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***Information Communication Technologies and Firm Performance: Evidence for UK Firms***

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# Information Communication Technologies and Firm Performance: Evidence for UK Firms

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**Abstract**

A recent literature has begun to recognise that ICT is heterogeneous and the effects from improving communication are distinct from those that improve the storage and processing of information. In this paper we use the arrival of a new communication technology, ADSL broadband internet, to study the effects of communication ICT on firm performance. To do so free from endogeneity bias, we construct instruments using the infrastructure underlying broadband internet - the pre-existing telephone network. We show that, after placing various restrictions on the sample, instruments based on the timing of ADSL broadband enablement and the cable distance to the local telephone exchange satisfy the conditions for instrument relevancy and validity for some types of ICT. We find in turn, that communication-ICT causally affects firm size (captured by either sales or employment) but not productivity.

JEL classification: D22, D24, O3

Keywords: ICT, firms, instrumental variable

## 1. Introduction

Over the last few years, the economics literature has begun to question the standard modelling assumption of aggregating information and communication technologies (ICT) into a homogenous capital when considering its impacts on firm performance. Instead, it has been recognised that ICT provides firms with a variety of ways to store, process and transmit information, which in turn generate new knowledge and improved coordination and communication across production lines and with customers. These can have different effects on management and organisation, and consequently the size, human-capital intensity and productivity of the firm. For example, Garicano and Rossi-Hansberg (2006) demonstrate this point in relation to a model of organisational structure. Improved communication technologies lead organisations to rely more on top-level managers who solve problems, increasing the centralisation of the firm, whereas technologies that improve the access to and processing of information tend to decentralise decision-making. Distinct ICT investments may therefore have heterogeneous impacts on firm performance.

While this distinction between the communication versus storage/processing characteristics of ICT has added new insights and therefore opportunities for empirical research, it has left in place familiar endogeneity concerns. Firms do not randomly select into adopting ICT technologies but choose to do so fully aware of the possibilities that the technology offers. Growing evidence shows that management practices, for example, are both a key determinant and outcome of technology adoption. Firms with more sophisticated managerial ability are more likely to adopt technology (Bloom et al., 2012). In addition, by facilitating new types of management practice, organisational change is one of the key mechanisms through which the productivity effects of ICT are realised (Hubbard, 2003; Bartel et al., 2007; Brynjolfsson et al., 2008; Giacarno and Heaton, 2010; Giacarno, 2010; Bloom et al., 2012).

In this paper, we employ a novel instrumental variable approach utilising the arrival of a new communication technology, ADSL broadband internet, to study the effects of communication ICT on firm performance. OECD (2008) provides a detailed description as to how internet technologies have allowed faster and more reliable communication along the supply chain as well as creating greater opportunities to communicate with new customers, expanding the potential market of the firm. The computing literature indicates that the several complementary forms of ICT grew alongside the spread of the internet which included both hardware, such as Pentium PCs; and software, such as virtual private networks (VPN)[1], e-commerce and enterprise resource planning (ERP)[2] (Forman, 2002). Firms with better external connection speeds should be more likely to use complementary forms of ICT intensively. The instruments we construct exploit plausibly exogenous spatial variation in broadband connections due to historic supply-side differences in firms' access

[1] The minimum requirement for broadband access being a PC with a Pentium processor (BT, 2015). A VPN is a private network that uses the internet to connect remote sites, for example regional offices, or users to the main company network.

[2] ERP brings together several data applications into a single platform to facilitate the storage and real-time acquisition of information, including human resources, sales and production data.

to the infrastructure underlying broadband internet, the telephone network.[3] The mapping of the telephone network in the UK, and the construction of instruments based on this, represents the primary contribution of the paper to the broader literature on ICT.

During our period of study, business internet connections in the UK were predominantly either narrowband (dial-up) or Asymmetric Digital Subscriber Line (ADSL) broadband technologies, both of which rely on the subterraneous fibre-optic and copper wire telephone network for their delivery. Our instruments focus on the role played by the local telephone exchange as a hub within the infrastructure of this network. Every firm or household is connected to a pre-determined telephone exchange with no prospect of switching exchanges. Owned by British Telecom (BT), the locations for these exchanges were often decided at the birth of the telephone network back in the 19th century and its growth around the Second World War. There are 5,630 exchanges in the UK, indicating that the spatial variation we exploit is far more disaggregated than regional, local government or even city-level.

