Economic Geography 2019

An analysis of the determinants of mobile and fixed coverage in the UK

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1. Overview

The 2018 Communications Market Report[1] showed that almost 9 in 10 UK adults are now online, with 64% saying it is an essential part of their life, for business, banking, shopping, entertainment, and socialising. People increasingly expect to be able to access the internet wherever they are, which requires investment by fixed and mobile operators.

A variety of factors will influence fixed and mobile operators to increase the reach and quality of their networks. This decision to upgrade a fixed and/or mobile network is essentially a commercial judgement for the network operator. They will likely assess the profitability of upgrading a network in an area by considering the potential demand for services as well as the costs of providing those services.

In this paper, we use statistical techniques to investigate the commercial drivers behind an operator's decision to upgrade its network. In particular, we consider the drivers behind Openreach's decision to commercially upgrade its cabinets to fibre-to-the-cabinet (FTTC), and the factors determining the level of 3G and 4G mobile coverage available to consumers. We then explore whether these commercial drivers determine regional differences in network coverage across the fixed and mobile landscape.

[1] Ofcom (2018) Communications Market Report

2. Introduction

Purpose of the report

All of us are increasingly reliant on the internet for business, banking, shopping, entertainment, and socialising. We increasingly expect to be able to access the internet wherever we are, and it is now more important than ever before for people and businesses to have access to good quality, reliable broadband and mobile connections.

Being able to access the internet wherever we are is heavily dependent on operators (fixed and mobile) continuing to invest in increasing the reach and quality of their networks. This decision to invest in fixed and mobile networks is essentially a commercial judgement. Network operators will likely assess the profitability of upgrading a network in an area by considering the potential demand for services as well as the costs of providing those services.

Given the importance of fixed and mobile connectivity to consumers, Ofcom has prioritised a range of work to improve the availability of communications services. This year's work is summarised in Ofcom's Annual Plan for 2019/20.[2] To inform and complement these work areas, we have conducted statistical analysis to investigate the local cost and demand factors that:

a) affect Openreach's decision to commercially upgrade its cabinets to fibre-to-the-cabinet (FTTC) connections; and

b) affect mobile network operators (henceforth MNOs) local entry decision and therefore the level of 3G and 4G mobile coverage provided to consumers in different areas.

In addition, we assess the extent to which regional differences in commercial FTTC rollout and (3G and 4G) mobile coverage can be explained by these factors.

A summary of our main findings

The main findings of our analysis are summarised below.

The effect of local cost and demand factors on coverage

Fixed and mobile coverage share common commercial drivers. Population density has a significant impact on both the probability of commercial upgrades to FTTC and the provision of 3G and 4G coverage. Further, the probability of a commercial FTTC upgrade and good 3G and 4G coverage is higher in urban and more affluent areas.

There are also important determinants specific to fixed and mobile coverage:

[2] Ofcom's 2019/20 Annual Plan.

Determinants of fixed coverage

A greater average distance between the street cabinet and the premises it serves leads to a lower probability of a commercial FTTC upgrade. This is because broadband speeds deteriorate with distance over copper lines negatively affecting demand for FTTC.

In contrast, a greater distance between the exchange and the street cabinet increases the probability of commercial FTTC rollout. This is because cabinets that are further away from the exchange will receive a greater speed uplift from a FTTC upgrade, as they would have suffered from a larger degree of attenuation prior to the upgrade. This could therefore boost demand for the technology.

Higher ADSL download speeds in the premises' area lead to a lower probability of a commercial FTTC upgrade because where premises experience higher standard broadband speeds, FTTC may not offer a significant speed uplift for consumers.

Determinants of mobile coverage

A challenging terrain and a large backhaul distance have a negative impact on the probability of 3G and 4G coverage because of the increased costs of increasing the reach and quality of their networks.

Implications for regional variations in coverage

Across the UK's nations and regions there are significant variations in the level of commercially provided fixed and mobile coverage. We show that most of this regional variation can be explained by the demand and cost factors outlined in our analysis.

Yet there are certain regions where commercial coverage is lower than we would expect given the underlying level of local cost and demand factors:

- There appear to be unexplained factors (not captured by our local cost and demand factors) in Scotland, the South West, and Wales that negatively affect both Openreach's decision to commercially upgrade cabinets to FTTC and the MNOs decision to provide full 4G coverage in these regions.
- There also appear to be unexplained factors that negatively affect the MNOs decision to provide 3G coverage in Scotland.

For fixed coverage, the potential shortfall in commercially provided FTTC coverage has largely been filled by public funding. A combination of commercial and public funding results in a good level of FTTC coverage across the UK – on average 95% of premises served by Openreach are connected to either FTTC or FTTP cabinets.

For mobile coverage, the overall level of commercially provided (3G and 4G) mobile coverage across the UK is good. Though we hope that our analysis will stimulate further dialogue in areas where coverage is slightly lower than expected to explore possible solutions.

The structure of this report

The report is structured as follows:

- Section 3 sets out what we mean by fixed and mobile coverage and the measures of coverage that we use in this study;
- Section 4 discusses the demand and cost factors likely to affect the level of fixed and mobile coverage that we include in our analysis;
- Section 5 describes the econometric methodology that we employ to analyse the impact of each of the cost and demand factors (outlined in Section 3) on coverage;
- Section 6 presents the results from applying the econometric methodology (outlined in Section 5) in terms of the impact of each cost and demand factor on the probability of fixed and mobile coverage;
- Section 7 discusses whether these cost and demand factors explain the regional variations in fixed and mobile coverage that we observe in the UK; and
- Section 8 sets out the conclusions we draw from our study.

3. Measures of coverage in this study

In this section, we explain what we mean by fixed and mobile coverage and set out the measures of coverage that we use in this study. We then present data to show how levels of fixed and mobile coverage vary across the UK's nations and regions.

The measure of fixed coverage

In this report, we study fixed coverage by considering whether Openreach has upgraded its street cabinets to fibre-to-the-cabinet (FTTC). We are interested in this technological decision because it determines the type and quality of broadband that users receive.

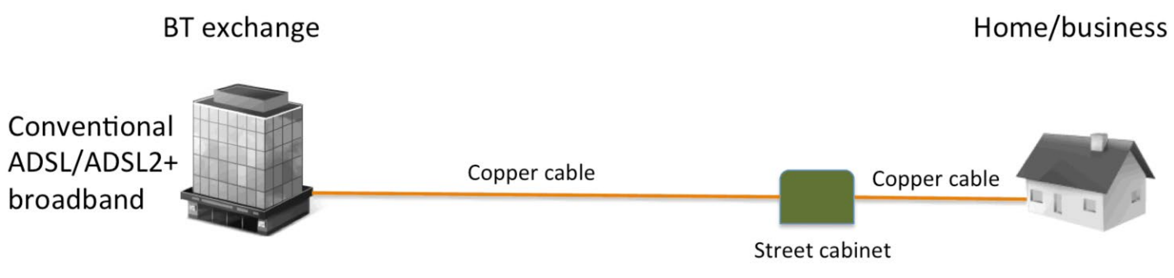
Our study focuses on Openreach since it has the most extensive UK fixed network and it has not been possible to perform a joint analysis of different operators' investment decisions. This is because other operators' network configurations differ from Openreach, which means that we cannot map their broadband investment decisions with Openreach's decision to upgrade cabinets – a necessary step for a joint empirical analysis.

Furthermore, in this study we focus on FTTC (which we describe in more detail below) rather than on investment in full-fibre networks. This is because full-fibre broadband networks are still in the early stages of deployment and, consequently, there is not sufficient data available to analyse this type of deployment.

Standard broadband

Standard broadband, which has download speeds of up to 30 Mbit/s, is provided using a technology called ADSL or (more modern) ADSL+ technologies.[3] Importantly, as we illustrate below in Figure 1, standard broadband is carried along copper cables from (in most cases) the BT/Openreach exchange to a local (green) street cabinet and then to homes/businesses.

Figure 1: The provision of standard broadband

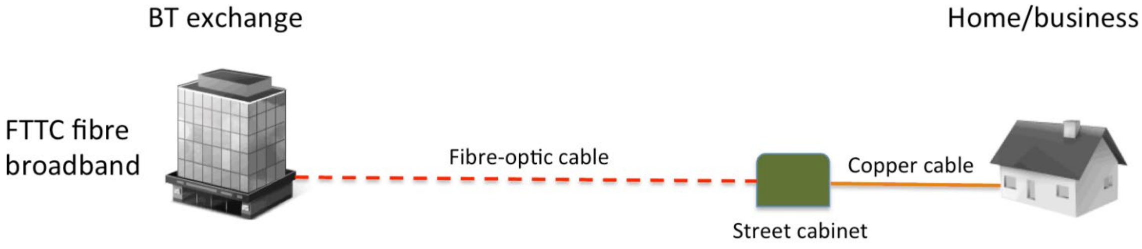


[3] ADSL stands for asymmetric digital subscriber line. It is a data communications technology that enables faster data transmission over copper telephone lines than a conventional voiceband modem can provide. ADSL+ technologies are enhancements to the original ADSL technology and can provide higher speeds.

Superfast broadband

In many parts of the UK, Openreach has overlaid fibre between its exchange and the street cabinet, as we illustrate below in Figure 2.[4] This is referred to as FTTC[5] and facilitates the delivery of superfast broadband, which offers download speeds above 30 Mbit/s.

Figure 2: The provision of superfast broadband



Our study of fixed coverage focuses on Openreach's decision to roll out FTTC to provide this type of superfast broadband. To empirically study Openreach's decision to upgrade its cabinets to FTTC, we have collected data on 100,358 Openreach cabinets across the UK from the September 2018 Connected Nations report.[6]

The focus of our analysis is the decision to upgrade cabinets from copper cable to FTTC. Therefore, we have dropped 7,289 FTTP cabinets from our sample, leaving us with a sample of 93,069 Openreach cabinets. According to our data, 87% of the cabinets in our sample have been upgraded to FTTC. 53% of these have been upgraded to FTTC commercially, while the remaining 34% were upgraded using public funding. We want to understand the drivers behind the 53% of cabinets that were commercially upgraded to FTTC.

The measure of mobile coverage

Alongside our analysis of fixed coverage, we have conducted a study into the determinants of mobile coverage levels. We assess the level of mobile coverage in a given area of the UK by counting the number of operators with 'good coverage'. An operator is considered to provide good coverage if its reported mobile phone signal strength is equal to or exceeds a defined signal strength threshold (set

[4] We note that in some parts of the country Openreach has bypassed FTTC and has upgraded directly to full fibre (i.e. fibre to the premise or FTTP) - see Figure 4 below.

