)G.Fast is unable to support VR/AR in the ambitious innovation use case, just like the baseline, and thus the incremental economic output still remains at zero.

Figure 123 Relative % change in incremental demand compared to baseline

		1. 100% FTTP	2. 100% FTTP with re-use	3. Fibre to 5G	4. FTTP with FWA/LRVDSL	5. G.Fast
Ambitious Innovation						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	74%	64%	51%	62%	57%
	Zero demand	152%	130%	101%	126%	114%
Roll-out speeds						
	50% faster	33%	21%	1%	18%	11%
	50% slower	-78%	-61%	-11%	-57%	-64%
Compression						
	50% Compression over 10 years	28%	23%	25%	23%	81%
Moderate Evolution						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	55%	51%	50%	50%	50%
	Zero demand	110%	101%	100%	100%	100%
Roll-out speeds						
	50% faster	10%	2%	0%	2%	1%
	50% slower	-62%	-43%	-1%	-39%	-10%
Compression						
	50% Compression over 10 years	0%	0%	0%	0%	0%

D.8.4 Online Learning

For the Online Learning use case only the ambitious innovation scenario is impacted by our sensitivity testing, since our baseline technology can achieve out moderate evolution bandwidth requirements in all years (so incremental economic output enabled by UFBA is zero).

In the ambitious innovation scenario, incremental demand is particularly sensitive to changes in roll-out speeds for our FTTP technology scenarios (which have relatively slow roll out in the base case), but not for scenario 3 (fibre to 5G) scenario. 50% faster roll-out of technology only results in a 7% increase in incremental demand relative to the baseline for scenario 3 (fibre to 5G), whereas 50% faster roll-out increases incremental economic output by 33% in scenario 1 (100% FTTP).

Figure 124 Relative % change in incremental demand compared to baseline assumption

		1. 100% FTTP	2. 100% FTTP with re-use	3. Fibre to 5G	4. FTTP with FWA/LRVDSL	5. G.Fast
Ambitious Innovation						
Maximum addressable market at maturity						
	50% Higher	50%	50%	50%	50%	50%
	50% Lower	-50%	-50%	-50%	-50%	-50%
Speed of adoption						
	5 years	8%	10%	16%	11%	14%
	10 years	6%	7%	8%	7%	8%
	20 years	-8%	-8%	-8%	-8%	-8%
Counterfactual Demand						
	50% Lower	208%	191%	158%	187%	170%
	Zero demand	480%	421%	326%	410%	363%
Roll-out speeds						
	50% faster	36%	25%	7%	23%	13%
	50% slower	-78%	-60%	-20%	-56%	-33%
Compression						
	50% Compression over 10 years	0%	0%	0%	0%	0%
Moderate Evolution						
Maximum addressable market at maturity						
	50% Higher	N/A	N/A	N/A	N/A	N/A
	50% Lower	N/A	N/A	N/A	N/A	N/A
Speed of adoption						
	5 years	N/A	N/A	N/A	N/A	N/A
	10 years	N/A	N/A	N/A	N/A	N/A
	20 years	N/A	N/A	N/A	N/A	N/A
Counterfactual Demand						
	50% Lower	N/A	N/A	N/A	N/A	N/A
	Zero demand	N/A	N/A	N/A	N/A	N/A
Roll-out speeds						
	50% faster	N/A	N/A	N/A	N/A	N/A
	50% slower	N/A	N/A	N/A	N/A	N/A
Compression						
	50% Compression over 10 years	N/A	N/A	N/A	N/A	N/A

Source: Frontier

ANNEX E ASSUMPTIONS COMMON TO ALL USE CASE ANALYSIS

This annex sets out the assumptions common to all use cases. These assumptions are used to estimate:

- The economic multiplier; and,
- Consumer surplus associated with incremental expenditure.

E.1 The use of economic multipliers

E.1.1 What is the multiplier effect, and why is it important?

The **total economic impact** of additional economic activity in one sector comprises of two effects: the **direct effect** and the **multiplier effect**.

The **direct effect** is an increase in output in the economy as a result of a change in final demand in a sector – additional activity in a sector such as VR will lead to an increase in output in the economy through expenditure on wages for more coders, material purchases for headsets, etc.

The multiplier effect measures the **indirect** impact that incremental economic activity in a sector generates in both its supply chain (as measured by increased economic activity in those supplier sectors), and the additional income effect produced as a result of increased employment.

Multiplier effect defines the additional economic impact generated indirectly from incremental economic activity. There are two types of effects:

- Indirect Effect: the additional expenditure in the sector's supply chain, following the incremental activity within the sector. Those in the upward supply chain will purchase more goods and services– leading to an additional increase in output in the supply chain.
- Induced Effect: the income effect of hiring more workers in the sector to meet an increase in final demand. As these workers gain greater income, there will be additional household expenditure on goods and services that would not occur if not for the initial increase in activity in the sector.

E.1.2 Estimating the output multiplier

The output multiplier as it is most commonly known and used to measure the indirect effect of any economic activity is defined as the ratio of direct and indirect output changes, to the direct output change due to a unit increase in final demand. For our study we used the relevant output multipliers produced by the Office of National Statistics in the UK. [250]

[250] ONS produces annual Supply & Use Tables (SUT's), which are used in Input-Output analysis to produce the Leontief Matrix and Inverse tables in order to determine the multipliers for each sector

THE OUTPUT MULTIPLIER: THE ECONOMIC THEORY

The output multiplier considers the interdependency of different sectors by observing how the **inputs** to certain industry are the **outputs** of a number of upstream sectors.[251] This relationship uses an intermediate consumption matrix tabulating each sector in the economy as a producer (input), and also as a consumer (output) across all sectors in the economy ("Use Table"). [252]

Multiplying a change in final demand (or the incremental economic activity in the sector) by that sector's output multiplier will generate an estimate of direct plus indirect impacts upon output throughout the economy.

If, for example, the incremental economic activity in the Audio Visual Entertainment sector was £1m (taking the output multiplier from below):

£1m x 1.580 = £1.58m direct + indirect impact on output in the economy

The input output multipliers used in this analysis are set out in Figure 125 below.

[251] ONS produces annual Supply & Use Tables (SUT's), which are used in Input-Output analysis to produce the Leontief Matrix and Inverse tables in order to determine the multipliers for each sector

[252] The Leontief matrix calculated in the Leontief inverse tables is produced by q = ((I-A)^-1)f where q = total demand, f = final demand and A is a matrix built of:

(Consumption of industry x's products by industry y)/ Total production in x

See https://www.math.ksu.edu/~gerald/leontief.pdf and https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed 2010 file for further information on calculating the Leontief matrix.

Figure 125 Economic Multipliers for relevant sectors for our study

Sector:		Output Multiplier
IT		
	Computer programming, consultancy and related services	1.443
	Computer, electronic and optical products	1.603
Health:		
	Human health services	1.165
	Human health services - Non-market	1.359
	Health services - Non-profit institutions serving households	1.446
Education:		
	Education services	1.204
	Education services - Non-market	1.376
	Education services - Non-profit institutions serving households	1.246
Audio Visual Entertainment:		
	Motion picture, Video and TV programme production, sound recording & music publishing services and programming and broadcasting services	1.580
	As above, Non-Market	1.762

Source: ONS Multipliers & Effects tab: https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed

Note: Non-profit institutions serving households (NPISH) – include charities, universities, religious organisations, unions and associations that provide goods/services for free or at below market prices

Non-market is defined as "output that is provided free, or at prices that are not economically significant, to other units". In the UK this definition covers a range of services, mostly provided by central or local government, including health, education, defence and public administration (inc.BBC)

E.1.3 Interpreting multiplier effects in our economic evaluation

The Input-Output method of analysis as used above is a straightforward method of producing an estimate of the indirect effect on output (the output multiplier) from incremental economic activity in a sector.