External communication speeds of the firm were affected by their connection to the telephone exchange in two ways. Firstly, it affected the choice of internet technologies that could be accessed by the firm.[4] The differences in the maximum connection speeds allowed by narrowband and broadband technologies were large: ADSL broadband offers connection speeds of up to 8mpbs compared to 64kbps for narrowband. Firms connected to ADSL enabled exchanges therefore had access to superior external communication speeds and reliability compared to firms attached to exchanges enabled only for narrowband. Using data from the Office of the Telecoms Regulator (OFCOM), we have precise information on the internet technologies available from each local exchange at each point in time.[5]

Secondly, holding other factors constant, the longer the cable distance between the customer and the telephone exchange (known as the local loop), the slower are ADSL broadband speeds. Lab-based engineering tests by BT showed that for the earliest form of ADSL, speeds begin to deteriorate for customers with a cable distance greater than 2,000 metres, while those customers with a local loop distance greater than 3,500 metres were typically denied connections to broadband services.[6] At these distances, the connection speeds of broadband converge to those of narrowband. These distances are relatively short but the impacts on internet connection speeds are significant. Importantly, it is worth noting that these local loop distances did not affect the performance of the telephone (Macassey, 1985), so it is unlikely to have

[3] There also exists cross-time variation in these internet connection speeds. For reasons we explain below we do not use this information as part of the identification strategy.
[4] The time period we study coincides with the upgrading of the telecom infrastructure by BT to support ADSL broadband. This took place from 1999 to 2007 in the UK. We discuss BT's ADSL enablement programme in much more detail later in the paper.
[5] In our analysis we use data for 5,536 exchanges. Our micro data on firms excludes Northern Ireland.
[6] Disqualification was explained by poor line quality. This could also occur for customers with a local loop length of less than 3.5km if the line was deemed incapable of holding a broadband connection of sufficient speed.

affected the historic location choices of firms. We have available to us data on local loop distances for 1.66 million postcodes (equivalent to zip codes) in the UK.

The effect of local loop distance on ADSL broadband speeds was particularly strong for a brief period within our data. From late 2001 to 2002, BT began introducing further changes to the supply-side infrastructure, implementing a technology called Rate Adaptive Digital Subscriber Line (RADSL).[7] This technology adjusted the speed of internet connections depending on the length and quality of the local loop, boosting connection speeds for those customers furthest from the telephone exchange and extended the qualifying distance to receive BT broadband from 3.5 to 5.5 kilometres. As we describe in the paper, RADSL reduces the importance of the length of the local loop for ADSL broadband speeds, and we establish empirically that the relationship with firm-ICT weakens in a manner consistent with this. To maintain the relevancy of this instrument we therefore apply it to a cross-section of firm ICT decisions in the year 2000. A consequence of this is that we are only able to capture the short-run performance impacts of ICT.

We investigate the relationship between ICT with ADSL broadband enablement of the local telephone exchange (positive) and the local loop distance from an enabled exchange (negative) for this year within two very different, but equally information-rich, UK firm-level datasets. To ensure compatibility with the existing literature, and to enable the use of a broad range of firm performance measures we first present results using data from the Office for National Statistics (ONS). Known as the Annual Business Inquiry (ABI), this is the same data source used to study the effects of ICT on the productivity of US-owned firms in the UK by Bloom et al. (2012), on offshoring by Abramovsky and Griffith (2006) as well as many other topics. From this data we have precise information on the location of firms and key indicators of performance that extends for time periods before, during and after the rollout of ADSL. Its disadvantage is that ICT exists only as a homogenous aggregated measure of ICT capital stock.

To examine the possible heterogeneous effects from different types of IT hardware and software we use a comprehensive dataset on firm ICT investments, the Ci Technology Database (CiTDB), produced by the Aberdeen Group (formally known as Harte Hanks). The CiTDB data was previously used by Bresnahan et al (2002) and Brynjolfsson and Hitt (2003) for the US and Bloom et al (2012) and Bloom et al (2013) for the UK. Within this data firm establishments are surveyed annually, providing specific information on hardware and software usage, including the number and type of personal computers, various forms of software like business management systems and intranet hardware. This provides important detail on the types of communication-ICT that firms may be incentivized to use as a result of enhanced broadband connection.

To preview our main findings, we find from the ONS data evidence of a strong statistically significant effect of our instruments on firm ICT capital. When using the CiTDB database of firm ICT we find some types of ICT

[7] This was also known as 'extended reach ADSL'. Unfortunately, we have been unable to obtain information on the introduction of RADSL into various exchanges across the UK.

are affected by the instruments and some are not, indicating the value of our disaggregated approach. The instruments are correlated with the different measures of PC hardware (the number of PC computers, Pentium and portable PCs per employee) but not those of ERP or VPN software. We find some evidence that the adoption of the use of ERP software and VPNs occurs somewhat later (as the quality, security and reliability of these forms of ICT improved) and for firms that use PCs intensively because of the instrument.[8]

Using the ONS data we find significant employment and output effects from ICT capital stock and, consistent with this, strong positive effects on revenue from measures of PC hardware in the CiTDB. That these effects are somewhat larger than the OLS estimates indicates strong effects from the instrument on the compliant population. However, we uncover no statistically significant effect on firm productivity.[9] ADSL broadband provided small and medium sized firms low cost access to internet technologies for the first time allowing them create websites and develop e-commerce sales and extend their market reach. That is it lowered communication costs with customers. Communication ICT therefore appears to be associated with increases in the scale of firms rather than their productivity.