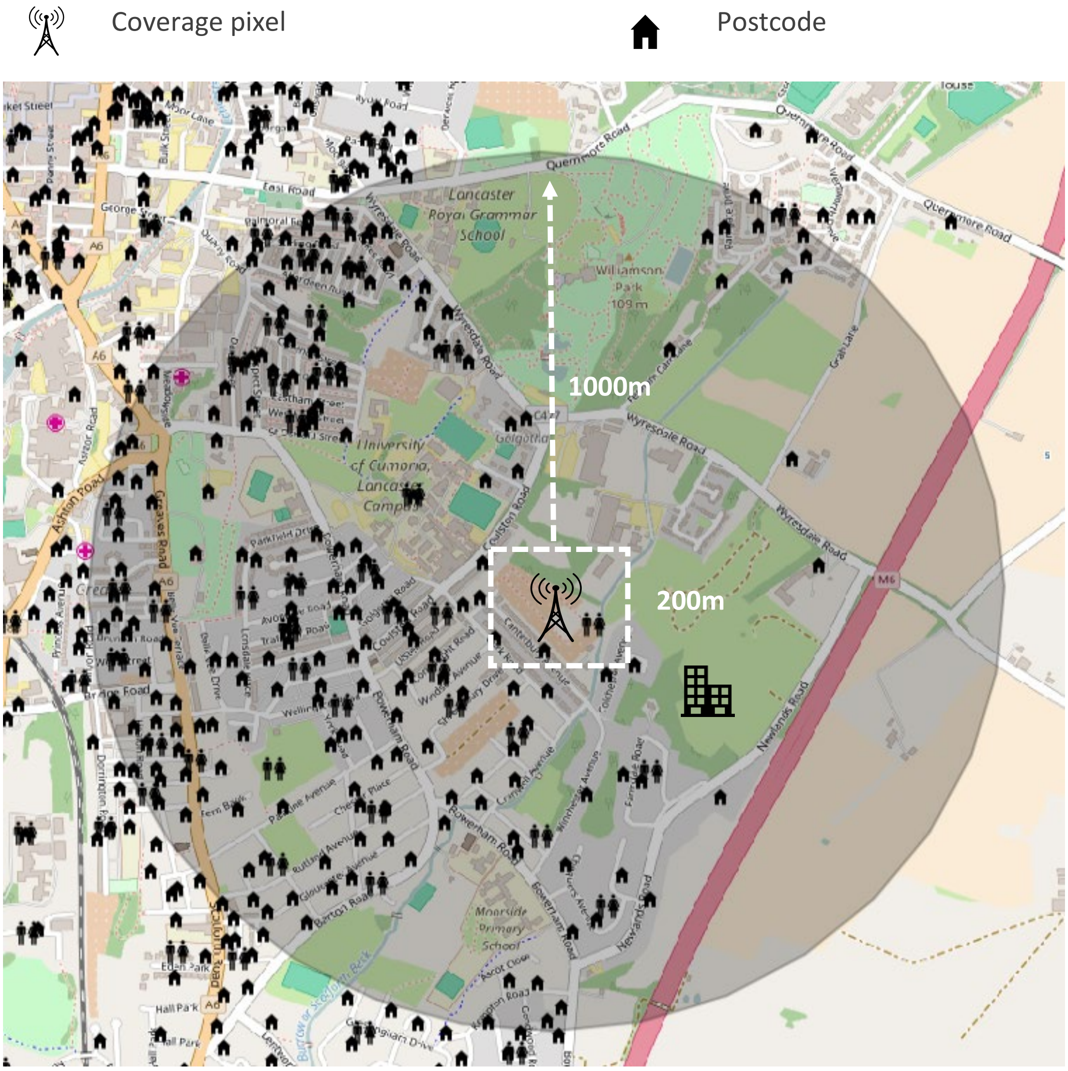
[5] Fibre-to-the-cabinet or FTTC refers to the broadband network architecture that involves running optical fibre cables from the telephone exchange to the street cabinet. The street cabinet then connects to premises (which can be households or businesses) via copper cables to provide broadband. Fibre has the advantage of being immune to interference and does not suffer the signal attenuation experienced by copper. Therefore, replacing a portion of the network architecture with fibre should lead to faster broadband speeds for the end customer.

[6] Ofcom (2018), Connected Nations

at -100dBm for 3G and -105dBm for 4G).[7] If all four operators in an area provide good coverage then we say that the area has 'full coverage'.

In measuring mobile coverage, we divided the entire UK land mass into 200m by 200m areas. We refer to each of these areas as a 'coverage pixel'. To illustrate our analysis, consider Figure 3 below, which shows a coverage pixel (a 200m by 200m area) and the associated coverage area (the full shaded area) in a medium sized town.

Figure 3: Coverage area with an illustrative example of a backhaul location



We collected data from MNOs on predicted outdoor 3G and 4G coverage for September 2018 and counted the number of operators meeting our standard for good coverage in each coverage pixel. In total, we collected coverage data for just over 2 million pixels across the UK to construct a dataset of mobile phone signal strength across the UK.

[7] These signal thresholds are consistent with those used in the Connected Nations Report, see Ofcom (2018) Connected Nations Methodology

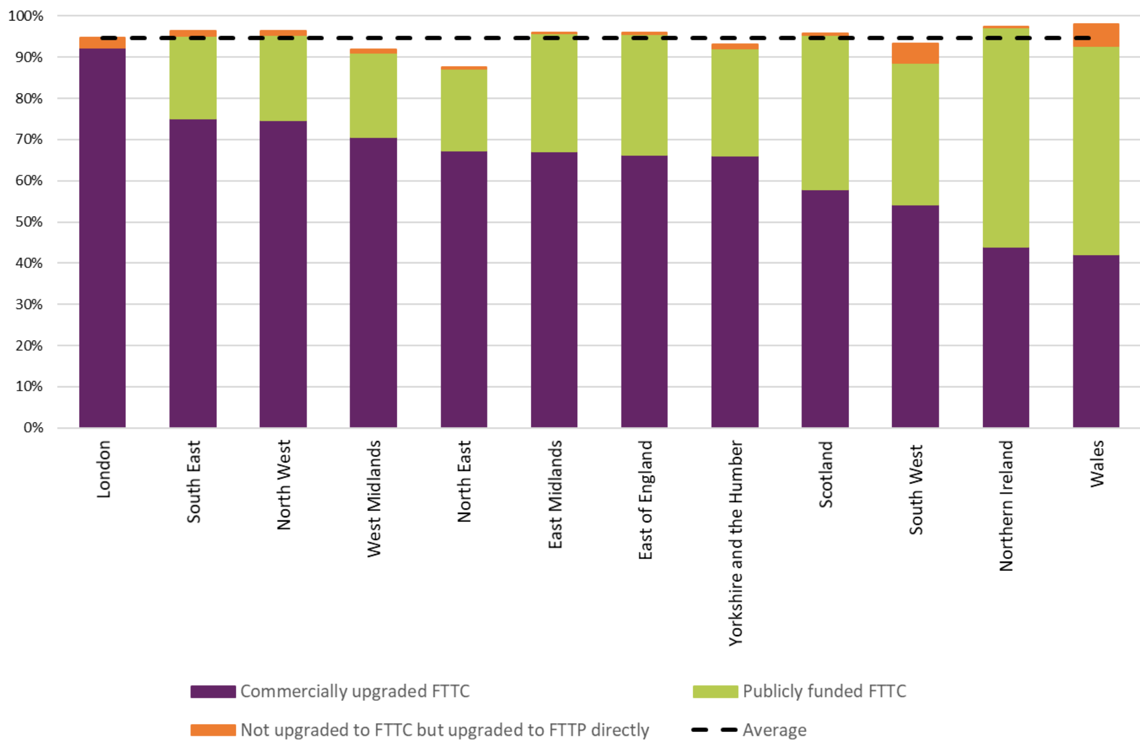
Variation in coverage across the UK

In the following sub-section, we discuss the average level of fixed and mobile coverage received in each of the UK's nations and regions.

Openreach fixed coverage in the UK

Figure 4 below shows the proportion of the premises served by Openreach that receive coverage from cabinets that have been upgraded to FTTC or FTTP in each region. On average, 95% of the premises served by Openreach are connected to a cabinet that has been upgraded to either FTTC or FTTP, as represented by the dashed line.

Figure 4: Proportion of premises served by Openreach via FTTC or FTTP across the UK nations and regions

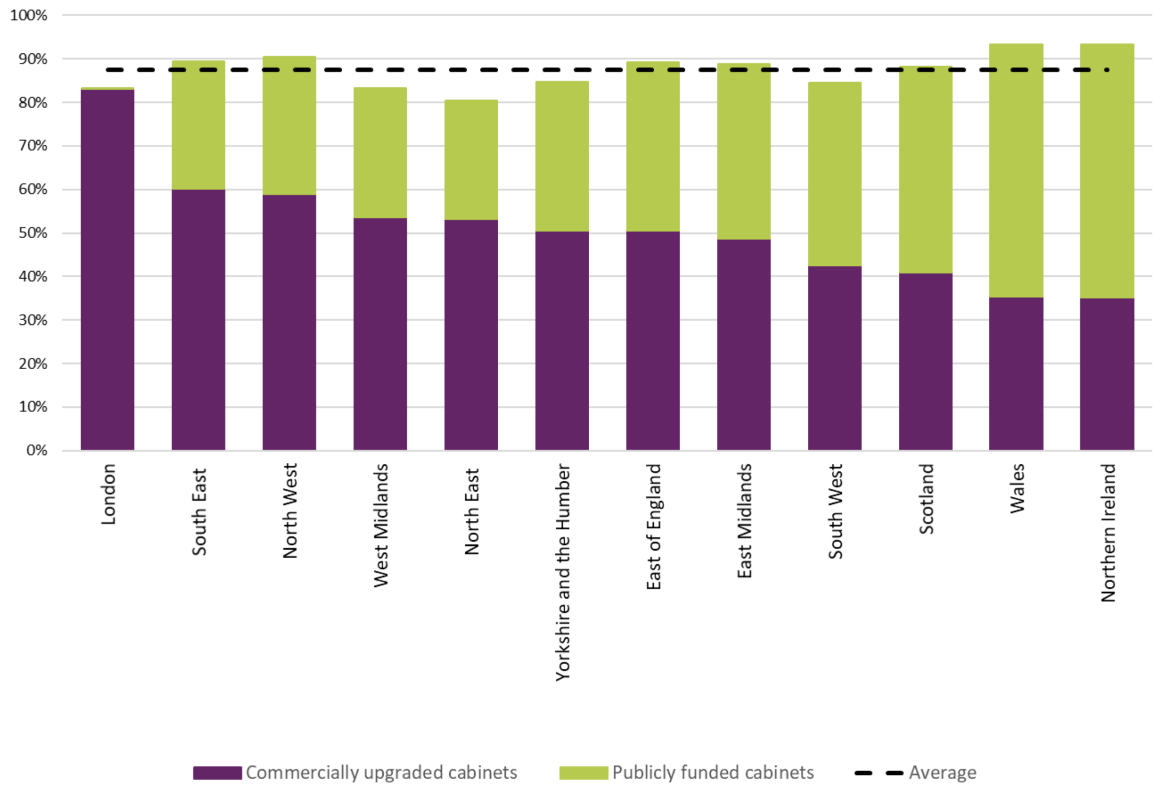


From the chart above we observe that there is some variation in the level of fixed coverage available to the premises served by Openreach in each of the UK's nations and regions. In certain regions, such as the North East, the proportion of premises connected to an Openreach's cabinet via FTTC or FTTP is slightly below the 95% Openreach's national average. This may not necessarily mean that the North East is "under-served" because this variation may just reflect that there are other providers serving premises in these regions. It is interesting to note that, whilst there is some degree of variation in the total level of Openreach fixed coverage between regions, there is far more variation in whether fixed coverage has been publicly or commercially funded by Openreach.

As mentioned above, the specific measure of fixed coverage we consider in this study is whether Openreach has upgraded its street cabinets to FTTC. We focus on the street cabinet as Openreach makes its investment decision on whether or not to upgrade a cabinet, which then determines the quality of broadband received by premises.

In Figure 5 below we show the proportion of cabinets upgraded to FTTC in each region. As our empirical analysis solely focuses on upgrades to FTTC we have dropped all FTTP cabinets from our sample. Therefore, the graph below only shows FTTC upgrades for all the cabinets in our sample. As seen from the graph, 87% of all Openreach's cabinets have been upgraded to FTTC.[8]

Figure 5: Proportion of cabinets commercially and publicly upgraded to FTTC by Openreach across the UK nations and regions



As in Figure 4, there is some variation in the level of cabinets that have been commercially and publicly upgraded in each of the UK's nations and region. In particular, we observe that most cabinets in London have been commercially upgraded to FTTC. While in other areas, such as Scotland, Northern Ireland and Wales, there has been a substantially lower proportion of commercial upgrades to FTTC.

The focus of our study lies in the commercial drivers behind the decision of upgrading a cabinet to FTTC. Therefore, in the remainder of the report we focus on the cabinets that Openreach has commercially upgraded.

