The Arrival of Fiber Broadband and Digital Premium Gaps: Evidence from Housing Market Responses [*]

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Abstract

Using the universe of housing transactions in England and Wales between 2008 and 2017, we measure the perceived value of fiber broadband to homebuyers. We exploit the discontinuity across the boundary of areas that were fiber enabled in different years. We find a house price premium of 0.7%, which increases to 1.8% for London. Examining the neighborhood characteristics shows that the strongest response comes from neighborhoods with a higher share of skilled residents, especially those engaged in digital occupations. Neighborhoods with a higher share of work-from-home residents exhibit a larger premium, highlighting the productive value of high-speed home broadband.

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1 Introduction

Data-intensive digital services and platforms have become an important part of modern life. Access to high-speed internet is a prerequisite for using these services that can transform the way we work, learn, or use healthcare. During the last decade, fiber-optic broadband emerged as a breakthrough technology, expanding access to high-speed internet at an affordable cost.[1] Despite its wide array of benefits and governments' commitment to expanding service coverage, this new broadband technology has not diffused evenly across all parts of the population. This disparate pattern might stem from the uneven returns to high-speed internet due to a lack of 'analog' complements, such as skills and opportunities. According to the World Development Report (2016), this gap in returns to digital technologies is one of the major headwinds in universal access to digitization benefits (World Bank Group, 2016).

In this paper, we examine the perceived value of fiber broadband to households and measure the heterogeneous value across neighborhoods with different characteristics in terms of skills, occupations, and work arrangements. We study the transition from standard broadband to superfast fiber broadband across the UK. The transition was triggered by a nationwide rollout of fiber-to-the-cabinet (FTTC) infrastructure that began in 2009. By 2013 majority of the urban postcodes had access to FTTC infrastructure. Still, the previous-generation asymmetric digital subscriber line (ADSL) broadband was the dominant technology in 2013 and was being used by 70% of users. Gradually, it was replaced by FTTC which captured half of the market share by the end of 2019.

We study how homebuyers respond to FTTC availability by measuring the premium prices that they are willing to pay for properties located in FTTC-enabled areas. To this end, we devise an empirical strategy that exploits the sharp discontinuity in high-speed broadband availability across neighboring postcodes that are connected to the FTTC infrastructure in different years. Our identification strategy requires granular mapping of the FTTC network in the UK. To construct this mapping, we first collect FTTC activation dates for the universe of postcodes in the UK. We also collect information on the distribution points of FTTC broadband, commonly known as street cabinets, including their locations and which postcodes they serve. This detailed knowledge of FTTC infrastructure helps us in two ways. First, we compute the distance between each postcode and the connecting cabinet, from which we deduce whether a postcode is well-situated to access the FTTC infrastructure.

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[1] Between 2014 and 2019, monthly fixed internet spending (per GB of data) declined by 80% while monthly data usage has increased by 443% for UK households (Ofcom Communication Market Report, 2020).

Second, by using the FTTC activation dates at the postcode level, we join adjacent postcodes to construct areas with the same activation year. We then locate the boundary lines between areas with different activation years and exploit the sharp geographic discontinuities in FTTC availability across the lines.

To test the validity of our boundary design, we first examine the broadband speed across these boundaries. We find a sharp jump in download speed when one side of the boundary line is activated while the other side remains inactivated. We do not observe this speed gap in the placebo cases for which neither side of the boundary line is yet activated. We then proceed with our main estimation which compares prices of the properties in these closely located postcodes that are connected to FTTC in different years. Specifically, we measure whether early FTTC activation and the proximity to FTTC infrastructure are capitalized in house prices, thereby estimating the digital premium of access to FTTC broadband.

Using this empirical design, we find a house price premium of 0.7% caused by FTTC activation. Properties located within 200 meters of the cabinet get a premium of 0.97% while those located farther away than 400 meters get no premium. The variation of premiums with distance closely replicates the technical features of FTTC broadband which gives a significant speed boost within a shorter distance from the cabinet. Moreover, we find significant heterogeneity in the house price responses across different regions and neighborhoods. The response for the London region (1.7%) is more than twice the response for the rest of the country (0.7%).[2]

To understand what drives the price responses, we examine the heterogeneous premium across neighborhoods. We propose a simple conceptual model which suggests that the value of home broadband comes both from its consumption and productive use. Consumption-related use facilitates household consumption of online products and services. Productive use enhances a household's ability to work from home (partially or fully) and generate income. To examine the role of productive use, we consider neighborhood composition of occupation and work arrangements using the 2011 Census. Our results suggest that neighborhoods with a relatively higher share of skilled occupations show a stronger response both in London (2.2%) and for the rest of the country (1%). The skill complementarity of FTTC broadband is even more pronounced when we examine the results by neighborhood composition of digital occupations. After mapping the digital skill requirements of a large sample of job postings from 2012-13 to the occupation level, we find that the house price response within 30 km of

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[2] We use the word digital premium and FTTC premium interchangeably throughout the paper.

London is as high as 3.4% for the neighborhoods in which a higher share of the population is engaged in digitally-intensive occupations.

Compared to the previous-generation ADSL technologies, the distinguishing features of FTTC broadband are its high upload speed and the reliability of connections. This is largely due to shorter copper loop lengths running from each property to the cabinet. These features are beneficial to all users but are particularly important for those who work from home (WFH). To check this, we estimate the price premiums for properties across neighborhoods with different concentrations of the WFH population. We find that London neighborhoods with above-median WFH shares show a 2.5% premium while this effect drops to 0.9% for places outside London.

This paper contributes to several strands of literature. First, we design an empirical strategy that estimates the perceived value of access to fiber broadband. We follow the hedonic price approach, developed by Rosen (1974) and Roback (1982), which exploits rent and housing prices to infer the value of local (dis-)amenities, such as proximity to nuclear plants (Gamble and Downing, 1982), school quality (Black, 1999), air pollution (Chay and Greenstone, 2005), transport access (Gibbons and Machin, 2005), hazardous waste sites (Greenstone and Gallagher, 2008), and crime risk (Linden and Rockoff, 2008). We contribute to this literature by developing an empirical strategy to study the amenity of access to fiber broadband. The validity of hedonic price estimates often relies on careful empirical designs that isolate the quasi-exogenous variation in access to the amenities. To achieve this, we construct granular boundaries of fiber activation and study the changes in the prices of neighboring properties located across these boundaries in a difference-in-differences setup. The combination of narrow boundary discontinuity and temporal variation in fiber activation limits the impact of potential confounding factors that manifest themselves in cross-sectional setups (Black, 1999; Gibbons and Machin, 2005; Greenstone and Gallagher, 2008).

Our results also contribute to the broader literature that examines the economic and social effects of broadband access. This includes studies on health outcomes (Amaral-Garcia et al., 2019; DiNardi et al., 2019), education (Dettling et al., 2018; Sanchis-Guarner et al., 2021), civic engagement and political participation (Falck et al., 2014; Gavazza et al., 2019; Geraci et al., 2022), labor market outcomes and productivity (Akerman et al., 2015; Hjort and Poulsen, 2019), trade (Malgouyres et al., 2021), sex crime (Bhuller et al., 2013), and credit (D'Andrea and Limodio, 2019). The closest work to our paper is Ahlfeldt et al. (2017) which examines the effect of ADSL broadband on house prices between 1995 and 2010. What sets our paper apart is our focus on next-generation broadband technologies delivered via fiber networks that began to take off after 2010.

Our work is among the first to study the causal effect of a speed upgrade following the rollout of fiber broadband. DeStefano et al. (2020) examine the postcode-level timing of fiber broadband availability and use a firm's distance from the local telephone exchange as an instrument to measure the adoption of cloud computing and its impact on firm growth. It is important to note that, before the rollout of FTTC broadband, access to high-speed internet was determined by the distance from local exchanges (LEs). This is because the previous broadband technology (ADSL) relied heavily on the telephone exchange network. With the deployment of fiber, the geography of high-speed broadband access has changed drastically. The connection speed for FTTC broadband is determined by the distance from a cabinet, rather than the distance from LEs. However, the lack of information on cabinet networks forced previous papers either to limit their study periods before the FTTC rollout or rely on strong assumptions about cabinet deployment and their locations. We fill this gap by collecting granular information on cabinet networks and measuring distances between the properties and their respective cabinets. Moreover, unlike the UK's LE network that was designed in the 1930s—long before the introduction of broadband, the location of FTTC cabinets can not be considered exogenous. We overcome this empirical challenge by constructing a quasi-experimental sample in the vicinity of FTTC activation boundaries.

Our paper also relates to the literature on differential gains from high-speed broadband. Previous work has shown that access to high-speed broadband at the workplace disproportionately benefits skilled workers (Akerman et al., 2015; Hjort and Poulsen, 2019). Our paper provides evidence that skill level and participation in digital work are also important factors in explaining differential gains from high-speed home broadband. Existing literature suggests that the value of home broadband might reflect the gains from better search technology, lower information friction, and better employer-employee matches for connected households (Zuo, 2021; Gürtzgen et al., 2021; Denzer et al., 2021; Bhuller et al., 2019). However, basic ADSL broadband often suffices for activities such as browsing or gathering information. What differentiates fiber broadband is its high upload speed and reliable connections, both of which are essential for WFH. Our study offers empirical evidence supporting the importance of high-speed broadband for WFH even before the COVID-19 pandemic. This aligns with the recent findings by Chiou and Tucker (2020), who demonstrate that the income loss during the pandemic was tied to the lack of access to high-speed internet at home and the inability to work remotely. In this context, our paper also relates to the literature studying the link between WFH, housing demand, and household preferences for different amenities (Brueckner et al., 2021; Stanton and Tiwari, 2021; Mondragon and Wieland, 2022).

The rest of the paper is organized as follows. Section 2 gives an overview of broadband rollout and take-up in the UK. Section 3 describes the data and summary statistics and Section 4 outlines our empirical strategy. We discuss our results in Section 5 and Section 6 concludes.

2 Background

2.1 A Brief History of Broadband in the UK

The commercial deployment of broadband infrastructure in the UK has gone through several major upgrades. Each upgrade is linked to the topology of the network built during the first half of the twentieth century by the incumbent – British Telecom (BT). The infrastructure consists of regional aggregation points, called local exchanges (LEs), which were initially connected to each subscriber's residence or business premise through copper lines. The LEs are in turn connected to a backbone national network allowing users to make phone calls. Based on this fixed infrastructure, internet connections in the 1990s ran through the legacy public switched telephone network (PSTN) with a maximum speed of 56 kbps.[3]

The first wave of upgrades took place during 2000-2008 with the introduction of ADSL technologies (ADSL, ADSL Max, and ADSL2+). While the actual network remained intact during this process, active equipment (i.e., powered with electricity) was installed in every LE, thus enabling users to increase their connection speeds by one or two orders of magnitude compared to the PSTN service.[4] During this round of upgrades, the length of copper lines running from the LE to each property largely determined the actual speed experienced by users (Ahlfeldt et al., 2017). For example, while ADSL2+ connections could provide a maximum speed of 24 Mbps for properties up to 1km away from the LE, subscribers residing more than 3km away from the LE would only get one third of that speed (around 8Mbps).[5]

FTTC Broadband. Deployment of fiber brought the next major upgrade and provided a significant speed boost compared to the ADSL connections. In 2008 BT announced that it

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[3] In some places where ISDN was available the speed could rise up to 64kbps.

[4] Each version of ADSL implements a different standard from the International Telecommunications Union (ITU) that improves the line's performance characteristics in terms of speed and reliability over the same copper medium.

[5] See `https://www.broadbandspeedchecker.co.uk/guides/adsl-and-distance.html`.

would invest £1.5 billion to connect ten million UK homes using FTTC technologies within the next few years.[6] Under this plan, newer (and smaller) aggregation points called street cabinets were constructed within the LE catchment areas. The connection between the LE and the cabinets used fiber cables which have a higher data transmission speed, whereas the cabinets were connected to the surrounding properties using copper lines (see Figure 1). This brought the distribution nodes closer to the properties and effectively reduced the length of the copper lines used. Combined with the new active equipment in the cabinets, the reduced distance allowed for much "denser" data streams to travel over the same last-mile connections. As a result, FTTC connections could offer a maximum download speed of 80 Mbps.

A few points about the FTTC activation process are worth noting. First, BT's rollout took place in multiple phases and predominantly targeted urban areas. Between 2009 and 2013, at least 80% of the postcodes activated each year were urban postcodes.[7] Figure 2 shows how the availability of different broadband technologies changed over time. Most of the ADSL-type activations were completed by 2007. As Figure 2 shows, FTTC activation started in 2009 and the maximum number of unit postcodes were connected in 2012. The bulk of the commercial rollout was completed by 2013-14. After that, largely rural postcodes got FTTC activated through the Building Digital UK (BDUK) programs.[8]

Second, due to the use of fiber cable for the first leg of FTTC connections – that is, the connection between the LE and cabinets – FTTC broadband speed does not vary with the distance between a property and the LE. Fiber cable lines have practically zero losses over these distances. For FTTC connections, it is the distance from the street cabinet that affects the actual speed. For example, although the maximum download speed could be as high as 80 Mbps within 100 meters of the cabinet, the speed drops to 60 Mbps around 500 meters away, and to 30 Mbps around 1 km away from the cabinet.[9]

Other Broadband Technologies. During the same period, a much smaller scale investment for fiber-to-the-premises (FTTP) technologies also took place. Compared to FTTC,

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[6] ISPreview, 2008: BT reveals major £1.5bn next-gen fibre broadband plans, Source: https://www.ispreview.co.uk/news/EkEyEpAFykbCFYrArU.html

[7] Based on authors' own calculations.

[8] The BDUK program is an initiative of the Department for Digital, Culture, Media & Sport (DCMS) that aims to support broadband delivery through state aid or voucher programs in areas that are not considered as 'commercially viable' by the private sector.

[9] See `https://www.increasebroadbandspeed.co.uk/chart-of-bt-fttc-vdsl2-speed-against-distance-from-the-cabinet`

a full-fiber connection (like FTTP) uses fiber all the way from a local exchange (and later from the cabinet) to each property. But the number of postcodes with FTTP connections remained low, with less than ten thousand postcodes activated during this period (Figure 2). Another major commercial provider playing a part in superfast broadband delivery is Virgin Media, a cable broadband provider, which launched its 50 Mbps broadband service in 2008, followed by an upgrade to 100 Mbps in 2010.[10] Virgin Media delivers broadband services using its own network infrastructure which consists of the same coaxial cable that it uses for cable TV services. Its infrastructure covers only half of the UK and remained the same during the initial phases of the FTTC rollout.[11]

2.2 Broadband Coverage and Take-Up

In this section, we examine the nationwide trend in superfast broadband take-up in the aftermath of the FTTC rollout. The coverage or availability of new technology alone does not guarantee its universal take-up (Greenstein and Prince, 2006). Figure 3a illustrates that the take-up of superfast broadband has been slower than its availability. The Office of Communications (Ofcom) defines superfast broadband as connections that deliver download speeds of at least 30 Mbps, which are typically supported by fiber-based or cable broadband technologies. From Ofcom's data, we can see that 91% of the premises in the UK had access to superfast broadband by 2017. However, less than 40% of the premises took up superfast broadband subscriptions. In recent years, the gap between coverage and take-up has narrowed to some degree. Nonetheless, as of 2021, approximately one-third of the premises still do not have superfast broadband subscriptions.

We then examine how the broadband technology mix has changed using data reported in Ofcom's 2020 Communication Market Report. Figure 3b reports the number of connections for each type of technology as a proportion of the total number of fixed broadband connections during that year. From this figure, we can see a gradual transition towards FTTC technologies. In 2013, ADSL held 70% of the broadband market and the market share for FTTC was only 10%. Since then the share of FTTC connections gradually increased but ADSL remained the dominant technology until 2017. By 2018, FTTC surpassed ADSL for the first time, and in 2019, it captured half of the market, with ADSL's share dropping to 27%. During this period, FTTP had a relatively low market share, reaching only 3% in 2019.

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[10] See `https://www.globenewswire.com/news-release/2008/12/15/389811/156365/en/Virgin-Media-Launches-the-UK-s-Fastest-Broadband.html`, and also `https://www.thinkbroadband.com/news/4441-virgin-media-announces-100-mbps-broadband-amp-q3-2010-results`.

[11] See Ahlfeldt et al. (2017) for more details.

Note that cable broadband held a steady share of the market at 19-20% throughout this period, which supports our previous assertion that cable coverage remained mostly unchanged during our study period.