As a final exercise, we consider the types of ICT and human capital that were associated with the improved performance from communication ICT. Here we find that the firms which use more PCs because of their location relative to the telephone exchange were also more likely to use web design software and employ more IT workers, in particular programmers. These are consistent with the reasons for the increase in the scale of the firm through improved communication with customers. These results also link with the broader literature showing that the largest gains to ICT are realised by firms that make complementary investments (Hitt and Yang 2002; Brynjolfsson et al., 2002; Bresnahan et al, 2002; Bloom et al. 2013), such as software and human capital.

In order to consider our instruments valid, and permit a causal interpretation of our findings, the instruments must not be correlated with firm performance other than through ICT investment. Given that the instrument relies on spatial variation in firms' external communication speeds through the supply-side of the technology, obvious candidates for these confounding factors are geographic variables. Of particular concern are confounding factors that determine the location of firms, such as agglomeration economies, which are also correlated with the timing of ADSL enablement of exchanges and local loop distances. Our approach to this issue draws on the historical accounts of ADSL enablement by BT, and the technology of the internet itself. Using these insights we motivate a number of sample restrictions; test for robustness to the inclusion of additional control variables; and present a series of falsification tests. As described within the paper itself, the restrictions to the sample are particularly stringent and result in our use of firms attached to

[8] In the case of ERPs, it might also be explained because many of the necessary advances in security and encryption applications complementary with this software occurred later into that decade.
[9] Calculation of productivity is only possible using ONS data (see later data discussion).

just 20% of UK telephone exchanges.[10] Using this sub-set of exchanges we are able to demonstrate that the instruments have a strong relationship with ICT only for those firms and time periods suggested by the historical account. Outside of this they have no explanatory power, including for time periods in which exchanges were not yet ADSL enabled. This latter test is important as it rules out the presence of pre-existing trends that generate a correlation between our instruments and ICT variables. The instruments are also robust to the addition of a number of controls for agglomerations, other locality-specific characteristics as well as firm characteristics. Alongside these various tests the instruments pass all of the standard tests for instrument validity, including those for weak instruments, and over-identification. Taken together these results suggest that the analysis captures the causal impacts of communication ICT.

The remainder of the paper is organised as follows. In Section 3 we consider the related literature and describe the contribution of the paper. Section 4 describes our firm-level data and empirical methodology. Section 4 discusses the details of the UK rollout of ADSL and the construction and plausibility of our instruments. In this section we present evidence that our instruments are correlated with measures of firm ICT and consider various objections to their use. Section 5 presents our main estimation results, first using the ONS data and then the more detailed information from the CiTDB data. We use section 6 to draw some conclusions from the paper.

## 2. Related Literature

This paper adds to our understanding of the effects of ICT on firm performance. The existing literature has focussed predominantly on ICT as a composite capital, imposing an assumption that its effects are homogenous across different technologies (see the reviews by Draca et al, 2006 or Cardona et al., 2013).[11] By concentrating on the effects of communication ICT this paper most closely fits with the more recent strand of this literature questioning this assumption. Prominent works here include Garicano and Heaton (2010), Garicano and Rossi-Hansberg (2006) and Bloom et al. (2013). We are also motivated by this literature to suggest suitable instruments for communication-ICT, the construction of which forms the primary contribution of the paper. As far as we are aware there are no studies that have used cross-sectional variation in broadband speeds (captured by local loop distance) as an identification strategy. This focus on cross-section variation in the use of ICT as a means of identification, contrasts with more typical approaches measuring effects based on the timing of ICT adoption or using cross-time variation in the costs of investment as an instrument. A number of examples might be found using this approach. Of the papers using

[10] Concerns over instrument validity are a further reason for our application of the instrument to just a single year, 2000.

[11] See also Lichtenberg (1993), Brynjolfson and Hitt (1994, 1995, 2002, 2003), Dewan and Min (1997), Hendel (1999), Lehr & Lichtenberg (1999), Black & Lynch (2001, 2004), Hubbard (2003), Bartelsman et al. (2011) study U.S. firms while Greenan and Mairesse (1996), Greenan et al (2001), Forth & Mason (2003), Bloom et al. (2005, 2012) study European firms.

the timing of adoption, Aral et al. (2007) consider various types of software adoption and find an effect from the implementation of ERP software. Abramovsky and Griffith (2006) and Akerman et al. (2015), use cross-time changes in the percentage of households that have subscriptions for broadband internet connections as instruments in the UK and Norway respectively. Our data also has available cross-time changes in ADSL enablement, which are likely closely related to household broadband adoption. We find however, that when considered in this way the instrument does not pass tests for its validity.

In using (local loop) distance as an instrument we are closest to Bloom et al. (2013) who use distance of a firm from the headquarters of SAP, the market leader in ERP software technology, to predict ERP use. The distances that we use as our instrument are obviously much shorter than these. Forman et al. (2012) construct instruments for US county-level internet use based on the adoption of an earlier version of internet called Arpanet, the number of programmers and a Bartik index of internet investment outside of the county of interest. To the extent that the former two instruments capture differences in the cost of internet access, our instrument choice builds on this approach. We also build on De Stefano et al. (2014) who use a cluster of telephone exchanges in rural and sub-urban North East of England that were enabled for ADSL earlier than neighbouring exchanges to study the effects of broadband use. We differ in our use of variation in the incentive to use ICT within the area of an ADSL enabled telephone exchanges, the exchanges in our restricted sample being located in urban areas. [12]

## 3. Data and Empirical Specification

The estimations are performed on data drawn from four main sources, two of which contain detailed information on firm ICT, performance and location and two provide details of the UK telephone network used to construct our instruments.