The estimate however, must be interpreted with caution as this method of estimation is subject to strong assumptions which in reality may not hold:

- Multipliers assumes elastic supply for producers in the supply chain of a sector, and therefore fails to take into account *capacity constraints*. That is it assumes, shifts in demand only result in changes in output, with no changes in real prices.[253]
- The underlying models are *static across time*. They reflect the interrelationship of economic sectors at a certain point in time. These therefore can't observe any structural changes within sectors in response to

[253] http://farmdoc.illinois.edu/policy/choices/20032/2003-2-06.pdf

the change in final demand, and as such this may lead to over or underestimate the impact of any incremental activity.[254]

- Multipliers fail to allow for *international feedback effects*. For example if a producer in the supply chain of the sector starts outsourcing activities to other countries quickly as final demand increases, this will not appear in the static multiplier.[255]

E.2 Assumptions for consumer surplus estimation

Consumer surplus is derived whenever the price a consumer actually pays is less than they are prepared to pay. A demand curve indicates what price consumers are prepared to pay for a hypothetical quantity of a good, based on their expectation of private benefit as illustrated in the Figure below.

Based on some simple assumptions about the demand curve this report estimates the potential consumer surplus enabled by changes in the potential demand for the use case. Data on the nature and shape of demand curves are unlikely to be readily available, we thus make assumption. In particular in our study, we assume linear demand curves.

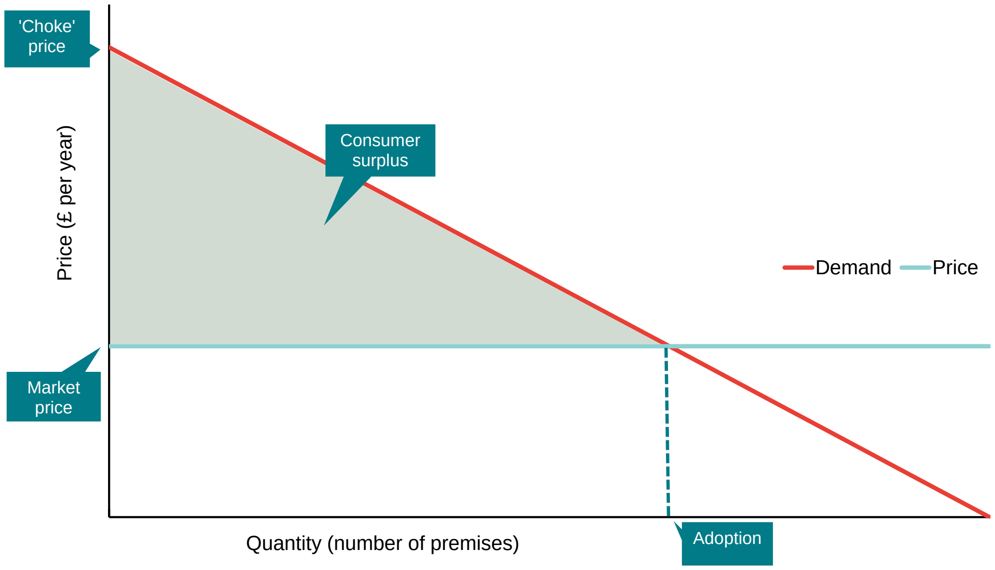
The ‘choke price’ is the price at which point demand would fall to zero (i.e. the highest price a consumer of the particular use case is willing to pay). In practice the choke price is difficult to measure, but it is possible to make reasonable assumptions on how it relates to market price. Based on previous relevant estimates in the literature[256] we assume the choke price is 150% of market price across all use cases (see Figure 126). So for example, if the market price of a use case is £50, the choke price would be £75.

[254] Katz and Suter (2009) note that “with the caveat of the static nature of input-output tables, we believe our estimates are quite reliable”.

[255] https://www.economicsnetwork.ac.uk/sites/default/files/Dave%20Clark/1002a.pdf

[256] See Hausmann (1997) “Valuing the Effect of Regulation on New Services in Telecommunications”.

Figure 126 Illustration of consumer surplus estimation



Source: Frontier

ANNEX F SUPPLEMENTARY EVIDENCE AND ASSUMPTIONS FOR USE CASE ANALYSIS

F.1 Purpose of this annex

This annex provides additional detail on the technical requirements and modelling assumptions used for each of our use cases.

F.2 VR/AR applications

F.2.1 Technical characteristics to support AR/VR

The download bandwidth required for VR and AR is highly sensitive to the resolution. For example, a 360-degree 4K 2D experience (which gives a retinal experience similar to 1080P HD TV), generally used for VR today, requires around 25-50 Mbps[257] The download bandwidth required to support AR is less clear than VR at this stage, however devices that have been released to date require around 25-50 Mbps (all of which are in HD resolution)[258]. We assume that, all technical characteristics being equal, AR will require the same or less bandwidth than VR, since only a part of the user's field of view needs to be augmented, rather than all of it in VR.

Improvements in the technical characteristics could lead the bandwidth requirement to vastly increase: "next-generation" 360° VR or AR experience, could require 50–600 Mbps, depending on resolution and other technical characteristics such as depth and field of view. A retinal experience similar to watching a 4K TV is expected to require in the region of 400-600 Mbps.[259]

It is conceivable that the bitrate of VR and AR could actually grow much higher still. Today's VR headsets use "monoscopic" (2D) 360 video;[260] a "steorescopic"[261] version could require bandwidth in the range of 200 Mbps-5 Gbps.[262] For example, a 3D 24K VR headset, which is both stereoscopic and sends 8k megapixels to each eye, is estimated to require around 3.3 Gbps.[263]

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257 http://blog.advaoptical.com/virtual-reality-check-are-our-networks-ready-for-vr

258 See for example: https://www.microsoft.com/en-us/research/project/holoportation-3/; and http://www.winlab.rutgers.edu/~gruteser/papers/p44-nguyen.pdf (page 47) (accessed on 1st October 2017).

259 See for example: https://www.forbes.com/sites/valleyvoices/2016/02/09/why-the-internet-pipes-will-burst-if-virtual-reality-takes-off/; https://www.mushroomnetworks.com/infographics/bandwidth-requirements-for-virtual-reality-vr-and-augmented-reality-ar---infographic-; http://www.ieee802.org/3/ad_hoc/ngrates/public/16_11/wang_ecdc_01a_1116.pdf

260 A monoscopic a flat equi-rectangular video displayed on a sphere

261 A stereoscopic VR/AR creates more realistic 'depth' by using two lenses side by side to give each eye a different vantage point (see http://fortune.com/2016/01/05/virtual-reality-game-industry-to-generate-billions/ accessed on 1st October 2017).

262 Qualcomm "VR and AR: Pushing Connectivity Limits"

263 Huawei Technologies "Update of Ethernet Bandwidth Forecast in 5G Application"

Number of devices per household

The number of VR and AR devices households use could also significantly increase the required bandwidth. For example, in the future a VR/AR experience could be a social activity where friends/family all 'visit' the same place while sat in the same room. A family of four all wearing VR headsets could require 100 Mbps at lower resolution; in 4K this could be over 2 Gbps.

Compression assumption

Our compression assumption is that the required bandwidth to deliver AR and VR will fall by 20% every 10 years.

Other network technical characteristics

Immersive experiences require low latency connections for a good experience.[264] The reason for this is that latency needs to be sufficiently low to convince the user's body that they are in another place (estimated to be less than 20 milliseconds "motion-to-photon" latency[265]). If latency is not sufficiently low it runs the risk of the user getting 'virtual reality sickness' through disorientation from the users sensory information being out of sync (e.g. sight and sound). For competitive online VR and AR gaming, latency is also important as "lag" can seriously reduce a gamer's chance of winning.[266]

In light of this, the lower latency broadband technology, such as FTTP could potentially provide a better VR/AR experience than other technologies (even if they provide sufficient bandwidth).