To summarize, we find that although superfast broadband, enabled by FTTC technologies, quickly became available across most parts of the country, its take-up was slow. As a result, low-speed connections (i.e., ADSL) still represented a significant share of commonly-used technologies. The factors behind this slow take-up are important to understand, especially in light of the UK government's recent goal to expand the gigabyte broadband coverage to 85% of the UK premises by 2025 (Hutton, 2021). As our discussion shows, coverage alone does not guarantee that people will adopt high-speed broadband. Adoption depends on the economic values gained by the households from the usage of high-speed broadband. In this paper, we set to measure how people value FTTC deployment using housing price appreciation and how this valuation varies across neighborhoods with different skill or work-related attributes.

3 Data and Summary Statistics

We combine data from a number of sources to assess homebuyers' perceived value of fiber-enabled properties. This section describes the data sources and provides some descriptive statistics.

3.1 Housing Price Data

We collect property sale prices from 2008 to 2017 using the Price Paid Data (PPD) of the UK HM Land Registry. Under the Land Registration Act 2002 and the Land Registration Rules 2003, the UK HM Land Registry records all transactions and changes in property ownership rights including mortgage, lease, or right of way (Coulomb and Zylberberg, 2021). This granular data covers almost all residential property transactions in England and Wales. In addition to the sales price, it also provides other information about the property, such as the full address, types of buildings (detached, semi-detached, terraced, flat/maisonette, and others), and the construction period of the property. From this data, we exclude a small share of properties, reported as 'others', that do not fall into the four main categories of property types. Additionally, we have information about the date that the properties were constructed, and more specifically whether the property was built during the past ten years.

The second source of property-level data is the Energy Performance Certificates (EPCs) that help supplement the relatively limited property characteristics provided by the PPD. The aim of these certificates is to provide information about the energy performance of a building, but they also include other property characteristics such as total floor area in square meters, the age of a building, and the number of rooms. We match this information with the property transaction data using precise address matching. We exclude a few observations when the reported number of habitable rooms is zero or more than twelve. We also exclude the properties that fall outside the range defined by the 0.1 and 99.9 percentile values of total floor area or price per square meter. The EPC data has a good coverage and accounts for 85.3% of registered property sales available in the PPD.

Neighborhood Characteristics. To study how housing market reactions to FTTC activation vary across neighborhoods, we augment our analysis with information from the 2011 Census. In this paper, we refer to middle layer super output areas (MSOAs) as neighborhoods. These are census-defined geographies with a population of 15,000 people (or 6,000 households). Using census data we first calculate the MSOA residents engaged in high-skilled occupations as a proportion of all working residents. Second, we use the four-digit occupation classes based on the Standard Occupational Classification (SOC) 2010 and construct an index of digital occupation intensity for neighborhoods. We measure the digital intensity of occupations using the universe of online job postings in 2012 and 2013 across the United Kingdom that is collected by Lightcast.[12] Furthermore, we calculate the incidence of WFH for each MSOA using census data. All this information helps us characterize different segments of the population that might exhibit higher returns to the provision of the new fiber broadband infrastructure.

3.2 Broadband Technologies

The key information required for this paper is the precise spatial and temporal description of FTTC deployment. To collect this, we web-scrape different datasets from online resources that are built using data sourced from Openreach Limited, a subsidiary of BT. Openreach maintains the telephone cables, ducts, cabinets, and exchanges connecting nearly all homes in the country. We first extract information on the local distribution nodes (i.e., street cabinets) including their exact locations and FTTC activation dates. In total, we find information on 104,425 cabinets. We link the cabinets to their respective LEs which are the regional distribution hub. A second dataset helps us to establish the link between each unit

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[12] Formerly known as Burning Glass Technologies.

postcode in the country and the cabinet through which it is fiber enabled. Armed with this very granular information, we calculate the straight-line distance between the postcode of a property and the postcode in which the connecting cabinet is located. The activation dates help us determine when FTTC becomes available at each postcode and the distance from the cabinet helps us gauge the range of FTTC speed available in the postcode.

Broadband Speed. Among other information, we also make use of the postcode-level information on broadband speed published by Ofcom as part of its Connected Nations series. Ofcom publishes this data annually since 2013 and we use it to check how speed varies across neighboring postcodes with and without FTTC connections.

Descriptive Statistics. In Table 1, we report the summary statistics for the key variables of our analysis. The average sale price is £194,030 during the study period from 2008-17. In our sample, we truncate the sales price to £500,000. The average property in our sample has 4.5 rooms and 85 square meters of floor area. 19% of them are detached homes, 33% semi-detached, 34% terraced houses, and the rest are flats (or maisonettes). 20% of the sold properties were leasehold. Only 1% of the houses in our data are newly built and only 17% of the properties are built since 1990.

The average distance of the properties in our sample is 280 meters from the cabinets and 1.56 kilometers from the LEs. We report the average broadband speed for the last four years of our study period. During this period, the average download speed increased from 27 Mbps to 49 Mbps in our sample postcodes.

4 Empirical Strategy

4.1 Spatial Discontinuity in FTTC Activation

In this section, we explain how we use spatial discontinuity in FTTC activation to estimate house price differentials. The ideal experiment would involve comparing two otherwise similar properties, one with an FTTC connection and another without, to see whether the FTTC-activated property sells at a higher price. To measure this FTTC premium in a quasi-experimental setup, we compare the sale prices of properties across neighboring postcodes that have been activated in different years.

When BT undertook the plan to connect millions of households with fiber broadband, the massive scale of the operation put engineers and other resources in high demand. Hence, Openreach (the infrastructure division of BT) carried out the task in multiple phases. The bulk of the commercial rollout was completed in eleven phases from 2009 to 2013-14. During each phase, BT announced an upgrade of a list of LEs. Usually, the entire area within an LE would not get fiber enabled at the same time. As discussed in Section 2, FTTC activation involves deploying fiber from an LE to the street cabinets. With the line between the local exchange and street cabinet upgraded, a fixed number of adjacent properties could get FTTC broadband. According to a report by the House of Commons Culture, Media and Sports Committee (2016), Openreach or other broadband delivery programs often prioritized areas that are easier to connect, creating a 'patchwork' of connections across the premises.[13] For the median local exchange in the UK, the first round of FTTC upgrade installed 57% of the cabinets, serving 72% of the premises in the area.[14] This gradual rollout over several phases–both within and across LE areas–resulted in a fragmented coverage of FTTC availability across the country. Figure 4 shows an example of the variation in FTTC rollout for Central London.

The endogenous nature of the rollout means that we cannot readily compare areas activated in different years. We circumvent this problem by focusing on the boundary of such areas and by comparing postcodes that got FTTC activated with the postcodes that narrowly missed it. This strategy gives us a sample of properties located in adjacent postcodes which share similar local amenities (or disamenities). To locate the boundary of areas with different activation years, we first merge adjacent postcodes with the same year of FTTC activation and construct larger polygons.[15] The boundaries of these polygons provide sharp discontinuities in the availability of FTTC broadband. We hereafter refer to these boundary lines as 'activation boundaries'. Our identification comes from exploiting the spatial discontinuity in FTTC activation within a narrow distance from these activation boundaries. This approach relies on the assumption that the local characteristics (e.g. access to supermarkets, parks, or stations) change gradually as we go farther away from the boundary while FTTC availability sharply changes across the boundary.

Figure 5 illustrates our discontinuity design. The green area shows postcodes that have been FTTC enabled since 2011. Some of the adjacent postcodes, shown by the yellow area, were not activated until 2015. The red dashed line between the green and yellow areas is the activation boundary that shows a sharp divide in FTTC availability between 2012 and

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[13] See CMS Committee, Establishing world-class connectivity throughout the UK, Second Report of Session 2016–17, HC 147, Published on 19 July 2016.

[14] From authors' own calculations.

[15] See Appendix A.1 for more details.

2015. The red dots in the figure mark locations of properties sold in these postcodes. Our study design involves comparing neighboring properties located in such pairs of areas across the activation boundary.[16]

4.2 Validity of Discontinuity Design: Evidence from Speed Data

In this section, we present evidence that broadband speed shows a discontinuous jump across the boundary lines following FTTC activation of the early-activated side. We use the distance of our sample postcodes from the activation boundary and plot the average download speed on both sides of the boundary. By the year Ofcom makes this data available, many areas in our sample are activated on both sides of the boundary. Hence, we check for this speed discontinuity using only a subsample of postcodes. Figure 6 shows how broadband speed responds after one, two, and three years of activation. The vertical line at zero represents the activation boundary. We measure the distance of postcodes from the boundary in meters along the horizontal axis. The right side of the vertical line (i.e., positive distance values) shows postcodes that have already been activated and the left side (i.e., negative distance values) shows postcodes that are not activated by that year. We use data from 2013-2016 to plot the average download speed for each fifty-meter bin. Panel 6a, 6b, and 6c show how download speed changes after one, two, and three years of activation, respectively. For example, for the year 2013, we compare treated postcodes in which one side of the boundary is activated in 2012 (i.e., one year of activation) with neighboring (control) postcodes that are not going to be activated until a year later (in 2014). Stacking four years' observations from 2013-2016 this way, Panel 6a shows a slight jump in download speed when one side remains activated for a year. The sharp discontinuity is more visible after two or three years of activation (Panel 6b or 6c).[17] These figures confirm that the sharp discontinuity in FTTC availability translates into a discontinuous jump in the actual broadband speed available to the customers. Also, the gradual widening of the speed gap aligns with what we know about take-up rates slowly catching up with the availability of FTTC broadband.

The lack of data for earlier years does not allow us to check whether pre-FTTC broadband speed was the same across boundaries for the entire sample. For this reason, we perform a placebo check only for the postcodes that are not activated (or just activated) in 2013 or 2014 (Figure 7). Panel 7a compares postcodes that are just activated (i.e., zero year of

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[16] The average distance of the properties in our housing dataset is 170 meters from the activation boundary. In our preferred specification, we use properties that lie within 200 meters from the boundary.

[17] Note that the average download speed reported here is calculated based on actual speed collected by telecoms operators and is influenced by customer subscriptions, distance from cabinets, and network disturbances, among other factors.

activation) on one side of the boundary with postcodes on the other side not getting activated for another two years. Panel 7b depicts pairs of areas where one side of the boundary is activated the next year (i.e., -1 year of activation) and the other side is activated two years later. From these figures, we do not see any speed differences before FTTC activation or immediately in the year of activation. This exercise supports the idea that prior to FTTC activation the neighboring postcodes across these boundaries had access to similar broadband technologies and the availability of FTTC broadband infrastructure created a marked difference in available speed across the boundaries.

4.3 Estimation

We focus on BT's commercial FTTC rollout by considering only urban postcodes across boundaries for which at least one side was activated by 2013.[18] To keep the local characteristics similar on both sides of the boundary, we also restrict our sample to the properties located within 200 meters of the boundary.[19] Using the sample of properties sold between 2008 and 2017, we estimate the following hedonic pricing equation:

$$ln(price)_{ijkt} = \beta_1 FTTC\ activated_{jkt} + \Gamma X_{ijkt} + \mu_j + \rho_{kt} + \epsilon_{ijkt} \tag{1}$$

In the equation above, i indexes properties sold, j indexes postcodes, k indexes grids in which the boundary is located, and t indexes years. We use the log of the sale price of a property as the dependent variable. *FTTC activated* is a binary indicator for the year after the street cabinet of a postcode gets FTTC enabled. X includes property characteristics, such as total floor area, indicators for property type (detached, semi-detached, terraced, or flat), lease type (freehold or leasehold), an indicator for newly-built properties, and categories for age. μ denotes postcode fixed effects and ρ denotes grid fixed effects. We construct the grids by dividing the entire country into one-by-one kilometer cells (see Figure 4). This helps us to identify the location of each boundary. If a cell is from a dense neighborhood and therefore includes multiple boundaries, we break down the cells further into 100 square meters blocks. We use these grids to control for time-variant location fixed effects across both sides of the boundary while controlling for time-invariant fixed effects by unit postcodes. In other words, each grid-boundary pair helps us capture the trends in local housing markets (across activation boundaries) while the postcode fixed effects help us control for any specific

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[18] FTTC activation in early years was concentrated in urban areas. Since 2014, a mix of urban and rural postcodes were activated. This is due to the government's support for rural rollout programs under BDUK. To keep our sample homogeneous, we drop any rural postcodes even if they were activated by 2013.

[19] We check our results for different distance values from the boundaries and find similar estimates.

characteristics of the housing blocks.[20]

We cluster the error term (ϵ) at the level of treatment variation in our design. In this case, these are the areas across each side of the boundary within a grid cell. This approach follows Bertrand et al. (2004) and helps to overcome the potential serial correlation and heteroskedasticity problems. A few points about our sample construction process are important to note here. Our sample comes from urban areas, where property sale data is less sparse. Still, we take several steps to make sure that we have enough observations to estimate the granular fixed effects in our hedonic regression. First, we check that we have sufficient observations from both sides of the activation boundary. Second, we restrict our sample to postcodes that have at least five transactions over the sample period. Finally, we exclude grids that have less than fifty observations, which is the bottom quintile of the grid size distribution. A final restriction on the grid cells is that we only consider those grids that have at least 10% of the observations on the early-activated (or late-activated) side of the boundary.[21] These steps bring down our effective sample to 206,579 property transactions across 49,094 postcodes.

Our identification relies on the staggered difference-in-differences (DID) design in which the treatment (FTTC activation in this case) occurs over different years. The two-way fixed effects (TWFE) model has been a canonical specification of the ordinary least square (OLS) model to estimate the causal effect in such setups. However, several recent papers have shown that in the presence of treatment effect heterogeneity, the TWFE estimates can be biased despite satisfying the conventional (strict) exclusion condition of parallel trends (and no anticipation). This problem occurs when treatment effect varies over time or across treated groups (Borusyak and Jaravel, 2017; Goodman-Bacon, 2021; Sun and Abraham, 2021; De Chaisemartin and d'Haultfoeuille, 2020; Callaway and Sant'Anna, 2021).

In particular, the bias occurs when the TWFE estimation compares the late-treated units and the early-treated units while the latter serves as the control group. In this case, the estimate will suffer from a downward bias proportional to the increase of the treatment effect over time. This might apply to the current setup since the adoption of FTTC broadband takes time to mature and become widely adopted by the users as illustrated in Figures 3a and **??**.

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[20] Unit postcodes in the UK have a size of fifteen households on average. It can identify houses up to specific blocks (or even a large building).

[21] This restriction on grids is to ensure that we have sufficient observations on both sides of the boundary so that our boundary-specific year fixed effects could capture any year-to-year fluctuations in local housing markets.

Following Goodman-Bacon (2021), Sun and Abraham (2021), and Callaway and Sant'Anna (2021), we limit our post-treatment sample to the periods during which we can compare each treated group to the not-yet-treated groups. For example, in our sample, each pair of neighboring postcodes across the activation boundary has an early and late FTTC activation side. We track each pair from 2008 up to the date when FTTC broadband becomes available for the late adopter. Hence, our sample design is such that the area with the early activation year acts as a treated group and the area with the late activation year acts as a control group that never gets treated during this period.

Robustness Checks. Our first set of robustness checks relaxes the restrictions on sample construction discussed earlier. Specifically, we check our main results without imposing any restrictions on the number of observations per grid cell and without restricting the sample within 200 meters from the boundary. We also check the sensitivity of the estimates to the inclusion of property characteristics. As an additional exercise, we test our estimates by the distance of each property from its cabinet. As explained in the previous sections, FTTC broadband provides strong speed uplift for properties located within a shorter distance from the cabinet. To test this hypothesis, we include interaction terms between the FTTC activation dummy and indicators for a range of distances, such as <200 meters from cabinets, 200-400 meters from cabinets, and > 400 meters from cabinets. Specifically, we estimate the following regression:

$$\begin{aligned} ln(price)_{ijkt} = \beta_1 FTTC\ activated_{jkt} + \beta_2 FTTC\ activated_{jkt} \times \mathit{(0.2\text{-}0.4\ km\ from\ cabinet)}_{jk} \\ + \beta_3 FTTC\ activated_{jkt} \times (> \mathit{0.4\ km\ from\ cabinet})_{jk} \\ + \Gamma X_{ijkt} + \mu_i + + \rho_{kt} + \epsilon_{ijkt} \end{aligned}$$

According to the technical properties of FTTC, we expect to see higher house price premiums for properties located closer to the cabinet compared with the ones that are farther away. In Appendix Section A.3, we also check the sensitivity of our results to the exclusion of postcodes that might have cable coverage. Note that we do not observe the availability of cable broadband directly. We infer the presence of cable or full fiber from observing the maximum download speed reaching above the 80 Mbps threshold, which is the highest attainable speed for FTTC.