As in Bloom et al. (2012) the basis of our firm-level data on performance and homogeneous ICT is the Annual Business Inquiry (ABI) provided by the Office for National Statistics (ONS) in the UK. This covers all industrial sectors (aside from finance) from 1997 onwards, allowing us to capture the sectors that use ICT intensively. From this dataset we use employment, revenues and TFP as measures of firm performance. TFP is estimated using the Levinsohn-Petrin (LP) estimator, which we use to control for the effects of unobservable productivity shocks on the choice of inputs by the firm. The LP estimator overcomes this endogeneity bias using purchases of materials and fuel as instruments (Van Beveren, 2012). To construct estimates of ICT capital we use establishment level IT expenditure data collected by the ONS and the STATA-code provided Bloom et al. (2012). This provides a total ICT capital stock for each firm, calculated using a perpetual

[12] We exclude the exchanges from North East England used in that study because they are owned by Kingston Communications rather than BT.

investment method.[13] This data also includes the postcode location, which we use later to merge to the telecoms infrastructure data.[14]

In further analyses, we examine the potential heterogeneous effects across different types of ICT using a comprehensive dataset on firm ICT investments, the Ci Technology Database (CiTDB), produced by the Aberdeen Group (formally known as Harte Hanks). Firms are surveyed annually, providing detailed information on hardware and software usage such as the number of computers, various forms of software like business management systems, intranet infrastructure, the number of employed IT specialists and so on. The dataset, available for the years 1999 to 2005, also provides descriptive information on each firm such as turnover, employment, sector, in addition to its postcode location. The CiTDB has been used in a number of empirical papers on ICT and firm and industrial performance such as Bresnahan et al. (2002), Brynjolfsson and Hitt (2003) Bloom, Draca and Van Reenen (2011), Bloom et al. (2013) and Forman et al. (2014).

Since the CiTDB is sold to large firms who in turn use the data for marketing purposes, Aberdeen Group has substantial market pressure to ensure that the quality of data accuracy remains high. To ensure this, the Aberdeen Group carries out random data quality audits. Moreover, the Aberdeen Group guarantees the quality of its data, by promising to refund their customers if error for any sample is greater than 5%. The CiTDB however only surveys firms with 100 employees or more.[15] Given the different sampling frames of the CiTDB and ONS data it has not proved possible to merge these data.

This paper exploits the detailed CiTDB information on software and hardware used by the firm. Our measures are informed by drawing on the computing literature of firms' ICT investments to exploit broadband technology (Forman, 2002). For hardware we use the total numbers of PCs, the number of portable-PCs and to capture the quality of PCs, the number with Pentium processors. To remove differences in size we express these relative to employment within the firm.[16] Pentium PCs were viewed as the minimum requirement for the use of ADSL broadband at this time, while we include portable PCs for the rather obvious reason that they should be more likely to make use of improvements in communication technologies given their function as mobile hardware (BT, 2015). For software we consider whether the firm uses any type of management software commonly known as 'enterprise, resource, planning' (ERP). This software includes components related to sales orders by the firm alongside those related to inventories, human resources and accountancy. The CiTDB also includes information on specialist sales software,

[13] The estimation files made available by Bloom et al. (2012) allow for the possibility of separately constructing IT hardware of software capital stocks. We choose not to use this data, preferring the detail offered by the CiTDB data. The results from the paper are unchanged when we use either of these two measures.
[14] During the robustness stage, the Business Structure Database and the National Statistics Postcode Directory datasets will be merged into the panel to provide additional control variables; firm age and urban/rural dummies respectively.
[15] This sampling restriction is made at the firm level, thus the CiTDB does contain plants with less than 100 workers that are a part of a firm with more than one site.
[16] As software is typically non-rival across users within the same company (if enough licenses have been purchased) we do not divide software by employment. The results are unchanged when we do not diving ICT hardware by employment.

including e-commerce. The numbers using specialist e-commerce software is rather small and so we include this with other types of ERPs to generate a second measure of software use. In each case these are dummy variables equal to one if the firm uses any type of this software and zero otherwise.

To construct our instruments we draw information from the ADSL Broadband Database which was made available by the office of the regulator for telecommunications in the UK, OFCOM, and a dataset produced by a UK based telecom consultancy firm called *PointTopic*. The ADSL dataset provides the location (postcode) and date for ADSL enablement for each telephone exchange in the UK. The *PointTopic* data is available at the postcode level, for which there are 1.66 million in the UK.[17] The *PointTopic* data includes information on the telephone exchange each postcode is connected to, the length of the local loop (the cable distance between the telephone exchange and the postcode) and the number of households and businesses attached to an exchange. We merge these datasets with the micro data from the ONS and CiTDB based on the postcode location of the firm.

