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Who's Superconnected and Who's Not? Investment in the UK's Information and Communication Technologies (ICT) Infrastructure

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Abstract

The Information and Communication Technologies (ICT) infrastructure sector has dramatically expanded over the past decade as the demand for increased digital connectivity has increased from both companies and consumers. Broadband investment has been increasingly associated with positive economic growth and digital connectivity is seen as an essential ingredient with which to increase productivity, employment and create new enterprises. Hence, there is concern that companies and consumers in particular locations are disadvantaged if they are unable to obtain sufficient connectivity. At the present time there has been limited analysis of where new investment has taken place, why it has taken place in specific locations, and what the key economic and socio-economic drivers have been influencing this. The role of regulation in this process is also important to understand.

This article draws on two unique, uncensored infrastructure datasets from the UK's telecommunications regulator Ofcom to assess the factors driving investment in fixed and mobile ICT infrastructure. The fixed infrastructure model utilised modem sync speed measurements from over 20 million premises, aggregated to 7004 Middle Super Output Areas (MSOA) (97.3 %) in England and Wales, to provide comprehensive micro-geographic analysis for the first time. The mobile model employed the average data transfer per premises as a network capacity-demand metric for 173 counties and Unitary Local Authorities (ULAs) (98.3 %) in England, Scotland and Wales. Using predictors at a range of spatial scales, multilevel modelling utilising Markov Chain Monte Carlo (MCMC) methods was used to estimate both the fixed and mobile broadband infrastructure models.

The results confirm many of the prevailing postulates of existing telecommunications theory, namely, that dense, wealthy and well-educated areas are attractive investment hotbeds for telecommunication technologies. In the UK's fixed ICT infrastructure market, inter-platform competition was found to have a positive impact on investment compared to the mixed results found for intra-platform competition. On the whole, telecommunication investment in the UK appears to be driven by the same drivers as the much documented U.S. case, but further spatially granular research needs to be undertaken to examine the market dynamics between the incumbent and different forms of induced competition across the telecommunication network.

Keywords: ICT infrastructure; Fixed & mobile broadband; Infrastructure investment; Spatial; Urban & regional economic development

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Background

The Information and Communication Technologies (ICT) sector has expanded considerably over the past decade as the demand for increased digital connectivity has increased from both companies and consumers. The speed of technical change in both the supply of ICT infrastructure, and the means by which firms and individuals demand digital connectivity services, has been dramatic, leading to a new global epoch of interconnectivity and hence a new stage in contemporary capitalism (Devriendt et al. 2008, Grubesic *et al.* 2011; Tranos, 2011). Indeed, we have seen the convergence of voice, video and data services heightening the importance of fast and reliable digital connectivity. Broadband investment has been associated with positive economic growth (Holt & Jamison, 2009; Czernich et al. 2011; Koutroumpis, 2009, Kolko, 2012, Qiang *et al.* 2009, Röller & Waverman, 2001), increasing productivity, employment and the creation of new enterprises (Katz, 2009; Malecki & Moriset 2008; Kandilov & Renkow, 2010). For example, it has been estimated that firms can increase their productivity by between 7-10 % regardless of their location (urban versus rural) or the intensity of their information usage (Grimes et al. 2012), providing they have the necessary human capital (Mack & Faggian, 2013).

There is concern that companies in particular locations are disadvantaged if they are unable to obtain sufficient connectivity. Places with large technological endowments, which include ICT infrastructure, contribute to the vitality of entrepreneurial and innovative activities. This is particularly the case for high-tech industries like software or knowledge-based services which intensely utilise technology (Heger et al. 2011). Indeed, Henderson et al. (2007) identified infrastructure as one of the five key factors driving regional entrepreneurship along with human capital, amenities, financial capital and the local economy. Moreover, connectivity through ICT infrastructure has been found to have a positive impact on innovation, enhancing a region's patenting activities (Vinciguerra et al. 2011). Due to new technological innovations, the emergence of the digital economy has led to new spatial economic industrial location patterns (Feldman, 2002), predominantly reinforcing the existing dominance of cities due to the market and non-market advantages which they purvey (Glaeser et al. 1992; Glaeser, 2010; Glaeser, 2011). Although not always physically visible, leading global cities have reinforced their existing competitive advantage by becoming digital hubs for new technological infrastructures serving the Internet and subsequent digital economy (Tranos 2013). Evidently, a positive *evolutionary* dynamic is at play.

There is no doubt that the emergence of the digital economy is intrinsically interconnected with the emergence of new telecommunication infrastructure networks. An example being the replacement of copper and coaxial cable by fibre, wireless or other advanced methods of connectivity (Karlsson, 2004). As well as there being fundamental changes in the different transmission mediums used, there are also multiple transmission technologies being newly implemented in the network infrastructure. For example, we have seen advances made in the technologies used at the exchange, as fixed narrowband communications are upgraded to faster variants of broadband Digital Subscriber Line (ADSL, ADSL2+, VDSL, FTTP) or cable technologies. The quality of the connection obtainable over DSL is however highly variant depending particularly on the geographic distance of the premises from the nearest telephone exchange or street cabinet, and therefore how much copper the signal must travel over as a transmission medium (Grubesic & Horner, 2006). Over copper the broadband signal suffers attenuation as well as interference known as cross-talk, whereby both factors can lead to speed and reliability issues. Next Generation Access (NGA) is a driving force of change in fixed communications and involves the replacement of copper in the network infrastructure with fibre fixed lines to deliver improved connectivity to end users. A comparable dynamic is also seen in wireless methods of transmission as 2G network coverage is replaced by 3G and 4G LTE.

At the present time there has been limited analysis of where new investment has taken place, why it has taken place in specific locations, and what the key economic and socio-economic drivers have been influencing this. Certainly few studies have taken a spatial approach to understanding aspects of the 'digital divide' (Vicente & López 2011). It is evident that fixed and mobile ICT infrastructure are necessary factors of production required to remain competitive in the contemporary digital economy, and also for consumers to participate in an advanced and modern society. Yet to inform robust decision making we still need to understand the factors that are driving investment at a geographically granular level in ICT infrastructure and the role the regulatory regime has played. This article addresses these issues by drawing on recent experience of the United Kingdom. Section 2 examines the market, regulatory and policy context in which fixed and mobile ICT infrastructure is positioned. Section 3 examines the key factors that are driving broadband demand and Section 4 then reviews the broad contextual background and identifies key research questions. Section 5 sets out the methodology and Section 6 the data used. Section 7 presents model outputs and key findings. Section 8 draws together key conclusions and highlights where further research might usefully be progressed.

Fixed and mobile ICT infrastructure in context

ICT infrastructure is a classic example of a complex adaptive system, and is comprised of a variety of complementary fixed and mobile, communication and computation systems (Vogelsang, 2010). It plays a key role in enabling a wider ICT ecosystem which is itself comprised of an evolving variety of networked elements, platforms, applications, digital services, content and consumer demands (Fransman, 2010; Bauer, 2010). ICT infrastructure is one key component of the fifth Kondratieff long wave - the ICT revolution - which has continually been shifting employment patterns towards increasingly information-intensive economic activities. However, the seamless web of digital connectivity services enabling this is merely the end product of a complex process fused together by the regional, national and global investment strategies of network operators and their governing financial actors. Moreover, the deployment of infrastructure and its associated services are intrinsically dependent on a mix of economic, geographic, historical and regulatory factors (Rutherford, 2011). As ICT infrastructure is a necessary fixed factor of production in the contemporary digital economy, it can thus impact on the current and future economic development of different places. Not only can it lead to the production of new goods and services, but it can also horizontally increase the productivity of more industrial sectors across the economy through process and organisational improvements.