5 Results

This section presents the findings of our paper. Section 5.1 shows our main estimation of housing price responses to FTTC activation using the spatial discontinuity at the boundary of areas activated in different years. We also check the robustness of our results and examine differential price responses across locations. In Section 5.2, we propose a stylized model that shows why households value superfast broadband. We then estimate the heterogeneous responses across neighborhoods with different characteristics to see which group gains the highest digital premium. In Section 5.3, we use our causal estimates to check the cost-effectiveness of FTTC installation.

5.1 Housing Price Responses to FTTC Activation

5.1.1 Main Results

Our estimates use the variation in house prices across boundary lines to measure the FTTC premium. We show these baseline results in Table 2. Column 1 shows our preferred specification in which we restrict our sample to the properties located within 200 meters from the activation boundaries. Our estimation shows that FTTC activation increases house prices by 0.7%. This estimate is statistically significant with standard errors clustered at each side of the boundary within a grid. Our main specification includes postcode fixed effects, year fixed effects at the grid-boundary level, and a set of controls for property characteristics. In Columns 2 to 4, we show that the price response is robust to relaxing some of the restrictions we impose to construct our sample. Column 2 excludes the restriction that at least 10% of the observations within each grid should come from treated (or untreated) postcodes. We impose this restriction to ensure that each grid has sufficient observations on both sides of the boundary. Column 3 relaxes the 200 meters limit on the distance from the boundaries and includes properties located farther away from the boundary.[22] Column 4 reports the results without including the property-level controls. In all cases, we get statistically significant point estimates which vary from 0.7 to 0.83%.

Price Responses by the Distance from the Cabinets. Column 5 in Table 2 presents the results for the regression, including interaction terms between the FTTC activation dummy and the discrete categories measuring the distance from the cabinet. We measure the straight-line distance between the postcode centroids of the property and the cabinet which connects the property to the FTTC infrastructure. We examine the price responses

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[22] In the unrestricted sample, 99% of the properties sold lie within 766 meters of the activation boundary.

to FTTC activation of properties located within 200 meters, 200-400 meters, and beyond 400 meters from the cabinet. We find strong price effects for the first two distance bins, i.e., within 400 meters of the FTTC cabinet. The effect diminishes down after 400 meters. These findings are consistent with the technical properties of FTTC connections—the speed boost is the strongest for the properties located closer to the cabinet and dissipates as the distance from the cabinet increases.[23]

Parallel Trend across Boundaries before Activation. In Figure 8, we show the dynamic effects of FTTC activation. Prior to FTTC activation, house prices appear to be the same across the postcodes that are activated early (i.e., treated) and activated late (i.e., untreated throughout the study period). Following activation, we see a jump in house prices and the effect amounts to 1% after three years of activation. This figure confirms the validity of our design that after controlling for property characteristics, postcode fixed effects, and grid-boundary-year fixed effects, there is no prior systematic price difference in the areas considered across the activation boundaries. The bottom panels of Figure 8 plot the dynamic effects when we relax some of the restrictions imposed on the sample. Panel 8b and 8c respectively produce the corresponding dynamic-effect regressions of Columns 2 and 3 of Table 2. Both panels show similar price jumps following activation.

5.1.2 FTTC Premium across Locations: London vs. the Rest

We next examine how FTTC premiums vary across locations. Table 3 reports the estimates for the Greater London region and the rest of England and Wales. In Greater London, we observe a statistically significant price increase of 1.7% due to FTTC activation. For the rest of the country, we find a 0.7% FTTC premium, which is close to our baseline estimate. Since London has a smaller sample, we expand the sample size by including properties located within a 30 km radius of the center of London. We calculate the straight-line distance between the postcodes in our sample and the centroid of London. We use 30 km as a cutoff point because the 2011 Census data shows that almost 90% of the working population in England commute within this distance. The extended sample includes parts of the East and South East of England in addition to the Greater London area. Columns 3 and 4 of Table 3 present these results. We estimate an FTTC premium of 1.8% for properties within 30 km of London. For the rest, the price premium is only 0.6%, which is approximately one-third of the estimated premiums observed in London and its surrounding areas. These findings suggest that location is a strong indicator of the gains from FTTC broadband.

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[23] We also test the sensitivity of the cabinet distance bins with a range of other technologically meaningful bins (less than 250 m and more than 250 m) and the results always show very similar behavior.

One of the contributing factors to stronger price responses in London could be the early exposure to the FTTC rollout. London was prioritized during the early phases of the rollout. Among the boundaries compared across 508 grids in London, 74% were activated on one side of the boundary by 2011, and 97% were activated by 2012. For the rest of the country, only 40.4% of grids were activated by 2011, and 76% were activated by 2012 on one side of the boundary. As we have seen in our comparison of broadband speed across the boundary (Figure 6), there is a lagged response in FTTC take-up. The early exposure to FTTC availability could mean that we see a more mature response for the London market compared to the rest of the country.

London is also ahead of other UK regions in terms of economic performance. According to Office of National Statistics (ONS) estimates, labor productivity measured by gross value added per hour is 1.5 times greater in the London region than the average of other UK regions. Large urban hubs like London often work as economic centers, supported by agglomeration forces (e.g. knowledge spillovers) and modern transport networks (Heblich et al., 2020), which attract businesses and workers from the rest of the country. In 2010, the City of London had the highest job density with 68 jobs per working-age resident, which was significantly higher than the national average of 0.76 jobs per working-age resident.[24] In the next section, we take a closer look into the issue of how differential economic characteristics of the local residents could give rise to heterogeneous FTTC response.

5.2 Heterogeneous Responses to FTTC Activation

We first propose a simple model to discuss how households benefit from high-speed broadband. This exercise provides the basis for our analysis of how different neighborhood compositions lead to uneven responses to FTTC activation. Specifically, we examine the occupational composition and work arrangement of neighborhoods in order to characterize locations with varying economic incentives to use FTTC broadband.

5.2.1 A Simple Stylized Model of Broadband Choice

We consider a simple model of household consumption choice to guide our heterogeneity analysis across neighborhoods. As in Glaeser and Gottlieb (2009), we assume households optimally divide their income between the consumption of a non-housing good, C, and a housing good, denoted by H. The housing good is a combination of different amenities. We denote the amenity related to the quality of home broadband by h_b, whereas h_s denotes

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[24] Source: The London Datastore.

the continuum of all other amenities. Spending on broadband amenities not only allows the household to derive utility but it could also increase household income. In this setup, the household's problem can be written as follows:

$$\begin{aligned} max_{\{C,h_s,h_b\}} \quad & U(C,H(h_s,h_b)) \\ & s.t. \\ & C+P(h_s,h_b) \preceq W(h_b) \end{aligned} \tag{2}$$

In the budget constraint, $P(h_s,h_b)$ shows the price of the housing good that is a hedonic function of broadband amenity h_b and other amenities h_s. The price of the non-housing good is normalized to 1 and $W(h_b)$ shows the income of the household that depends on the quality of broadband at home. For a utility-maximizing household, the optimal choice is obtained where the indifference curve is tangent to the offer curve. This allows us to infer the household's perceived value of the amenity from the local slope of the hedonic price function at the optimal level. This is the well-known insight in Rosen (1974) which suggests that the premiums in housing prices (or rents) reflect the household's willingness to pay for their amenities. Solving for the shadow cost of the budget constraint, the first order condition with respect to the broadband amenity (h_b) gives us the following:

$$P_{h_b}(h_s,h_b)|_{h_s^*,h_b^*} = \underbrace{\frac{U_{h_b}(C,H(h_s,h_b))}{U_C(C,H(h_s,h_b))}|_{C^*,h_s^*,h_b^*}}_{Consumption\,amenity} + \underbrace{W_{h_b}(h_b)|_{h_b^*}}_{Production\,amenity} \tag{3}$$

The left-hand side of equation 3 shows the premium price of the housing good for a higher broadband quality, while the right-hand side captures the household's willingness to pay. Unlike the traditional hedonic price model, the perceived value of home broadband has two distinct components capturing the effects of both increased utility and a relaxed budget constraint. The consumption amenity facilitates households' consumption of online products and services. In this regard, it is akin to physical consumption amenities such as restaurants and gyms [25]. The production amenity captures the perceived benefit for households from enhancing their ability to fully or partially WFH and earn more.

The literature on early-generation broadband technologies highlights the importance of their productive use. For example, information search or browsing results in better employer-employee match (Zuo, 2021; Gürtzgen et al., 2021; Denzer et al., 2021; Bhuller et al., 2019). Two distinguishing features of fiber broadband enhance its productive amenities significantly

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[25] See the list of papers that study the effect of access to the consumption amenities on local residents' welfare: Glaeser et al. (2001); Couture (2016); Davis et al. (2019); Su (2022)

compared to the previous generation of ADSL technologies. These are high upload speeds and reliable connections (Ofcom, 2022). The distinctive characteristics of fiber broadband could give rise to heterogeneous responses across neighborhoods in several ways. First, the literature on the impact of access to high-speed broadband at the workplace suggests that skilled workers experience higher gains (Akerman et al., 2015; Hjort and Poulsen, 2019). The production amenity could also generate similar skill-biased benefits that apply to home broadband. In particular, the gain can be high for specific types of occupations that require workers to stay digitally connected or work longer hours.[26] Second, the group that receives the most benefit from productive amenities is the WFH population. The recent evidence from the pandemic supports the existence of this channel. During the COVID-19 pandemic, social distancing measures forced many individuals to work remotely. However, the extent of individual adaptability and income loss varied substantially across different groups (Sostero et al., 2020; Bick et al., 2020; Stantcheva, 2022; Bonacini et al., 2021). Chiou and Tucker (2020) show that a substantial part of these differences can be explained by the disparity in individual access to high-speed internet at home. Based on these insights, we next examine how the perceived value of access to fiber broadband varies across neighborhoods with different work patterns.

5.2.2 Heterogeneous Premium: Occupational Composition

To measure the skill-biased premiums of FTTC broadband, we characterize neighborhoods using two metrics. First, we use a simple measure of the neighborhood share of skilled or professional occupations. For this part of the analysis, we consider census-defined middle layer super output areas (MSOAs) as neighborhoods, which represent smaller areas within the local authority boundaries.[27] Second, we calculate the share of residents engaged in digital occupations to locate the clusters of the digitally savvy population who are likely to be early adopters of new technology.[28] To capture the baseline composition of neighborhoods, we use the census data from 2011, which comes from the early period of the FTTC rollout. The census classifies all employed residents (aged 16 and over) into occupational groups using the Standard Occupation Classification (SOC) 2010. We calculate the MSOA share of employed

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[26] In an early paper, Autor (2001) outlines how the internet could reshape labor service delivery as workers do some or all of their work from home or outside the office. We expect this trend to only strengthen over time as technologies evolve to deliver faster internet. The author also argues that, with the internet increasing workers' productivity at home, it could encourage workers to channel more hours from leisure to work.

[27] MSOAs have a minimum population of 5,000 and an average population of 7,200. Based on the 2011 Census, there are 7,201 MSOAs in England and Wales.

[28] The underlying assumption is workers with similar characteristics cluster geographically.

residents who are engaged in professional or high-level managerial jobs.[29] Using separate median values for the sample within and outside the 30 km radius around London, we divide the neighborhoods into two groups: MSOAs with relatively low (below-median) shares of professional occupations and high (above-median) shares of professional occupations.

For our second measure, we use job postings data from Lightcast in 2012 and 2013 to determine the digital intensity of occupations. Using the information on the required skills from the job adverts, we calculate a measure of the digital intensity of occupations by the share of job postings within each four-digit occupation code that ask for information technology (IT) related skills.[30] Using this measure of digital intensity, we then calculate a weighted sum of residents employed in different digital occupations at the neighborhood level. We then calculate the share of digital-intensive occupations out of the total number of working residents in all occupations.[31] Finally, we divide the neighborhoods located within or beyond the 30 km radius of London using separate median values for the share of digital occupations.

Table 4 presents our results by neighborhood shares of professional and digital occupations. Each column shows a separate regression estimated for a subsample. Columns 1 and 2 report the results for neighborhoods close to London. Neighborhoods with above-median shares of skilled professionals show a strong FTTC premium of 2.2%, whereas the neighborhoods with below-median shares exhibit a point estimate below 1% which is statistically insignificant. The skilled neighborhoods outside London also exhibit a statistically significant FTTC premium of around 1%. In Panel B, we divide the neighborhoods by their shares of digital occupations. London neighborhoods with above-median shares of digital occupations show a large FTTC premium of 3.4%. Outside London, the magnitude of the FTTC premium is about a fifth of the estimate for London.

These results highlight the gap in the digital premiums between neighborhoods with high and low-skilled (or digital) occupations. This gap could be driven by an income ef-

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[29] The following sub-major groups of SOC 2010 fall into this category: 11 (Corporate managers and directors), 21 (Science, research, engineering, and technology professionals), 22 (Health professionals), 23 (Teaching and educational professionals), and 24 (Business, media, and public service professionals).

[30] Appendix Figure A1 shows the top-twenty IT-related skills for the twenty most frequently occurring three-digit occupation groups.

[31] We define the neighborhood share of digital occupation as,

$$\%\ \textit{digital occupation} = \frac{\sum_{SOC}(\%\ \textit{requiring digital skills} \times \#\ \textit{employed at 4-digit SOC})}{\textit{Total}\ \#\ \textit{employed residents}}.$$

fect—residents engaged in high-skill occupations are also high earners and could afford to spend more on consumption amenities that arise from bandwidth-intensive digital services, e.g., streaming or gaming. However, as we show in Appendix Table A2, the larger FTTC premium in skilled neighborhoods does not solely occur from high-income (or low-deprivation) neighborhoods. In panel A of the table, we divide the neighborhoods into four groups: low-skill & low-income neighborhoods, low-skill & high-income neighborhoods, high-skill & low-income neighborhoods, and high-skill & high-income neighborhoods. We use the average income of neighborhoods from the year 2011-12 and divide the sample by the separate median values within and outside London. We also calculate the average deprivation rank of the MSOAs to classify them based on their level of deprivation. The skilled neighborhoods show a strong and significant response regardless of income status or levels of deprivation, which provides suggestive evidence that these results are not driven by income (or consumption).

On the contrary, the differential response could stem primarily from the differences in productive amenities which are tied to neighborhoods' skill or occupational composition. Akerman et al. (2015) documents the skill complementarity of workplace broadband adoption for high-skilled workers engaged in non-routine abstract tasks. For home broadband connections, a similar productive use can arise if workers bring work at home. Although WFH was less frequent in the early 2010s, it was more prevalent among skilled workers. According to the American Time Use Survey (ATUS) around 15% of working hours were performed at home in the US from 2011 to 2018. Moreover, data processing services, specialized design services, and other professional services are the top three industries in terms of the share of work done at home, which was above 50% even before the pandemic. In terms of occupations, computer scientists and artists appear in the top-five remote work occupations (Hensvik et al., 2020).

5.2.3 Heterogeneous Premium: WFH Share

Another group who might strongly benefit from high-speed internet is the WFH population. The pandemic has made it evident that high-quality and stable home internet connections are essential to ensure higher productivity of remote workers (Barrero et al., 2021). Although our setup precedes the pandemic, this is also a period of rising alternative work arrangements or solo self-employment activities in the UK (Tatomir, 2015; Giupponi and Xu, 2020).[32]

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[32] The share of self-employment rose from 13% in 2008 to 14.9% in the first quarter (Jan-Mar) of 2016, contributing greatly to UK's economic recovery from the 2007 recession (ONS, 2016).

Our measure of WFH comes from the census origin-destination files and includes both employees and self-employed personnel who use their homes as the premise of work.[33] Using this information, we calculate the incidence of WFH as the MSOA share of working residents who mainly work from home. The median share of WFH in our sample is 8.7%, with the sample within 30 km from London showing a slightly higher WFH share of 9.4% (8.6% for the rest of the country). Using the median values for London and the rest, we divide the sample into neighborhoods with high and low shares of WFH. Table 5 reports these results. Among neighborhoods close to London, the ones with a lower share of WFH do not show any significant response, whereas neighborhoods with above-median WFH show a 2.5% price jump. We find the opposite pattern outside London—neighborhoods with a lower share of the WFH population show a stronger response (0.9%) to FTTC activation.

We next divide the WFH population into those who work as employees (i.e., teleworkers) and those who are self-employed or freelancers.[34] We examine the results based on the share of each type of WFH. For both types, we find that London neighborhoods with a higher share of teleworkers or self-employed workers show a larger FTTC premium (2.1% and 2.4%, respectively). Areas outside the 30 km radius of London show an interesting pattern—neighborhoods with a higher share of employees working from home show a statistically significant response, whereas neighborhoods with a higher share of self-employed workers do not show a similar response. The lack of response outside London in neighborhoods with a high concentration of self-employed individuals could result from differential characteristics of self-employed workers in those neighborhoods. According to the 2011 Census, a higher share of WFH in London is concentrated in high-skill occupations such as professional or technical occupations, whereas outside London a relatively larger share is engaged in trades. In terms of industries, London has a notably higher share of WFH in financial, real estate, professional and administrative activities.