For reasons we make clear below, the focus of our preferred specification is on a sub-set of exchanges in the year 2000. The panel data from the ONS consists of 45,904 firm-year observations from 1999 to 2005 for which we have data on ICT capital. The cross-section we use in our estimation contains 3,352 establishments. Within the CiTDB data we have available 58,283 firm-year observations for which we have employment and revenue information. Restricting the sample to the year 2000 this number falls to 4,871. We provide summary statistics for the main variables from both the ONS and CiTDB datasets for the year 2000 for various sub-groups of the data in Table 1. We explain the construction of the various sub-groups of data further below.

Using the first column from the table (labelled estimation sample) we find that the mean ICT capital stock is £59,000 with a standard deviation of £71,000. There are 10% of firms that use ERP software (22% that use either ERP or specialist sales software), the average number of PCs per employee is 0.5, while the number of laptops per employee is just 0.07. Within the ONS data the average revenue per firm is £7.9 million whereas in the CiTDB data it is £39.4 million, consistent with CiTDB sampling larger firms.

These various measures of ICT are positively correlated with firm performance in the expected manner (see Table A1 in the Appendix). The ICT capital stock constructed from ONS data is positively correlated with firm output, employment, TFP and average wages, and that the different types of software and hardware are correlated with firm revenues from the CiTDB data. The results from this table present a consistent picture of the relationship between ICT and firm performance, no matter how it is measured. Firms that use more ICT are larger and more productive.

[Table 1]

[17] Postcodes in the UK typically relate to 14 domestic houses or a medium sized firm.

*Estimating Equation*

We focus on a cross-section of data (for 2000), at the beginning of broadband roll-out across the UK, therefore our analysis captures the short-run performance effects of ICT. To capture the relationship between ICT and firm level outcomes we adopt the regression model set out in equation (1), where Y refers to firm output, employment and TFP for each firm *i*. ICT is measured as the ICT capital stock when using the ONS data and by various components of ICT hardware and software when using the CiTDB data (in which case Y is a measure of revenue only). As we estimate this equation on a cross-section of data we supress time subscripts from the equation. We also include in the model $X_i$, a vector of control variables that also impact productivity. When using the ONS data we include in these controls the age of the firm, multi-plant status as well as foreign ownership. When using the CiTDB data we are more limited in the availability of firm characteristics and we are able to include a measure of employment and multi-plant status only. In all regressions we include regional fixed effects and add the local loop distance as a control. $\alpha$, $\beta$ and $\gamma$ are parameters to be estimated and $\mu_i$ is the error term.

$$Y_i = \alpha + \beta ict_i + \gamma_X X_i + \mu_i \qquad (1)$$

We are interested in particular in the effects of ICT on the firm, captured in the model by $\beta$. A firm's ICT investment is an endogenous decision that is likely to be correlated with omitted variables captured by the error term, which renders OLS estimates biased. For the short-run effects that we capture the direction of this bias could be in either direction. It is likely to be biased upwards if the ICT variable captures the superior management of firms that adopt new technologies and that these firms undertake the complementary investments in human capital and organisational structure of the firm. Indeed there now exists a large literature that explores the relationship between ICT, firm performance and complementary investments (see for example Anderson et al. 2000; Bresnahan et al., 2002; Brynjolfsson et al. 2002; Van Ark and Inklaar, 2005; Akerman et al., 2015). To correct for this endogeneity bias we adopt an instrumental variable two stage least squares (2SLS) approach, exploiting variation in the determinants of ICT that are uncorrelated with adjustment costs or unobservable managerial differences.

## 4. ADSL Broadband as an Instrument

In this section of the paper we provide a description of the instruments employed to predict ICT capital. This includes a description of ADSL broadband technology, the period of the rollout programme that we study and initial evidence of a correlation with ICT software along with a number of other tests for instrument relevancy and exogeneity.

*Internet Connections and the Telephone Network*

The main methods for connecting to the internet at the start of the 21st century were narrowband (also known as dial-up) and Asymmetric Digital Subscriber Line (ADSL).[18] ADSL offers considerably faster internet connection speeds compared to narrowband, up to 8mpbs and 64kbps respectively. These differences in speed are large and therefore matter for the effectiveness of external communication for the firm. ADSL is now the dominant form of broadband access for households and firms in the UK, for example, by 2012 over 85% of firms and 55% of households had ADSL broadband connections (ONS, 2013).