Given that most VR and AR applications are likely to be recreational in nature, the reliability of the broadband connection is likely to be less of an issue for other use cases. However frequent outages or significant variability in speeds may still prove frustrating certain in circumstances (e.g. for competitive gamers).

"Ambitious innovation" and "moderate evolution" scenarios

To reach our bandwidth assumptions in "ambitious innovation" and "moderate evolution" we assume a mix of three broad types of VR/AR devices:

- "**Basic" VR/AR** – today's HD and monoscopic VR/AR devices, with a bitrate of 25-50Mbps (we assume a mid-point of 38 Mbps);
- "**Advanced" VR/AR** – ultra HD and monoscopic VR/AR devices, with an estimated bitrate of 50-500 Mbps (we assume a mid-point of 275 Mbps); and
- **"Ultra-advanced" VR/AR** – ultra HD and stereoscopic VR/AR devices, with an estimated bitrate of 200 Mbps – 5 Gbps (we assume a mid-point of 2.6 Gbps).

[264] See M. Bredel and M.Fidler "A Measurement Study regarding Quality of Service and its Impact on Multiplayer Online Games" (2010).

[265] http://www.chioka.in/what-is-motion-to-photon-latency/

[266] Ibid

The bandwidth requirement in our “moderate evolution” scenario assumes the following:

- ‘Basic’ VR/AR is used by all adopters until 2025;
- from 2026 onwards assume “Advanced” VR/AR becomes the new ‘premium’ standard *and* begins to grow in popularity; and
- from 2040 onwards we assume that “Advanced” VR/AR is used by all adopters.

This results in an implied average bandwidth per household that increases (as users take up more advanced devices and services) but is offset by decreases (due to our compression assumptions). The combination of the effects means the average stays in the range of 38-162 Mbps.

In our “ambitious innovation” scenario we assume the following development:

- All adopters use “Basic” VR/AR in 2020;
- “Advanced” VR/AR begins to enter from 2021, reaching 25% market penetration by 2025, and used by all of adopters by 2040;
- “Ultra-Advanced” VR/AR, assuming this becomes the “premium” standard from 2040, and grows to 50% market penetration by 2050; and
- Throughout the period we assume 2 devices per household (to reflect the possibility of multiple simultaneous usage)

This leads to an average bandwidth per household requirement that grows quickly over time: starting at 75 Mbps in 2020, and growing to around 1.5 Gbps by the end of the period.

Figure 127 below shows the average bandwidth requirement over time for each scenario.

Figure 127 VR and AR – average bandwidth over time under each scenario

Scenario		2020	2025	2030	2035	2040	2045	2050
"Moderate evolution"	“Basic” VR/AR penetration	100%	100%	75%	50%	25%	0%	0%
	“Advanced” VR/AR penetration	0%	0%	25%	50%	75%	100%	100%
	“Ultra-advanced” VR/AR	0%	0%	0%	0%	0%	0%	0%
	Compression improvements	100%	90%	81%	73%	66%	59%	53%
	Average bandwidth per device (Mbps)	38	34	79	114	142	162	146
	Number of devices	1	1	1	1	1	1	1
	Average bandwidth per household (Mbps)	38	34	79	114	142	162	146
"Ambitious innovation"	“Basic” VR/AR penetration	100%	75%	50%	25%	0%	0%	0%
	“Advanced” VR/AR penetration	0%	25%	50%	75%	100%	75%	50%
	“Ultra-advanced” VR/AR penetration	0%	0%	0%	0%	0%	25%	50%
	Compression improvements	100%	90%	81%	73%	66%	59%	53%
	Average bandwidth per device (Mbps)	38	87	127	157	180	506	764
	Number of devices	2	2	2	2	2	2	2
	Average bandwidth per household (Mbps)	75	174	253	314	361	1,011	1,528

F.2.2 Average revenue per user (ARPU)

The table below sets out the ARPU assumption for VR and AR. This reflects expenditure on VR/AR devices and services, and an assumed inflation rate based on technology efficiencies over time.

Devices

We assume that in the "moderate evolution" scenario devices are priced at £200 on average (based on typical prices for a standard device today).[267] In the "ambitious innovation" scenario we assume that the more advanced devices are priced at £300, and on average households have two devices.

A further assumption is that the devices are kept and used on average for five years, meaning to reach an 'annual' price for the device we amortise the price of the devices over the five years.[268]

Services

In addition we assume on average households purchase 3 VR/AR subscriptions or downloads per year, at £50 each.[269] As noted above we expect gaming to be a primary driver of demand for VR and AR, but in theory demand could be derived from a range of applications, from different sectors.

Figure 128 ARPU assumptions

Description	Assumption	Rationale
ARPU (2018) – "moderate evolution"	£194 per year	Based on 1 device (at £200), and 3 subscriptions or downloads per year (at £500 each)
ARPU (2018) – "ambitious innovation"	£283 per year	Based on 2 devices (at £300 each), and 3 subscriptions or downloads per year (at £50 each)
Inflation assumption (real)	-1% p/a	Technology efficiencies will increase the cost of technology each year

Source: Frontier

Notes: We assume that each device is kept for 5 years, and amortize cost of this period to get 'average' annual expenditure. Assume that each subscription/download priced at £50.

F.3 Premium audio-visual display

We set out our assumptions on the bandwidth requirements for premium audio-visual displays. Over time users will increasingly switch to more advanced displays, and compression improvements will reduce the bandwidth required to offer a given resolution. These two effects are estimated over time for a "typical"

[267] Based on the average price of VR headsets today (source: http://www.currys.co.uk/gbuk/tv-and-home-entertainment/gaming/virtual-reality/430_4538_32216_xx_xx/xx-criteria.html accessed on 18th September 2017).

[268] Based on the average lifetime of laptop and desktop computers (source: "*Life cycle assessments of consumer electronics—are they consistent? Int J Life Cycle Assess*" (2010) by Anders S.G. Andrae and Otto Andersen.

[269] Based on average price of video games today (source http://www.game.co.uk/en/games/playstation-4/ accessed on 18th September 2017).

household that uses premium audio visual display in the assumptions set out below.

F.3.1 Bandwidth requirement

The download speed is a function of:

1. Screen resolution
2. Number of screens/streams
3. Compression assumptions

Resolution and type of screen

Screen resolution is the primary driver of bandwidth demand of an individual TV. As noted above, the bitrate increase proportionately with the number of pixels.

4K Entertainment streaming requires around 25 Mbps for a good experience[270] and streaming sports in 4K requires around 44 Mbps.[271] 8K therefore will need around 50-90 Mbps. Although not yet in existence (and noting the uncertainty around whether they ever will), it follows that higher resolution screens could require upwards of 100 Mbps.

Depending on how the market develops, the bandwidth requirement could in fact jump much higher still. For example, a screen created using multiple light-field cameras could produce an extremely high bitrate (one experiment used 64 cameras each at 26 Mbps to get this effect - resulting in a total of around 1.6 Gbps).[272] Digital cinema is also high very bitrate 4K digital cinema tests have shown required streaming bandwidth of 300 Mbps-1Gbps).[273]

Number of devices per household

As well as screen resolution, the other key driver of bandwidth is the number of streams running simultaneously. Today over half of TV owning households have more than one TV, and around 11% have four or more TVs.[274] If, in the future, simultaneous ultra HD streaming becomes common the bandwidth demand could be significant.

Compression assumption

Our compression assumption is that the required bandwidth to deliver VR and AR will fall by 20% every 10 years.