In terms of policy, the Digital Agenda for Europe is pivotal in delivering NGA (also known as superfast broadband) which is not just required to nurture the digital economy but has also been heralded to encourage social and economic cohesion (European Commission, 2014). The European Commission wishes to remove the so called "digital divide" and harness ICT to remove barriers between urban and rural areas, central and peripheral locations, and even between social groups within society. Indeed, as broadband access has become more ubiquitous there has been a shift in the focus of policy makers to *access quality*. Europe has the aspiration of providing Internet access speeds to all EU citizens of 30Mbit/s, with over 50 % of citizens subscribing to a connection over 100Mbit/s, by 2020. EU Structural and Rural Development Funds have been utilised to support poorly connected places, yet it was not until recently that the Commission (2014) released its Digital Agenda Toolbox, aiming to help regional and national authorities develop a better understanding of the digital growth potential of the Digital Agenda. ICT infrastructure (along with services, applications and products) plays a central role in the guidance. On the other side of the Atlantic, the Obama administration has followed a similar agenda. Congress approved $7.2 billion under the American Recovery and Reinvestment Act of 2009 to enhance broadband infrastructure in regions of poor connectivity. Moves have been made to provide user-friendly tools to help policymakers assess broadband availability in the U.S (e.g. Kolko, 2010). Even with China's dominance in global production, Premier Li Keqiang unveiled a plan to invest $323 billion in expanding its fixed and wireless broadband connectivity in order to spur Chinese service sector development (Oughton, 2013).

Traditionally, improvements in infrastructure have been considered to be a classic supply side intervention (McCann, 2013). Thus, improving the physical accessibility of lagging regions has been a central priority of the European Union which has subscribed heavily to this perspective in recent decades (Crescenzi & Rodríguez-Pose, 2008). However, infrastructure is not the only bottleneck to development as weak education and skills have held back vigorous economic change in lagging regions (Pike et al. 2006). Moreover, in much the same way that roads can work to take economic activity into *and* out of a region, increases in ICT infrastructure investment have the potential to increase competition in local economies (Rodríguez-Pose, 2002). Frequently the economic benefits of infrastructure investment have often been over estimated for political gains, while costs have been underestimated (Ansar et al. 2014), especially with regard to 'mega' infrastructure projects (Ansar, 2013). Moreover, the bi-directional causality between infrastructure investment and economic growth has long been debated since (Aschauer, 1989), and hence the causal direction does not clearly run from investment to economic growth. This interdependence between supply and demand is what characterises infrastructure research. However, ICT infrastructure endowments still influence corporate decision making, employment and entrepreneurial activity. Hence, Mack & Grubesic (2014) advocate greater public intervention in private ICT infrastructure markets to overcome disparities in provision.

Infrastructure investment and the revenue generation for network operators are driven by key economic, technological and regulatory parameters in ever competitive markets. The pursuit of financial viability in investment is central, especially in legacy network industries where there are large sunk costs and uncertainties (Tselekounis & Varoutas, 2013). Viability is also severely impacted on by population density, topology and expected demand, particularly when there is the possibility for new and superior technologies to enter the market (Götz, 2013). The regulatory approach adopted for the fixed telecommunications industry over the past decade in Europe has been attributed (among others) to the work of Cave (2006), whereby competitors in the market have been encouraged to progressively make investments in network assets; thus, '*climbing the ladder of investment*'[1]. Cave's perspective is proclaimed to promote consumer welfare through offering choice, variety, competitive prices and increased innovation, by always aiming to induce sustainable infrastructure-based competition, although some have only found weak empirical evidence for the existence of this theory (Bacache et al. 2014). The governance and regulatory regime has such a profound impact on investment in NGA that different regimes, from regulatory holidays to risk-sharing among competitors, have been explored (Nitsche & Wiethaus, 2011; Inderst & Peitz, 2012). The policy approach to regulating ICT infrastructure is essentially a trade-off between short and long-term policy objectives and whether one wants to achieve static or dynamic investment gains (Bauer, 2010).

Indeed, competition within the industry has also played a critical role, particularly as it has arisen from (a) inter-platform competition (DSL versus cable), (b) facilities-based intra-platform competition (DSL incumbent versus Local Loop Unbundling), or (c) services-based intra-platform competition (DSL incumbent retail versus bitstream access & resale) (Bouckaert et al. 2010). The introduction of intra-platform competition is one of the most recent developments and has resulted in the introduction of the regulatory process of Local Loop Unbundling (LLU). This allows multiple telecommunications operators to use existing connections between the telephone exchange and the consumer's premises, without the need for building additional duplicate infrastructure. As a result, the 'rungs of the ladder' are provided to new entrants who are able to lease access from the incumbent owner of the physical infrastructure network. Yet this regulatory paradigm has not been without criticism (see Bourreau et al. 2010), especially as the intrinsic relationship between access, investment and disparate geographies has on the whole been overlooked. This is especially pertinent in the UK where there has been concern over a lack of broadband access for (predominantly) rural areas. Cave's (2014) recent review highlights the need for regulatory change as over the past decade we have moved from simply unbundling copper to delivering fibre-based NGA.

Related studies on the determinants of ICT infrastructure supply and demand

Regions vary considerably in their economic endowments and socio-economic characteristics which indeed reflect their ICT requirements. Thus, by way of example, the extensive literature on urban agglomeration espouses the innovation and productivity benefits of firms who locate in urban areas because they have access to a critical mass of specialised suppliers, buyers, thick labour markets as well as infrastructure assets and services (Jacobs, 1969; Brakman et al. 2009; Glaeser, 2010; McCann, 2013). The self-reinforcing effects of agglomeration in cities and regions subsequently lead to a cyclical process where competitive locations reinforce their existing advantage in the business environment through a dynamic, evolutionary feedback process (Martin & Sunley, 2012). From a theoretical perspective, ICT infrastructure investment focuses on delivering specific services to businesses, residential consumers or both. The increased penetration potential of devices and services resulting from high population densities is a key factor in driving investment, yet the historical legacy of each operator's network continually affects strategy and market behaviour in a path dependent way.

In a spatial analysis of US broadband services Grubesic (2010) identifies the key factors driving the demand for broadband. They are population density, education and income levels, as well as the age of the population. Investment in ICT infrastructure is more likely to take place in locations with larger populations because network operators require a large number of customers who are willing to pay, often premium prices, for new digital connectivity services like broadband. Hence, it is also attractive for locations to have a large number of highly-paid residential consumers who have the necessary disposable income to pay for new services. Although broadband diffusion is often an urban-rural debate, Vicente & López (2011) argue that it is the cultural and intuitional factors that most impact on adoption. In the US, age and race appear to have an effect on ICT infrastructure investment in the empirical literature, to the extent that younger, whiter populations are correlated with high levels of broadband provision (Grubesic 2006a).