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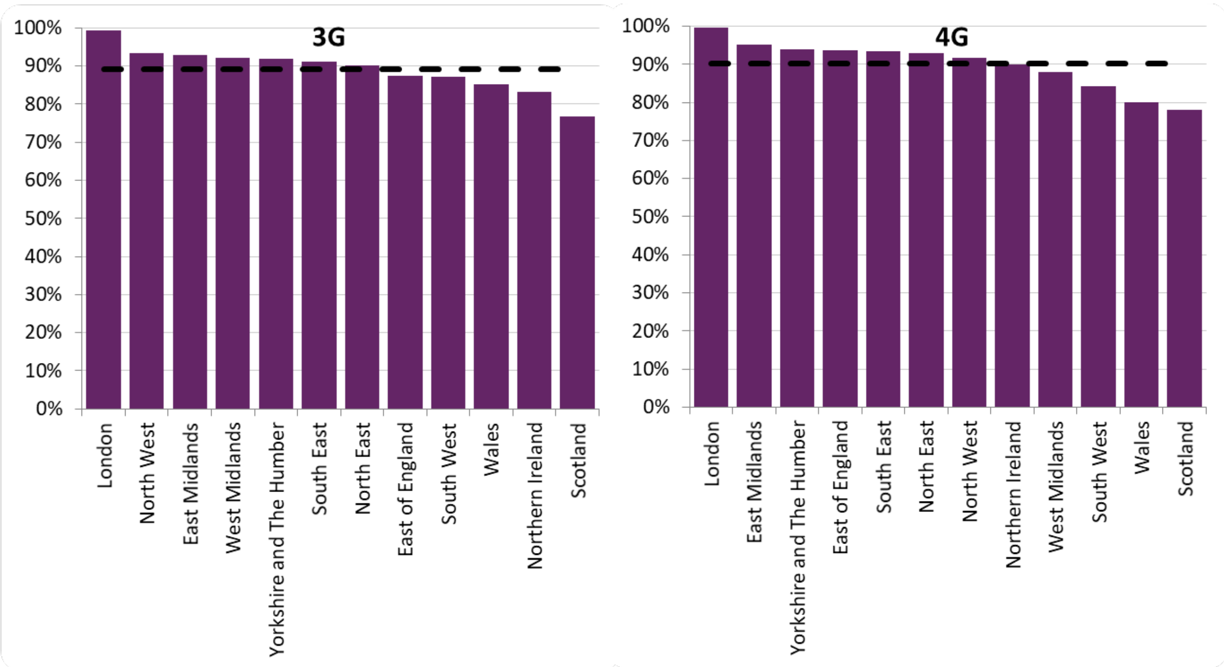
[8] This graph has been obtained by mapping the data from Figure 4 to a cabinet level and excluding FTTP cabinets. We expect the average proportion of FTTC upgrades at the cabinet level to be lower than the average proportion of premises receiving FTTC as each cabinet can serve more than one premise.

Mobile coverage across the UK

Figure 6 below shows the regional variation in mobile coverage for 3G and 4G technologies. This is based on the measure of mobile coverage described in the previous section, that is, the number of operators with good coverage. According to our data, the average UK region receives 90% full 3G and 4G coverage (i.e. a good coverage level from all four MNOs).

Figure 6: Mobile coverage by all four MNOs across the UK nations and regions



As with fixed coverage, we observe a degree of regional variation in the level of mobile coverage. We can see that there are generally more areas in London that have full 3G than the UK average, while the opposite is true for areas in Scotland, Northern Ireland and Wales. A similar pattern arises for 4G as a greater proportion of areas in London have full 4G than the UK average, while the opposite is true for areas in Scotland, Wales and the South West.

Based on this simple graphical analysis, it may appear that certain areas of the UK are 'under-served' in terms of commercially provided fixed coverage by Openreach and commercially funded mobile coverage. In the rest of the study we aim to understand what underlies this variation in commercial coverage between regions. To do so, we look at a set of factors that are likely to drive a network providers' decision to invest in mobile and fixed coverage – we describe these factors in the next section.

4. Drivers of coverage included in this study

The decision to invest in fixed and mobile coverage in an area is essentially a commercial judgment. Network operators will likely assess the profitability of upgrading a network in an area by considering the potential demand for services as well as the costs of providing those services.

In each local area there are a variety of potential factors that influence this commercial judgement. The factors that we consider in this study can be grouped into the following broad categories:

a) Local demand factors – variables that capture the likely level of demand for fixed and mobile services in an area. For instance, the population density of a local area, as well as its composition in terms of age and affluence;

b) Local cost factors – variables that determine the cost of providing fixed and mobile services in a given area. For fixed coverage, this includes variables such as the distance between the cabinet and the exchange which needs to be overlaid with fibre. Variables such as the characteristics of the local terrain and the proximity of cell sites to mobile infrastructure influence the costs of providing 3G and 4G mobile services; and

c) Location-specific indicators – these are variables used to capture unobserved variations in demand and costs specific to a particular region or urban location. For example, an indicator for Scotland will allow us to capture effects on coverage not picked up by our other variables, such as population or topography, which are specific to Scotland.

Below, we outline the set of demand and cost factors that we use in this analysis. These variables should capture the considerations of Openreach to commercially roll-out FTTC and that an MNO makes when considering whether to provide mobile coverage in an area. We begin by describing the factors common to both fixed and mobile coverage that influence this commercial judgement, and then outline the factors specific to fixed or mobile coverage. For a more detailed description of how we collected data on our variables of interest and associated summary statistics – see Annex 1.

Factors common to both fixed and mobile coverage

Affluence

One potential determinant of coverage is the affluence of an area. In both the fixed and mobile studies, we record the approximate percentage of the population in a coverage area that reside within a household classified in socioeconomic groups A, B or C1.[9] We expect demand for fixed and mobile services to be higher in more affluent areas, which means they should be more profitable for operators to serve. Hence, there should be a positive relationship between affluence and coverage levels.

[9] These socioeconomic ratings A, B and C1 are typically allocated to occupations that can be described as more affluent. For example, C1 are occupations that can be described as "Supervisory, clerical and junior managerial, administrative and professional". See Annex 1 for more detail.

Demography

The level of fixed and mobile coverage is likely to be affected by the demography of an area. To capture this potential determinant, we measure the approximate percentage of the population aged 25 or under in each area. We would expect a larger working age population to increase the probability of investment in fixed and mobile coverage as there is likely to be higher demand and ability to pay for services. Therefore, there should be a negative relationship between the proportion of the population aged 25 or under and the level of coverage.

Population

A key factor determining the profitability of providing fixed and mobile services is the population density of an area. An area with a larger population is likely to have a higher demand for fixed and mobile services than one with a lower population density. In both studies we record the population of areas – see Annex 1 for more detail. In our study of fixed coverage, we measure the number of premises served by every cabinet in our data. For mobile coverage, we measure the population within a coverage area. We expect to see a positive relationship between the population of an area and its coverage levels.

Rurality

The level of coverage that operators provide in an area is likely to be influenced by whether the area is rural or urban. In our studies we have considered the impact of rurality by including a variable that identifies the coverage/cabinet area as either urban or rural. We would expect the cost of providing coverage in rural areas to be higher for both fixed and mobile operators, and so all else equal, we would expect coverage to be lower in rural areas.

Factors specific to fixed coverage

Average ADSL download speeds

As well as factors common to both fixed and mobile coverage, there are also factors which are likely to be specific determinants of fixed coverage. One of these factors is the average standard broadband (ADSL) download speed received in an area. We measure this using the predicted average standard broadband (ADSL) download speed in the area reached by a cabinet in Kbit/s. We would expect a higher demand for FTTC in areas where premises experience lower standard broadband speeds, because FTTC would offer a greater speed uplift for consumers in such areas.

Competition

The decision to upgrade to FTTC may also be shaped by the level of competition from other fixed operators in a given area. Therefore, in our study we factor in the level of competition faced by Openreach from Virgin Media in a given area. However, we recognise that Virgin Media is likely to decide whether they want to upgrade their cabinets based on the same demand and cost factors as Openreach, and so the same unobserved factors driving upgrade decisions would be present for both operators. This means that not much will be able to be inferred from our specific results with respect to this variable.

Distance between the cabinet and the exchange

With FTTC technology, the connection between the exchange and cabinet is upgraded to fibre – as can be seen in Figure 2 above. The relationship between this distance and the likelihood of an FTTC upgrade is ambiguous because there are two countervailing effects. On the one hand, cabinets that are further away from the exchange will receive a greater speed uplift from a FTTC upgrade, as they would have suffered from a larger degree of attenuation prior to the upgrade. This could therefore boost demand for the technology. On the other hand, a greater distance between the exchange and the cabinet increases the costs of upgrading a cabinet to FTTC since it is necessary to replace a longer length of copper cable with fibre. The exact impact on fixed coverage will therefore depend on the relative size of these two effects.

Distance between the cabinet and premises

Another factor we consider is the average distance between the cabinet and premises. With FTTC technology, the connection between the cabinet and premises is still copper – see Figure 2 above. Since broadband speeds deteriorate with distance over copper lines, premises which are closer to the cabinet should see a greater broadband speed uplift with FTTC. This could therefore boost demand for the technology, meaning that cabinets with a shorter average distance to their premises should have higher chances of being commercially upgraded to FTTC.

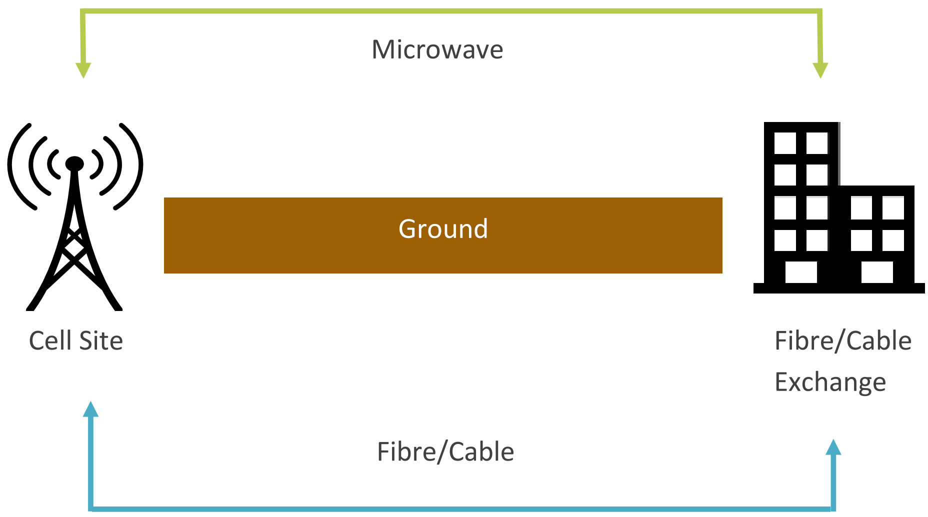
Factors specific to mobile coverage

Distance to mobile backhaul

In using mobile services, a user's mobile handset receives signals from a cell site, and in turn, each cell site receives and sends data to the core network. The distance between the cell site and the core network is known as the backhaul distance.

MNOs can make this backhaul connection in various ways, as we illustrate in Figure 7 below. The connection can be via fibre or cable, which directly links an MNO's cell site to its backhaul network at the relevant fibre or cable exchange. Alternatively, the connection can be made wirelessly using fixed wireless links.

Figure 7: Example of fibre/cable (blue) and microwave (green) connection of a cell site to its core network[10]



The backhaul distance and the type of connection used by MNOs affects the cost of providing mobile services. To account for this, we measure the distance between each area and the nearest backhaul location under each of the potential options outlined above. We expect the probability of full coverage to be lower in an area that is further away from the backhaul network, because MNOs are likely to face a higher cost of rolling out mobile infrastructure to areas further away from the core network.

Topography of coverage area

The topography of a coverage area is also likely to affect the level of mobile coverage. In this study, we capture two elements of topography – the median height above sea level and the standard deviation of the height. It is likely to be more expensive to provide mobile coverage in areas that are higher above sea level and have a more variable terrain. Therefore, we would expect mobile coverage to be lower in such areas.

Summary of the drivers of coverage

Table 1 summarises all the local cost and demand factors we are considering in each study and an indication of their likely effect on the level of (fixed and mobile) coverage:

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[10] Note Figure 7 shows a very simple example of how a cell site is connected to its core network. Cell sites can be connected to the core network in many ways. For example, multiple cell sites could be connected to a central cell site, which is connected to the exchange building (similar to a hub and spoke model). There are likely to be different cost implications from using different types of connections to the core network. We have not modelled connections to the core network in this level of granularity as we believe that our general hypothesis holds on average. Further work would be needed to understand the impact of more complex connection types.

Table 1: Summary of variables used in our studies and their expected impact on coverage

	Mobile EG variables	Fixed EG variables	Expected impact on coverage	
			Mobile	Fixed
Factors common to mobile and fixed coverage				
Affluence	Percent in socioeconomic groups A,B,C1	Percent in socioeconomic groups A,B,C1	Positive	Positive
Demography	Percent under 25	Percent under 25	Negative	Negative
	Percent over 60	N/A	Negative	/
Population	Population density	Number of premises	Positive	Positive
Rurality	Rurality	Rurality	Negative	Negative
Factors specific to mobile or fixed coverage				
	N/A	ADSL download speed	/	Negative
	N/A	Distance between the cabinet and the exchange	/	May be positive or negative
	N/A	Distance between premise and cabinet	/	Negative
	N/A	Competition from Virgin Media	/	May be positive or negative
	Distance to backhaul	N/A	Negative	/
	Median height of area	N/A	Negative	/
	Standard deviation of area height	N/A	Negative	/

5. Econometric methodology

A central objective of this study is to quantify the effect that each cost, demand, and location-specific factor has on the likelihood that Openreach will commercially upgrade a cabinet to FTTC, and on the probability of good 3G and 4G coverage in a certain area. In this section we discuss why and how we use econometric analysis to achieve this aim.