Our results suggest that neighborhoods with larger clusters of WFH population get a higher value from high-speed broadband. This finding comes from a period prior to the pandemic and for early generations of teleworkers and freelancers. The wider gap in FTTC premium across London neighborhoods shows that London has been ahead of the curve in terms of establishing hybrid and digitally intensive work arrangements.

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[33] The census data provides a tabulation of residents by their areas of the workplace. A separate code identifies those who mainly work at or from home. The questionnaire asks, "in your main job, what is the address of your workplace?" The answer provides either the full address of work or chooses one of the following options: mainly work at or from home, offshore installation, or no fixed place.

[34] This division is available only at the local authority level. We use the respective shares to extrapolate the division at the MSOA level.

5.2.4 Heterogeneous Premium by Work Location

In this section, we examine how the price response varies based on work locations. Since the digital premium is much higher for the London area, we examine to what extent the connectivity to the core economic areas of London matters. Using the 2011 Census origin-destination files, we calculate commuting outflows from each MSOA to the fourteen local authorities which constitute Inner London.[35]

Within Inner London, the three boroughs of the City of London, Westminster, and Camden have the highest concentration of economic activities and draw a large share of commuters from the surrounding areas. We also calculate the percentage of commuting to these central locations. Using the median values of commuter shares, we divide the MSOAs into two groups: neighborhoods with above-median (high) connectivity and below-median (low) connectivity to the economic center of London.

Figure 9 shows our estimated FTTC premium for different neighborhoods. Note that we estimate the response using the sub-sample for Outer London and outside the London region separately since the median commuting share varies widely across these two regions.[36] Our estimates show that, outside London, neighborhoods with high or low commuting shares to Inner London boroughs exhibit similar price responses. However, the premium is much larger and statistically significant for Outer London MSOAs that have above-median shares of commuters to Inner London. The left panel shows the results by neighborhood commuting share to the top-three boroughs of Inner London. The FTTC premium gets as high as 3.5% in neighborhoods with a high share of commuters to the three central boroughs. These results show that within London variation in FTTC premium is also related to the degrees of connectivity of different neighborhoods. Neighborhoods with stronger ties to the economic center of London perceive higher gains from FTTC activation.

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[35] These are Camden, City of London, Hackney, Hammersmith and Fulham, Haringey, Islington, Kensington and Chelsea, Lambeth, Lewisham, Newham, Southwark, Tower Hamlets, Wandsworth, and Westminster. In 2010, Inner London had a job density of 1.23 compared with a job density of 0.59 in Outer London and 0.77 in England. The average earnings by place of work was £696.1 in Inner London, £562.5 in Outer London and £504.5 in England (Source: Nomisweb).

[36] We do not use Inner London neighborhoods for this analysis as they have very few observations. Outer London constitutes nineteen local authorities that form the outer circle of the London region and has a median share of commuters of 28.5% to Inner London and 13.5% to the central locations of the City of London, Westminster, and Camden. For the areas outside Greater London, these shares are 2.4% and 1.4% respectively.

5.3 Cost-Effectiveness of Fiber Broadband Deployment

In the previous sections, we estimate the marginal willingness to pay for access to fiber broadband and examine how it varies across different subsamples of neighborhoods. In this section we put our causal estimates into context considering the cost-effectiveness of access to fiber broadband. First, we calculate the marginal value of fiber broadband spending,[37] which we define as the ratio of the marginal benefit of access to fiber broadband to households to the marginal cost of deployment. Our estimates show that every £1 spent on fiber broadband returns £2.4 on average and only 4.1% of neighborhoods do not have a premium high enough to justify the cost. Nevertheless, our baseline regression abstracts from substantial geographical differences in fiber premium across neighborhoods. The premium in London goes as high as £4,989 while it falls to £861 for the rest of the urban neighborhoods. Taking these regional differences into account, we find that although the average return of fiber infrastructure spending increases to £3.1, the share of low-premium neighborhoods that fail the cost-effectiveness test surges to 12.8%.

Second, we take one step further and account for geographical differences within and outside of the London areas. We have established previously that the fiber premium changes significantly across neighborhoods according to their shares of skilled workers, digital occupations, and WFH population. Taking into account these heterogeneities in our estimates, the marginal value of fiber broadband spending roughly stays the same ranging between £2.9 and £3.5. Nevertheless, the share of urban neighborhoods that fail to justify the deployment cost rises between 17% and 25%.

Third, using these differences in fiber premium across neighborhoods, we do a simple counterfactual analysis. We examine how the surge in WFH practices during the pandemic could change the perceived value of high-speed home broadband and alter our overall cost-benefit analysis. Our estimates show that with the WFH share changing from its 2011 level to the level observed in 2021, the share of urban MSOAs that fail to pass the cost-effectiveness test falls from 23.5% to 3.4%. The rest of the section discusses in detail how we calculate the marginal willingness to pay and deployment cost for FTTC broadband across different neighborhoods.

Willingness to Pay for Fiber Broadband: To calculate the marginal willingness to pay we use our hedonic price estimates. According to Kuminoff and Pope (2014), hedonic

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[37] This measure is inspired by the marginal value of public fund (MVPF) that is the ratio of the marginal benefit of a policy for society to its marginal cost to the government (Finkelstein and Hendren, 2020).

regressions measure the capitalization effect which is based on the market responses and could be different from the WTP measures. Kuminoff et al. (2013) discuss under what condition the estimates could be construed as welfare. While these are strict conditions, Banzhaf (2021) shows that under less restrictive conditions, quasi-experimental hedonic estimates could give a lower bound of welfare with respect to the ex-post price function. A complete welfare analysis of fiber technologies is beyond the scope of this paper. But we could use our causal estimates to measure how the gains from FTTC broadband are distributed across neighborhoods.

Sample Representativeness: The validity of this exercise depends on our sample being representative of all the neighborhoods (i.e., MSOAs) in England and Wales, which requires additional checks. The sample used in our regression analysis focuses on urban postcodes following BT's rollout strategy in the early phases (see Section 4.3). Since we employ a boundary discontinuity approach, we use postcodes that fall within a shorter distance from the boundaries. In this process, we only use 9% of the property sales that occurred during this period. Hence, using our regression estimates to calculate neighborhood-level premiums requires extrapolation to out-of-sample areas.

We check the comparability of our regression sample, which we refer to as the 'boundary sample', with the geographic composition of the out-of-sample areas. Our sample covers a wide geographic area with observations occurring from all nine geographic regions of England and also from Wales. London is under-represented in our sample and we have a relatively larger sample from South East and East of England. In total, we have observations from 3,393 MSOAs in our boundary sample, which covers more than half of the urban MSOAs. Table A3 compares the housing characteristics across our boundary sample and out-of-sample properties. We also report summary statistics for rural properties.

Compared to our sample, out-of-sample postcodes are more urban, that is, they cover a larger proportion from metropolitan areas. The average house price is slightly higher for out-of-sample properties, but the log of price, price per square meter, and the size of the properties are quite comparable. Column (2) in the table also shows a larger share of flats and leasehold properties—both seem to be a result of having more properties from London. Other property characteristics are comparable. Column (3) provides a sharp contrast between urban and rural properties and shows why we should not generalize our results to rural properties. In Figure A4 we show how property prices and sales have changed over the years across different samples. The price growth and sales (normalized by the level in 2008) both seem to diverge after 2014. But they largely move in the same direction across the samples. Finally, Table A4 compares the in-sample and out-of-sample areas in terms of demographic or economic characteristics. Using the 2011 census, we report this information at the output area (OA) level which is the finest geography available in the census.[38] We find that the out-of-sample OAs have a higher population density. Compared to our sample, the population in column (2) is slightly younger and more ethnic. The occupation and employment characteristics are largely comparable across samples.

Based on this discussion, we conclude that generalizing our estimates to out-of-sample areas applies these results to more urban and densely-populated areas compared to our sample. To some extent, this problem should be alleviated by the use of separate estimates for London and the rest of the country.

To calculate the average premiums across neighborhoods, we use our baseline estimate from Table 2 as well as the coefficients from Table 3, the latter giving separate marginal WTPs for London and the rest. We then multiply these coefficients by the median house prices of each MSOA in 2011. The average neighborhood has an FTTC premium of £1,259 according to our baseline model. When we take location differences into account, this number increases to £4,989 within 30 km of London and to £861 outside 30 km of London. To make a rough cost-benefit comparison, we compare these premiums to the deployment costs for FTTC upgrades, sourced from a technical report which was released prior to the infrastructure upgrade (Analysys Mason, 2008).

FTTC Deployment Costs: For the London region, we estimate the costs of £519 per property connected. This number is £533 for the rest of the urban postcodes. To calculate these costs we map our MSOAs to different geotypes used in Analysys Mason (2008). The cost of fiber deployment for these geotypes ranges between £381 for Inner London to £710 for cities with less than 200K population. To calculate the deployment cost for London and the rest, we take a weighted average of the costs in which we use the share of each type of MSOA (based on their population, density, etc.) as weights. The cost also includes a £100 for the engineer's visit which is required for installation in the early phases. Appendix A.2 discusses how we calculate the deployment costs in more detail.

We compute the marginal value of fiber spending across all urban MSOAs. According to our baseline model, which does not account for heterogeneity, we find that a £1 spent on

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[38] There are 19,762 OAs in our sample which is 11.03% of the total 179K OAs found in the housing data.

fiber broadband returns £2.4 on average.

Heterogeneity in FTTC Premiums across Locations: Using separate estimates for London and the rest increases the average return to £3.1, with a return as high as £9.6 for the London area and £1.6 for areas outside the 30 km radius around London. This simple extension of our baseline model, which takes into account the regional differences, reveals a sharp contrast in terms of the cost-effectiveness of fiber in different parts of the country. Our estimates show that all properties within 30 km of London easily pass the cost-benefit test, whereas 12.8% of the neighborhoods outside London with a low premium fail to justify the cost. We then examine how incorporating neighborhood heterogeneity changes our analysis.

Heterogeneity in FTTC Premiums across Neighborhoods: We check the cost-effectiveness of fiber installation considering the differences in the neighborhood share of skilled workers, the share of digital occupation, or the share of the WFH population. For this part, we utilize the four coefficients reported in columns 1-4 of Panel A in Table 4, which provide distinct estimates for below- and above-median neighborhoods based on the share of skilled workers, both within and outside London. We multiply these coefficients by the median house prices of each neighborhood in 2011, which gives us monetary values of FTTC premiums. We also calculate the premium values based on the neighborhood differences in the share of digital occupations (Panel B of the same table) and the differences in WFH share among employees (Panel B in Table 5). We compare these premiums with the cost of deployment to see how the marginal value of fiber broadband spending changes.

Figure 10 summarizes our findings based on different models. Our baseline model which does not consider heterogeneity suggests an average return of £2.4. Only 4.1% of urban neighborhood falls below the cost cutoff according to this model. When we consider regional differences, the average return increases to £3.1. However, the share of neighborhoods falling short of the cost cutoff also jumps to 12.8%. For our different models of neighborhood heterogeneity, we find that the marginal value of fiber broadband spending ranges between £2.9 and £3.5, while a larger share of neighborhoods (between 17% and 25%) show premiums less than the deployment cost. The comparison of cost-effectiveness across different models reveals an important message: while the large average return makes a strong case for fiber rollout, our heterogeneous estimates also show why commercial providers could be reluctant to rollout across all neighborhoods even within urban areas.

Changing Neighborhood Characteristics—Rise in WFH Share: Considering the heterogeneity in FTTC premiums also allow us to study a counterfactual case in which the characteristics of the neighborhoods change. Unlike the share of skilled workers or digital occupations, which changes gradually, WFH practices became more widespread during and in the aftermath of the pandemic. An implication of this change is that the perceived value of high-quality internet access at home is likely to increase for a significant part of the working population—both within and outside of London. In this part, we carry out a simple counterfactual analysis to see how the surge in WFH practices can alter the cost-effectiveness of fiber infrastructure spending. To this end, we calculate the FTTC premiums across neighborhoods considering the WFH share in 2021. We consider WFH share among employees (as opposed to the self-employed population) since this is the share that should see a drastic increase during the pandemic.

Figure 11 shows how the distribution of neighborhood premiums changes with the increasing share of the WFH population.[39] Note that our distribution of FTTC premiums applies to the reference population in these neighborhoods, not to the actual population who were living in these neighborhoods in 2021. An average neighborhood in 2011 gets £1,564 of premium value, which gives £2.9 as the marginal value of fiber spending. The share of urban neighborhoods that do not pass the cost-benefit test is 23.5% according to the 2011 distribution. For the level of increase observed in WFH share among employees in 2021, all the neighborhoods are above the 2011's median WFH share. Hence, we use the above-median coefficients (from Table 5 Panel B) to translate the benefits into monetary values. This gives us a higher marginal value of fiber spending at £3.8 for 2021. Moreover, most of the gains occur in neighborhoods that were at the lower end of the distribution, which means that with WFH share increasing at the 2021 level, only 3.4% of the urban neighborhoods fall below the cost threshold. This result lends strong support to a near-universal fiber coverage given that the change in WFH practices continues to persist.

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[39] Our measure for WFH share in 2011 comes from the 2011 census origin-destination files. Since the origin-destination files for the 2021 census is not released yet, we use the Annual Population Survey (2021) to gauge how WFH share changed across occupations. We use these occupational weights to calculate the shift in WFH practices at the neighborhood level using the number of residents in each three-digit occupation code from the 2021 census data. We plan to update our results with the direct measure of WFH at the neighborhood level once the 2021 census data is released.

6 Conclusion

The UK government is committed to investing in the digital infrastructure that is necessary to unlock the benefits of a digital economy. One of these core digital infrastructures which have seen marked improvement over the last decade is fiber broadband. High-speed broadband, enabled by fiber-optic cables, could transform the way we work, learn, or use healthcare and other services. And yet recent experience during the COVID-19 pandemic has revealed large disparities in broadband access. To shed light on the gap in digital access, the early literature on computer and internet use focused on the urban-rural divide. Studies have also shown internet adoption and usage to vary across income, education, and age. In this paper, we show how the skill or work patterns generate uneven responses to more recent generations of high-speed broadband.

We study the rollout of fiber-to-the-cabinet broadband that began around a decade ago in the UK. We examine the homebuyers' willingness to pay for FTTC connections using the sharp discontinuity at the boundary of areas that are FTTC enabled in different years. We find that the house price premium, generated by FTTC activation, is larger in London and its surrounding areas. Our results show that the response varies across neighborhoods with different compositions of skilled occupations. We also find that the neighborhoods with a higher concentration of digital occupations or WFH demonstrate a stronger response to FTTC availability. This latter part of our work might indicate a shift in the demand for high-speed broadband fuelled by the changing work arrangements during and after the pandemic.

Our paper is the first to map the infrastructure of fiber broadband and devise a strategy to estimate the causal effect of access to fiber broadband on housing values. Given the ongoing attempts for a full-fiber rollout, it is important to understand how the existing economic and social factors interact with new technology. Although network providers or regulators often claim success by pointing to near-complete coverage of services, our results highlight that the adoption is often a slow process and unevenly distributed based on the perceived benefits of new broadband technology. Without additional interventions, the expansion of full fiber alone might not suffice to achieve universal adoption across all regions.