A study by Mack & Ray (2014) highlights the importance of broadband for Knowledge Intensive Business Services (KIBS) and the operations of service firms. Moreover, the literature shows that KIBS have been found to be a defining element in innovation-oriented European regions and their absence characterises poor performing regions - this highlights their importance for economic development (Corrocher & Cusmano, 2014). The employees of these firms are also likely to be highly educated and highly technologically savvy to the extent that they consume a wide variety of digital services themselves. Mack & Grubesic (2009) identified that information, finance & insurance, and professional, scientific and technical employment are highly correlated with broadband provision. A statistically significant relationship exists between broadband and establishments, but the intensity of this depends on firm size and industry. Smaller businesses are more correlated with broadband provision than medium or large businesses often because operators avoid trying to serve large firms and institutions who seek specialist high-bandwidth infrastructure instead. Total population, median age and household density were also all positive demand-side determinants (Srinuan & Bohlin, 2013). Grubesic (2006b)) determined that large non-white populations and median age were negative demand-side determinants.

Dauvin & Grzybowski (2014) estimated broadband diffusion in the EU using NUTS 1 regional data and used a range of supply and demand determinant factors to do this. This included infrastructure data on prices, inter-platform and intra-platform competition, along with socio-economic data covering income per capita, number of households, computer penetration, population density and education level. They concluded by emphasising the importance of analysing the determinants of broadband diffusion, especially in terms of competition and regulation, and found that policies which promote both inter- and intra-platform competition are important for broadband diffusion. Supply-side regulatory factors influence the demand position.

The determinants of accessing fixed broadband were modelled at the household level using a demand component by Flamm & Chaudhuri (2007). They found that in the US this is a function of price, urban or rural location, age, gender, race, marriage status, employment status, income and education. Importantly, they recognised the existence of a 'digital divide' and that poor, less educated and non-white individuals and communities are detrimentally affected as a consequence of a lack of access to digital connectivity. In Sweden, Srinuan et al. (2012) found that price, housing tenure and age were major determinants of broadband connections. Prieger (2013) found that while mobile broadband is less available in rural locations in the US, it still helps to fill the connectivity gap in fixed broadband coverage.

Even within OECD nations the diffusion of broadband occurs at differing rates (Lin & Wu, 2013), with the likes of Denmark and the Netherlands leading this group of wealthy countries. However take-up in the UK, for example, was modest until recent years. In a study by Bouckaert et al. (2010) the three areas impacting on broadband diffusion in OECD countries were (a) competition variables (inter, facility and services-based platform competition), (b) broadband service variables (speed & price), and (C) market demographics (population density, population dispersion, GDP & PC penetration). The results suggest that inter-platform competition has been the key driver of broadband penetration, while intra-platform competition has had more modest effects. This study demonstrates that competition and service variables in the supply of infrastructure combine with demand-side factors to influence investment. This implies there is a high degree of interdependency between ICT infrastructure supply and demand. In contrast, Gruber & Koutroumpis (2013) found little evidence globally, across 167 broadband markets, that inter-platform competition across technologies (e.g. cable) accelerated broadband diffusion, instead pointing to the benefits of inter-firm and intra-platform competition on the incumbent's Digital Subscriber Line (DSL) platform.

The UK context

Current statistics indicate that the UK, much like mainland Europe, is dominated by DSL technologies. Almost all premises (>99.9 %) were connected to an ADSL-enabled British Telecom (BT) exchange at the end of 2013 for fixed broadband (Ofcom, 2014c) and the majority (95 %) were connected to an LLU-enabled BT local exchange. The regulator estimates that under half of UK premises were able to receive Virgin Media's cable broadband services in June 2014, and 69 % of UK premises were able to receive BT Openreach/Kcom's fibre broadband services. NGA access in 2014 reached 78 % (>20 million) of UK premises. Historically cable has only been available in urban areas. The main cable operator Virgin Media, recently announced a £3 billion investment plan to upgrade and extend their network to pass another 4 million businesses and households, offering speeds up to 152Mbit/s. BT – the incumbent operator with the largest market share – is planning to upgrade its network via the deployment of G.fast technology which is claimed to enable 'ultra-fast' speeds up to 500Mbit/s within the next decade.

The process of change in the ICT infrastructure sector and what this means for the economic competitiveness of cities and regions has however received little attention, partly because of a lack of available data. The UK's service-led economy is unevenly dominated by London while other regions suffer from ageing industrial structures which are often uncompetitive in today's international marketplace (Gardiner et al. 2013). Global ICT infrastructure gravitates towards London as a mega-city-region due to its dominance in the advanced producer services industry and here these specialised employment structures co-evolve with changing ICT infrastructure technologies (Reades & Smith, 2014). Yet away from London, important questions have been raised over the viability of delivering NGA to the remaining population, especially the bottom 10 % of premises, which has risen to the top of the political agenda (Analysys Mason, 2013). Figure 1 illustrates the average sync speed for fixed ICT infrastructure at the Middle Super Output Area (MSOA).

The UK is ranked 8th on the global ICT Development Index (International Telecommunication Union, 2013) and the urgency to maintain a competitive edge is reinforced by the UK's dominance in the service sector. Although this index is based on metrics for infrastructure access, ICT use, ICT skills and ICT impact, the UK is persistently outperformed by the Nordic countries and many of the East Asian fibre nations (such as Japan and Korea). In the Nordic case, this is due to a long tradition of comprehensive state aid broadband policies, supplemented by strong involvement by municipalities and energy companies (Briglauer & Gugler, 2013), which contrasts strongly with the UK's more Laissez-faire, '*ladder of investment*'