To study the relationship between the factors outlined in the previous section and the level of coverage (discussed in Section 3), we could just plot a graph of coverage against each factor. For instance, we could plot a graph of coverage against affluence to get a sense of the effect of affluence on coverage. The problem with this type of simple graphical analysis is that multiple variables simultaneously determine the decision of fixed and mobile operators to provide coverage. Graphical analysis does not allow us to distinguish the effect of one factor from others and so will not tell us the true effect of any single variable.

For example, both Openreach and an MNO's investment decision are likely to be simultaneously driven by both the affluence and rurality of an area (in addition to many other drivers). As a result, if we were to solely base our understanding of Openreach's decision to commercially upgrade or an MNO's decision to invest in coverage on a simple plot of our measure of (fixed or mobile) coverage against affluence, this may lead to one of two errors:

i) If affluent towns tend also to be more rural, a chart of affluence against fixed or mobile coverage may appear to show that there is a very weak relationship between affluence and the decision to upgrade. This is because the positive effect of affluence could be offset by the impact of higher costs of upgrading networks in rural areas;

ii) Conversely, if less affluent towns tend also to be more urban, then we may conclude from a simple chart that low affluence in an area has a strong positive effect on the decision to upgrade, when in fact we are conflating the effect of affluence and rurality.

Given the risk of these errors, we use regression analysis to improve our understanding of the individual factors influencing the level of fixed and mobile coverage across the UK. Specifically, we undertook two sets of multiple regression analysis – one for fixed and the other for mobile. Regression analysis allows us to analyse the impact of each of our local cost and demand factors on coverage while holding all other factors constant.

The statistical techniques used in both sets of regression analysis are similar. In both cases we are modelling a decision made by an operator. For fixed coverage, we are considering Openreach's decision on whether to commercially upgrade a cabinet to FTTC. While for mobile coverage, we adopt a relatively simple entry model where we treat each coverage pixel as an area that a potential MNO can decide to enter and invest in.

We use a regression technique that links the outcome of these decisions – Openreach's decision to commercially upgrade a cabinet and the MNOs decisions to enter and invest in good mobile coverage in a pixel – to the cost and demand factors outlined in Section 4. In addition, in our regressions we include regional dummies to control for region-specific factors not captured by the cost and demand variables that may influence operators’ decision to expand coverage.

We conduct our regression analysis with two central aims:

i) To assess whether and to what extent the possible cost, demand, and location-specific factors influence the likelihood of Openreach commercially upgrading a cabinet to FTTC, and the likelihood of good 3G and 4G mobile coverage; and

ii) To assess the extent to which regional differences in commercial FTTC rollout and mobile coverage (3G and 4G) can be explained by these factors.

6. The effect of local cost and demand factors on coverage

This section presents the impact of each cost and demand factor, discussed in Section 4, on the probability of Openreach commercially upgrading a cabinet to FTTC and on the probability of full 3G and 4G coverage in an area.

Applying the regression techniques outlined in Section 5, we obtain a set of regression results (see Annex 2 for the full regression tables). These regression results show the direction and relative magnitude of each factor on coverage, but do not tell us the exact impact a factor has on the probability of Openreach commercially upgrading a cabinet to FTTC or the likelihood of good 3G and 4G coverage.

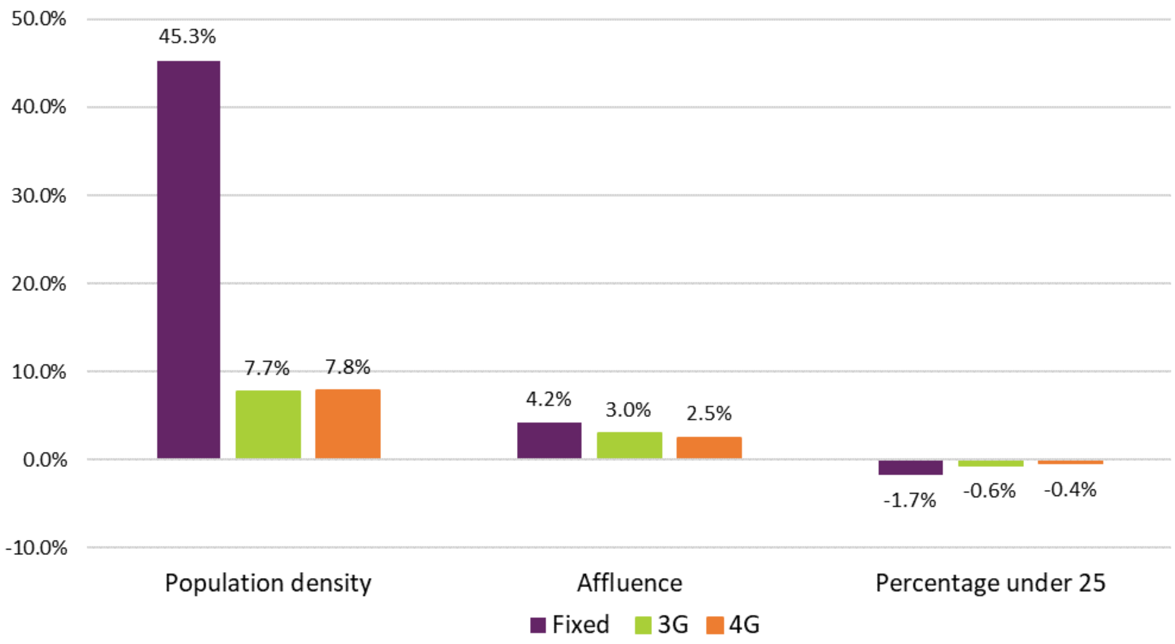
To measure the impact of each factor on the probability that a cabinet is commercially upgraded or on the probability of good 3G and 4G coverage, we calculate the marginal effects for each variable. Depending on whether the variable is binary or continuous, the marginal effect tells us how the probability of a cabinet being commercially upgraded or receiving good 3G/4G coverage changes if a single (cost, demand, location-specific) factor increases from zero to one (for binary factors) or from the 25th percentile to the 75th percentile for continuous factors.

Below, we first present the marginal effects for variables that are common to both of our studies. We then move on to discuss the marginal effects of factors specific to each study. Tables containing the full set of marginal effects can be found in Annex 3.

The impact of factors common to both fixed and mobile coverage

Figure 8 below illustrates the marginal effects for factors common to both studies. Each bar of the graph tells us the change in probability of Openreach commercially upgrading a cabinet to FTTC or the change in probability of good coverage when we move from the 25th percentile value of a factor to the 75th percentile value of a factor.

Figure 8: Marginal effects for the common commercial drivers



As we see from the graph, a large proportion of the variation in the probability of both fixed and mobile coverage is due to population density. For fixed coverage, an area at the 75th percentile for the number of premises has a 45.3 percentage points higher probability of being commercially upgraded compared to an area at the 25th percentile.[11] For mobile coverage, an area at the 75th percentile for population density has a 7.7 and 7.8 percentage points higher probability of receiving full 3G and 4G coverage than a coverage area at the 25th percentile.

The composition of the local area also has an impact on both mobile and fixed coverage. For both, the more affluent an area is, the more likely it is to receive superfast broadband via commercially funded FTTC, as well as good 3G and 4G coverage. Further, all else equal, the higher the proportion of people aged 25 or under, the less likely an area is to receive superfast broadband via commercially funded FTTC upgrades and receive good 3G and 4G coverage from all MNOs.

In addition to the continuous variables above, the categorical variable of rurality is also a key determinant of both fixed and mobile coverage. In both studies, we find that the more rural an area is, the less likely it is to receive good mobile coverage or superfast broadband through a commercial FTTC upgrade. Cabinets in rural areas have a 31% lower probability of being commercially upgraded compared to those in urban areas. Similarly, a rural area has a 7% lower probability of having full mobile coverage for 3G and a 4% lower probability of full mobile coverage for 4G. This reflects the higher costs of providing coverage to rural areas.

[11] We recognise that the magnitude of this factor is partially explained by the fact that the number of premises served by a cabinet varies a lot in our sample.

The impact of factors specific to fixed coverage

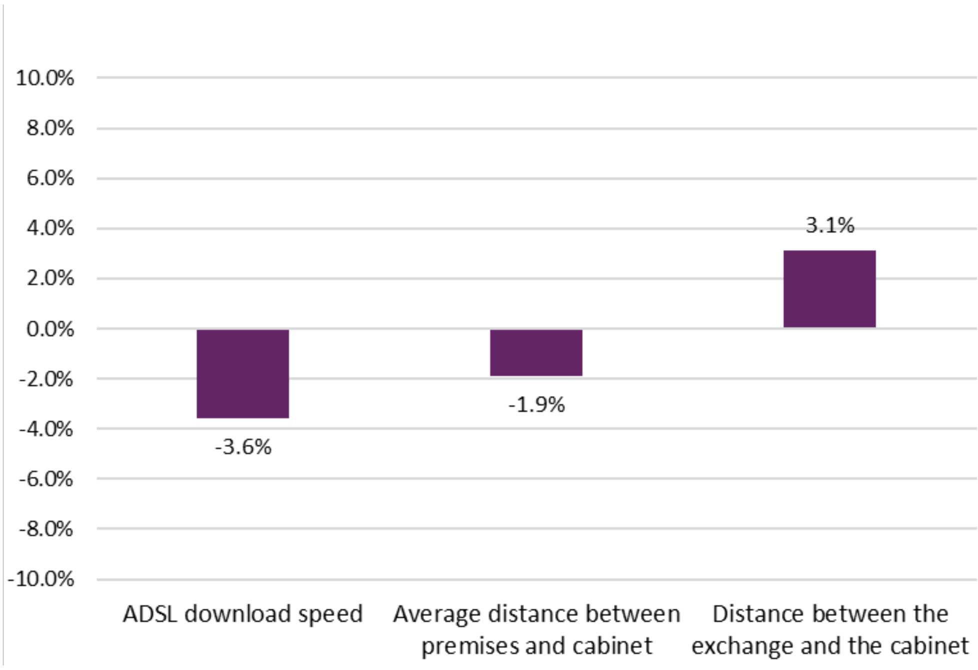
In addition to the above, we find that the following factors also have an impact on fixed coverage, as seen in Figure 9 below:

- Areas with higher average ADSL (standard broadband) download speeds have a lower chance of being commercially upgraded to FTTC. This is because the speed uplift following an upgrade is unlikely to generate substantial increases in demand for FTTC services.

- Areas with higher average distances between the premises and the cabinet have a lower chance of being commercially upgraded to FTTC because broadband speeds deteriorate with distance over copper lines.

- In addition, areas with longer distances between the exchange and the cabinet have a greater probability of being commercially upgraded to FTTC. This is likely due to the increase in demand caused by the greater speed uplift from the upgrade.