Both narrowband and ADSL broadband rely for their delivery on the subterraneous Public Switched Telephone Network (PSTN). The PSTN, shown in Figure 1, is configured such that each firm/household is connected to a street-cabinet, the connections from which are in turn aggregated at pre-determined local exchange using copper wires. The exchange is further connected to the fibre-optic backbone of the PSTN. There are 5,630 telephone exchanges in the UK and the typical exchange is connected to 4,700 households and 250 businesses. These exchanges are geographically dispersed and are unequal distances apart. All exchanges are capable of providing narrowband (dial-up) internet connections to customers but required some investment to deliver ADSL broadband. ADSL was used in many countries as a lower-cost solution for telecommunications companies to provide broadband internet access, in particular for its household customers.[19] Most cities have a number of local exchanges. The largest city in the UK, London, has 185 exchanges (London had a population in 2001 of 7.3 million), while a medium sized city such as Nottingham has 6 exchanges (and a population of 215,000). In the UK, with the exception of 37 exchanges in the North East of England, the PSTN is owned and operated by British Telecommunications (BT). We focus only on exchanges that are owned by BT. The locations of these exchanges were often decided at the birth of the telephone network back in the 19th century and its growth around the Second World War. All suppliers of broadband and narrowband internet services used this telephone network, except for a small part which uses the infrastructure set out for cable-TV.[20]

[Figure 1]

The cable between the customer and the telephone exchange is known as the local loop. ADSL broadband speeds depend on the length of this cable, the diameter of the conductors in the wire, the metal used

[18] It was not until 1997-1998 that BT considered using DSL for broadband delivery (BT, 1998). Up until that point the telephone network had been used to provide narrowband internet access only.

[19] Akerman et al. (2015) justify their use of household broadband use during a government sponsored broadband enablement programme in Norway to look at firm broadband adoption by the fact that the programme was targeted at firms. While BT also appears to have considered household access to broadband as a key determinant of its ADSL enablement programme, we understand that firms also played part of this. For that reason we do not motivate our instrument in the same way.

[20] Competition between BT and other internet service providers only existed in the billing of internet connections and other value added services such as email and web hosting. The ability of other providers to install their own ADSL equipment, so-called Local Loop Unbundling, was negligible until at least 2005. By this year fewer than 2% of telephone lines were "unbundled" for other providers to offer services (Cadman, 2005). This was not the case in other European countries, for example by 2005 the proportion of unbundled telephone lines in France was more than 55%, with similar figures for Germany (60%), Italy (45%) and Spain (25%).

(usually copper but sometimes aluminium), the quality of the joints, other services provided in the same bundle of wires and noise ingress (much of which is at the customer premises). Engineering tests by BT showed that when measured in the absence of these additional factors, for the earliest form of ADSL, connection speeds deteriorate for cable lengths beyond 2,000 metres (see Figure 2). At the start of the ADSL enablement programme, BT would not connect customers with a cable-distance greater than 3,500 metres unless they had a high-quality line.[21] Speeds could be upgraded by replacing copper wiring with fibre-optic cables, but the subterraneous nature of much of the PSTN means this is very costly and was not done until after our sample period.[22]

Distance from the local exchange was of much less importance when using the cables for telephony and narrowband internet connections and it is unlikely firms would select to be close to the exchange on the basis of this technology. Through the use of a technology called loading coils, the quality of telephone calls could be maintained using copper wiring for distances up to 16 kilometres and there was no deterioration in quality until 5 kilometres (Macassey 1985). These are well outside of the limits of the effects of distance on ADSL connections allowed by BT in 2000. In addition, loading coils are not compatible with ADSL.

[Figure 2]

As already described in the introduction, from June 2001 BT implemented a technology called Rate Adaptive Digital Subscriber Line (RADSL) that reduced the effects of cable length on broadband speeds. This technology extended the distance up to which BT would connect a customer to its broadband services up to around 5.5 kilometres.[23]

*UK Rollout of ADSL*

Our sample period coincides with the rollout of ADSL by BT, which generates further spatial variation in the speed of internet that firms can access.[24] Broadband enablement using ADSL required that the local exchange be equipped with DSL capability and the end-user premises were fitted with a modem and micro-filter device (ADSL splitter), but also required that the exchange have suitable air conditioning, connection to the internet backbone and a reliable electricity supply (Guardian, 2002).[25] The large number of telephone

[21] The presence of these additional factors in determining connections speeds leads us away from constructing our distance instrument as a series of dummy values set at exactly 2km. and 3.5km.
[22] Using fibre optic wiring to connect homes to local exchanges did not occur in the UK until 2009.
[23] This was managed by adjusting the up-load speed.
[24] As in many other countries ADSL was seen as a cost-effective way of improving internet access speeds. British Telecom had a near monopoly on telephone infrastructure within the UK over this time period. In August 2000 telecoms regulator Oftel mandated BT to fully unbundle their local loop and in 2001 that BT to offer access to the telephone network on "cost-orientated terms". However, as of 2003 the UK had one of the highest unbundling charges in Europe such that by the end of 2002 only 200 exchanges were equipped for an unbundled local loop. There had been very little take-up of fully unbundled (telephone) lines (1,600 by mid-October 2002).
[25] BT insisted on using its own engineers for line modification and equipment installation (BBC 1999a)

exchanges combined with a limited number of BT engineers meant that ADSL was rolled out across exchanges over a period of time stretching from November 1999 to September 2007. BT gave relatively short notice of the start of the programme; as of February 1999 BT still had not informed the public of any plans for broadband service (BBC 1999a). BT also provided limited pubic information once the programme had commenced; BT only announced exchanges to be enabled in the forthcoming 6 months.[26] This would tend to suggest that anticipation effects are unlikely to be present. Broadband services were offered to customers connected to enabled exchanges from 2000 onwards. In Figure 3 to Figure 6 we show the location of enabled exchanges in the UK for the years 1999, 2001, 2003 and 2005.