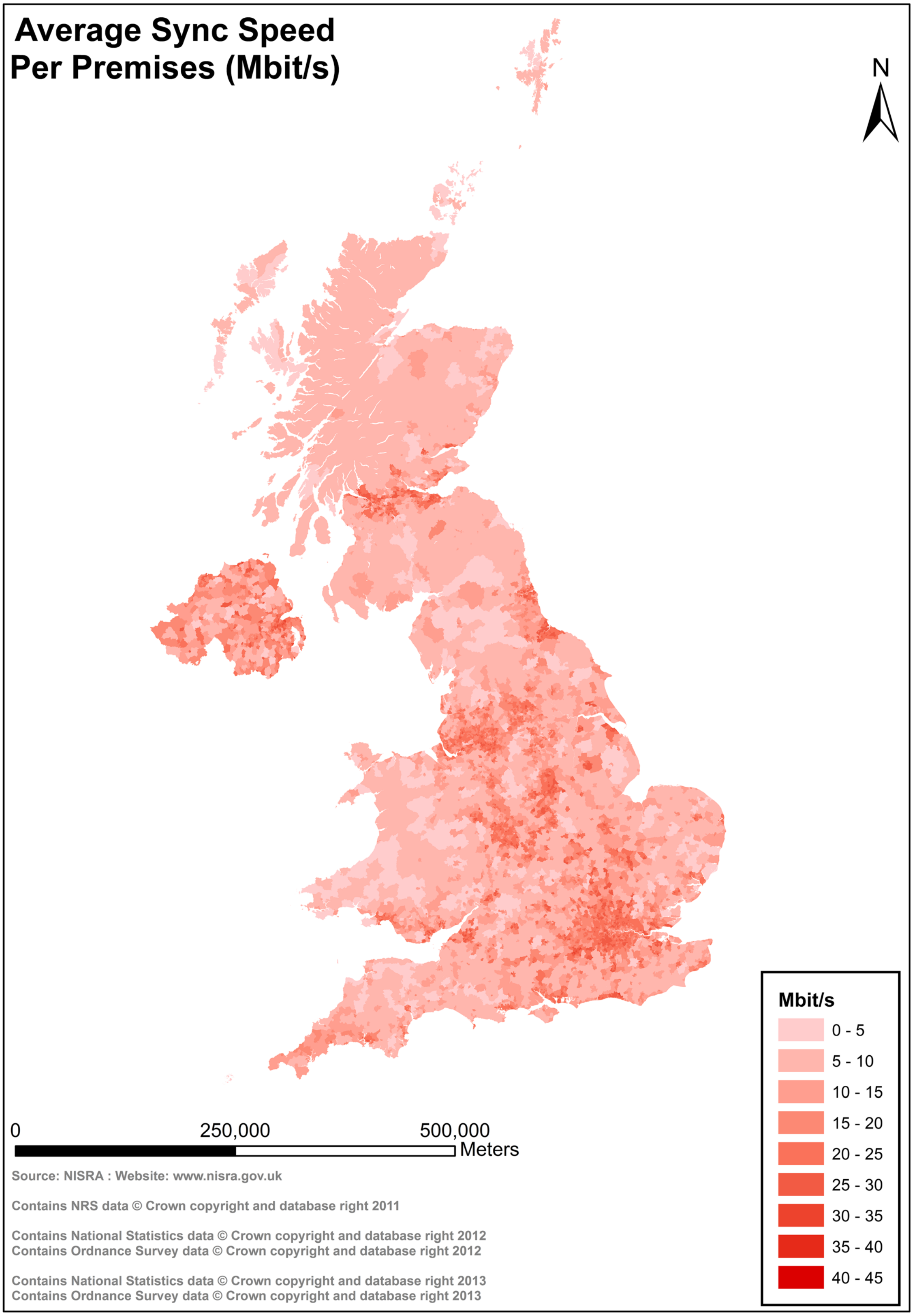

Fig. 1 Average sync speed per premises by MSOA (Mbit/s)

regulatory approach which aims to create a framework for private investment with limited supply-side subsidies (Ruhle et al. 2011).

The UK has one of the largest weekly Internet usage (87 %) and broadband take-up rates (83 %) in the EU (Ofcom, 2014a), and has one of the fastest growing digital economies (Nathan et al. 2013). In fact, the UK leads the G20 nations in this regard with its digital economy expected to contribute 12.4 % of GDP by 2016 (BCG, 2012). The availability and increased penetration of faster broadband speeds has been liberally estimated to add £17 billion to the UK's annual GVA output by 2024, an increase of 0.07 % (SQW, 2013). Moreover, an exploratory study by Liebenau et al. (2009) found that a £5 billion investment in UK broadband networks could potentially create 280,500 total jobs, echoing economic analyses carried out elsewhere (e.g. Katz et al. 2010). Figure 2 illustrates the average total mobile data transfer (upload/download) per premises by Unitary Local Authority (ULA).

Access to digital connectivity services has become a popular topic in the British media. A special focus has been placed on (almost always rural) communities being poorly served by fixed broadband and mobile forms of communication. Under New Labour in 2009, the Digital Britain Report (Department for Business, Innovation & Skills, Department for Culture, Media and Sport, 2009) introduced the Universal Service Broadband Commitment (USBC) which aimed to deliver 2Mbit/s to all premises by 2012. Digital connectivity has also been a top priority of the Coalition Government since it took power in 2010 but the date for achieving this policy has been revised many times and currently stands at 2017. Like many European countries, the UK telecommunication sector is subject to its historical legacy of having a publicly-owned telecommunication monopolist. The incumbent (BT) still owns the largest proportion of the fixed infrastructure. There is ongoing debate over how best to regulate the industry.

Methods

By employing spatially granular data on ICT infrastructure, the nested structure inherent in the units of observation is amenable to multilevel modelling (MLM). This methodology has been widely applied in urban and regional economics for example to look at inequality (Li & Wei, 2010), the geography of innovation (Srholec, 2010), human capital in firms (Ployhart & Moliterno, 2011), and labour market externalities and productivity (Eriksson & Lindgren, 2008). Using MLM similar individual observations are clustered into higher-level units. Observations which share the same higher-level unit are more likely to have similar values because they share the economic and socio-economic processes that transcend artificial spatial boundaries, indirectly incorporating spatial clustering effects (Lawson et al. 2003). Hence, a primary goal of MLM is to account for non-independence between observations and adjust inferences on parameter estimates accordingly (Browne, 2012). The standard errors produced when using clustered information are generally more conservative than when clustering is ignored. Moreover, MLM in spatial economic research enables the quantification of economic and socio-economic phenomena across different geographic levels enabling us to disentangle different sources of variation whereby each cluster represents a parallel regression line (Goldstein, 1987; Browne, 2012; Arcaya & Subramanian, 2014). This emphasises the profound impact of different spatial contexts on economic activity. Mack et al. (2011), after studying the importance of broadband provision to knowledge intensive firm location, point to the need for methodologies on this topic to utilise data at a variety of spatial scales to better understand the relationship between firms, industrial sectors and broadband infrastructure. This methodology is able to do this by incorporating predictors at different levels of the hierarchy.

A random-effects multilevel model was selected where the random differentials present are assumed to be outcomes of a process that is predicting them and are conceptualised as coming from a distribution (Goldstein, 2011; Arcaya & Subramanian, 2014). This results in three practical benefits: (a) information between spatial units is pooled, so all data contribute to the combined estimation of fixed and random parts, (b) statistical power is borrowed from other statistical units to boost robust estimation, and (c) unreliable level one fixed estimates are shrunk towards the overall level one estimates (Ibid.). Given that both models only represent a proportion of the UK, it would be highly desirable to be able to generalise the results. Hence, our interest is primarily in examining the variability across lower and higher units. The challenge for fitting complex MLMs is estimating the data-level regression coefficients along with the group-level model. The most direct way to do this is by using Bayesian inference as it treats the group-level model as 'prior information' in estimating individual-level coefficients (Gelman & Hill, 2007).

Indeed, recent scientific discourse has focused on the fact that too many studies lack reproducibility. Often when frequentist statistical methodologies are used they can be the source of the problem as classical significance has long been claimed to be biased against the null hypothesis (Edwards, 1965). This leads to false positives in the quest for scientific knowledge which ultimately leads to researchers drawing incorrect inferences. The majority of regional science up until the 1990s was based on frequentist statistics, as detailed by Anselin's (1988) thorough review of the spatial econometric literature. The technique of Markov Chain Monte Carlo (MCMC) estimation has enabled the sophisticated modelling of large data sets with