“Moderate evolution” and “ambitious innovation” scenarios

For our bandwidth scenario we assume some mix over time over the following three types of screen:

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270 https://help.netflix.com/en/node/306?ui_action=kb-article-popular-categories accessed on 18th September 2017

271 https://www.engadget.com/2015/07/17/bt-sport-ultra-hd-pricing/ accessed on 2nd October 2017

272 See http://www.csbio.unc.edu/mcmillan/pubs/EGRW02_yang.pdf (accessed on 2nd October 2017).

273 https://www.hindawi.com/journals/aot/2016/8164308/ accessed on 21st September 2017

274 http://www.barb.co.uk/tv-landscape-reports/tracker-number-tvs/ accessed on 25th September 2017

- **"4K"** – 3840 pixels × 2160 lines "ultra HD" screens, available today (we assume a bandwidth requirement of 44 Mbps[275]);
- **"8K" -** 7680 pixels × 4320 lines "ultra HD" screens (we assume a bandwidth requirement of 88 Mbps); and,
- **"Light-field"** – use of multiple light-field cameras to create a 'screen' (we assume a bandwidth requirement of 1 Gbps)[276].

In our "moderate evolution" scenario we assume that:

- 4K begins at 100% penetration (of "premium audiovisual display" market); and
- From 2021 8K begins to enter the market as the new "premium" product, growing to 20% penetration by 2025 and 100% penetration by 2045.

In our "ambitious innovation" scenario we assume that:

- 4K begins at 100% penetration (of "premium audiovisual display" market);
- from 2021 8K begins to enter as the new "premium" product, growing to 25% penetration by 2025 and 90% by 2040;
- Light-field enters as the new "premium" from 2040, reaching 30% penetration by 2050; and
- each household has two screens on average (meaning the 'peak' bandwidth requirement reflects each streaming simultaneously).

[275] In line with BT's suggested bandwidth for streaming sport (see https://www.engadget.com/2015/07/17/bt-sport-ultra-hd-pricing/ accessed on 2nd October 2017).

[276] We note the estimate discussed above is 1.6 Gbps. However this estimate is 2002 and we therefore expect technology improvements have brought (we assume 20% every 10 years).

Figure 129 Next-generation screens - average bandwidth over time under each scenario

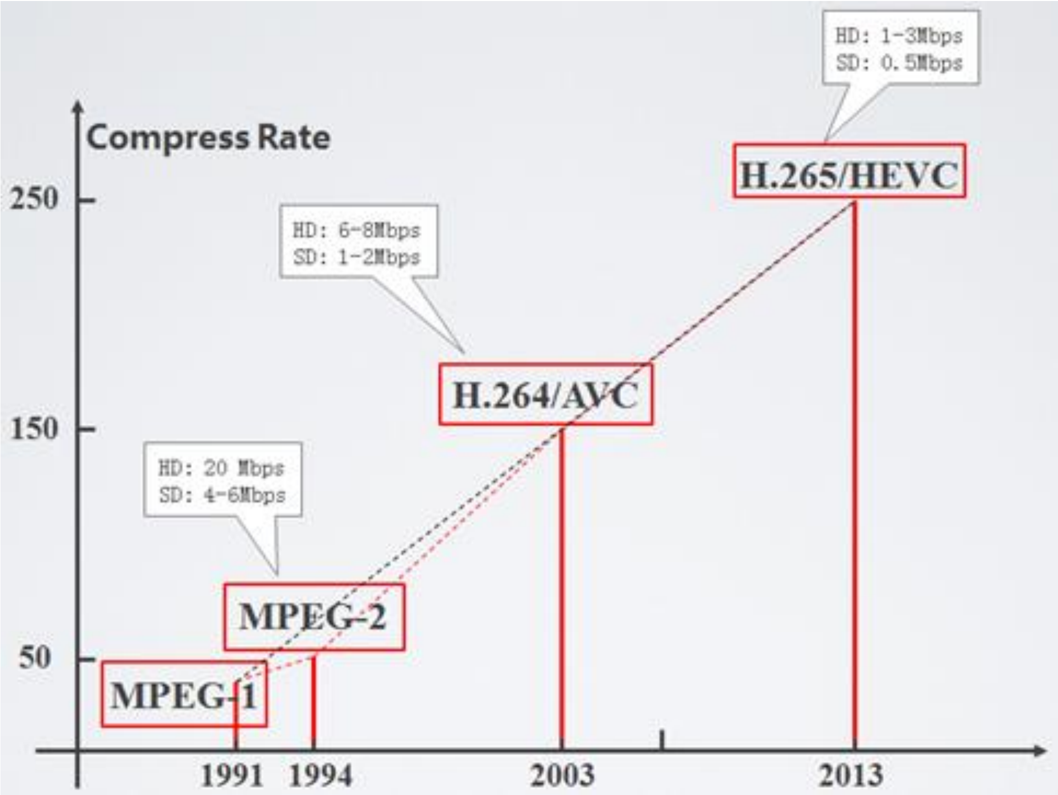
Scenario		2020	2025	2030	2035	2040	2045	2050
"Moderate evolution"	"4K"	100%	80%	60%	40%	20%	0%	0%
	"8K"	0%	20%	40%	60%	80%	100%	100%
	"Light-field"	0%	0%	0%	0%	0%	0%	0%
	Compression improvements	100%	90%	81%	73%	66%	59%	53%
	Average bandwidth per device (Mbps)	44	48	50	51	52	52	47
	Number of devices	1	1	1	1	1	1	1
	Average bandwidth per household (Mbps)	44	40	45	48	51	52	47
"Ambitious innovation"	"4K"	100%	75%	25%	0%	0%	0%	0%
	"8K"	0%	25%	75%	95%	90%	80%	70%
	"Light-field "	0%	0%	0%	5%	10%	20%	30%
	Compression improvements	100%	90%	81%	73%	66%	59%	53%
	Average bandwidth per device (Mbps)	44	50	62	97	118	160	192
	Number of devices	2	2	2	2	2	2	2
	Average bandwidth per household (Mbps)	88	99	125	195	235	319	384

F.3.2 Compression assumptions

The efficiency at which video can be encoded and supplied to endusers is essential for understanding the bandwidth requirements of different use cases. The delivery of video is central to the provision of audio-visual content and VR. It is also likely to be a main driver for bandwidth for Telehealth, and Education. We have therefore made an assumption about the improvements in video encoding compression technology that we are likely to observe over the coming 32 year period up to 2050.

Historically we note that there have been improvements leading to approximately 50% reduction in bandwidth required to deliver a given video resolution every 10 years (for example see Figure 130). However, for the reasons set out below we assume that compression standards will not continue at this rate, but at a lower rate of 20% per 10 years.

Figure 130 Video compression rates for different encoding standards



Source: http://device-camcorder-tips.blogspot.co.uk/2015/01/hevc-solution-for-android.html

Compression standards are agreed internationally by bodies such as the ITU and ISO. The various compression standards define algorithms to encode the visual display, and minimise the data required to offer a moving image in a given resolution. The technologies use a range of different approaches to interpolate the image in between “frames” (i.e. a full resolution still image of the video at points in time). In doing so, data for a full frame image may be provided every half second, and for the frames in between the algorithm forecasts the likely image given a forward and backward analysis of the full frames. More sophisticated compression techniques achieve greater encoding efficiency, though there is a trade-off that there is greater computing power required to encode, and decode, the signal.

In assessing the future bandwidth requirements of ongoing display technologies we have made an assumption that future increases in encoding efficiency required to deliver peak performance of different resolutions. We assume that the future rate of observed increases in efficiency in encoding will be lower than the rate of observed efficiency from previous generations (MPEG-2, MPEG-4, H.264, HEVC).

We consider that further improvements in encoding technology may be constrained for a number of reasons.