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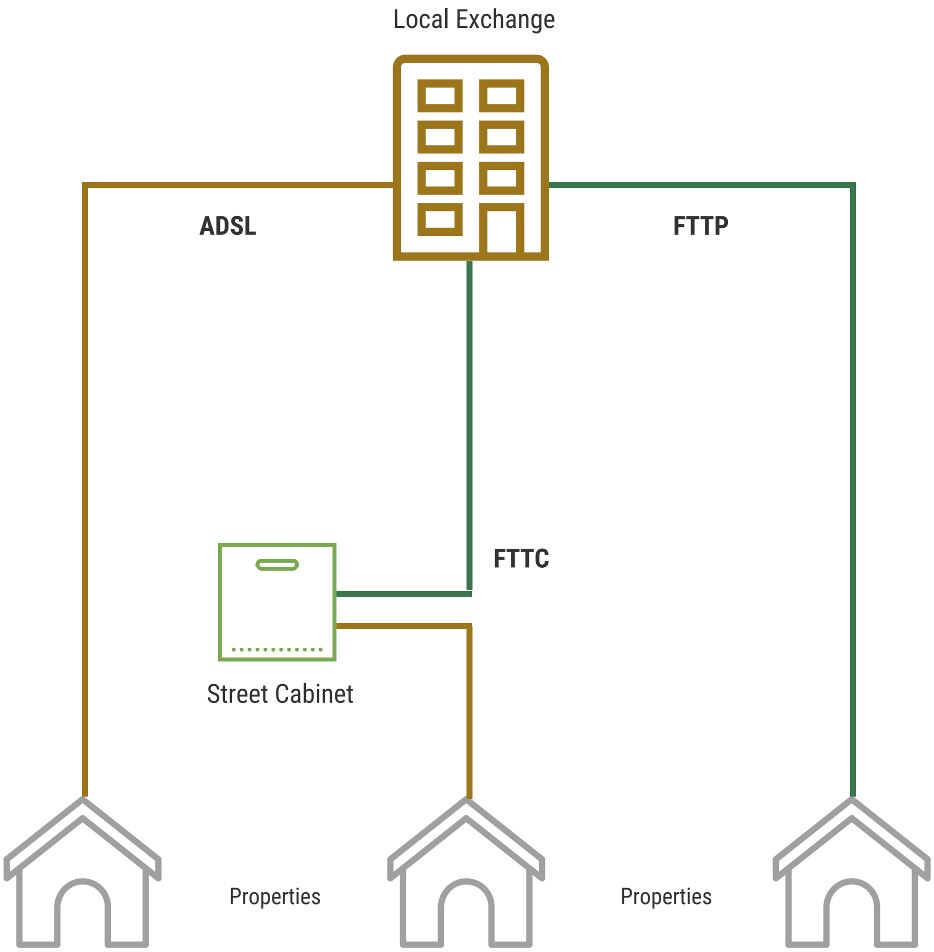
Figures

Figure 1

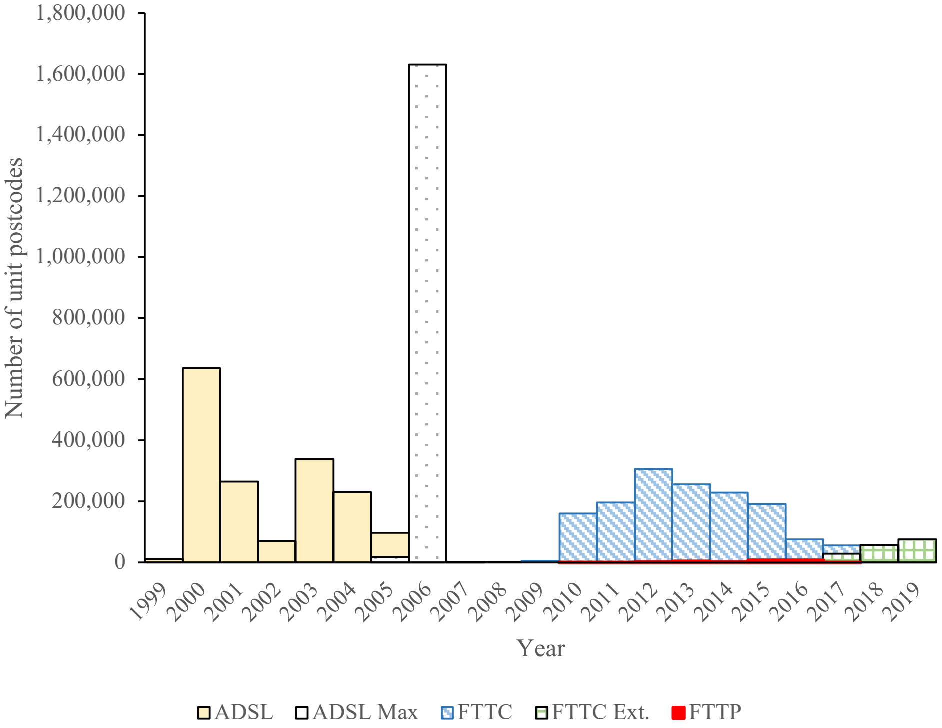
Topography of different broadband technologies



Note: This figure shows how different broadband technologies connect properties. Asymmetric digital subscriber line (ADSL) technologies use copper cables for the connection between the local exchange (LE) and properties. Fiber-to-the-cabinet (FTTC) technologies install fiber cable between the LE and street cabinets, whereas copper is used for the last leg from the street cabinets to the properties. Full fiber technologies, such as fiber-to-the-premises (FTTP) deploy fiber all the way up to the premises.

Figure 2

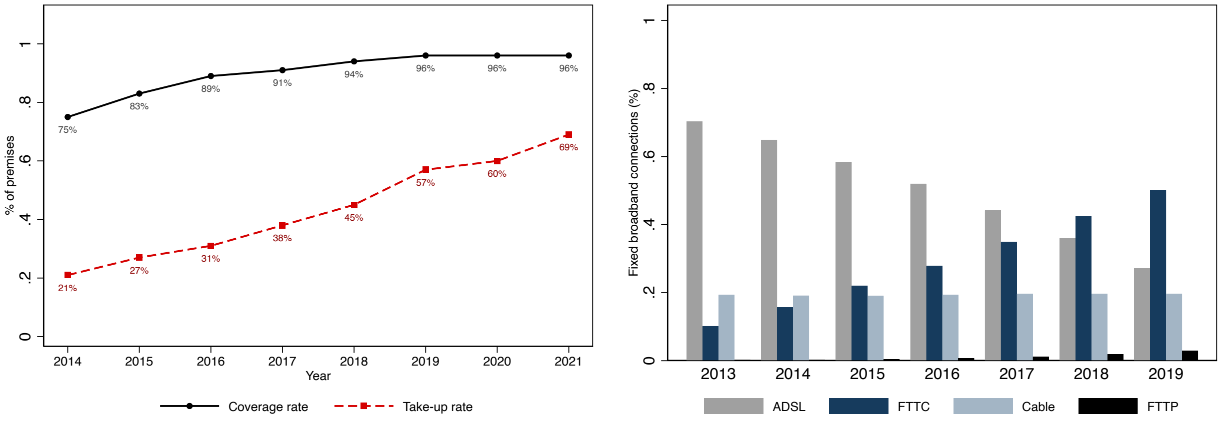
Types of broadband activation by year



Note: This figure shows the number of postcodes with different types of broadband technologies activated by year. ADSL activation was complete in most of the postcodes by 2005-06. FTTC activation started in 2009 and the bulk of commercial rollout by BT was completed by 2013-14. Since then FTTC rollout, supported by the Building Digital UK (BDUK) programs, took place predominantly in rural postcodes. Starting in 2017, a wave of FTTC extensions (FTTC Ext.) upgraded the cabinets to connect additional properties. Although BT initially promised to connect 1.5 million homes with full fiber, FTTP rollout remained low during this period. Note that the UK has around 1.8 million active unit postcodes.
(Source: Authors' own calculations.)

Figure 3

Change in superfast ($\geq$30 Mbps) broadband take-up over time



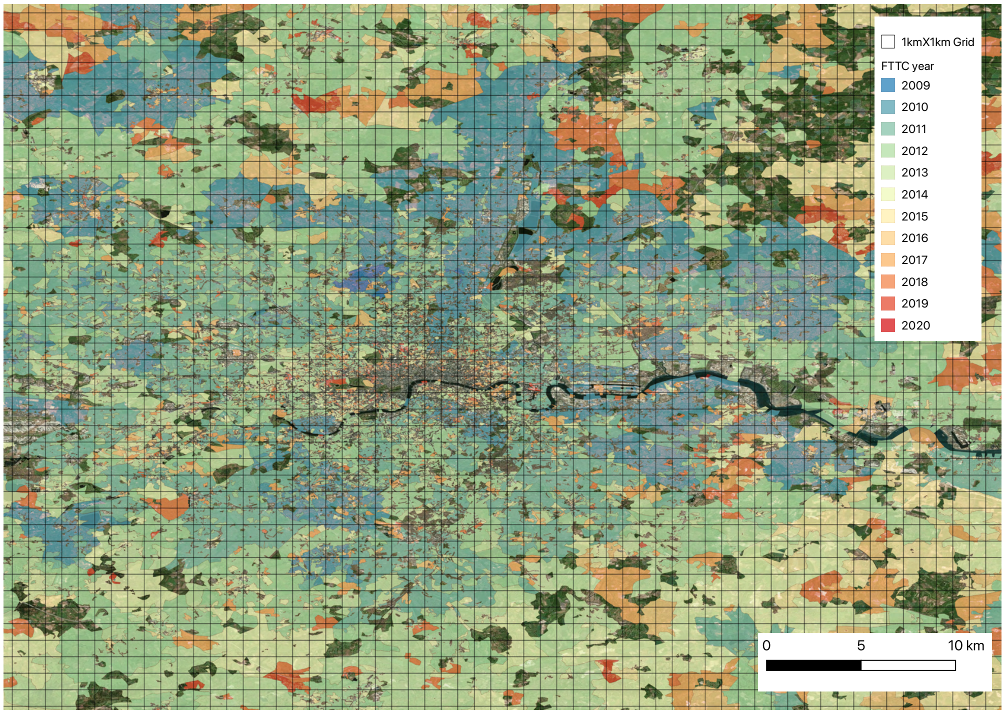
(a) Availability vs. takeup

(b) Change in technology mix

Note: This figure shows how the availability of FTTC brodaband resulted in its gradual take-up. Panel 3a reports the coverage and take-up of superfast broadband, which refers to connections with at least 30 Mbps speed and is typically supported by fiber-based or cable broadband technologies. The black (solid) line shows the percentages of premises in the UK that have superfast coverage, whereas the red (dashed) line shows the percentage of premises that have taken up superfast broadband. By 2017, 90% of the premises were covered by superfast broadband but the take-up rate was less than 40%. Panel 3b shows how the technology mix delivering superfast broadband changed during this time. The figure reports the shares of different types of technology connections between 2013 and 2019. We can see a gradual transition from ADSL (including ADSL2+ and ADSL Max) to FTTC technologies. In 2013, ADSL held 70% of the broadband market and the market share for FTTC was only 10%. In 2018 FTTC surpassed ADSL in terms of market share for the first time. By 2019, FTTC captured half of the fixed broadband market and the share of ADSL dropped to 27%. Cable held a steady share of the market at 19-20% throughout this period. The market share of FTTP remained low, reaching 3% by the end of the period. Note that we do not report a remaining technology category (‘other’) that is less than 1%.
Source: Ofcom Connected Nations Reports and Communications Market Report, 2020.

Figure 4

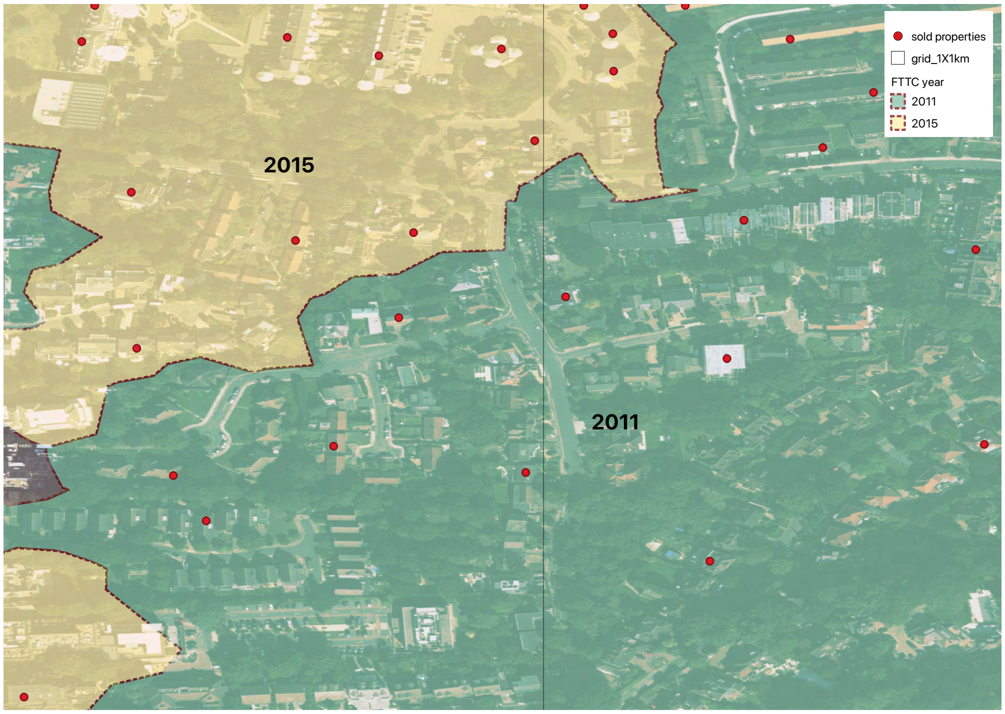
Grid areas and FTTC activation years



Note: This map shows the 1×1 km grids that are constructed to identify the location of the activation boundaries. Note that we further break down the dense grids (i.e., with more than one activation boundary) into 100 square meters grids. The activation areas (i.e., the polygon of postcodes activated in the same year) are shown using different shades of color. The map shows that there is enough variation in the timings of FTTC activation. The map shows a part of Central London.

Figure 5

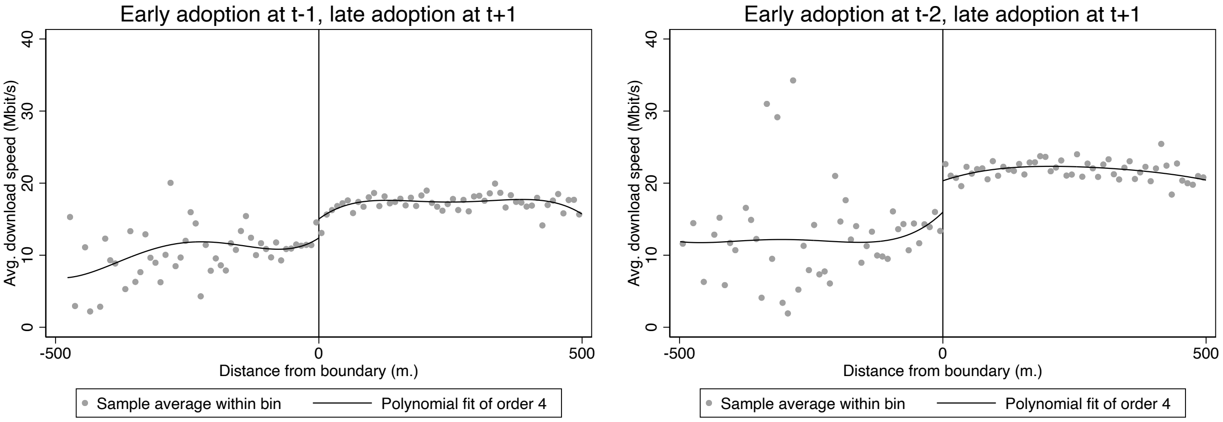
Variation in FTTC activation across neighboring postcodes



Note: This figure shows a typical example of an activation boundary from our data. The southeast side (green) of the boundary has been FTTC enabled in 2011 and the northwest side (golden-yellow) is activated later in 2015. The red dots show sold properties.