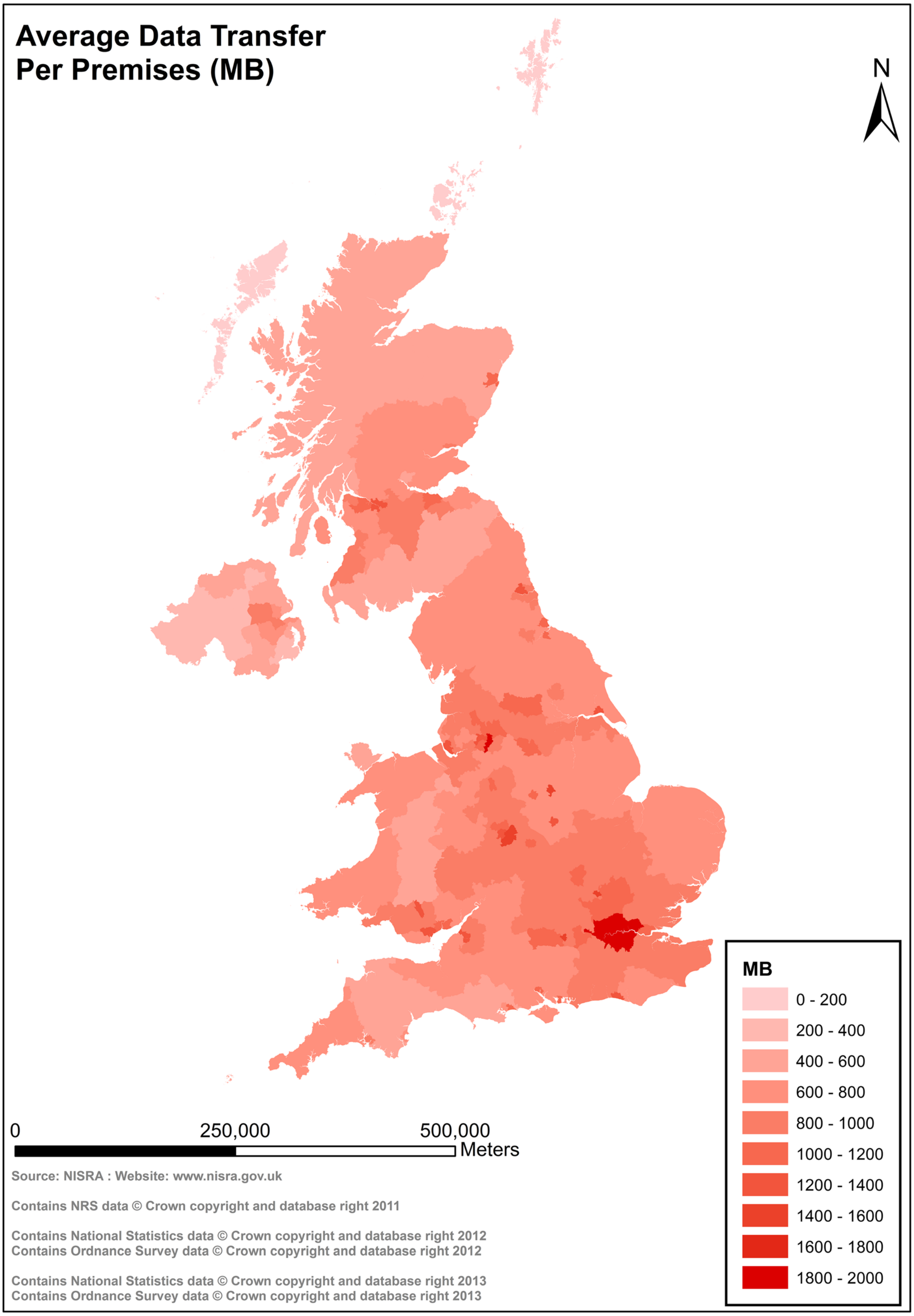

Fig. 2 Average mobile data transfer per premises (MB) (June 2013)

cross-sectional correlation (Mills & Parent, 2014), with recent developments enabling Bayesian MLM analysis for complex geographically clustered data (LeSage & Pace, 2009). The use of MCMC estimation enabled the specification of more complex multilevel models which would not have been possible to estimate using frequentist statistical techniques.

In this article all analyses utilised Bayesian inference using Markov Chain Monte Carlo (MCMC) algorithms in the multilevel modelling software MLwiN 2.30. To reduce burn-in, starting values were obtained for each model using standard Iterative Generalized Least Squares (IGLS)/Restricted Iterative Generalized Least Squares (RIGLS) before running the MCMC sampler with low-informative priors. Following Gelman et al. (2013), Geyer (2011) and Mills & Parent (2014) caution was paid to (a) early iterations of the chain being misrepresentative and (b) the Markov chain being autocorrelated. With regard to the former, the early iterations from the chain were discarded, with the burn-in period being set to 5,000 iterations. With regard to the latter, inference from correlated draws is less precise than from independent draws and hence the thinning value was set to 10 to ensure satisfactory sample mixing. A number of pilot runs were carried out to determine these values. According to Gelman et al. (2013) providing the chain has converged, an MCMC sample of 100 independent draws is more than sufficient for accurate posterior inference, although we significantly exceed this number running the chain long enough to generate an effective sample size of >100,000 for each parameter. Early iterations of the chain were discarded.

Data

Although data is generally limited for ICT infrastructure (see Lehr et al. 2008 for a comprehensive discussion), this article draws on two unique infrastructure datasets from the UK's telecommunications regulator Ofcom. Access to sufficiently granular data is one of the largest research challenges facing researchers from drawing more definite conclusions (Holt and Jamison, 2009) and hitherto there has been a lack of comprehensive micro-geographic data for the UK's ICT infrastructure (SQW, 2013:5). This is an improvement on the types of data available in other countries which often contain little to no information on providers, platforms or speeds (Mack et al. 2011).

The dependent variable used in the fixed broadband infrastructure model is the average modem sync speed derived from over 20 million premises measurements and averaged at the MSOA. This data covers the seven main DSL and cable service providers; BT, Virgin Media, EE, O2, KCom, Talk Talk and Sky (Ofcom, 2013). Complete data were generated for 7004 MSOAs (97.3 %) in England and Wales and all variables were continuous, as detailed in Table 1.

Measuring broadband is of some debate (Bauer et al. 2010), but sync speed measurements are certainly one of the most robust ways of measuring infrastructure capacity (and by proxy investment) as they overcome some of the limitations associated with speed test measurements (as used in other studies e.g. Riddlesden & Singleton, 2014). Sync speed measures are unique in their ability to provide accurate diagnostics of the capacity between the telephone exchange and the premises (without physically placing a diagnostic box in each premises) and are the favoured metric of the UK's regulator (Ofcom, 2013). The sync speed is the downstream data rate at which the ISP's equipment in the local exchange or cabinet sends data to the customer's broadband modem and represents the highest possible speed at which data can be transferred across the line (Ibid.). This will depend on the technologies enabled at the exchange (ADSL, ADSL2+, VDSL, FTTP, cable), and the quality of the transfer medium between the exchange, cabinet and modem. The data released by Ofcom into the public domain is usually heavily censored but the regulator provided the researchers with uncensored estimates of the average modem speed at the MSOA making this a unique analysis of the UK's ICT infrastructure. While the researchers were provided with a novel and more spatially granular uncensored dataset, this geographic scale still enabled the regulator to protect the market sensitive data they collected from the operators under their legal powers. After obtaining the Ofcom infrastructure data, the rest of the variables were available directly from ONS Nomis with the exception of the population density variable which was constructed using population and surface area measurement data.

The mobile broadband infrastructure model utilised the average data transfer per premises (download and upload) as the dependent variable, which acts as an indicator of network capacity-demand (Ofcom, 2013). This was provided at the ULA level in England, Scotland and Wales. Table 2 describes the continuous variables explored in the mobile broadband infrastructure model, including which level the predictors reside, their data sources and descriptive statistics. After obtaining the Ofcom infrastructure data, the other variables were generated from the same sources as the fixed model, but aggregated in accordance with the relative geography.