[Figure 3] [Figure 4] [Figure 5] [Figure 6]

Akerman et al. (2015) adopt an identification strategy that, like us, exploits the rollout of ADSL, in their case in Norway. They note that this gives them variation in internet access both spatially and across time, in their case because of a government funded enablement project. In this paper we focus on spatial rather than the cross-time variation. We justify this choice on the basis of the historical accounts which make clear that the ex-ante timing of enablement was determined by BT in a desire to maximise it commercial return. Exchanges with short local loops were less costly to enable, with large urban areas typically having both short local loops and larger numbers of potential customers. For the UK a claim of instrument validity based on temporal variation is therefore more difficult to support. We demonstrate our restricted cross-section (both in terms of the number of exchanges and by time) is however plausibly exogenous. To understand the reasons for this requires some further background on BT's ADSL rollout programme and its determinants.

Ex-post, the rollout of broadband by BT can be seen to have progressed in three waves, with a first break occurring in the second half of 2002 and a second break in 2005. We label these, wave one (covering the years 1999-2002), wave two (2003-2005) and wave three (2006-2007). The first break, announced in November 2001 occurred as a consequence of the poor take-up of broadband internet by households.[27] At the start of the program such a break was unplanned and therefore unlikely to have been anticipated by customers (households and businesses). Wave two began under a new scheme with a separate set of determinants for the enablement of a specific exchange. In 2005 (announced April 2004), BT scrapped this and pursued a policy of "universal" access, meaning a target of access to 99.6% of homes and businesses. This represents the second break in the timing of the rollout programme. The three waves can be seen clearly from a graph of exchange enablement over time (Figure 7) and within Table A2 in the Appendix. The first break is particularly clear: enablement begins in 1999, ceases in the final months of 2002, before resuming rapidly again in 2003. In wave one, 20% of exchanges had been enabled, representing connections

[26] It was the view of some that the delays in starting ADSL roll-out across the UK by BT were to protect its monopoly on ISDN and leased lines. According to Deshpande (2013) BT started the roll-out in 1999 only because cable broadband services were launching that same year (note the infrastructure for cable was laid in the 1990s).
[27] Poor take up by households was blamed on ADSL connections being expensive, wholesale prices were £40-£150 per month.

to 63% of UK commercial premises and 60% of households. Enablement was more rapid in wave two, such that by the end of 2005, which forms the end of the firm-level data available from the ONS, 98% of all exchanges were enabled. In the empirical analysis we exclude all exchanges except those enabled in wave 1, although we also discuss these in relation to wave two and wave three exchanges in some of the robustness tests.

[Figure 7]

The determinants of the timing of enablement differed significantly across these three waves. BT's ambition in wave one was to enable exchanges within the major urban conurbations, often entire cities were enabled in a short period of time. BT resumed the roll-out in wave two with a demand-driven registration system which we describe in more detail in the Appendix. The demand-driven system of wave two makes it highly unlikely that the timing of ADSL enablement is exogenous, leading to our focus upon firms connected to wave one exchanges (see below).

The differences between the phases of the rollout programme are evident from Figure A1 where we plot the (log) number of households and business connected to an exchange against the date of its enablement and from the correlations with local loop distance and the number of households and businesses in Appendix Table A3. The correlation in Figure A1 shows that across the three phases, wave one enabled exchanges had on average larger numbers of potential households and business customers than those enabled in wave two. The regressions in Table A3 show that within wave two the sequencing of enablement had a much stronger correlation with exchange size, with larger exchanges more likely to be enabled earlier than smaller exchanges (regressions 2 and 3 in Appendix Table A2). Within wave one the sequencing of enablement is much less obviously driven by exchange size however. There is no correlation with the number of businesses attached to an exchange, but there is between the number of households and the length of the local loop. We provide further justification and evidence for this choice below. For this reason we included these as control variables in the regressions. In wave three the last exchanges that were enabled up to the end of the data period in 2007 tended to serve small numbers of firms and households. While not clear from the figure, perhaps not surprisingly, they also tended to be rural exchanges.

*Construction of Instrumental Variables*

Using the insights on the historical legacy of the telephone network, the ADSL broadband rollout by BT, and the change in the ADSL technology to RADSL we identify two potential instruments to explain cross-section variation in firm's ICT use. The first is constructed only for firms attached to exchanges enabled in wave one (1999-2002) enablement of local telephone exchanges for ADSL broadband. Here we anticipate that the returns to communication and coordination technologies are higher for firms connected to an enabled exchange such that they are likely to have greater ICT. To make this clear, for each firm we construct an ADSL availability variable that is coded as 0 if the exchange that the firm is attached to was not ADSL enabled in 2000, but was enabled by the end of wave one of BT's rollout programme in 2002; is coded as 1 if the exchange that the firm is attached to was ADSL enabled by the end of 2000; and is set to missing if the exchange the firm is attached to was enabled in wave two (2003-2005) or three (2006-2007) of BT's programme. The year 2000 represents the first complete year of ADSL enablement in the UK and provides a reasonable number of enabled versus non-enabled exchanges under wave one of BT's enablement programme (59.2% of wave one exchanges were enabled in 2000). It also represents the last year before BT introduced RADSL, which as we show below, reduces the importance of cable-distance for internet connection speeds.