- First, a full image refresh "Eye Frame" is necessary every ½ second. Therefore, regardless of the encoding technique, there is a limit to the minimum data which is required to be transmitted as a complete new image has to be transmitted every half second. Otherwise a user scrolling through content would face a delay between choosing to view a video and it appearing.
- Second, compression relies on algorithms being able to predict an image given what has gone before and what will follow after. However, there is a natural limit on the extent to which this type of interpolation can be done.
- Third, more sophisticated encoding standards may be less suitable for some types of live programming, because the choice of type of encoding standard may not be optimal in live programming. When encoding recorded programming, for instance when used on a Blu-ray recording of a feature film, the precise form of the encoding technology may be hand chosen or designed to given the maximum quality. This is not possible for live recording. Furthermore, in order to encode the visual data it is necessary to delay the live feed. More sophisticated encoding would require a longer delay to maximise the efficiency of the encoding which could harm the value of the "live" recording. For example if it relates to sport, a 30 second delay in the live feed could reduce the value of the experience from user's perspective.
- Fourth, more sophisticated compression requires more sophisticated computing power for the user and broadcaster. Given that a significant driver of video bandwidth is on mobile devices, this would imply that more sophisticated compression could act as a larger drain on device batteries.

Therefore, while previous evolutions of compression technology (which occurs approximately every ten years) have broadly halved the bandwidth required to deliver a given resolution of display with each generation of encoding, we consider that this rate of change may not continue into the future. Therefore we assume that video compression will continue but at a lower rate 20% per 10 years.

F.3.3 Foregone AR VR demand as a result of network constraints

To estimate the forgone demand as a result of network constraints it is necessary to consider what the likely demand would be assuming network constraints are present.

The analysis considers how would a "constraint" impact the level of incremental economic activity – whether this be in terms of lower ARPUs for VR/AR, alternative devices, or some consumers "at the margin" choosing not to buy VR/AR, which reduces total demand. Our assumption is that although a constrained version of VR or AR would exist, consumers are likely to view this as a reasonably different alternative. For example, consumers are likely to value "basic" VR significantly less than "advance" or "ultra-advanced'' VR, should they become the 'premium' standard.

Based on this, our assumption is that economic activity would fall by 50% in the constrained scenario.

F.4 Smart homes / next generation comms / upload of user generated content

Existing use of smart devices in the home are set out below.

There are various appliances which can be connected, some for use in recreation or convenience (e.g. Amazon's "Echo"), whilst others are mainly beneficial in making the home more energy efficient such as "smart" meters. Both use cases for smart home technologies have potential for significant take up. Most households will be host to at least some degree of smart technology within the next decade, particularly as the government is aiming for 100% take up of smart meters by 2020[277]- which if successful would result in 27.1m households using smart home technologies[278].

Other "smart home" technologies have been slow to gain traction with consumers, largely due to price barriers[279]. Systems such as Phillips Hue lightbulbs require a substantial investment by the household; it would cost around £540[280] for the average household in the UK to install a complete set of Phillips Hue bulbs. Over time however we would expect the price of such appliances to fall however, and therefore take off will increase. In the US, the number of smart home devices purchased is estimated to over double within this decade[281], There may however be a plateau in take-off; some consumers may only opt-in to purchasing the "essential" smart home technologies, such as those that save both the environment, and their money.

[277] https://www.gov.uk/guidance/smart-meters-how-they-work

[278]https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2016

[279] PWC connected home report p.4

[280] http://www.energysavingtrust.org.uk/sites/default/files/reports/PoweringthenationreportCO332.pdf - 34 lights per home x (34 simple white Hue lights) + Hue Bridge. Prices taken from http://www.currys.co.uk/gbuk/smart-tech/smart-tech/smart-home/philips-hue-white-wireless-bulb-b22-10138737-pdt.html

[281] 83 Million in 2015, 193 million in 2020. http://uk.businessinsider.com/internet-of-things-smart-home-automation-2016-8?r=US&IR=T

Exhibit 4. Smart home security products and their estimated bandwidth

Home Security Product:	Cost, per camera	Storage Service	Bandwidth Requirement, per camera
Nest – Cam Indoor camera with 130-degree field of view	£159	Cloud based storage service - £8pm for 10 day video history per camera	720p: uploads 60Gb of bandwidth pm 200 and 500 KB/s upload bandwidth 1080p: uploads 140GB bandwidth pm 450 and 1,200 KB/s upload bandwidth
Netgear Arlo- Pro Outdoor 720p camera with 130-degree field of view	£300	Recordings can be saved locally (USB) as well as the cloud. 1GB is free for 7 days, £6.49 for 10GB for 30GB days.	Base station uses a dedicated 2.4GHz Wi-Fi network only Arlo cameras can see 700 kbps required
Adobe Starter Kit- Includes window/door sensors, and a motion sensor camera with 90 degree field of view(snapshot x3 images)	£240	Pictures can be saved free for 3 days, £175 per year for 24-7 professional monitoring, 3G cellular backup and 90-day timeline storage	Starter camera alone does not transmit live streaming, so bandwidth will be minimal A 720p video camera can be added to the starter kit

Source: https://kb.arlo.com/3201/How-much-bandwidth-does-an-Arlo-camera-use-when-it-is-capturing-video

http://www.trustedreviews.com/reviews

F.5 Education applications

Bandwidth requirement

As noted above, bandwidth requirements for distance learning are highly sensitive to the mode of delivery. For example, emailing and small file downloads with flexible timings do not require much bandwidth at all, and can be comfortably delivered using today's speeds. However, if the sector develops in the direction of synchronous learning using high bitrate methods such as ultra HD, VR and AR, the bandwidth demand could be significant. The bandwidth requirement is a function of:

1. Device
2. Mode of delivery
3. Resolution
4. Compression improvements

Device

As discussed in the “Virtual and Augmented Reality” and “Premium Audio-visual display” use cases, the bandwidth requirement for a VR or AR video is higher than for a TV or computer screen (all else being equal) due to the need to send a greater number of pixels to achieve the same retinal experience. For example HD video requires around 5-8 Mbps, whereas HD VR or AR requires in the region of 30 – 50 Mbps download speed. With 4K resolution or higher – and other technical improvements to VR/AR - the differential between VR/AR and regular screens could be much higher.

Mode of delivery

Distance learning resources more typically used in asynchronous distance learning, such as email and text documents, will be very low bandwidth and not likely to impose a constraint on today’s networks.

The use of video will drive up bandwidth demand. In synchronous distance learning the need to “live-stream” could create large data volumes (particularly in HD or ultra HD resolution). Similarly streaming of a recorded lecture or downloading of a large video will require higher bandwidth than other modes of delivery. In an interactive version – where the lecturer can see and interact with the student - this will be a demand on the upload bandwidth, as well as the download.

Resolution

All else being equal, the resolution of a video stream will proportionately increase the bandwidth requirement.

Compression improvements

Our compression assumption is that the required bandwidth to deliver distance learning will fall by 20% every 10 years (in line with assumption for AR and VR and next-generation screens)

Other network technical characteristics

Ubiquity of networks could also be an important issue for distance learning. For example, under scenarios (4.) and (5), the c. 10% of households with FWA/LRVDSL connections could have insufficient upload speeds to have “attended” lectures where two-way interaction is required. Also students in very rural areas are likely to value the convenience of distance learning even more than those in urban areas, since the alternative of travelling to an educational institution is likely to be less accessible to them.