Results & discussion

Multilevel models were estimated using IGLS/RIGLS for the fixed and mobile infrastructure models respectively, followed by estimation using MCMC methods (Browne & Rasbash, 2009). Although more complex MLM specifications were explored, the models reported here met all of the necessary MLM assumptions. The Bayesian Deviance Information Criterion (DIC) (a generalisation of Akaike's Information Criterion) was used to compare models as it

Table 1 Fixed Broadband Model Variables

Variable	Description	Level	Source	Obs.	Mean	Std. Dev.	Min.	Max.
Average.Sp$_{ij}$	Average fixed broadband speed (Mbits/s)	MSOA	Ofcom 2014a	7004	17.75	6.47	1.83	31.89
Connection. Density$_{ij}$	Total number of connections divided by the total number of domestic premises	MSOA	Ofcom 2014a/ OS Codepoint	7004	0.72	0.09	0.32	1.83
P.Tert$_{ij}$	Percentage of tertiary employment (%)	MSOA	Nomis 2012	7004	90.8	9.12	39.52	100
P.KIBS$_{ij}$	Percentage of employment in Knowledge Intensive Business Services (KIBS) (%)	MSOA	Nomis 2012	7004	24.45	9.27	0	82.61
Occupation$_{ij}$	Percentage of the population with Level 3 & 4 occupations (managers, professionals, skilled trades etc.) (under the Standard Occupation Classification, 2010) (%)	MSOA	Nomis 2012	7004	51.47	10.8	22.8	85.7
PML$_{ij}$	Percentage of Medium (50-249 employees) and Large (250+ employees) Firms using workplaced-based employment (%)	MSOA	Nomis 2012	7004	2.32	2.58	0	16.49
Median.Age$_{ij}$	Median age of the population	MSOA	Nomis 2012	7004	39.75	6.25	20	63
P.Owner$_{ij}$	Percentage of home owners (%)	MSOA	Nomis 2012	7004	64.48	16.9	7.3	96.5
Students$_{ij}$	Percentage of adults (>18 years of age) in full time education (%)	MSOA	Nomis 2012	7004	4.92	6.53	0.8	82.5
P.Edu$_{ij}$	Percentage of the population with a degree (%)	MSOA	Nomis 2012	7004	21.89	9.53	3.51	62.62
P.Claim$_{ij}$	Percentage of the working population claiming a state benefit (%)	MSOA	Nomis 2012	7004	2.56	1.96	0.06	17.38
P.Non.White$_{ij}$	Percentage of the population that are non-white (%)	MSOA	Nomis 2012	7004	12.9	17.52	0.4	94.4
P.Econ. Active$_{ij}$	Percentage of the population that are economically active (%)	MSOA	Nomis 2012	7004	69.69	5.72	26.8	87.7
P.Cable$_{j}$	Percentage of exchanges with cable enabled (%)	LAD	Sam Knows 2013	348	57.19	40.65	0	100
P.LLU$_{j}$	Percentage of exchanges with Local Loop Unbundling (LLU) (%)	LAD	Sam Knows 2013	348	78	27.35	0	100
LLU.Count$_{j}$	Average number of service providers at LLU enabled exchanges (%)	LAD	Sam Knows 2013	348	4.44	2.61	0	9.75

Table 2 Mobile Broadband Model Variables

Variable	Description	Level	Source	Obs	Mean	Std. Dev.	Min.	Max.
$Data_{ij}$	Average data throughput per premises (upload & download) (MB)	ULA	Ofcom 2014b	173	610.3	168.48	256	1268
$P.Tert_{ij}$	Percentage of tertiary employment (%)	ULA	Nomis 2012	173	89.22	4.69	70.88	98.24
P.KIBS	Percentage of employment in Knowledge Intensive Business Services (KIBS) (%)	ULA	Nomis 2012	173	11.19	5.58	3.39	30.96
$P.ML_{ij}$	Percentage of Medium (50-249 employees) and Large (250+ employees) Firms using workplaced-based employment (%)	ULA	Nomis 2012	173	3.66	1.07	1.55	6
P. $Occupation_{ij}$	Percentage of the population with Level 3 & 4 occupations (managers, professionals, skilled trades etc.) (under the Standard Occupation Classification, 2010) (%)	ULA	Nomis 2012	173	50.01	5.2	39.3	64.8
P.Econ. $Active_{ij}$	Percentage of the population that are economically active (%)	ULA	Nomis 2012	173	68.79	3.28	61.1	78.4
$P.Students_{ij}$	Percentage of schoolchildren and students (>18 years of age) in full time education (%)	ULA	Nomis 2012	173	4.93	3.4	2	18.4
$Median.Age_{ij}$	Median age of the population	ULA	Nomis 2012	173	40.29	3.64	29	47
$Density_{ij}$	Population density in each MSOA (KM^2)	ULA	Nomis / ONS SAM	173	1155.32	1323.73	9	5285
$P.Claim_{ij}$	Percentage of the working population claiming a state benefit (%)	ULA	Nomis 2012	173	5.4	2.28	1.52	11.39
$P.Edu_{ij}$	Percentage of the population with a degree (%)	ULA	Nomis 2012	173	21.04	5.16	12.1	41.4
P.Non. $White_{ij}$	Percentage of the population that are non-white (%)	ULA	Nomis 2012	173	7.9	9.07	1.08	49.48
$Gva.Per.Cap_{j}$	Workplace based GVA per capita (income allocated to the region where the economic activity took place) (£)	Nuts 1	ONS, 2012	11	18714.38	2595.74	15401	37232
Patent. $Apps_{j}$	Patent applications to the EPO by priority year	Nuts 1	Eurostat 2011	11	176.68	140.25	39.95	550.9

Shetland, Orkney and Eileanan Star were outliers and were subsequently excluded

takes into account both model fit and complexity (Spiegelhalter et al. 2002). The average deviance $(\bar{D})$, the deviance of the expected value of the unknown parameters $\left(D(\bar{\theta})\right)$ and the effective number of parameters (*pD*) are also displayed for completeness. For each of the best fitting models the 2.5 %, and 97.5 % values of the posterior distribution were extracted to show the 95 % credible interval (CI). We report the results following the format of other Bayesian researchers in the field of regional science (e.g. Parent & LeSage, 2008), and take guidance from (Kruschke 2011:508) in reporting Bayesian analyses.

Fixed broadband model

The Bayesian diagnostic results are displayed in Table 3[2] after specifying nine different multilevel random-intercept models for using the fixed broadband data. Predictors were grand mean centred. The first thing to note in Table 3 is that after specifying the empty (null) model, all subsequent model specifications were a considerable improvement. The null model showed that 58 % of the variance in average fixed sync speed arose from inter-class differences, and 42 % arose from intra-class differences. After this, variables defined as important in the existing theory (e.g. employment in services, density and age) were entered into the model. Finally other empirical variables less defined in the literature were entered (e.g. ethnicity).

As there has been a hybridisation of frequentist and Bayesian approaches in MLM, significance values were still included in the results tables. For individual variables the ratio between the coefficient and the standard

Table 3 Fixed Broadband Model Runs and Diagnostics

Model	$\bar{D}$	$D(\bar{\theta})$	pD	DIC	
				Value	Ranking
Model 1	38232.84	37640.94	591.90	38824.74	1
Model 2	38233.85	37642.52	591.33	38825.18	2
Model 3	38231.51	37637.52	593.99	38825.51	3
Model 4	38243.84	37653.83	590.02	38833.86	4
Model 5	38311.63	37720.41	591.23	38902.86	5
Model 6*	38483.46	37920.20	563.26	39046.73	6
Model 7	38470.50	37893.80	576.70	39047.20	7
Model 8	38473.37	37897.66	575.70	39049.07	8
Model 9+	40249.71	39402.10	847.61	41097.32	9

+Empty model
*Removed significant variables with coefficients below 0.05

error was examined closely, as coefficients twice the size of the standard error indicates a significant effect (Wald test). Insignificant variables (p > 0.05) were removed from the model. Also, variables with small coefficients (<0.05) were removed, but had the effect of increasing the DIC (Model 6). The specification for the best fitting model (Model 1) is as follows and its posterior distribution has been reported in Table 4.