Figure 9: Marginal effects for the factors specific to fixed coverage



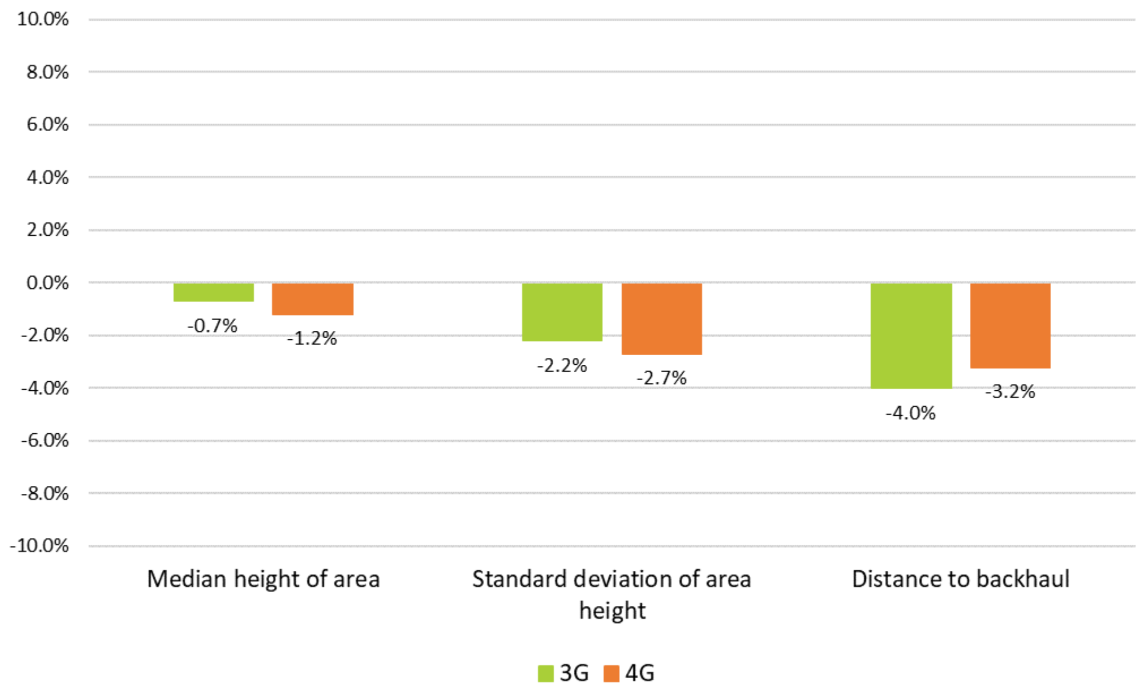
The results tables, accompanied by a more detailed discussion of these marginal effects can be found in Annex 3.1.

The impact of factors specific to mobile coverage

As seen by Figure 10 below, we also find that the following have an impact on mobile coverage:

- Local topography can affect the probability of good coverage. All else equal, the probability of receiving full 3G and 4G coverage is higher in a low-lying area than an area that is high above sea level.
- Additionally, we find that the probability of receiving full coverage between an area with flat terrain and more uneven terrain is also higher for both technologies.
- Distance to the backhaul network can further influence the probability of having full mobile coverage. All else equal, the closer an area is to the backhaul network, the more likely it is to receive full coverage for both technologies.[12]

Figure 10: Marginal effects for the factors specific to mobile coverage



The results tables, accompanied by a more detailed discussion of these marginal effects, can be found in Annex A3.2.

[12] We would expect the difference in the probability of full coverage between the 25th and 75th percentile to be larger in magnitude for 4G than for 3G for each factor. This is because 3G is a more mature technology and, therefore, more likely to serve the 25th and 75th percentiles evenly. However, we do not observe this outcome for affluence or distance to backhaul in 2018. A possible reason is that MNOs may be choosing to upgrade masts to 4G in areas less well served by 3G to improve general access to mobile data. MNOs may also be rolling out additional 4G masts to new locations which may mean that 4G coverage is better at serving the 25th and 75th percentiles than 3G. Further work would be required to explore the reasons for this effect.

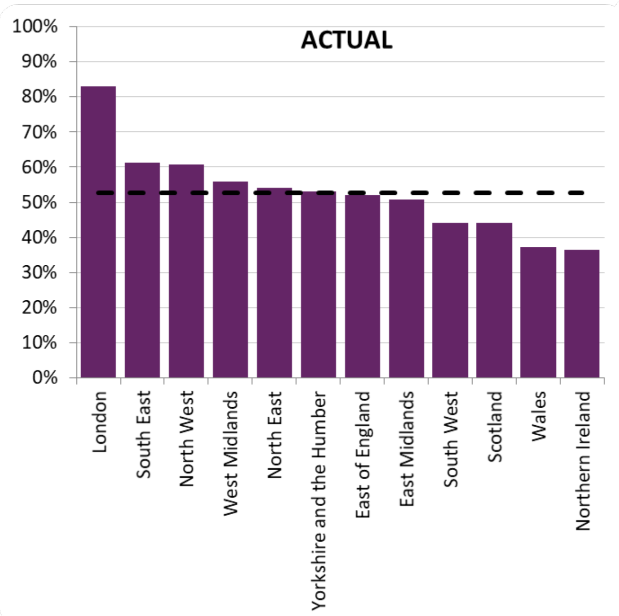
7. Implications for regional variations in coverage

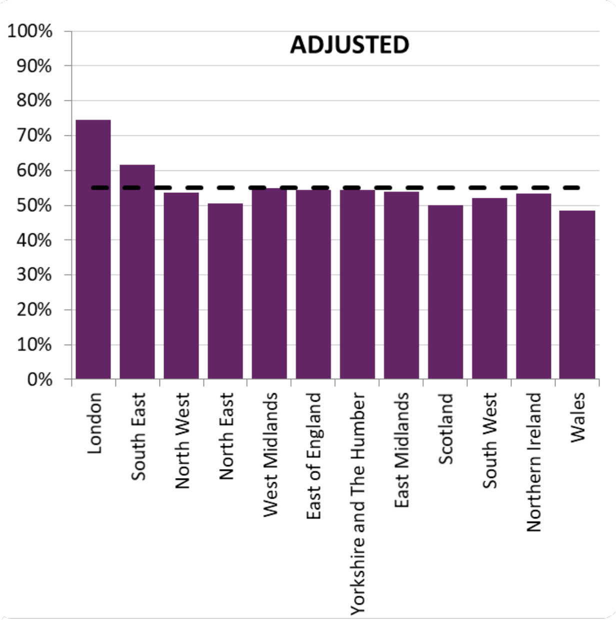
As set out earlier, commercially funded fixed and mobile coverage vary across the UK – see Figures 5 and 6. This may appear to suggest that certain regions of the UK are 'under-served' relative to other regions in terms of commercially provided fixed coverage by Openreach and commercially funded mobile coverage. In this section, we employ our econometric analysis to assess how much of the regional variation in coverage can be explained by regional differences in the outlined cost, demand, and location-specific factors.

Commercially funded fixed coverage by Openreach across the UK

In Figure 11 below, the left-hand graph shows the actual percentage of Openreach cabinets that have been commercially upgraded in the different UK regions in our sample. The right-hand graph shows, in contrast, a predicted level of cabinets that Openreach would have commercially upgraded in each region, if we assumed that the level of cost and demand factors in each region was the same (i.e. each region has the same number of premises per cabinet, level of affluence, rurality etc. as the UK average). The dashed line represents the UK average of Openreach's commercial upgrades.

Figure 11: Actual vs. adjusted probability of Openreach cabinets being commercially upgraded to FTTC across the UK nations and regions





From Figure 11, we can observe that after adjusting for the cost and demand factors described above, the apparent differences in commercial FTTC Openreach coverage between regions reduce significantly. This is reflected by the smaller variation about the UK average for adjusted coverage relative to actual coverage.

For instance, the actual probability of a cabinet being commercially upgraded in Northern Ireland appears to be below the UK average. Yet after accounting for the local cost, demand, and regional conditions, our model predicts that the probability of a cabinet being commercially upgraded in Northern Ireland does not differ too greatly from the UK average. This suggests that in Northern Ireland, most of the variation in upgrades is explained by cost, demand, and location factors.

In principle, if it were possible to perfectly capture and model all cost and demand factors that affected Openreach's decision to upgrade cabinets to FTTC, the level of adjusted FTTC coverage would be the same across all regions as all variation would be explained. In practice though, Openreach's commercial FTTC coverage decisions are likely influenced by factors that we do not control for or only measure imperfectly, which is reflected in the adjusted chart by certain regions having an adjusted coverage level that differs from the UK average.

Specifically, Figure 11 shows that there are unobserved demand, cost or other factors that negatively affect commercial FTTC coverage in Scotland, the South West, and Wales. However, we note here that the focus of this analysis is commercial FTTC upgrades. Areas such as Scotland, the South West, and Wales, which have relatively low proportions of commercial FTTC upgrades, have a large percentage of their cabinets upgraded to FTTC via public funding. Indeed, when we add publicly funded cabinet upgrades – as shown in Figure 5 above – all the areas we could identify as 'under-served' have at least 80% FTTC cabinet upgrades.

Therefore, due to public as well as private funding of cabinet upgrades, Openreach's FTTC coverage, which can provide superfast broadband, is generally good across the UK – 95% of premises are served by Openreach's cabinets via either FTTC or FTTP connections, as shown by the dashed line in Figure 4.

Mobile coverage across the UK – Actual and Adjusted

Figures 12 and 13 present similar analysis but for 3G and 4G mobile coverage respectively. In the two figures, the left-hand graphs show the actual level of 3G or 4G coverage provided in each region, measured as the number of operators with good coverage as outlined in Section 3. While the adjusted coverage graphs illustrate a prediction of the level of 3G/4G coverage by all four MNOs if each region were as densely populated, affluent, urban and hilly etc. as the UK average. As in the previous charts, the dashed line represents the UK average.

Figure 12: Actual vs adjusted geographic 3G coverage by all four MNOs across the UK nations and regions

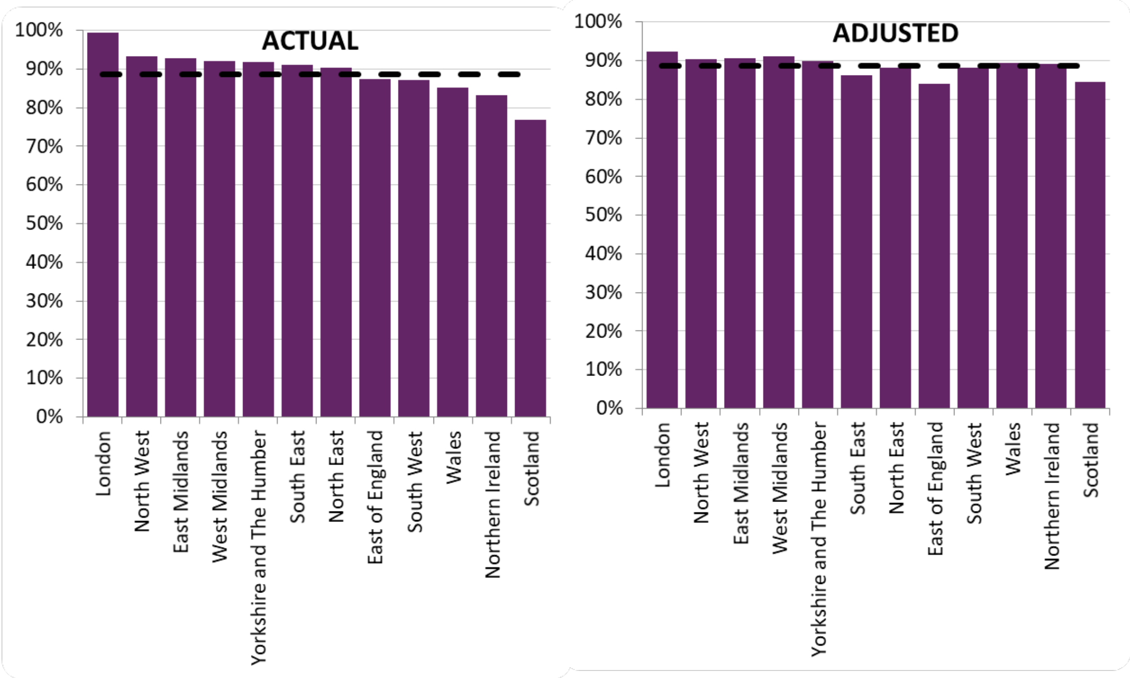
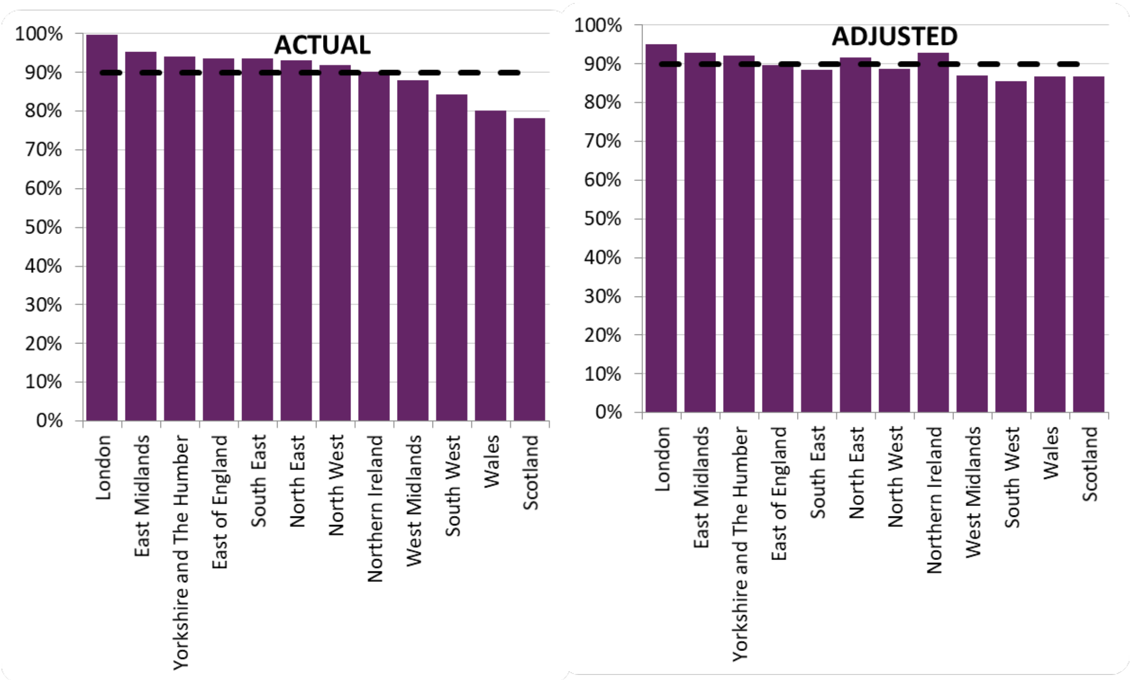