“Ambitious innovation” and “moderate evolution” scenarios

To form our bandwidth assumptions for the “ambitious innovation” and “moderate evolution scenarios, we assume a mix of four types of video-based delivery, based on the bandwidth assumptions in the “Virtual and augmented reality” and “Next-generation screens” use cases:

- **“HD” video –** lectures and other educational video streams in HD resolution (8 Mbps)

- **"4K" video**[282]**-** lectures and other educational video streams in HD resolution (44 Mbps)
- **"Basic" VR/AR –** virtual/augmented reality school trips, learning exercises. and holographic telepresence in 2D and HD resolution (38 Mbps)
- **"Advanced" VR/AR**[283] **–** virtual/augmented reality school trips, learning exercises and holographic telepresence in 4K resolution (275 Mbps)

By using the assumed split each year, as well as device bandwidth requirements and compression assumptions, the "average" bandwidth requirement for households can be derived.

Our "moderate evolution" scenario assumes the following market development:

- In 2020 100% of content uses HD video and 5% of content 4K video;
- "Basic" VR begins to enter the market from 2035, growing to 20% by the end of the period
- 4K grows to 80% by the end of the period, with HD video disappearing entirely.

In our "ambitious innovation" scenario we assume that:

- In 2020, 50% of content uses HD video and 50% use 4K video;
- By 2030, 4K grows to 75%, completely replacing HD;
- "Basic" VR enters in 2030;
- "Advanced" VR enters in 2035, growing to 4% by 2050.

This gives the implied average download bandwidth requirements shown in Figure 131. We note that there will also be some upload required for distance learning (e.g. two-way video conservations); however we do not expect this to be key to the experience or be constrained by any of the broadband technologies.

Figure 131 Distance learning - average bandwidth over time under each scenario

Scenario		2020	2025	2030	2035	2040	2045	2050
"Moderate evolution"	"HD" video	100%	95%	60%	30%	20%	10%	0%
	"4K" video	0%	5%	40%	60%	65%	70%	80%
	"Basic" VR/AR	0%	0%	0%	10%	15%	20%	20%
	"Advanced" VR/AR	0%	0%	0%	10%	20%	30%	40%
	Compression improvements	100%	90%	81%	73%	66%	59%	53%

282 Our assumption is that 8K resolution is not likely to be required for distance learning applications.

283 We do not include "Ultra-advanced" VR/AR for this use case under the assumption that education will be a relatively late adopting sector (as is the case for VR today) and therefore "Ultra-advanced" will not be used in the sector before 2050.

Scenario		2020	2025	2030	2035	2040	2045	2050
	Average bandwidth per device (Mbps)	8	9	18	24	24	23	23
	Number of devices	1	1	1	1	1	1	1
	Average bandwidth per household (Mbps)	8	9	18	24	24	23	23
"Ambitious innovation"	"HD" video	50%	25%	0%	0%	0%	0%	0%
	"4K" video	50%	65%	75%	70%	60%	50%	40%
	"Basic" VR/AR	0%	0%	10%	25%	20%	20%	20%
	"Advanced" VR/AR	0%	0%	0%	10%	20%	30%	40%
	Compression improvements	100%	90%	81%	73%	66%	59%	53%
	Average bandwidth per device (Mbps)	26	31	34	48	58	66	72
	Number of devices	1	1	1	1	1	1	1
	Average bandwidth per household (Mbps)	26	31	34	48	58	66	72

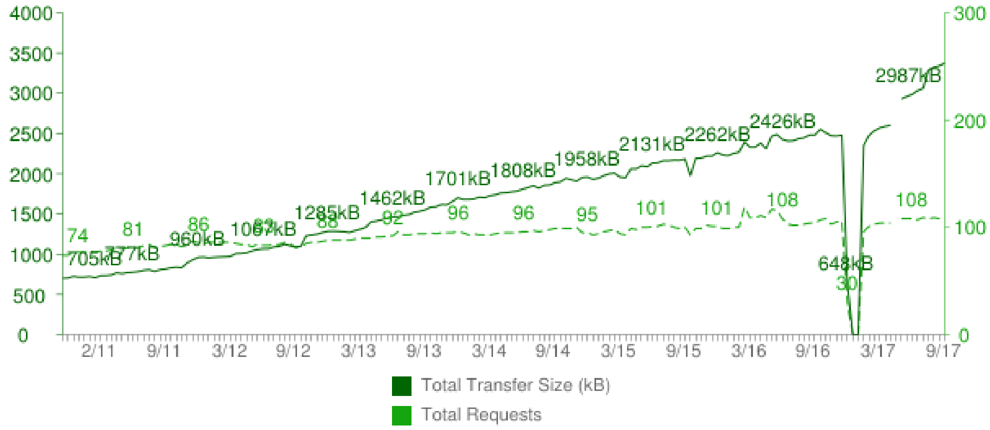
F.6 General web browsing

In addition to the specific use cases which are described above, it is expected that households will continue to use broadband to browse the internet to access data, make purchases, browse retailers, use social networks etc.

Typically these activities can be delivered using existing use cases. However, as noted in section 4 these activities happen in combination with other use cases.

Typical web page size has been growing over time. For example one source estimated that the average web page has grown over time from 0.7MB per page in 2011 to almost 3MB per page in 2017 (see Figure 132). This represents a 27% CAGR.

Figure 132 Total web page size and total requests



Source: http://httparchive.org/trends.php?s=All&minlabel=Nov+15+2010&maxlabel=Sep+15+2017#bytesTotal&reqTotal

The reasons for the increase include the increased use of images, embedded videos, the use of custom fonts, and the inclusion of more adverts of greater sophistication.

These trends are likely to continue, though may reach a natural limit as video techniques to minimise the time to load are used to load web pages (for example loading video and images in low resolution as the page loads, then over time increasing the resolution).

Furthermore, expectations will continue to evolve such that slow loading web pages will not be tolerated. This is because higher loading times are negatively correlated with measures of user-interest in the site. For example a recent report[284] found that faster loading times lead to higher ad viewing, longer sessions on the website, and lower "bounce rates"[285] .

We therefore assume that average web page size will increase to between 5MB-6MB per page by 2035 for most users, though some web pages could reach up to 10MB by 2035 (this would imply 7% CAGR) between now and 2035 which does not seem implausible.

[284] Doublkeclick (owned by Google) (2016)The need for mobile speed: How mobile latency impacts publisher revenue. See: https://www.doubleclickbygoogle.com/articles/mobile-speed-matters/

[285] Bounce rates describes the percentage of visitors to a web page that exit the site before exploring any other pages within the same site.

ANNEX G HOUSEHOLD SEGMENTATION

G.1 Purpose of this annex

This annex provides a detailed explanation of the approach taken for segmenting household in terms of their propensity to use technology. Once established, this segmentation feeds in to our assumptions for the household “app stack” analysis, where we consider how simultaneous usage of different broadband use cases could lead to technological constraints.

G.2 Segmenting households by adoption of technology

Different households will have different adoption patterns of technologies. This is for two reasons. First the composition of households differ and it is well understood that generally the younger users tend to be higher users of technology than older users. Therefore the age composition of the household can affect its demand for technology. Second there is a degree of heterogeneity in attitudes to technology, even from users of the same age. Therefore this segmentation analysis combines data on household composition with data on attitudes to technologies to segment UK Households by their attitudes and take up of technology.

This Annex describes the household segmentation framework used throughout this report. Household consumption depends on individual data consumption. In the first part of this section, we describe individual segmentation. Our conclusion is that teenagers and young adults have the highest data consumption across the different age groups considered, while retirees have the lowest.

In the second part of the section we describe household composition in the UK. This is based on an analysis of ONS data. We identify six household types: adults, 16-44; adults, 45-64; families without children; families with young children; families with older children; retirees.