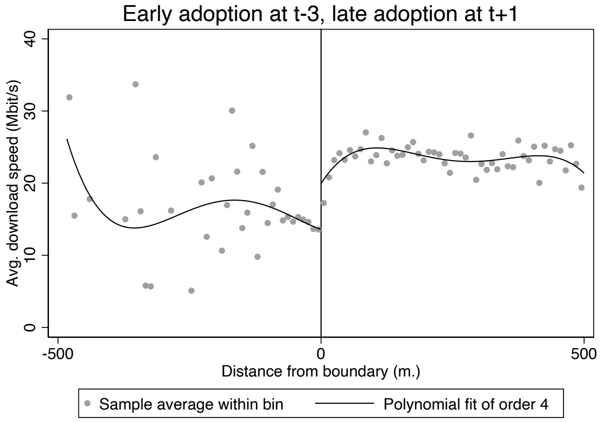
Figure 6

Discontinuity in average download speed across boundaries



(a) 1 year of activation

(b) 2 years of activation

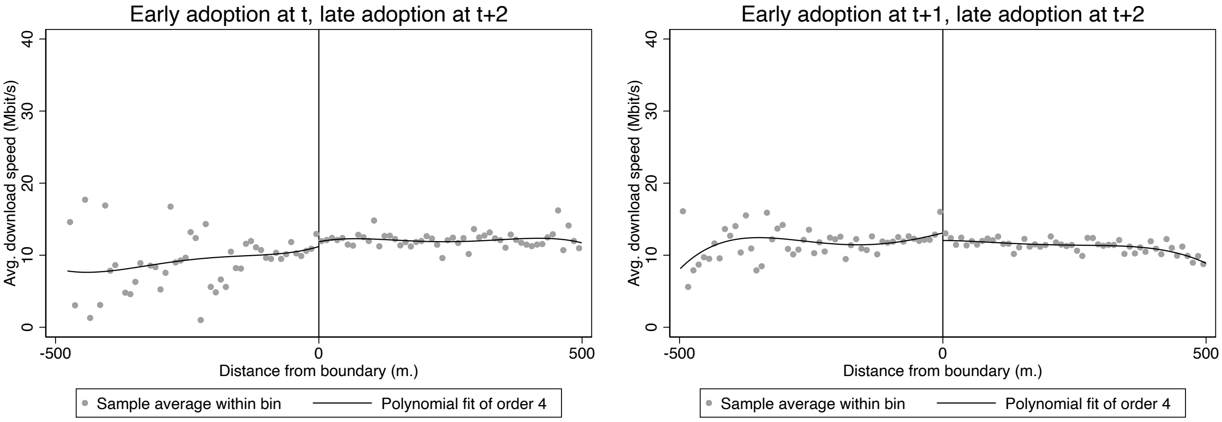


(c) 3 years of activation

Note: The figure checks discontinuity in broadband speed across activation boundaries. The horizontal axis measures the distance (in meters) of a postcode centroid from the boundary. The average download speed (in Mbit/s) is plotted on the vertical axis for each 50 meters distance bin. In all three figures, the left side of the cutoff shows postcodes that are not activated until the next year. The right side of the cutoff shows postcodes that have been activated for one, two, or three years, respectively. These figures show a sharp discontinuity in broadband speed across the boundary especially two or three years after activation. The figure uses Ofcom's postcode-level data from the Connected Nations series from 2013-2017. The plots are produced using the 'rdplot' package in Stata. The line shows a quadratic fit of the raw data separately on each side of the cutoff.

Figure 7

Discontinuity in average download speed across boundaries (placebo check)



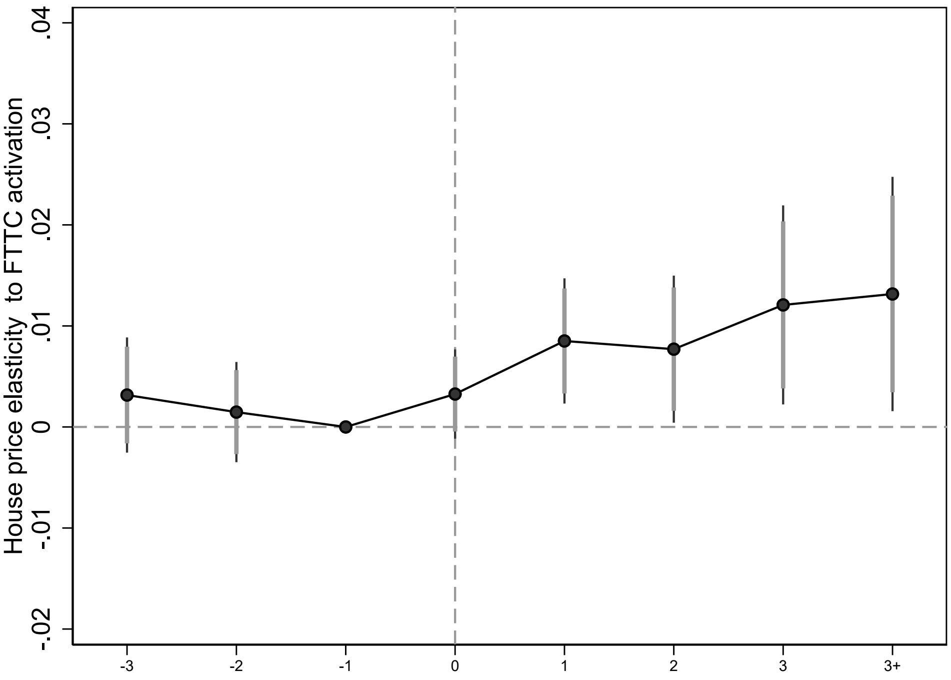
(a) 0 year of activation

(b) -1 year of activation

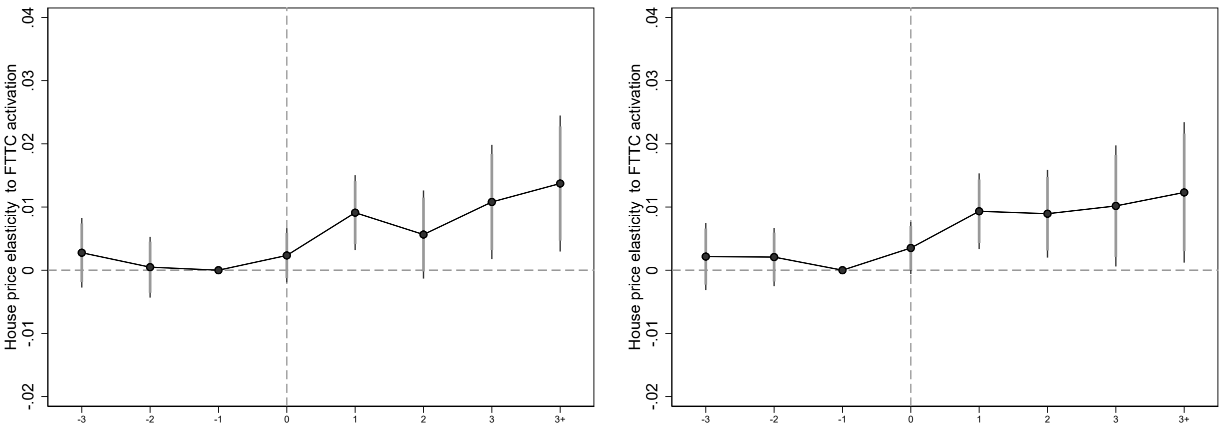
Note: The figure checks discontinuity in broadband speed across activation boundaries. The horizontal axis measures the distance (in meters) of a postcode centroid from the boundary. The average download speed (in Mbit/s) is plotted on the vertical axis for each 50 meters distance bin. Panel 7a compares postcodes that have been activated in the same year (right) with postcodes that are activated two years later (left). Panel 7b compares postcodes that are activated one year later (right) with postcodes that are activated two years later (left). Neither panel shows any visible difference in broadband speed before activation or immediately in the year of activation. The figure uses Ofcom's postcode-level data from the Connected Nations series from 2013-2014. The plots are produced using the 'rdplot' package in Stata. The line shows a quadratic fit of the raw data separately on each side of the cutoff.

Figure 8

Housing price response to FTTC activation



(a) Baseline



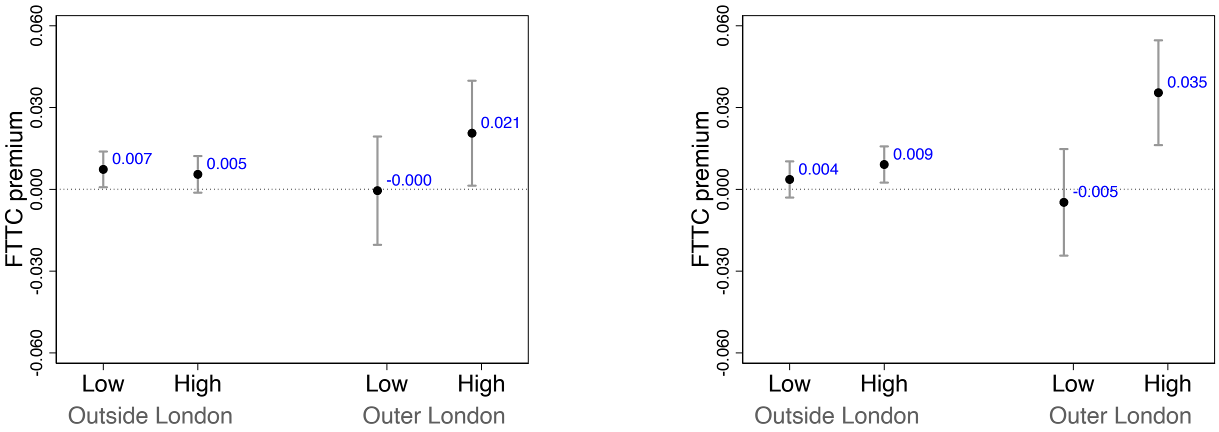
(b) Without grid restriction

(c) Without boundary restriction

Note: The figure depicts the dynamic of house price response to FTTC activation. It indicates the parallel trends hold between the early and late adopters before the activation of FTTC broadband. Panel 8a shows the baseline identification, Panel 8b shows the result without any restriction on grid cells, and Panel 8c shows the results without any restriction on the distance from boundaries.

Figure 9

FTTC premium by neighborhood (MSOA) commuting share



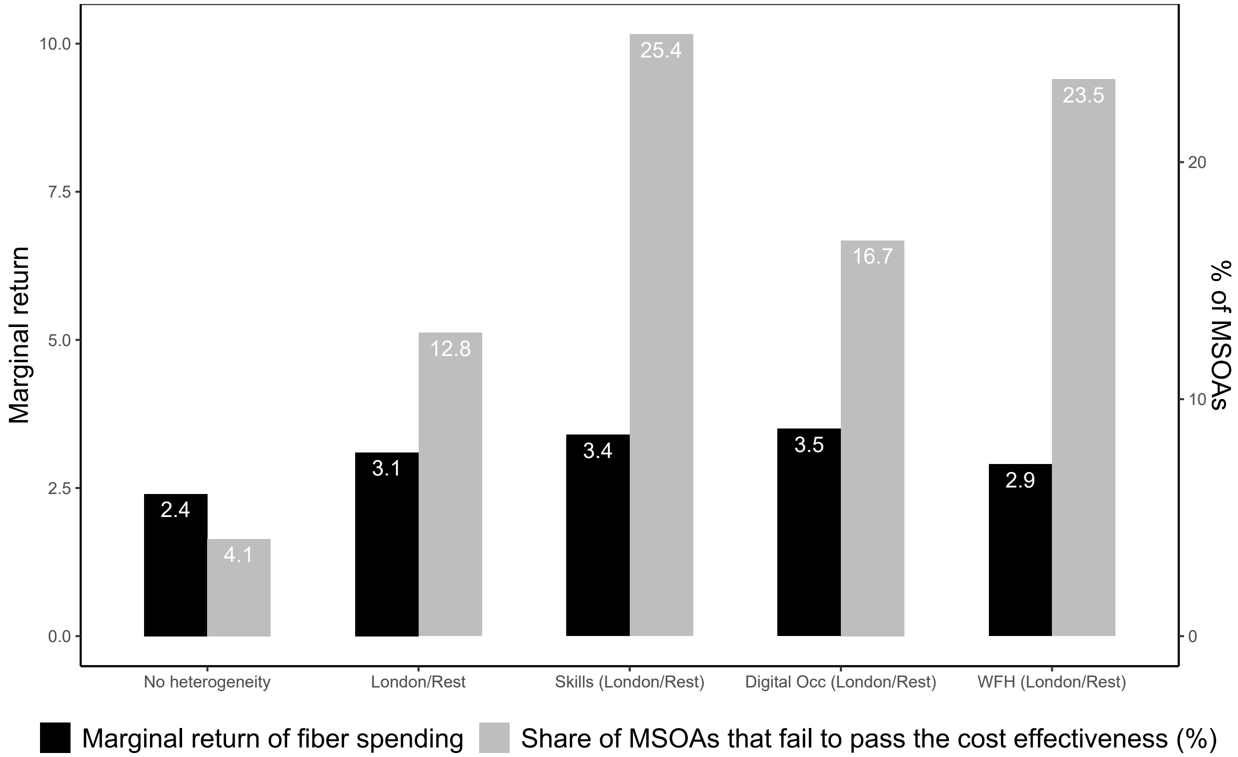
(a) MSOA share commuting to Inner London boroughs

(b) MSOA share commuting to City of London, Westminster, and Camden

Note: The figure shows FTTC premium estimated for subsamples with different degrees of connectivity to London's economic center. Panel (a) shows MSOAs with below median (low) and above median (high) share of commuters to Inner London boroughs. Panel (b) classifies MSOAs using the share of commuters to the top-three Inner London boroughs, namely, the City of London, Westminster, and Camden. Note that we use separate median values for Outer London and other areas outside the London region because the median share of commuters varies drastically across these places. Outer London has a median share of commuters of 28.5% to Inner London and 13.5% to the central boroughs of the City of London, Westminster, and Camden. For the areas outside the London region, these shares are 2.4% and 1.4%, respectively.

Figure 10

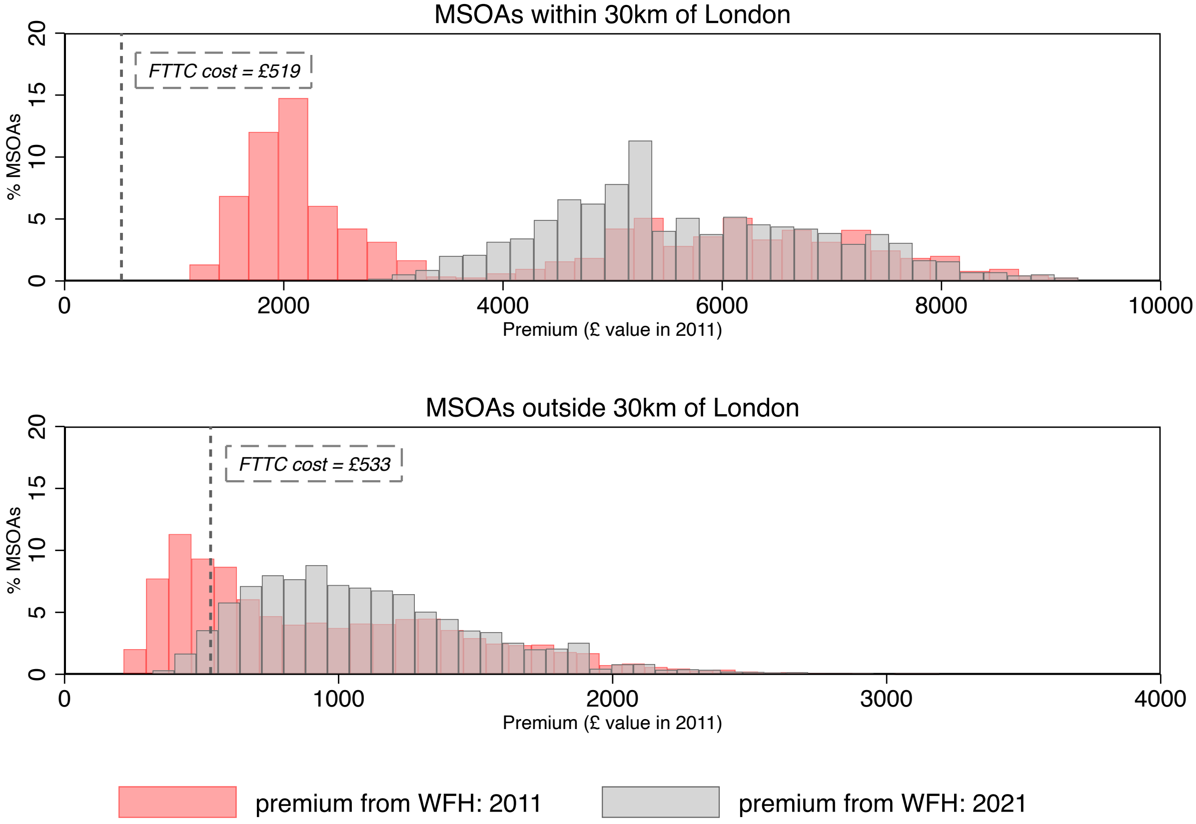
Cost effectiveness of fiber broadband



Note: The figure shows how taking into account differences in neighborhoods alters the overall cost-effectiveness of fiber broadband spending. Although accounting for the heterogeneity increases the estimated average marginal return to fiber spending it reduces the number of MSOAs that pass the cost-effectiveness test. In our ‘No heterogeneity’ estimates, we use our baseline coefficient (column 1 of Table 2) to calculate the FTTC premium for all urban neighborhoods. The second group is ‘London/rest’, which uses separate coefficients (columns 3 and 4 of Table 3) to distinguish between London neighborhoods and the rest. In ‘Skills(London/Rest)’ we use four coefficients from columns 1-4 of Panel A in Table 4 that allow us to further differentiate between neighborhoods with high and low share of skilled workers within London and the rest of the urban neighborhoods. In ‘Digital Occ (London/Rest)’ we use the four coefficients from columns 1-4 of panel B in table 4 to divide neighborhoods in London and the rest according to their intensity of digital occupations among their residents. In ‘WFH (London/Rest)’, we use the four coefficients from panel B in table 5 and divide the neighborhoods based on the share of WFH among workers engaged in institutional employment (as opposed to self-employed). In all cases, we multiply these coefficients by the median house prices of each neighborhood in 2011. Moreover, we use the FTTC installation cost per property connected sourced from Analysys Mason (2008), which are £519 for the London region and £533 for the rest of the urban neighborhoods.