Figure 13: Actual vs adjusted geographic 4G coverage by all four MNOs across the UK nations and regions



Similar to the analysis for fixed coverage, after adjusting for demand and cost factors, the differences in 3G and 4G coverage substantially reduce between regions. However, as in FTTC coverage decisions, there are certain regions that have an adjusted coverage level that differs from the UK average. This implies that there are likely to be factors that we do not control for or only measure imperfectly in our analysis that affect 3G and 4G coverage. Specifically, as can be observed from Figure 12, there are unobserved demand, cost or other factors in Scotland leading to 3G coverage levels being lower than the UK average. From Figure 13 we can also see that there are unobserved factors in the South West, Wales and Scotland, which mean that 4G coverage is lower than the UK average.

8. Conclusion

The main findings of our analysis are summarised below.

The effect of local cost and demand factors on coverage

Fixed and mobile coverage share common commercial drivers. Population density has a significant impact on both the probability of commercial upgrades to FTTC and the provision of 3G and 4G coverage. Further, the probability of a commercial FTTC upgrade and good 3G and 4G coverage is higher in urban and more affluent are.

There are also important determinants specific to fixed and mobile coverage:

Determinants specific to fixed coverage

A greater average distance between the street cabinet and the premises it serves leads to a lower probability of a commercial FTTC upgrade. This is because broadband speeds deteriorate with distance over copper lines negatively affecting demand for FTTC

In contrast, a greater distance between the exchange and the street cabinet increases the probability of commercial FTTC rollout. This is because cabinets that are further away from the exchange will receive a greater speed uplift from a FTTC upgrade, as they would have suffered from a larger degree of attenuation prior to the upgrade. This could therefore boost demand for the technology

Higher ADSL download speeds in the premises' area lead to a lower probability of a commercial FTTC upgrade because where premises experience higher standard broadband speeds, FTTC may not offer a significant speed uplift for consumers

Determinants specific to mobile coverage

A challenging terrain and a large backhaul distance have a negative impact on the probability of 3G and 4G coverage because of the increased costs of increasing the reach and quality of their networks

Implications for regional variations in coverage

Across the UK's nations and regions there are significant variations in the level of commercially provided fixed and mobile coverage. We show that most of this regional variation can be explained by the demand and cost factors outlined in our analysis.

Yet there are certain regions where commercial coverage is lower than we would expect given the underlying level of local cost and demand factors:

- There appear to be unexplained factors (not captured by our local cost and demand factors) in Scotland, the South West, and Wales that negatively affect both

Openreach's decision to commercially upgrade cabinets to FTTC and the MNOs decision to provide full 4G coverage in these regions.

- There also appear to be unexplained factors that negatively affect the MNOs decision to provide 3G coverage in Scotland.

For fixed coverage, the potential shortfall in commercially provided FTTC coverage has largely been filled by public funding. A combination of commercial and public funding results in a good level of FTTC coverage across the UK – on average 95% of premises served by Openreach are connected to either FTTC or FTTP cabinets.

For mobile coverage, the overall level of commercially provided (3G and 4G) mobile coverage across the UK is good. Though we hope that our analysis will stimulate further dialogue in areas where coverage is slightly lower than expected to explore possible solutions.

A1. Data

Fixed coverage data

To build our dataset on fixed coverage, we started by matching each cabinet to the exchange it is connected to and to the premises it is serving. We then matched each premise to the corresponding ONS output area[13] and each output area to its corresponding census data to extract information on age and affluence of that area.[14]

To illustrate, consider the example for one cabinet in Figure A1.1.1:

- Our dependent variable is the type of FTTC upgrade that the cabinet (blue square) has received (public, commercial, or no upgrade);
- The number of premises is the total number of households or businesses that is served by that cabinet (house icons);
- ADSL (Standard broadband) Download speeds are averaged across all premises served by the cabinet;[15]
- A distance metric is calculated by taking the average of all distances between the cabinet and the premises that are served by the cabinet. An additional distance metric is estimated by calculating the distance between the exchange and cabinet;
- A competition variable is created by checking whether Virgin Media is present in at least 50% of the premises mentioned above;[16]
- Rurality information is obtained by assessing the location of the cabinet; and
- Information on age and affluence of the local population is obtained by averaging these metrics for the local population belonging to output areas that are served by the cabinet.

[13] Output areas were built by the ONS from postcode units based on data from the 2001 Census. We find this level of aggregation to be more suitable than an analysis by postcode, which would be too granular.

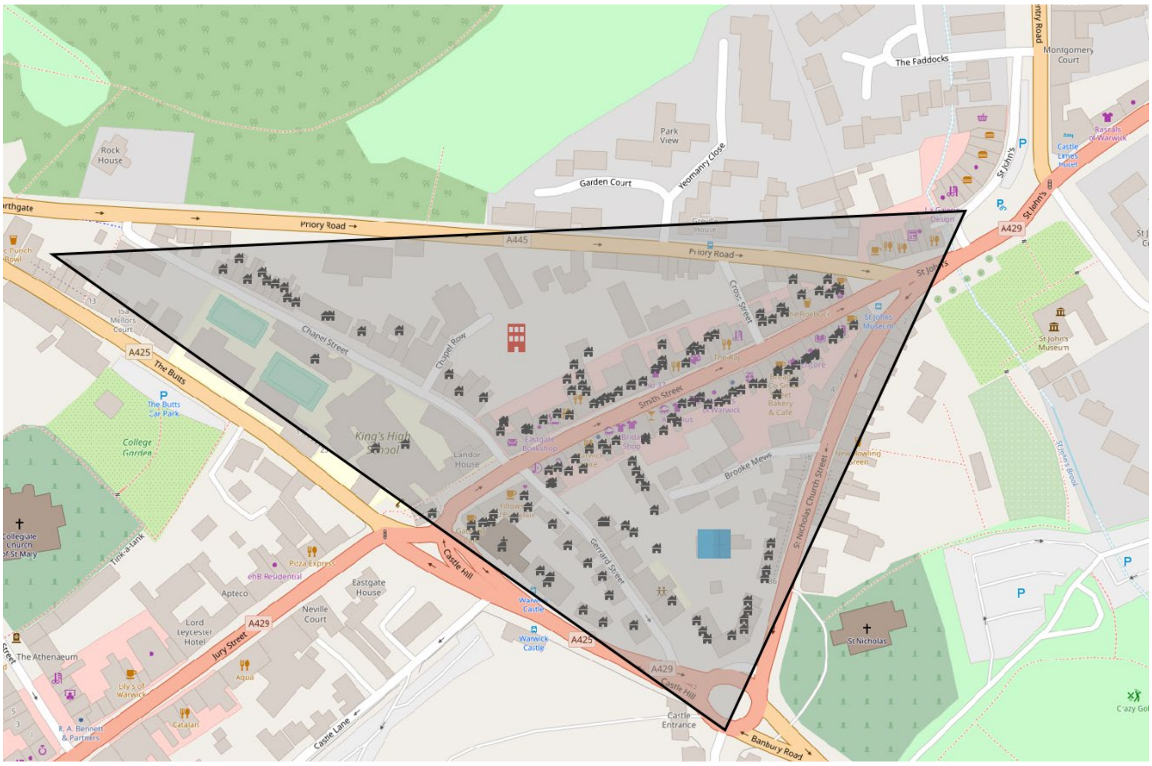
[14] We also drop outliers from our data by removing all cabinets that are more than 8km from their exchange or that have a more than 8km average distance to the premises they are connected to. We check the impact of these observations in Annex 3.

[15] We have tried to account for the variability in ADSL download speeds between premises, however, due to its correlation with the distance between the cabinet and the exchange we have not been able to include in our model any transformations of the variable that would capture its variability across premises.

[16] We arbitrarily chose 50% as our base scenario, but we have conducted robustness tests using a 10% and a 80% threshold, and see no significant changes in the results.

Figure A1.1.1: An illustrative example of our data

= Exchange = Cabinet = Premise



The full list of the variables included in our study of fixed coverage is given by Table A1.1.1 below.

Table A1.1.1: Variables included in our study of fixed coverage

Variable name	Remarks
upgrade_type	Our dependent variable. This is a categorical (dummy) variable that takes on the value of one if the cabinet has been commercially upgraded to FTTC, two if it has not been upgraded and three if it has been upgraded to FTTC via public funding.
adsl_avg_down	The predicted average Standard Broadband (ADSL) download speed in the area reached by a cabinet in Kbit/s.
avg_dist_prem_cab	The average distance between the cabinet and the premises in the area, measured in kilometers.
dist_ex	The distance (in kilometers) between the cabinet and the exchange.
number_premises	The number of premises within the area that can be served by a cabinet.

pct_num_abc1	The approximate percentage of the population within the cabinet's area that reside within a household classified within socioeconomic groups A, B or C1.[17,18]
pct_num_under25	The approximate percentage of the population within the cabinet's area that are aged under 25.[19]
regions	This is a categorical (dummy) variable that identifies the part of the UK that the cabinet is found in. This is either the nation in the case of Scotland, Wales and Northern Ireland or the region for England.
rurality	This is a categorical (dummy) variable that identifies whether the cabinet is located in an urban, semi-urban, or rural area.[20]
vm_50	This is a categorical (dummy) variable which takes on a value of one if Virgin Media is, on average, present in at least 50% of the premises reached by a cabinet.[21]

The summary statistics for the dependent variable (which takes on the categories of commercial upgrades, public upgrades, and no upgrades) and the continuous explanatory variables are presented in Table A1.1.2 below.

[17] These socioeconomic ratings are obtained from the National Readership Survey's (NRS) social classification system. A, B and C1 are typically allocated to occupations that can be described as more affluent. For example, C1 are occupations that can be described as "Supervisory, clerical and junior managerial, administrative and professional".

[18] We appreciate that these ratings are perhaps not the most relevant measures of affluence, so we have explored other measures such as using local unemployment rates, house prices and Index of Multiple Deprivation (IMD). We, unfortunately, found that these new measures were unsuitable. For unemployment rates, we have done some trial testing and we found that it made the overall results look unintuitive (it is likely that this is caused by the variable being highly collinear with other variables and we would need to do more work in the future to use this measure appropriately). For house prices, we found that relevant data (location, price etc.) were only easily available for England and Wales but these were either not collected or were not easy to obtain for the other nations. For IMD, we found that making comparisons using IMD is difficult since each nation uses its own criterion to calculate IMD (for example England places less weight on Income Deprivation than Scotland); IMD is also a relative deprivation measure within each nation and, therefore, comparisons of IMD score of areas between different nations would be erroneous.

[19] We chose this age threshold because we believe that individuals under 25 are less likely to be the bill payer, and therefore are less likely to have an impact on the fixed broadband decisions of their household. We checked this against similar age thresholds (such as the percentage of people aged 30 or under), and there were no changes in the results.

[20] We obtained data on the urbanicity of the cabinet location using the urban locale classification from Bluewave Geographics. Bluewave Geographics is a provider of digital mapping, geographic analysis and sampling services to market research and fieldwork sectors.

[21] We chose 50% as an arbitrary threshold and performed robustness tests using a 10% and 80% of the premises and saw no significant changes in the results.