Individual attitudes to technology

Children (age 6 to 15) have the lowest daily consumption of media and communication time across all age groups, but are more likely to engage in activities that require high bandwidth, such as video games. Children spend on average 6 hours and 20 minutes a day in media and communication activities, while adults 8 hours and 45 minute.[286] Of the time allocated to media and communication, children in the age group 6 to 11 spend 22% on gaming; for children 11 to 15 this percentage is 17%. This compares to an average of 4% for adults (16+).[287]

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286 Ofcom Digital Day research https://www.ofcom.org.uk/__data/assets/pdf_file/0017/94013/Childrens-Digital-Day-report-2016.pdf, page 5.

287 Ibid, page 5.

Teenagers are high consumers of data. For example, children in the age group 11 to 15 spend one fifth (21%) of total media and communication time on social media. This is even higher than the proportion spent on social media by adults in the age group 18 to 24 (18%).[288] With the exception of children in the age group 6 to 11, all groups are more likely to be using a mobile phone for their social media activities.[289]

When breaking down the adult population into different age brackets, we find that young adults (age group 16 to 34) spend more time on media and communication activities compared to adults (age group 35 to 54). Adults in turn spend more time on these activities compared to the older population (55+).[290]

Moreover, old adults spend the largest proportion of their media time watching audio visual content, and in particular on live TV (79% of total watching time).[291] This proportion is lower for both young adults (42%) and adults (59%), with both groups spending more time watching recorded TV or on-demand programmes.[292]

Overall, the older population is likely to be a low consumer of technology and use less broadband. This is confirmed by the proportion of time spend on TV, mobile and computer, as summarised in Figure 133.

Figure 133 Proportion of time spent on devices

Age group	TV	Mobile phone	Computer
Young adults (16-34)	29%	29%	26%
Adults (35-54)	36%	12%	23%
Older population (55+)	50%	3%	15%

Source: http://www.digitaldayresearch.co.uk/media/1087/aged-16-34-in-the-uk.pdf, page 24; http://www.digitaldayresearch.co.uk/media/1089/aged-55plus-in-the-uk.pdf, page 24; http://www.digitaldayresearch.co.uk/media/1088/aged-35-54-in-the-uk.pdf, page 24.

Information from Personicx reinforces the conclusions drawn above. Personicx's research identifies 5 groups for digital consumption Figure 134. In this report, we follow the same classification for digital consumption.

288 Ibid, page 20.

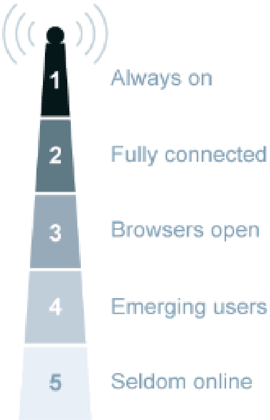
289 Ibid, page 22.

290 http://www.digitaldayresearch.co.uk/media/1087/aged-16-34-in-the-uk.pdf, page 11; http://www.digitaldayresearch.co.uk/media/1089/aged-55plus-in-the-uk.pdf, page 11; http://www.digitaldayresearch.co.uk/media/1088/aged-35-54-in-the-uk.pdf, page 11.

291 http://www.digitaldayresearch.co.uk/media/1089/aged-55plus-in-the-uk.pdf, page 12.

292 http://www.digitaldayresearch.co.uk/media/1087/aged-16-34-in-the-uk.pdf, page 12; http://www.digitaldayresearch.co.uk/media/1088/aged-35-54-in-the-uk.pdf, page 12.

Figure 134 Digital consumption classification



Source: Personicx, http://www.personicx.co.uk/personicx.html#id=2

Household composition analysis

Using ONS data, we group households into six groups:[293]

- **Adults, 16 to 44**. This group includes people 16 to 24 and 25 to 44 living alone in the UK in 2016.
- **Adults, 45 to 64**. This group includes all adults 45 to 64 living alone in the UK in 2016.
- **Families without children**. Includes all couples with no children currently living in the households. This does not necessarily indicate that the adults in the household have never had children.
- **Families with young children**. This group includes all households with children (whether couples or lone parents), where the age of youngest dependent child children is from 0 to 9.[294]
- **Families with older children**. Includes all household with children, where the age of youngest dependent child children is 10 to 18, as well as couples and lone parents with non-dependent children.[295]
- **Retirees**. Includes all people living alone who are 65 and over.

Figure 135 below summarises the household analysis described.

293 https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families

294 To split families with children (a total of 7.7m in the UK) into families with young and older children, we used statistics on the "age of youngest dependent child" from Wales and England. While a similar metric for the whole UK is not available, the proportion of household with children on total households is similar in England and Wales compared to the UK figure (i.e. 29.0% v 28.4%). The reader should also note is that this statistic is referring to the age of youngest dependent children in a household. As such, it is possible, for example that when the youngest child is 5-9, families might have a second kid of age 10+. This would add another layer of complication which is left aside as not crucial for the purpose of this report. See https://www.nomisweb.co.uk/census/2011/LC1113EW/view/2092957703?rows=c_ahthuk11&cols=c_dpchuk11.

295 Ibid. Our calculations assume that 63% of families with children have the youngest dependent child aged 0 to 9; 37% 10 to 18. Non-dependent children are those living with their parent(s), and either (a) aged 19 or over, or (b) aged 16 to 18 who are not in full-time education or who have a spouse, partner or child living in the household.

Figure 135 Household composition

	Segment	Number of households (2016)	Percentage of total number of households
1	Adults, 16-44	1.6m	6%
2	Adults, 45-64	2.4m	9%
3	Families without children	7.8m	30%
4	Families with young children	4.9m	19%
5	Families with older children	5.6m	22%
6	Retirees	3.6m	14%

Source: ONS, https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/datasets/familiesandhouseholdsfamiliesandhouseholds

Note: A household is defined as one person living alone, or a group of people (not necessarily related) living at the same address who share cooking facilities and share a living room or sitting room or dining. For the purpose of this analysis, we are not including in any of the six household segments identified in the table "Two or more unrelated adults" and "Multi-family households". This allows us to still cover 95% of total households in the UK. Percentages in column 3 are rescaled to reflect this change and the base of total household moves from 27.1m to 25.9m.

Results of segmentation

This subsection combines the evidence gathered on individual data consumption and on typical household composition in the UK to estimate household joint digital consumption.

To estimate the digital consumption by household type, we mapped information available on the Personicx website on individual data consumption to the corresponding six household types identified.[296]

Figure 136 summarises our findings, by household type.

Figure 136 Technology consumption by household type

Segment	Always on	Fully connected	Browsers open	Emerging users	Seldom online
Adults, 16-44	27%	26%	47%	0%	0%
Adults, 45-64	0%	20%	35%	46%	0%
Families without children	81%	19%	0%	0%	0%
Families with young children	34%	56%	11%	0%	0%
Families with older children	14%	55%	31%	0%	0%
Retirees	0%	0%	5%	21%	74%

Source: Frontier Economics based on ONS and Personicx data

Note: http://www.personicx.co.uk/personicx.html#id=2, accessed on 21 September 2017. ONS data are available at https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families and https://www.nomisweb.co.uk/census/2011/LC1113EW/view/2092957703?rows=c_ahthuk11&cols=c_dpchuk11

When considering total digital household penetration, we find that households segment in the way set out in Figure 137.

[296] Once clusters were mapped into household types, we rescaled each segment so that data consumption for each household type would add up to 100%.

Figure 137 Household digital penetration

	Always on	Fully connected	Browsers open	Emerging users	Seldom online
Household penetration	35%	31%	16%	7%	10%

Source: Frontier Economics

ANNEX H REVIEW OF RECENT LITERATURE WHICH ESTIMATES FUTURE DEMAND FOR DATA

There are a number of previous studies that have forecast the broadband bandwidth requirements for households. Many studies use variants of the bottom up approach used in this report. We summarise a literature review of forecasts.

The analysis in this report uses application based approaches. We identify and summarise the key results of studies that have attempted to assess the demand for broadband speed and capability suing these two approaches.