$$\begin{aligned} Average.Sp_{ij} = &\ Constant_{ij} + Connection.Density_{ij} \\ &+ P.Tert_{ij} + P.ML_{ij} + Median.Age_{ij} \\ &+ P.Edu_{ij} + P.Econ.Active_{ij} \\ &+ Occupation_{ij} + P.Non.White_{ij} \\ &+ Students_{ij} + P.Owner_{ij} + P.Cable_{j} \\ &+ P.LLU_{j} + LLU.Count_{j} + u_{j} + e_{ij} \end{aligned}$$

Unsurprisingly the connections density (3.53) had the largest impact on the speed, most likely for two reasons. Firstly, this coefficient could have been impacted on by premises being densely located close to the exchange and therefore still achieving acceptable speeds over copper. Indeed, DSL coverage is highly geographically nuanced based on premises location (Grubesic & Horner, 2006; Grubesic, 2008; Grubesic et al. 2010). Perhaps this is suggestive that in future research, it might be more appropriate to use the percentage of postcodes with NGA enabled instead of sync speed measurements as the dependent variable. This would remove the effect which arises from the geographic distance between the premises and the exchange. This was experimented with in this research but the models using postcode-level data failed to meet the necessary modelling assumptions because of complex level one variance. Another factor is that although the infrastructure might have been upgraded to NGA, you may still have a large number of premises located a long way from the telephone exchange. Therefore, because they are positioned on a very long local loop it affects the bandwidth obtainable and they might be unable to achieve the 2Mbit/s target. But secondly, network providers on the whole are more likely to invest the upfront capital cost to provide improved connectivity to dense areas because they can achieve the largest economies of scale with the least risk to their investment (because they have a large pool of customers to attract). As has often been the case in the UK dense urban areas are subsequently more likely to receive priority in the roll out of NGA infrastructure.

Table 4 Model 1 Posterior Distribution

Variable	Model Parameter	Lower 2.5 %	Mean	Upper 97.5 %	Std.
Constant	β_0	17.68	17.87	18.05	0.09
Connection. Density$_{ij}$	β_1	1.69	3.53*	5.38	0.94
P.Tert$_{ij}$	β_2	0.20	0.22*	0.23	0.01
PML$_{ij}$	β_3	0.02	0.06*	0.10	0.02
Median. Age$_{ij}$	β_4	−0.18	−0.14*	−0.10	0.02
P.Edu$_{ij}$	β_5	0.13	0.17*	0.21	0.02
P.Econ. Active$_{ij}$	β_6	0.10	0.13*	0.16	0.02
Occupation$_{ij}$	B_7	−0.26	−0.23*	−0.20	0.02
P.Non. White$_{ij}$	B_8	−0.05	−0.04*	−0.03	0.01
Students$_{ij}$	B_9	0.01	0.03*	0.06	0.01
P.Owner$_{ij}$	B_{10}	0.00	0.02*	0.03	0.01
P.Cable$_j$	B_{11}	0.08	0.09*	0.09	0.00
P.LLU$_j$	B_{12}	0.00	0.02*	0.03	0.01
LLU.Count$_j$	B_{13}	−0.62	−0.44*	−0.26	0.09
Level 2 Variance (n = 348)	$\sigma^2{}_j$	4.02	4.58	5.18	0.35
Level 1 Variance (n = 7004)	σ^2_{ij}	13.27	13.75	14.25	0.25

*$p < 0.05$
Results rounded to 2 decimal places

Next, the structure of the local economy in terms of service sector employment had a positive impact on the dependent variable (0.22). This could be because (a) services are often information intensive and therefore require more bandwidth, or (b) the employees of these firms are more intensive users of digital connectivity, and this stimulates investment in infrastructure by network providers because there is substantial demand. Similarly, the percentage of medium and large firms had a small but positive impact on average sync speed (0.06), most likely because these firms choose to locate in dense urban areas with well-educated populations, leading to large demand. A significant positive correlation was found between average sync speed and the education of the local population (0.17).

Out of the socio-economic variables we found that areas with a larger percentage of residents in high-level occupations has a negative effect on speed (-0.44) perhaps due to the location decisions of wealthy socio-economic groups choosing more peripheral and sparse sub-urban locations. The median age of the population also had a negative impact on speed (-0.14) and by proxy investment, in line with existing theory. As expected the percentage of economically active residents had a positive impact on the dependent variable (0.13), as did the percentage of students (0.03) and home owners (0.02). The percentage of non-white individuals in a location had a negative impact on sync speed (-0.04), potentially due to deprivation and therefore a lack of market demand for operators to invest.

The percentage of exchanges with cable available had an as expected positive impact (0.09) due to inter-platform competition. Moreover, the percentage of exchanges with LLU enabled also had a positive impact (0.02), but overall the results contrast with the findings of Gruber & Koutroumpis (2013). Their analysis found that diffusion and investment has taken place from intra-platform competition and less so from inter-platform competition, but it might be that the UK does not follow the same trend. It was surprising to find that the number of LLU operators at an exchange had a negative impact on speed (-0.44), implying on face value that more intra-platform competition leads to lower speeds. However, there are two potential explanations for this finding. Firstly, this negative correlation could be due to LLU operators being attracted to providing services in exchanges with the largest number of lines attached. More lines could lead to increased technological strain on the infrastructure through contention, cross-talk signal attenuation and due to physical space limits having more premises located on copper lines far away from the exchange. Secondly, an alternative explanation is that the larger the number of resellers using the incumbent's infrastructure via LLU, the more the incumbent is deterred from investing in NGA, as they would be less likely to reap full rewards from their investment. If this second explanation was true then the market strategy for the incumbent's DSL platform might be to directly compete with cable through NGA investment, but leave exchanges with a large LLU presence for investment at a later stage. Further analysis on this topic could be carried out with the data used here and could prove of great importance in explaining firstly this result and secondly the investment dynamics between the incumbent and other service providers. Ranking the number of lines attached to each exchange and examining the location characteristics of different parts of the distribution would prove a useful starting point.

Mobile broadband infrastructure model

The Bayesian diagnostic results are displayed in Table 5 after specifying nine different multilevel random-intercept models using the mobile broadband data. These models all had ULAs clustered within NUTS 1 Regions. All variables were log transformed and the dependent variable was normalised around the mean. The first thing to note in Table 5 is that after specifying the empty (null) model, all subsequent model specifications were a considerable improvement. The null model showed that 24 % of the variance in data traffic arose from inter-class differences, and 76 % arose from intra-class differences.

The approach used for model specification was identical to the approach used for the fixed broadband model. As we can see from Table 5, the model specifications using the predictor variables were a much better fit than the empty (null) model. As before, insignificant variables (p > 0.05) were removed from the model along with variables with small coefficients (<0.05). Model 2 had GVA.Per.Capita removed as it was insignificant but had a larger DIC than Model 1 when it was left in. Consequently, the specification for the best fitting model (Model 1) is as follows and its posterior distribution has been reported in Table 6.