Table A1.1.2: Fixed coverage study summary statistics

Variable name	(1) Min	(2) 25th percentile	(3) Median	(4) Mean	(5) 75th percentile	(6) Max
commercial_upgrade	0	0	1	0.535	1	1
no_upgrade	0	0	0	0.127	0	1
public_upgrade	0	0	0	0.338	1	1
adsl_avg_down	10	5,993	11,323	10,762	15,588	23,030
avg_dist_prem_cab	0.00100	0.168	0.236	0.319	0.344	7.033
dist_ex	0.00289	0.586	1.131	1.343	1.884	7.960
number_premises	1	156	294	305.8	435	3,191
perc_num_abc1	0	0.417	0.544	0.545	0.671	0.985
perc_num_under25	0	0.247	0.285	0.294	0.330	0.962

Mobile coverage data

MNOs typically deploy cell sites based on an assessment of local cost and demand factors in an area. This area is typically larger than the coverage pixel, we refer to this larger area as the 'coverage area'. We define the coverage area as an area that is covered by a circle of radius 1km around the coverage pixel.[22][23] For each coverage area we collected data on a set of variables.

[22] We use a 1km radius because this interval roughly corresponds to the range of a typical cell site across a variety of frequencies and environments. See for instance Table 8 in Recommendation ITU-R M.1768-1 (04/2013)

[23] Our results do not materially change when using different radii ranging from 0.5km to 2.5km.

Our analysis focuses on populated areas since the demand factors we use place a strong emphasis on demographic variables.[24] To illustrate our analysis, consider Figure A1.2.1 below which shows a coverage pixel (a 200m by 200m area) and the associated coverage area (the full shaded area) in a medium sized town.

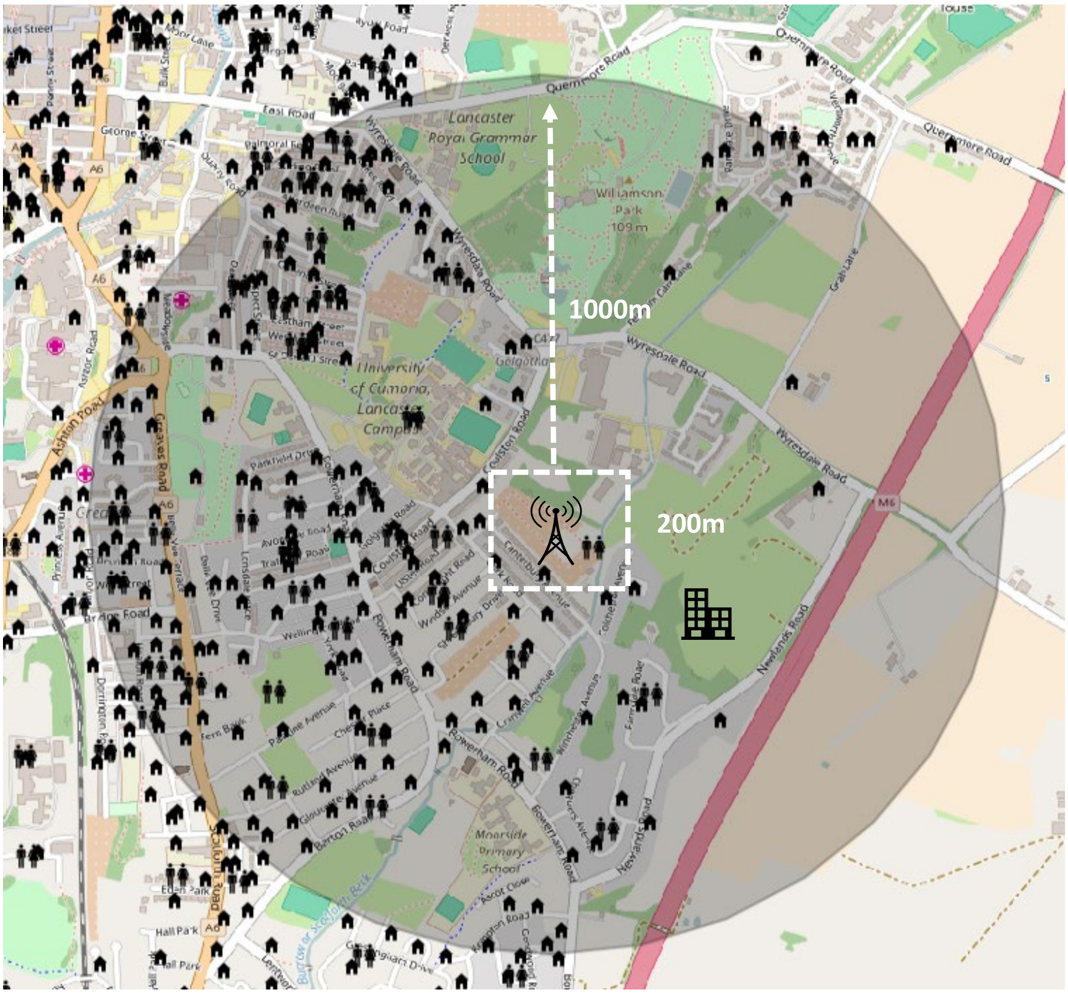
To illustrate how our dataset was built, consider Figure A1.2.1 below which shows a coverage pixel (a 200m by 200m area) and the associated coverage area (the full shaded area) in a medium sized town:

- Our dependent variable is the number of operators with good 3G/4G coverage in the 200m by 200m pixel at the centre of the image;
- The local population is obtained by summing the population numbers in all of the postcodes located within the coverage area;
- Information on age and affluence of the local population is obtained by summing over the number of people belonging to each age and affluence group in all of the output areas within the coverage area;
- Summary statistics for topography of the coverage area (median height and standard deviation of height) are obtained from the elevation database; and
- The distance metric is derived by calculating the distance between the location of the pixel and its closest mobile backhaul location.

[24] More specifically, our analysis relies on demographic variables (such as age, affluence etc), so we would not be able to analyse unpopulated areas with the current model. We have considered how we could extend the analysis, but this would require new variables (e.g. distance to major road, level of car and pedestrian traffic etc.). Currently, adequate data relating to these variables are not readily available.

Figure A1.2.1: Coverage area with an illustrative example of a backhaul location

	Coverage pixel		Postcode
	Census output area centroid		Backhaul location example



The full list of the variables included in our study of mobile coverage is given by Table A1.2.1 below.

Table A1.2.1: Variables included in our study of fixed coverage

Variable name	Remarks
num_3G_ops/num_4G_ops	The number of 3G/4G operators with good coverage in a 200m by 200m pixel (operators with signal strength equal to or above the threshold of -100 dBm for 3G and -105 dBm for 4G). This variable can take the value of 0, 1, 2, 3 or 4.
ln_pop	The population within the postcode sector. We measure population in natural logarithms.

pct_abc1	The approximate percentage of the population within the coverage area that reside within a household classified within socioeconomic groups A, B or C1.[25]
pct_under25	The approximate percentage of the population within the coverage area that are aged under 25.
pct_over60	The approximate percentage of the population within the coverage area that are aged 60 or over.
height_median	The median height above sea level, in metres, of the coverage area.[26]
height_stdev	The standard deviation of the heights of the coverage area.
urban_code	This is a categorical (dummy) variable that identifies the coverage area as either urban or rural.
dist_backhaul	The distance from the pixel to its nearest backhaul location.
region	This is a categorical (dummy) variable that identifies the part of the UK that the coverage area is situated within. This is either the nation in the case of Scotland, Wales and Northern Ireland or the region for England.

The summary statistics for the dependent variables in our mobile study (the number of 3G operators and the number of 4G operators) as well as the continuous explanatory variables in our analysis of mobile coverage are reported in Table A1.2.2 below.

[25] See discussion in footnotes 23 and 24 above on these socioeconomic ratings and their potential limitations.
[26]Topographic information was obtained from the Consortium for Spatial Information's (CGIAR-CSI) SRTM 90m Digital Elevation Database v4.1.

Table A1.2.2: Mobile coverage study summary statistics

Variable name	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
num_3g_ops	0	4	4	3.808	4	4
num_4g_ops	0	4	4	3.804	4	4
population	1	170	498	2270	2224	63382
pct_under25	0	24%	27%	27%	30%	95%
pct_over60	0	22%	27%	27%	32%	98%
pct_abc1	0	45%	56%	55%	66%	100%
heightmedian	-3	35	72	85	119	614
heightstdev	0	7	12	16	20	261
dist_backhaul	0	789	1318	1554	2102	19233

A2. Regression results

Fixed regression results

The results of our main regression are presented in Table A2.1.1 below.

Table A2.1.1: Results of fixed coverage regression analysis

	Probability of a commercial upgrade	Probability of a public funded upgrade
Population density		
number_premises	0.0156***	0.00826***
Demography		
perc_num_abc1	0.560***	-0.976***
perc_num_under25	-3.674***	-2.972***
Distances		
avg_dist_prem_cab	-1.063***	-0.314***
dist_ex	0.210***	0.0286
ADSL download speed		
adsl_avg_down	-1.35e-05**	2.00e-05***
Competition		
vm_50	-0.587***	-1.390***
Rurality		
semi-urban	1.081***	-0.0964
urban	1.110***	-1.281***
Region		
East of England	0.0122	-0.0395
London	-0.101	-6.801***
North East	-1.039***	-1.107***
North West	0.124	0.198
Northern Ireland	0.705**	0.900**
Scotland	-0.185	0.134
South East	0.445***	-0.160
South West	-0.564***	-0.587***
Wales	0.123	0.631***

West Midlands	-0.295*	-0.491***
Yorkshire and the Humber	-0.306*	-0.467***
Observations	89,364	89,364

*** p<0.01, ** p<0.05, * p<0.1

The results in the table above require careful interpretation. This is because the coefficients only provide an indication of the direction and scale of effects as well as the relative importance of different variables. To compute the precise impacts on the probability of a cabinet being commercially upgraded to FTTC, the marginal effects need to be calculated. These are discussed in Annex 3.1.

The directional effects of each explanatory variable in Table A1.1.1 in terms of the probability of a commercial upgrade relative to the base category of no FTTC upgrades can be summarised as follows:

- Distances: The larger the average distance between the premise and the cabinet (avg_dist_prem_cab), the lower the probability of Openreach upgrading that cabinet to FTTC (as reflected by the negative and significant coefficient). In Section 4 we mentioned how the distance between the exchange and the cabinet can affect Openreach's decision to upgrade its cabinets both from a cost and demand perspective. On the one hand, a large distance between the cabinet and the exchange may mean higher costs of laying down fibre. On the other hand, a large distance between the cabinet and the exchange leads to higher speed uplifts to the premises, thereby increasing demand. The positive coefficient on the exchange distance variable (dist_ex) suggests that the demand factor outweighs the cost factor.

- Number of premises: the more premises a cabinet is connected to (number_premises), the higher the probability that this cabinet will be commercially upgraded. This makes intuitive sense because when a large number of premises can be reached by upgrading a single cabinet, the expected demand for FTTC services is higher leading to an increase in the probability of Openreach upgrading this cabinet.

- ADSL download speeds: the higher the average ADSL download speed in the area (adsl_avg_down), the lower the probability of Openreach rolling out FTTC to this area. Again, the speed increment delivered by FTTC will be quite small in an area that is already enjoying higher ADSL speeds. This means that demand for FTTC will likely be lower in these areas, decreasing the probability that Openreach will upgrade the cabinet;

- Affluence: the more affluent an area is (perc_num_abc1) the more likely it is that a cabinet in that area will be commercially upgraded.

- Age: The negative and significant coefficient on the variable perc_num_under25 indicates that when there are large percentages of people aged under 25 in an area, there is a lower probability of cabinets being commercially upgraded to FTTC in that area. This may reflect the fact that this age group has less of a say on which broadband its household will choose. It may also highlight the fact that our measure of affluence could be imperfect.[27]

- Competition: The probability of a commercial FTTC upgrade relative to the cabinet not being upgraded at all is lower when Virgin Media is present in more than half of the premises in an area (vm_50). However, we recognise Virgin Media and Openreach would likely decide whether they want to upgrade their cabinets based on the same demand and cost factors, and so the same unobserved factors driving upgrade decisions would be present for both operators. This means that the presence of Virgin Media is likely to be endogenous. This means that interpretations of the results with respect to the presence of Virgin are unclear. There are a number of possible approaches that could be used but they all rely on the presence of an exclusion restriction (i.e. some variable that affects Openreach but not Virgin and vice versa). Correcting for this endogeneity is beyond the scope of this paper and so future work would be required to analyse competition more completely.