Figure 11

Change in FTTC premium from changing WFH share



Note: The figure plots the distribution of FTTC premiums calculated for the 2011 and 2021 WFH shares. We use the coefficients from Panel B of Table 5, which provides the heterogeneous effects for below- and above-median neighborhood (i.e. MSOA) share of employees who work from home. The medina WFH (employee) share is 3.9% for MSOAS within 30 km of London and 3.6% for the rest of the MSOAs. By 2021, all MSOAs project WFH (employee) shares above these median values. Hence, we use the above-median coefficients to calculate the 2021 values. Note that we calculate the monetary values using the median values of property prices at the neighborhood level. The red distribution shows the neighborhood-level premiums in 2011 and the gray distribution shows how the premiums would change in 2021 for the same population. The vertical (dashed) lines show the cost of FTTC installation per property connected sourced from Analysys Mason (2008). The 2011 distributions show that 23.5% of the urban neighborhoods have low premiums that do not meet the cost threshold. However, the shift in the distribution suggests that if WFH increases for the reference population to the level we observe in 2021, only 3.4% of all urban neighborhoods fall below the cost threshold.

Tables

Table 1

Summary statistics (2008-2017)

.	Mean	SD	Min	Max
Panel A: Housing sample (2008-2017)				
Sale price (£)	194029.95	95647.54	11000.00	500000.00
Number of rooms	4.46	1.38	1.00	12.00
Total floor area (sq. m.)	85.25	29.58	24.00	293.00
% Detached	0.19	0.40	0.00	1.00
% Semi-detached	0.33	0.47	0.00	1.00
% Terraced	0.34	0.47	0.00	1.00
% Flat/Maisonettes	0.14	0.35	0.00	1.00
% Freehold	0.80	0.40	0.00	1.00
% Leasehold	0.20	0.40	0.00	1.00
% Newly built	0.01	0.10	0.00	1.00
% Building age (<1900)	0.07	0.26	0.00	1.00
% Building age (1900-1949)	0.30	0.46	0.00	1.00
% Building age (1950-1975)	0.30	0.46	0.00	1.00
% Building age (1976-1990)	0.15	0.36	0.00	1.00
% Building age (1991-2006)	0.15	0.36	0.00	1.00
% Building age (2007 or later)	0.02	0.15	0.00	1.00
Distance from boundary (km.)	0.17	0.17	0.00	2.01
Distance from exchange (km.)	1.56	0.84	0.02	8.79
Distance from cabinet (km.)	0.28	0.31	0.00	21.43
Panel B: Broadband speed (2014-2017)				
Avg. download speed (Mbps) 2014	26.46	11.17	0.80	104.00
Avg. download speed (Mbps) 2015	33.03	14.74	0.80	131.60
Avg. download speed (Mbps) 2016	41.47	19.55	0.80	199.90
Avg. download speed (Mbps) 2017	49.21	24.49	0.80	646.90

Note: The table reports the summary statistics on the key variables from our housing and broadband data. Panel A shows the property-level information using the Price Paid Data (PPD) from 2008-2017. The average sale price was £194,030 during this period. Note that we report summary statistics for our entire housing sample in this table. The average price is slightly different for the sample of properties used in our preferred regression. See Table A3 in Appendix for summary statistics on our regression sample. Panel B reports the average download speed from Ofcom's Connected Nation series. Ofcom data is available from 2013. We do not report the 2013 data here because the mean download speed is truncated at 30 Mbps.

Table 2

Housing price response to FTTC activation (main results)

	Dependent Variable: *ln* (*price*)				
	Baseline	Robustness			Distance from cabinet
	Baseline (1)	No grid restriction (2)	No boundary restriction (3)	No control (4)	Distance (5)
FTTC activated	0.0074^{***}	0.0083^{***}	0.0077^{***}	0.0069^{**}	
	(0.0023)	(0.0022)	(0.0022)	(0.0032)	
FTTC activated for short distance from cabinet(<.2 km) 1					0.0097^{***}
					(0.0034)
FTTC activated for medium distance (.2-.4 km)					0.0085^{***}
					(0.0033)
FTTC activated for long distance (>.4 km)					0.0017
					(0.0044)
Postcode FE	Yes	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	No	Yes
Observations	197,168	228,697	267,320	197,168	197,168

Note: The dependent variable in all columns is the logarithm of the house price. ‘FTTC activated’ is a dummy variable that takes 1 for all years following the activation year of FTTC. *Grid* × *Boundary* is a set of year fixed effects for the neighboring pairs that are located in the same grid on each side of the FTTC activation boundary. ‘Grid’ is defined as an area that varies from 1 to 0.1 square kilometers. We restrict our samples to all postcodes that are within 200 meters of the boundary. House controls include a property type categorical variable (detached, semi-detached, terraced houses, and flat/maisonette), a dummy variable that shows whether the property is new, a dummy variable that shows whether it is sold on a freehold or leasehold basis, a categorical variable for age bands, a categorical variable for the number of rooms, and a continuous variable for the total floor area. Standard errors are in parenthesis and clustered on each side of the boundary. *** and ** denote statistical significance at the 1 and 5 percent levels, respectively.

Table 3

House price responses across locations

			Distance from London	
	Greater London	Rest	<30km	≥30km
	(1)	(2)	(3)	(4)
FTTC activated	0.0169***	0.0065***	0.0184***	0.0059**
	(0.0064)	(0.0024)	(0.0064)	(0.0024)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	16,237	180,926	21,805	175,351

Note: The table reports housing price responses to FTTC activation across geographies. Columns 1 and 2 show the results for the London region and the rest of the country, respectively. The next two columns divide the sample by the distance from London. Column 3 shows areas within 30 km from London and Column 4 shows areas more than 30 km away from London. The dependent variable in all columns is the logarithm of the house price. 'FTTC activated' is a dummy variable that takes 1 for all years following the activation year of FTTC. Each column includes postcode FEs, grid-boundary-year FEs, and housing controls. We restrict our samples to all postcodes that are within 200 meters of the boundary. Standard errors are in parenthesis and clustered on each side of the boundary. *** and ** denote statistical significance at the 1 and 5 percent levels, respectively.

Table 4

Price responses by neighborhood (MSOA) skill composition

	<30km (London)		≥30km (London)	
	(1)	(2)	(3)	(4)
Panel A: MSOA share of skilled (professional) occupation				
	Low	High	Low	High
FTTC activated	0.0088	0.0218***	0.0045	0.0101***
	(0.0115)	(0.0067)	(0.0035)	(0.0036)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	9,556	12,154	88,655	86,009
Panel B: MSOA share of digital occupation				
	Low	High	Low	High
FTTC activated	0.0008	0.0343***	0.0067*	0.0074**
	(0.0095)	(0.0084)	(0.0035)	(0.0035)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	9,725	11,967	92,926	81,723

Note: The table reports housing price responses to FTTC activation across neighborhoods (i.e., MSOAs) with different skill compositions. Columns 1 and 2 show results within 30 km from London and columns 3 and 4 show areas more than 30 km away from London. Panel A divides the neighborhoods into groups with below-median (low) and above-median shares of skilled (or professional) occupations. Panel B divides the neighborhoods into groups with below-median (low) and above-median shares of digital occupation. The dependent variable in all columns is the logarithm of the house price. Standard errors are in parenthesis and clustered on each side of the boundary. *** and ** denote statistical significance at the 1 and 5 percent levels, respectively.

Table 5

Price responses by neighborhood (MSOA) WFH practice

	<30km (London)		≥30km (London)	
	(1)	(2)	(3)	(4)
Panel A: MSOA share of WFH (total)				
	Low	High	Low	High
FTTC activated	0.0062	0.0249***	0.0093***	0.0023
	(0.0101)	(0.0073)	(0.0035)	(0.0034)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	10,485	11,275	87,083	87,664
Panel B: MSOA share of WFH (employee)				
	Low	High	Low	High
FTTC activated	0.0086	0.0209***	0.0046	0.0076**
	(0.0101)	(0.0076)	(0.0036)	(0.0033)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	10,543	11,202	87,900	86,810
Panel C: MSOA share of WFH (self-employed)				
	Low	High	Low	High
FTTC activated	0.0040	0.0245***	0.0096***	0.0022
	(0.0114)	(0.0065)	(0.0035)	(0.0035)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	10,258	11,473	86,854	87,951

Note: The table reports housing price responses to FTTC activation across neighborhoods with different levels of WFH. Columns 1 and 2 show results within 30 km of London and columns 3 and 4 show areas more than 30 km away from London. 'Low' refers to the below-median share of WFH and 'high' refers to the above-median share of WFH. The medians are calculated separately for within 30 km from London and outside 30 km of London. The dependent variable in all columns is the logarithm of the house price. Standard errors are in parenthesis and clustered on each side of the boundary. *** and ** denote statistical significance at the 1 and 5 percent levels, respectively.

A Appendix

A.1 Spatial Analysis of UK Broadband Data

The first step in this process is to obtain the shapefiles (polygons) for each UK postcode unit from the UK Ordnance Survey (OS hereafter), the national mapping agency for Great Britain. This dataset provides both the area that is covered by each postcode unit (six- or seven-digit codes depending on the area of the country) and the centroid of each unit. The postcode unit information used in this study is the most granular spatial information available from OS and there are approximately 1.7 million postcodes in the UK with an average of 15 properties per postcode unit (while some can reach 100 properties).

The next step is to combine our UK FTTC broadband data with the spatial postcode information. Our goal is to construct a map of adjacent areas that have been activated at different years during the FTTC rollout. However, this information is not readily available. To achieve this we use two separate sources of data:

1. The cabinet-level activation years for every cabinet in the UK scrapping information from resellers of Openreach data (a subsidiary of the incumbent operator in the UK – British Telecoms – that maintains the telephone cables, ducts, cabinets and exchanges that connect nearly all homes and businesses in the United Kingdom to the national broadband and telephone network).

2. The postcode unit coverage of each cabinet in the country (sources from resellers of Openreach data)

Combining these broadband data inputs we are able to add an activation year variable to our UK postcode unit shapefiles. Our spatial analysis is done in QGIS 3.22.3 and the steps followed are described below.

We first import all the UK postcode unit shapefiles (1.7 million shapefiles) and merge them into a UK shapefile. We then import the activation year data from Openreach and add the FTTC activation year data into the shapefile information. Next, we dissolve the UK file using activation year as our variable for merging adjacent postcode units together. This process leads to a spatial reconstruction of our data that allows us to study the changes across adjacent boundaries.

To construct our boundaries from the shapefile we use “Polygons to lines” from QGIS which creates a line boundary file for each year-activated “island”. As these “islands” may touch on various other regions with different activation years, we use the “Intersection” process from QGIS on the line file with itself. This results in a new lines dataset that differentiates across different activation year neighboring postcodes. For example, an ‘island’ that is activated in 2012 will now have separate parts of its boundary that connect it to a 2011 area (2012-2011 part of the island’s boundary), another for 2013 (2012-2013 part), etc.

Last we need to estimate the distance of each postcode unit to the right boundary. For this we use the postcode unit centroid coordinates from OS and we link this information with the intersected lines of the previous process. There are two separate ways that we achieve this. The first breaks the line boundaries into points that are 10 meters apart each and then we use the ‘line to points’ function to estimate the minimum distance from each postcode centroid to every point in the lines dataset. The second approach uses the ‘line to hub’ approach that involves the lines dataset directly from the postcode unit centroids. With both methods, we end up with a dataset that contains the distance from the nearest boundary and the allocation of each postcode centroid to the respective boundary. The comparison across both processes shows that they are actually identical. The distances we get at the end of this process are in meters.

Further from the allocation of postcodes (and properties) to different activation-year boundaries, we also introduce a grid to improve the identification within local housing markets. Our baseline grid is 1km by 1km square and we ‘intersect’ the points layer with the grid layer to allocate boundaries to grid cells. In areas where many boundaries appear within grid cells, we narrow our grid to 100m by 100m to match the local housing markets in greater detail.

A.2 Costs of FTTC Broadband Deployment

This section discusses how we calculate the FTTC deployment cost based on a technical report published by Analysys Mason prior to the broadband infrastructure upgrade. The report estimates FTTC/VDSL deployment cost for thirteen geotypes based on population density, town size, number of lines from an LE, and distance between LE and premises (Analysys Mason, 2008). To compute comparable cost estimates for our analysis, we map all the urban MSOAs to one of these geotypes. Out of these thirteen geotypes, seven geotypes represent urban areas, with a cost estimate that varies between £381 for Inner London to £710 for cities with less than 200K population.

The base case scenario in the report considers partial migration under which only lines requiring next-generation broadband services migrate. With a broadband penetration rate of 80%, and cable's market share being steady at 21%, the base case assumes half of the users who are not on cable would migrate to fiber connections. This amounts to a national take-up rate of 31% although the take-up rate varies slightly across different geotypes. The report considers the scenario in which installation happens gradually over the next few years and all the cost estimates used reflect this assumption. The cost components of FTTC deployment include the Optical Distribution Frame (ODF) in the exchange, the cabinet, active equipment inside the cabinet, costs of civil works (including costs of fiber-optic cable, ducts, and installation), line migration costs, and in-home wiring costs.[40] The cost estimates in the base case scenario do not include the costs of the engineer's visit which is estimated to add another £100 GBP per line.

To calculate the deployment cost for MSOAs within 30 km of London, we use the following cost estimates:

- For Inner London MOSAs we use £381 as estimated in the report.
- For Outer London MSOAs we use £441 which is the cost estimated for major cities with a population of more than 500K.
- For the remaining MSOAs that fall within the 30 km radius around London but lie outside the Greater London area (e.g., East and South East), most of them come from towns of less than 200K population. For these MSOAs, we use the deployment cost of £401 if the population density is above 500 people per square km. If the population density is less than 500 people per square km, we use type £710.

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[40] See Section 3 of Analysys Mason (2008) for the detailed methodology.

For deployment costs outside the 30 km radius around London, we use the following numbers:

- For MSOAs in major cities (greater than 500K population) we use the deployment cost of £441.
- For MSOAs in cities with a population between 200K and 500K, we use £432.
- For the rest of the MSOs in cities (or towns) with less than 200K population, we use the deployment cost of £401 if the population density is greater than 500 people per square km. If the density is less than 500, we use a cost estimate of £710.

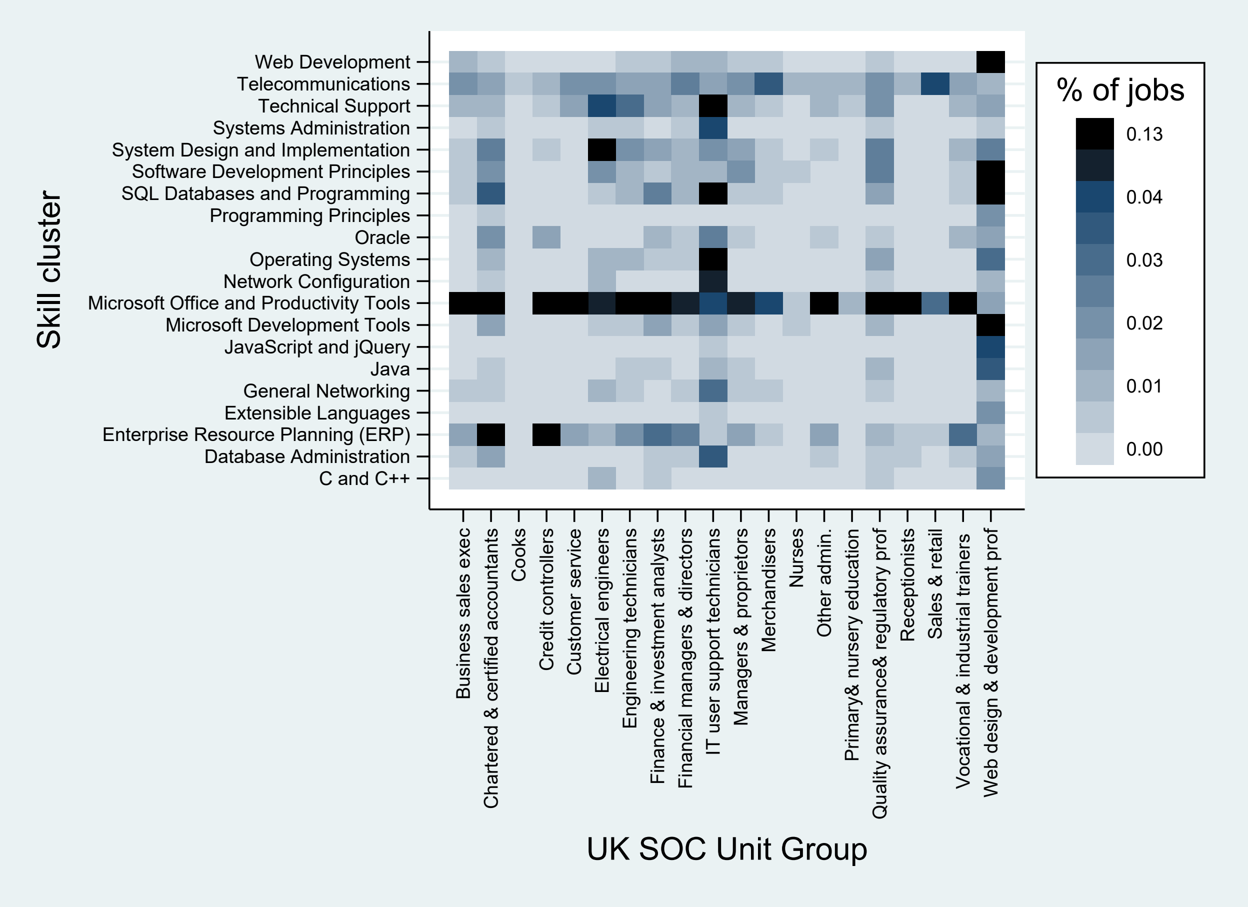
We then calculate the average deployment cost weighted by the number of MSOAs in each geotype and add another £100 for installation through an engineer's visit which was required in the early phases. Our cost estimate for MSOAs within 30 km of London is £519 and for MSOAs outside 30 km of London is £533 per property connected.