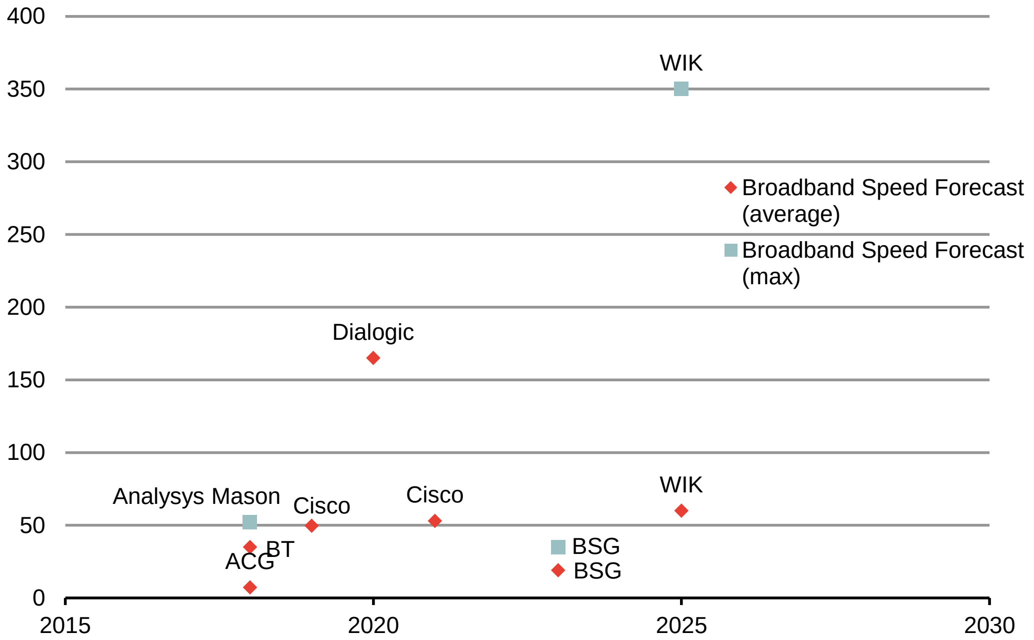
DIFFERENT APPROACHES TO FORECASTING

In forecasting demand there can be a number of metrics which can be relevant in different ways:

- **Total demand**. This estimates the total volume of data use. Total volume of data use has increased significantly in recent years as video has become more popular when accessed on dedicated video sites (YouTube or iPlayer) or via social network feeds or news outlets.
- **Peak demand**. This measures the peak data flow required by a household to meet demand at peak time. This considers a household’s combine usage at peak times. Peak usage usually occurs in the evening (while watching audio visual content) but may include usage from a number of different applications. Peak usage can be defined in different ways, but for example could be the maximum demand required on average over the highest use hour in an average month.
- **Median or top user**. Studies might focus on the median or average household demand, in which case there are many users whose demand is in excess of the median user. Alternatively the studies might consider the demand of the top 1% of users, in which case the demand would be in excess required of the remaining 99%.
- Some studies might focus on demand which is unconstrained by network capabilities, others might focus on actual use, whilst others still might focus on the actual capability of a household’s line (which may be significantly in excess of what is used).

Bottom-up application based approaches to assessing demand for broadband forecast how the use of broadband will grow and change over time on an application by application basis. Most reports focus on peak hours for bandwidth requirement, with the usual range being three to four hours over a month. Some reports look at the average bandwidth requirement over this period and others focus on just the peak requirement. Furthermore, several reports focus on just downstream bandwidth requirements, while others also look at upstream requirements. Overall, no report focuses on a time span of longer than fifteen years.

Figure 138 Forecast bandwidth demand, maximum and average (Mbps)



Source: ACG, Analysys Mason, BT, Cisco, Dialogic, Cisco, BSG, WIK

When making forecasts using the bottom-up approach a large number of assumptions regarding the development of each application, as well as their current usage are made.

Figure 139 Bottom-up application based approaches

Paper	Authors / publishers	Year	Country	Brief Summary	Forecasting methodology	Key Forecasts
Domestic demand for bandwidth	The Broadband Stakeholder Group	2013	UK	Forecasts of UK domestic demand for broadband for the period 2013-2023.	▪ A bottom-up analysis using current application peak hour bandwidth requirements to form a profile of household usage. ▪ Uses a probabilistic approach to model simultaneous use of different applications.	Median household demand will be 19Mbps in 2023, whereas the top 1% will require 35Mbps.
Can you ever have enough bandwidth?	BT	2014	UK	Forecasts of UK bandwidth requirements for broadband in 2025.	▪ A bottom-up analysis focusing on exemplar households and applications that will create future bandwidth demand. ▪ Uses current peak bandwidth requirements and usage patterns to make forecasts.	In 2025, 95 percent of the household will require less than 35Mbps.
International benchmark of superfast broadband.	Analysys Mason for BT	2013	UK	Mainly focuses on UK performance in superfast broadband relative to other countries but brief forecasts of UK broadband demand are made until 2018.	▪ A bottom–up analysis using a representative sample of household types. ▪ Focuses mainly on media services as the main driver of household bandwidth demand. ▪ The requirement for other services is set as 50% of the total bandwidth required for the concurrent media streams.	52Mbps will be sufficient to meet household demand in 2018.
Forecast of Residential Fixed Broadband and Subscription Video Requirements	ACG Research	2014	US	Forecasts growth in broadband bandwidth requirement for metro areas in the US.	▪ A bottom-up analysis based on projecting the average bandwidth requirements for individual applications in peak periods. ▪ Uses concurrency rates to calculate peak period metro area requirements.	Average household bandwidth requirements are estimated to grow at a five-year Compound Annual Growth Rate (CAGR) of 31 percent.

Paper	Authors / publishers	Year	Country	Brief Summary	Forecasting methodology	Key Forecasts
How the speed of the internet will develop between now and 2020?	Dialogic and TUE for NLkabel & Cable Europe	2014	Netherlands and other Western European Countries.	A study of how upload and download broadband bandwidth will change over the period 2014-2020.	▪ Aggregate traffic[297] is split into traffic per application which is then projected using growth factors based on the position of the application on the adoption curve and intensity growth. ▪ Bandwidth requirements are forecasted based on the assumption that bandwidth requirement grows pro–rata to traffic.	In 2020, the average user will require 165 Mbps downstream and 20 Mbps upstream.
Market potential for high-speed broadband connections in Germany in the year 2025	WIK for FTTH Council	2013	Germany	Forecasts the market potential in high-speed broadband connection in Germany until 2025.	▪ A bottom–up analysis using application bandwidth requirements and individual and SME usage profiles which are then aggregated. ▪ It is unclear how households are aggregated.	In 2025, downstream requirements will be 60-350 Mbps.
Bandwidth demand forecasting	Alcatel-Lucent	2014	UK	Forecasts of UK broadband demand until 2024.	▪ Monte Carlo[298] simulation techniques are used to model video traffic.	In 2018 75Mbps will be needed to support UDTV, HD, SD streams.
Nielsen's Law of Internet Bandwidth	Nielsen Norman Group	1998		A forecast of growth in high-end user's bandwidth demand.	▪ A fit on bandwidth data over the time period 1984 to 2014	A high-end user's connection speed grows by 50% per year

[297] Traffic refers to the total amount of data to be transferred in a given time period. It is usually measured as megabytes per day or month.

[298] Monte Carlo simulation models possible outcomes by using assumptions on probabilities of certain outcomes occurring. These probabilities are obtained based upon various assumptions. The use of Monte Carlo simulation in forecasting the demand for broadband controls for the large uncertainty surrounding the future demand for broadband, by producing a distribution of possible outcomes and the likelihood of that outcome occurring.

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