- Rurality: the coefficients show the effect of being in the urban and semi-urban category relative to the comparator category (rural). They indicate that cabinets in urban and semi-urban areas are much more likely to be commercially upgraded than those in rural areas. Again, this might reflect the higher costs of upgrading cabinets in rural areas described in Section 4.

- Region: this is a dummy variable that identifies the region of the UK in which a cabinet is located. The coefficients on these variables show the effect of being within the particular region of interest relative to the comparator region (East Midlands).

We have also performed a series of robustness tests from which we concluded that our results are robust both in terms of the direction and magnitude of coefficients.[28]

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[27] We checked the correlation between age and affluence and found it to be at an acceptable level to justify including both variables.

[28] Specifically, we performed tests on alternative specifications, looking at the existence of non-linear relationships between some of our continuous explanatory variables and our dependent variable. We checked that our results were not driven by specific data points by dropping outliers. We also tested a number of thresholds for Virgin Media presence, and our clustering choice.

Mobile regression results

Table A2.2.1: Results of 3G and 4G regression analysis (1km coverage area radius)

	num_3G_ops	num_4G_ops
Population density		
ln_pop	0.186***	0.211***
Demography		
pct_abc1	0.00819***	0.00759***
pct_under25	-0.00524**	-0.00384*
pct_over60	-0.0156***	-0.0153***
Topography		
heightmedian	-0.000513***	-0.000948***
heightstdev	-0.00954***	-0.0129***
Backhaul network		
dist_backhaul	-0.000186***	-0.000162***
Rurality		
urban	0.455***	0.296***
Region		
East of England	-0.395***	-0.239***
London	0.129	0.233
North East	-0.167**	-0.109
North West	-0.0264	-0.307***
Northern Ireland	-0.108	0.00640
Scotland	-0.365***	-0.426***
South East	-0.283***	-0.327***
South West	-0.174***	-0.490***
Wales	-0.0809	-0.425***
West Midlands	0.0276	-0.407***
Yorkshire & The Humber	-0.0604	-0.0621
Observations	2,077,771	2,077,771

** p<0.01, ** p<0.05, * p<0.1

Like the fixed regression results, the results in the table above require careful interpretation. Because the ordered probit model is a nonlinear model, the coefficients only give a partial picture of the impact of the variables on the probabilities of good coverage. The coefficients provide an indication of the direction and scale of effects as well as the relative importance of different variables. To compute the precise impacts on the probabilities of having good mobile coverage additional calculations are required. We discuss these computations in Annexes 3.2.

The directional effects of each explanatory variable in Table A2.2.1 can be summarised as follows:

- Population density: the variable ln_pop describes the population within the coverage area. As the size of the coverage area is fixed, ln_pop also describes population density. The positive and significant coefficient on ln_pop in both the 3G and 4G models across both years indicates that increased local population density has a positive effect on the likelihood of good 3G and 4G mobile coverage.

- Affluence: the variable pct_abc1 describes the affluence of the local population. A more affluent local population appears to have a positive influence on both 3G and 4G coverage.

- Age structure: the variables pct_under25 and pct_over60 describe the age profile of the local population. For 3G and 4G, the coefficients on pct_over60 are negative and significant at the 1% level. However, the coefficient for pct_under25 is only significant for 3G at the 5% level and for 4G at the 10% level. This provides some evidence that a larger "working age" population has a positive impact on the likelihood of good mobile coverage.[29]

- Topography: the variables height_median and height_stdev measure the height of the coverage area above sea level and the variability in height within the coverage area respectively. For both 3G and 4G, increasing both the height and variability of height appears to have a negative influence on coverage.

- Backhaul Network: the variable dist_backhaul measures the distance from the pixel to the closest location that allows access to the core backhaul network. A negative coefficient at the 1% significance level for both technologies implies that areas further away from the backhaul network will have a higher likelihood of receiving worse mobile coverage.

- Rurality: the variable urban_code identifies whether the coverage area is situated in a rural or urban area. The coefficients show the effect of being in the urban category relative to the comparator category (rural). The results indicate that there is a higher likelihood of good 3G and 4G mobile coverage in urban areas than compared to rural areas.

[29] The insignificance of pct_under25 could be due to a mixture of different effects. Firstly, it could be a one-off effect for May 2018. Secondly, it could be that demand for mobile services are rising over time for those that are under 25.

- Region: this is a categorical (dummy) variable that identifies the region of the UK in which a coverage area is located. The coefficients on these variables show the effect of being within the particular region of interest relative to the comparator region (in this case the East Midlands). We examine how the region in which a given coverage area is located affects the likelihood of 3G/4G coverage in detail in Section 7.

We have checked the robustness of our results by assessing how changing the radius size of the coverage area and the cluster size used for standard errors alters our results. We note that our results – both the direction and the magnitude of coefficients – are robust to changing these parameters.

A3. Marginal effects

Fixed marginal effects

Table A3.1.1 below shows the effect of the continuous explanatory variables on the likelihood of commercially upgrading a cabinet to FTTC, calculated as described in Section 5.

Table A3.1.1: Impact of continuous explanatory variables on the average predicted probability of a commercially upgrade to FTTC

Independent variable	Predicted probability of commercial FTTC upgrade at 25th percentile of variable	Predicted probability of commercial FTTC upgrade at 75th percentile of variable	Difference
number_premises	31.3%	76.6%	45.3%
perc_num_abc1	53.3%	57.5%	4.2%
adsl_avg_down	57.3%	53.7%	-3.6%
dist_ex	53.7%	56.8%	3.1%
avg_dist_prem_cab	56.6%	54.7%	-1.9%
perc_num_under25	56.4%	54.7%	-1.7%

Our key findings from the table above are:

- On average, a cabinet at the 75th percentile for the number of premises has a 45 percentage points higher probability of being commercially upgraded than a cabinet at the 25th percentile for the number of premises.

- The composition of the population in an area served by a prospectively upgraded cabinet matters. Specifically:
  - the more affluent an area is, the more likely it is that a cabinet in that area will be commercially upgraded. An area at the 75th percentile for affluence (where 67% of the population are classified as affluent) has a 4% higher probability of being commercially upgraded to FTTC compared to an area at the 25th percentile for affluence (where 41.7% of the population are classified as affluent); and

  - the larger the percentage of people aged 25 or under, the lower the probability of Openreach upgrading its cabinets. An area at the 75th percentile (where 33.0% of the population are 25 or under) has a 2% lower probability of being commercially upgraded to FTTC compared to an area at the 25th percentile (where 24.7% of the population are 25 or under).

- Areas with higher average ADSL (Standard broadband) download speed have a lower chance of being commercially upgraded to FTTC because this would likely lessen demand for FTTC services. An area at the 75th percentile for average ADSL download speeds (which corresponds to 15,588Kbit/s) has a 4 percentage points lower probability of being commercially upgraded compared to an area at the 25th percentile (which corresponds to 5,993 Kbits/s).

- Areas with higher distances between the exchange and the cabinet have a greater probability of being commercially upgraded to FTTC because the greater speed uplift could increase demand. An area at the 75th percentile (which corresponds to a 1.88 km distance between the cabinet and the exchange) has a 3 percentage points higher probability of being commercially upgraded compared to an area at the 25th percentile (which corresponds to a 0.58 km distance between the cabinet and the exchange).

- In addition, areas with higher average distances between the premises and the cabinet have a lower chance of being commercially upgraded to FTTC because broadband speeds deteriorate with distance over copper lines. An area at the 75th percentile (which corresponds to a 0.34 km distance between the premise and the cabinet) has a 2 percentage points lower probability of being commercially upgraded compared to an area at the 25th percentile (which corresponds to a 0.17 km distance between the premise and the cabinet).

Table A3.1.2 shows the effect of rurality on the average predicted probability of a cabinet being commercially upgraded to FTTC. A cabinet in an area that is classified as urban or semi-urban has, on average, a higher probability of being commercially upgraded to FTTC by, respectively, 30.7 and 13.7 percentage points compared to a cabinet in a rural area.

Table A3.1.2: Average predicted probability of a commercial upgrade by urban location

Rurality	
Rural	33.2%
Semi-urban	50.2%
Urban	63.9%

Mobile marginal effects

Table A3.2.1 below shows the effects of the continuous explanatory variables on the likelihood of full 3G coverage (all MNOs providing good levels of 3G coverage in an area). Table A3.2.2 shows the same for full 4G coverage (all MNOs providing good levels of 4G coverage in an area).

Table A3.2.1: Impact of continuous explanatory variables on average predicted probability of full 3G coverage

Independent variable	Predicted probability of full coverage at 25th percentile of variable	Predicted probability of full coverage at 75th percentile of variable	Difference
population	85.8%	93.5%	7.7%
pct_abc1	86.1%	89.1%	3.0%
pct_under25	87.8%	87.2%	-0.6%
pct_over60	89.3%	86.5%	-2.8%
height_median	88.1%	87.4%	-0.7%
height_stdev	89.5%	87.3%	-2.2%
dist_backhaul	90.9%	86.9%	-4.0%

Table A3.2.2: Impact of continuous explanatory variables on average predicted probability of full 4G coverage

Independent variable	Predicted probability of full coverage at 25th percentile of variable	Predicted probability of full coverage at 75th percentile of variable	Difference
population	86.7%	94.5%	7.8%
pct_abc1	87.3%	89.8%	2.5%
pct_under25	88.7%	88.3%	-0.4%
pct_over60	90.2%	87.7%	-2.5%
height_median	89.5%	88.3%	-1.2%
height_stdev	91.2%	88.5%	-2.7%
dist_backhaul	91.2%	88.0%	-3.2%

Our key findings are the following:

- A more densely distributed local population increases the probability of having full 3G and 4G coverage. A coverage area at the 75th percentile for population density (which corresponds to 710 people per km^2) has a 7.7 and 7.8 percentage points higher probability of receiving full 3G and 4G coverage respectively than a coverage area at the 25th percentile for population density (which corresponds to 54 people per km^2).

- The composition of the local population affects mobile coverage: a larger working age population and an affluent population increase the probability of good coverage. A coverage area at the 75th percentile for affluence (where 66% of the local population are classified as affluent) has a 3.0 and 2.5 percentage points higher probability of receiving full 3G and 4G coverage respectively than a coverage area at the 25th percentile for affluence (where 45% of the local population are classified as affluent).

- Local topography can also affect the probability of good coverage. All else being equal, the probability of receiving full 3G and 4G coverage between a low-lying area and an area that is high above sea level (as defined by the inter-quartile range between 35 and 119 metres above sea level) is around 0.7 percentage points higher for 3G and 1.2 percentage points higher for 4G in 2018.

- Additionally, we find that the probability of receiving full coverage between an area with flat terrain and more uneven terrain (as defined by the inter-quartile range in our dataset) is around 2.2 and 2.7 percentage points higher for 3G and 4G respectively.

- Distance to the backhaul network can further influence the probability of having full mobile coverage. The probability of full coverage between an area that is closer to its backhaul network and an area that is further away (as defined by the interquartile range between 1300m and 4000m) is approximately 4.0 percentage points higher for 3G and 3.2 percentage points higher for 4G.[30]

Moving on to the categorical variables in our study, Table A3.2.3 and Table A3.2.4 show, respectively, the effect of rurality on the average predicted probability of full 3G and 4G coverage.

Table A3.2.3: Average predicted probability of full 3G coverage by urban location

Rurality	
Rural	87%
Urban	94%

Table A3.2.4: Average predicted probability of full 4G coverage by urban location

Rurality	
Rural	88%
Urban	92%

[30] We would expect the difference in the probability of full coverage between the 25th and 75th percentile to be larger in magnitude for 4G than for 3G for each factor. This is because 3G is a more mature technology and, therefore, more likely to serve the 25th and 75th percentiles evenly. However, we do not observe this outcome for affluence or distance to backhaul in 2018. A possible reason is that MNOs may be choosing to upgrade masts to 4G in areas less well served by 3G to improve general access to mobile data. MNOs may also be rolling out additional 4G masts to new locations which may mean that 4G coverage is better at serving the 25th and 75th percentiles than 3G. We will explore the reasons for this effect in the future.

As shown by the tables above, an area classified as urban has, on average, a higher probability of full coverage compared to an area classified as rural by 7 and 4 percentage points for 3G and 4G respectively.