A.3 Additional Figures and Tables

A.3.1 Intensity of Digital Occupation

Figure A1

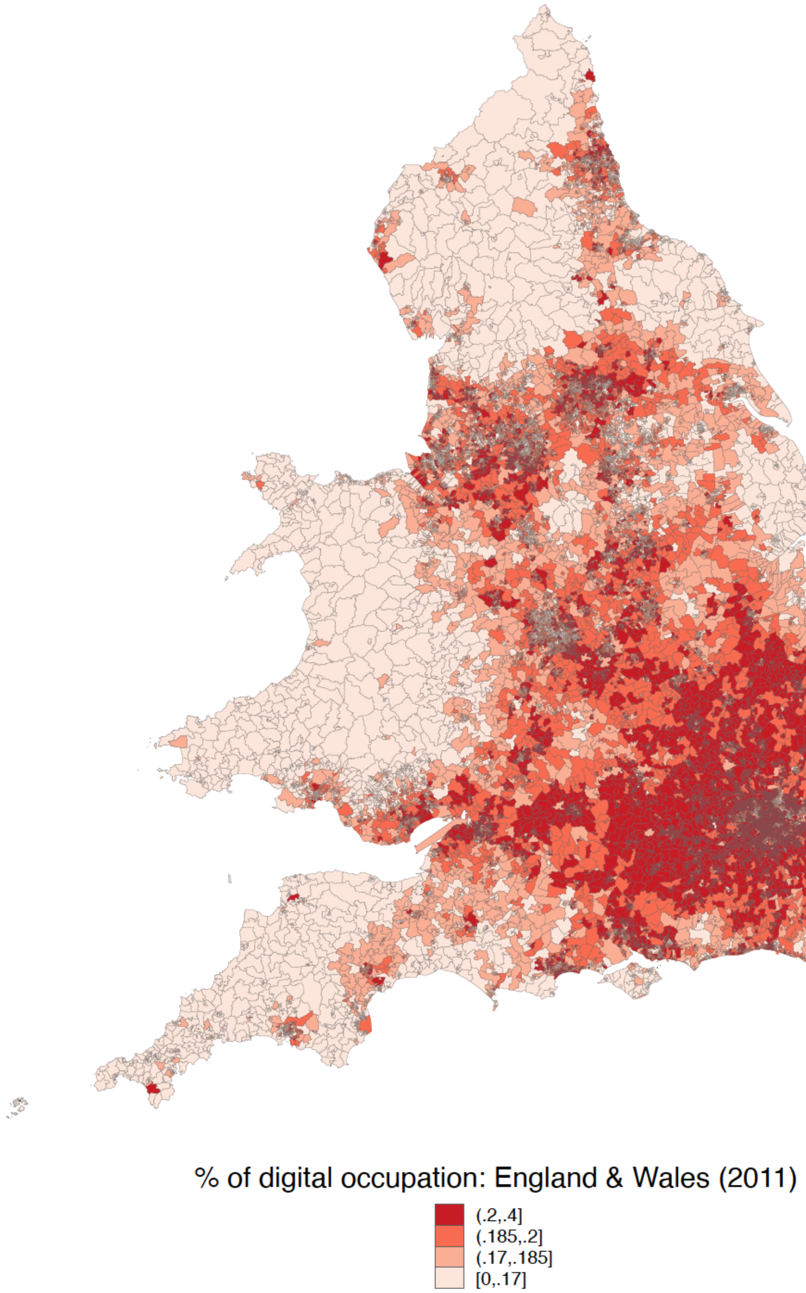
Mapping digital skills to occupations



Note: The figure shows the share of job postings across different skill clusters and 3-digit occupation codes. The vertical axis reports the top twenty of the most frequently mentioned skill clusters in job postings. The horizontal category reports the top-twenty 3-digit occupation groups by the SOC 2010 occupation classifications. We use the universe of job postings in 2012 from Lightcast. The skill clusters used come from Lightcast's skill classifications.

Figure A2

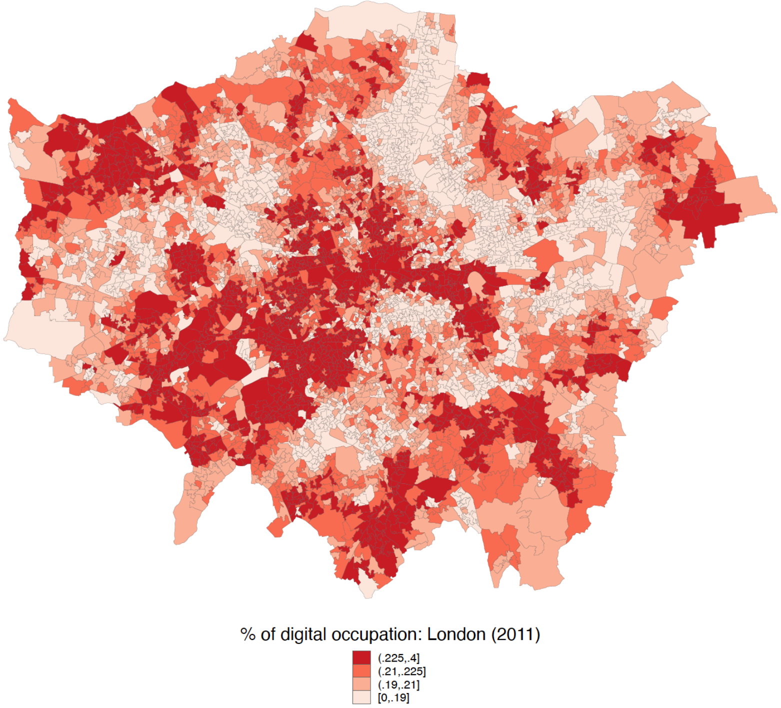
Distribution of digital jobs in England and Wales



Note: The figure shows the share of digital occupations calculated using Lightcast job postings data and the census 2011. The shares are reported at the LSOA level. The map shows the highest concentration of digital jobs is around London.

Figure A3

Distribution of digital jobs in London

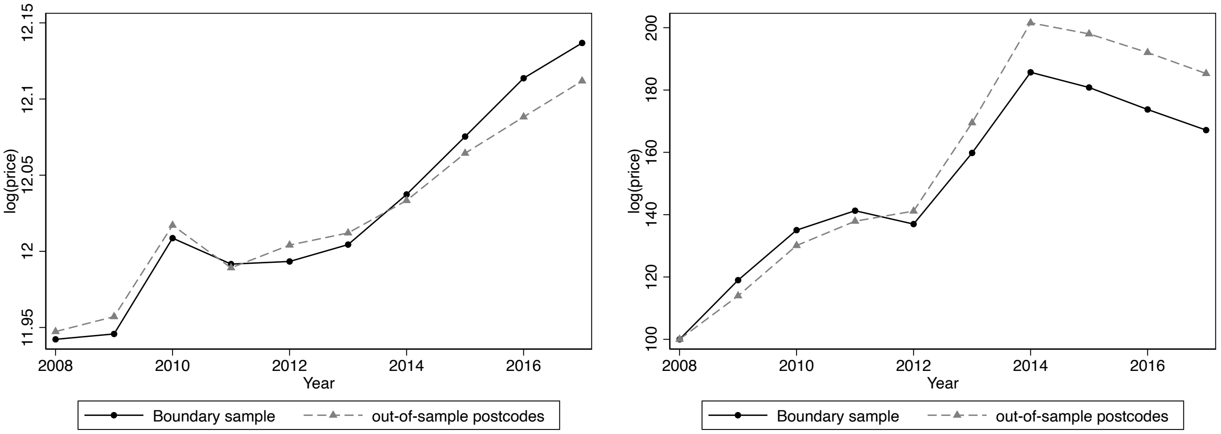


Note: The figure shows the share of digital occupations calculated using the Lightcast job postings data and the census 2011. The map shows the LSOAs in the London region.

A.4 Housing Data: Sample Comparison

Figure A4

Price comparison across samples



(a) Log price by year

(b) Sales (normalized) by year

Note: The figure shows how price and sales change over the years across different housing samples. 'Boundary sample' refers to the property sales that we use in our regression analysis. Out-of-sample postcodes represent the property sale records that are not used in our analysis. Property prices and sales seem to largely move in the same direction across these different samples.

A.4.1 Availability of Cable Broadband

Table A1

Robustness check–presence of cable broadband

	Full sample		<30km (London)		≥30km (London)	
	Cable	No cable	Cable	No cable	Cable	No cable
	(1)	(2)	(3)	(4)	(5)	(6)
FTTC activated=1	0.0023	0.0093**	0.0025	0.0469**	0.0020	0.0067*
	(0.0030)	(0.0037)	(0.0059)	(0.0188)	(0.0033)	(0.0038)
Postcode FE	Yes	Yes	Yes	Yes	Yes	Yes
Grid × Year	Yes	Yes	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	109,871	85,522	17,034	4,478	92,828	81,040

Note: The table reports housing price responses to FTTC activation for postcodes with and without the coverage cable broadband. The coverage is inferred from speed data if a postcode reaches above 80 Mbps maximum speed, the highest that an FTTC connection can reach, in any year between 2014-2017. The dependent variable in all columns is the logarithm of the house price. Standard errors are in parenthesis and clustered on each side of the boundary. *** and ** denote statistical significance at the 1 and 5 percent levels, respectively.

A.4.2 Income and Deprivation

Table A2

Responses across high and low skilled neighborhoods–income & deprivation

	Low skill share		High skill share	
	(1)	(2)	(3)	(4)
	Panel A: MSOA average weekly income			
	Low	High	Low	High
FTTC activated	0.0056	0.0082	0.0148**	0.0100***
	(0.0038)	(0.0068)	(0.0073)	(0.0037)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	81,665	16,403	22,406	75,499
	Panel B: MSOA average deprivation rank			
	Low	High	Low	High
FTTC activated	0.0060	0.0056	0.0245***	0.0080**
	(0.0039)	(0.0076)	(0.0090)	(0.0035)
Postcode FE	Yes	Yes	Yes	Yes
Grid × Boundary × Year	Yes	Yes	Yes	Yes
House controls	Yes	Yes	Yes	Yes
Observations	74,436	19,365	22,835	72,977

Note: The table reports housing price responses to FTTC activation across neighborhoods (i.e., MSOAs) with different skill compositions and levels of income or deprivation. Low (high) skill share refers to neighborhoods with a below-median (above-median) share of skilled (or professional) occupations. Low and high-income neighborhoods are classified based on the median value of 2011-12 total weekly income at the MSOA level. Deprivation is measured by the MSOA average deprivation rank. The sample is split into more and less deprived neighborhoods based on the median value of average deprivation rank. Note that we use different median values for the sample near London and the rest. The dependent variable in all columns is the logarithm of the house price. Standard errors are in parenthesis and clustered on each side of the boundary. *** and ** denote statistical significance at the 1 and 5 percent levels, respectively.

A.5 Representativeness of our Sample

Table A3

Comparison of in-sample and out-of-sample postcodes

	Boundary sample (1)	Out-of-sample (2)	Rural (3)
Sale price (£)	190178.52	192581.16	220361.69
Price per sq. m. (£)	2357.40	2372.12	2318.29
log of price	12.03	12.03	12.19
Number of rooms	4.40	4.40	4.89
Total floor area (sq. m.)	84.01	85.20	98.62
% Detached	0.18	0.17	0.40
% Semi-detached	0.31	0.30	0.30
% Terraced	0.36	0.34	0.25
% Flat/Maisonettes	0.16	0.19	0.06
% Freehold	0.79	0.75	0.92
% Leasehold	0.21	0.25	0.08
% Newly built	0.01	0.02	0.01
% Building age (<1900)	0.08	0.09	0.17
% Building age (1900-1949)	0.31	0.32	0.16
% Building age (1950-1975)	0.26	0.28	0.30
% Building age (1976-1990)	0.15	0.13	0.16
% Building age (1991-2006)	0.17	0.14	0.17
% Building age (2007 or later)	0.03	0.03	0.03
Geographic composition—type of urban area			
urban major conurbation	27.31	37.07	-
urban minor conurbation	4.60	4.14	-
urban city & town	67.77	58.38	-
urban city & town (sparse)	0.32	0.41	-

Note: The table reports summary statistics for different subsets of property data. We use the Price Paid Data (PPD) from 2008-2017. Column 1 reports the summary statistics for our regression sample, which we refer to as the 'boundary sample'. Column 2 shows property characteristics for urban postcodes that are not used in our regression. Column (3) shows information for properties located in rural postcodes. Compared with our sample, column (2) shows slightly larger house prices and a larger share of flats and leasehold properties. However, the log of price, price per square meter, size of the properties, and other property characteristics are quite comparable. Column (3) provides a sharp contrast between urban and rural properties—rural properties are bigger in size, more likely to be detached properties, and less likely to be leaseholds. Also, a larger share is built in the 19th century. The bottom panel compares the geographic composition and shows that a larger share of out-of-sample postcodes are located in major urban areas.

Table A4

Comparison of demographic characteristics (OA level)

	Boundary sample (1)	Out-of-sample (2)	Rural (3)
Population (count)	314.01	311.72	300.72
Population density (per hectare)	56.22	64.42	14.72
% Age: 0-15	18.69	18.69	17.10
% Age: 16-24	11.22	11.84	8.87
% Age: 25-44	27.90	28.58	21.59
% Age: 45-64	25.39	24.70	30.71
% Age: 65 and above	16.81	16.19	21.74
Median age (yrs.)	40.11	39.25	46.28
% Ethnicity: white	88.25	84.85	97.76
% Ethnicity: black	2.32	3.71	0.29
% Ethnicity: Asian	6.69	7.92	0.95
% Ethnicity: mixed, others	2.74	3.51	1.00
% employed: full-time	14.34	13.76	14.37
% employed: part-time	40.58	39.10	35.85
% self-employed	8.94	8.75	14.04
% unemployed	4.17	4.76	2.86
% managers, directors & senior officials	9.86	9.75	13.60
% professional occupations	16.65	16.59	17.20
% assoc. professional & technical occupations	12.16	12.18	11.87
% admin. & secretarial occupations	11.95	11.53	10.59
% skilled trades	11.45	11.03	14.63
% caring, leisure & other service	9.86	9.82	9.19
% sales & customer service	8.99	9.14	6.46
% process, plant & machine operatives	7.69	7.82	6.69
% elementary occupations	11.39	12.14	9.77

Note: The table compares demographic or economic characteristics using the 2011 census. We use information at the output area (OA) level which is the finest geography available in the census. Column 1 reports the summary statistics for our regression sample, which we refer to as the 'boundary sample'. Column 2 shows property characteristics for urban OAs that are not used in our regression. Column (3) shows information for properties located in rural OAs. Compared with our sample, out-of-sample OAs have a higher population density. They also have a population that is slightly younger and more ethnic. The occupation and employment characteristics are largely comparable across columns 1 and 2. The last column shows stark differences between urban and rural OAs.