Table 5 Mobile Broadband Model Runs and Diagnostics

Model	$\bar{D}$	$D(\bar{\theta})$	pD	DIC	
				Value	Ranking
Model 1	−230.31	−243.42	13.110	−217.20	1
Model 2*	−228.30	−239.84	11.54	−216.76	2
Model 3	−229.43	−243.21	13.780	−215.65	3
Model 4	231.23	−247.74	16.500	−214.73	4
Model 5	−229.52	−245.33	15.810	−213.72	5
Model 6	−226.70	−239.88	13.180	−213.52	6
Model 7	−225.46	−238.97	13.510	−211.94	7
Model 8	−156.06	−166.14	10.080	−145.98	8
Model 9+	−7.37	−16.94	9.57	2.19	9

+Empty model
*Removed GVA.Per.Cap as $p > 0.05$

$$\begin{aligned} Log.Data_{ij} = {} & Constant_{ij} + Log.P.Tert_{ij} \\ & + Log.P.ML_{ij} + Log.Density_{ij} \\ & + Log.Median.Age_{ij} + Log.P.Non.White_{ij} \\ & + Log.Gva.Per.Cap_{j} + u_j + e_{ij} \end{aligned}$$

Table 6 shows that the largest effect was from median age (-0.87) which had a negative effect on the network capacity-demand metric used as the dependent variable. This is in line with existing theory in that younger demographics are often early adopters of new technologies and consequently they are likely to use them more intensively than older demographics. Areas with younger populations therefore provide larger markets for mobile network operators to target. It is logical that infrastructure capacity will attempt to follow demand and

Table 6 Model 1 Parameters and Posterior Distribution

Variable	Model parameter	Lower 2.5 %	Mean	Upper 97.5 %	Std.
Constant	β_0	−4.37	−1.17	1.83	1.89
$Log.P.Tert_{ij}$	β_1	0.11	0.52*	0.94	0.21
$Log.P.ML_{ij}$	β_2	0.03	0.15*	0.27	0.06
$Log.Density_{ij}$	β_3	0.02	0.04*	0.07	0.01
$Log.Median.Age_{ij}$	β_4	−1.31	−0.87*	−0.42	0.23
$Log.P.Non.White_{ij}$	β_5	0.01	0.06*	0.1	0.02
$Log.Gva.Per.Cap_{j}$	β_6	−0.10	0.15	0.45	1.14
Level 2 Variance[a] (n = 10)	$\sigma^2{}_j$	0.00	0.00	0.01	0.00
Level 1 Variance[a] (n = 173)	σ^2_{ij}	0.01	0.02	0.02	0.00

*$p < 0.05$
[a]Variance is the estimated parameter
Results rounded to 2 decimal places

therefore we can deduce that there is likely to be greater investment in areas with younger demographics. The next largest effect was from service sector employment (0.52) in which we can draw inferences between service firms being more information intensive and their employees being more technologically savvy than in other sectors. Moreover, as was evident with the fixed ICT infrastructure model, the percentage of medium and large firms has a positive (albeit marginal) impact (0.15) on the dependent variable.

In terms of socio-economic variables the percentage of non-white individuals differed significantly between the fixed broadband and mobile broadband models. Whereas ethnic diversity had a marginal negative impact in the fixed ICT infrastructure model (-0.04), it had a marginal positive impact in the mobile ICT infrastructure model (0.06). This result might be due to mobile connectivity functioning as a gateway technology for broadband use. This has been found in deprived urban communities because smaller upfront investment is required for mobile devices (Mossberger et al. 2012).

Density appeared to have less of an impact (0.04) on the dependent variable than some of the other metrics used, which could be attributable to mobile technologies being able to cover larger geographical areas with lower capital investment costs than fixed ICT infrastructure. If so, then the technological differences between these infrastructures indicate that mobile (such as 4G and beyond) is a likely short-term solution to connecting those places which currently cannot meet the 2Mbit/s UK target. In comparison with the fixed model, a larger number of variables were dropped from the mobile infrastructure analysis. Further research needs to analyse the base mobile data from Ofcom, in order to explore these issues in greater spatial granularity. Moreover, there is also a time series developing which would enable greater investigation of directional causality and dynamics in mobile ICT infrastructure supply and demand. Understanding this dynamic would enable more robust causal inferences to be drawn as these are hard to address from cross-sectional data.

Conclusions

This article set out to examine the supply and demand factors that have driven investment in fixed and mobile ICT infrastructure utilising a spatially granular approach. It did this by analysing a novel, uncensored dataset for the first time from the UK's telecommunication regulator and then developing a multilevel modelling approach which would enable variables to be incorporated at a variety of spatial scales. The use of MCMC estimation enabled the specification of more complex multilevel models which would not have been possible to estimate using frequentist statistical techniques. The fixed broadband infrastructure model generally confirmed many of the existing postulates of existing telecommunications theory – that dense, wealthy and well-educated areas are attractive investment hotbeds for telecommunication technologies. The results showed that the actual economic structure of a local economy, in terms of service sector employment, had a positive impact on investment. In terms of supply, inter-platform competition appears to have had a marginal positive impact on average speed and investment, while intra-platform competition showed mixed results.

On the whole, the results were comparable across the fixed and mobile models, although the coefficients were larger in the mobile model. The only diverging results were for population density and ethnicity. The inherent distinction between how fixed and mobile technologies function explains why density had a larger positive impact in the fixed model. The ethnic diversity indicator was the only variable which was profoundly different in that it had a negative effect on investment in fixed broadband infrastructure, and a positive effect in the mobile model. This likely relates to socio-economic disparities and the fact that those in deprived areas are more likely to use mobile connectivity as a gateway technology because mobile devices are a low cost way to connect.

On the whole, telecommunication investment in the UK appears to be driven by the same drivers as the much documented U.S. case, but further research needs to be undertaken which examines the market dynamics between the incumbent and different forms of induced competition across different layers of the telecommunication network. From the results found, the recent announcement that the dominant cable operator is expanding its network reach to four million new premises is likely to have a positive effect on fixed broadband speed due to increased inter-platform competition. In terms of developing public policies which overcome the digital divide, further analysis needs to be conducted which focuses on the availability of digital connectivity in areas of ethnic diversity. While mobile connectivity helps to address the disparity in fixed ICT infrastructure, mobile has however traditionally been inferior to fixed forms of connectivity. In terms of economic development initiatives, given that the supply of ICT infrastructure was correlated with service sector employment, and medium and large firms, there should be a focus on (a) locations with predominantly primary or secondary employment, and (b) connectivity for SMEs. As these infrastructures are necessary factors of production required to remain competitive in the contemporary digital economy greater steps need to be taken to understand investment decisions at a geographically granular level in ICT infrastructure.

Endnotes

[1]See Bourreau et al. 2010 for a critical review and also Cave (2014) for a discussion of how the telecommunications sector has changed since the theory was first conceptualised.

[2]Fixed-effects models were explored in the analysis however they had a minimal impact on the coefficients, standard errors and were generally less effective fitting the data than random-intercept models.

Abbreviations

BT: British Telecom; DIC: Deviance Information Criterion; DSL: Digital Subscriber Line; ICT: Information and Communication Technologies; IGLS: Iterative Generalized Least Squares; KIBS: Knowledge Intensive Business Services; LLU: Local Loop Unbundling; MCMC: Markov Chain Monte Carlo; MLM: Multilevel Modelling; MSOA: Middle Super Output Areas; NGA: Next Generation Access; RIGLS: Restricted Iterative Generalized Least Squares; USBC: Universal Service Broadband Commitment.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

EO conducted the modelling work and wrote up the first draft of the article. PT edited the article and refined the literature review, aims and results. DA generated the choropleth maps and helped to prepare data for the analysis. All authors read and approved the final manuscript.

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