When using the ONS data this sample restriction means we have information for 4,848 firms in the year 2000. Of these, 2,303 were attached to telephone exchanges enabled in 2000 by BT, 1,049 were attached to exchanges non-enabled in 2000 (but which were enabled by the end of 2002) and 1,496 firms that were attached to exchanges enabled between 2003 and 2007. We use the 3,352 firms (2303+1049) attached to wave one exchanges in the majority of the regressions and include the 1,496 firms in various extensions of the main regressions. When using the CiTDB data we have data for 6,769 plants in the year 2000. Of these, 3,308 were attached to telephone exchanges enabled in 2000 by BT, 1,563 were attached to exchanges non-enabled in 2000 (but which were enabled before the end of 2002) and 1,898 firms that were attached to exchanges enabled between 2003 and 2007. When using this data we use the 4,871 firms (3,308+1,563) attached to wave one exchanges as the main sample. According to the information presented in Table 1, in the regression sample 66% of firms are attached to enabled exchanges in the ONS data in the year 2000, while it is 68% in the CiTDB data.

The second instrument uses the length of the local loop made available from the *Point-Topic* database.[28] Here we anticipate that because communication speeds are slower, firms that are further from the telephone exchange are likely to invest in less ICT. We provide further information on local loop distances across firms in Table A4 in the Appendix. According to the information in this table, in the ONS data the mean firm is 2.71 kilometres from an exchange (median is 2.92 kilometres) with a standard deviation of 1.75 kilometres. In the CiTDB data the mean (median) cable distance from the telephone exchange is 3.24 (3.18) kilometres with a standard deviation of 1.33 kilometres. Given that firm distance at the 90$^{th}$ (99$^{th}$) percentile is just 4.97 (6.02) kilometres indicates that we are using relatively small geographic distances within the analysis. These distances closely mirror those from the CiTDB data.

[28] As discussed in the introduction distance has been used as an instrument within the ICT literature by Bloom et al. (2013). They construct as an instrument the distance from the location in which one type of software they study, ERP, is produced. Distance then captures diffusion of this knowledge across space and the likelihood of adoption. It would seem obvious to say that local telephone exchanges are not of course centres for innovation and there is no reason to believe that this is the effect that we capture.

*Initial Evidence on the Correlation between the Instruments and ICT*

To produce consistent and efficient estimates IV methods require the fulfilment of what are commonly known as relevance and exogeneity conditions. The relevance condition requires that, conditional on the other covariates, the instrument and endogenous regressor are sufficiently correlated (Murray, 2010). The exogeneity condition requires that the instrument(s) are not correlated with the error term. We discuss the exogeneity condition in the next section and complete this section with a discussion of instrument relevancy.

In Table 2 we provide formal evidence on the power of our instruments to explain variation in the level of ICT capital across firms. Regression 2.1 uses the total ICT capital stock data from the ONS, while regressions 2.2 to 2.6 use the CiTDB for different measures of ICT hardware, and ERP and VPN software. In Table 3 we repeat these same regressions but restricting the sample to enabled telephone exchanges only such that we use the local loop distance as a single instrument. To control for the correlation between firm characteristics and ICT in all of the regressions we control for the age, ownership status of the firm (domestic or foreign) and multi-plant status of the along with region fixed effects. In Table 2 we also include the local loop distance not interacted with the ADSL enablement variable.[29]

We find some differences in terms of the power of the instruments to explain variation in ICT use across firms; our instruments seem to strongly predict ICT capital generally and our measures of hardware, but not software. Concentrating initially on Table 2 the enablement of the local telephone exchange and the local loop distance of the firm from the exchange are significantly correlated with ICT capital in regression 2.1 and the various measure of the number of PCs per employee (regressions 2.4 to 2.6) but not software (regressions 2.2 and 2.3) or the use of a VPN (regression 2.7). This result for software holds when we use ERP software alone, or combine it with a measure of specialist sales software. For the total ICT capital stock and the number and type of PCs we find that as expected the ICT intensity of the firm increases with the enablement of the local telephone exchange and decreases in the cable distance between the firm and the telephone exchange. These results are consistent with Varian et al (2002) who also finds that users of broadband invest more heavily in ICT.

The negative relationship with cable distance to the local telephone exchange remains when we restrict the sample to include firms attached to exchanges enabled by the end of 2000 in Table 3. This indicates that differences in the timing of ADSL enablement are not the explanation for the correlations we find for cable distance in Table 2. Amongst exchanges that were ADSL enabled, ICT capital of firms was lower the further it was located from the telephone exchange, where this was made up of a lower use of PCs. Again there is no significant relationship with the narrow measure of ERP software or use of VPNs. Cable distance has a

[29] It is not possible to include this variable as an additional control in Table 3 because the sample is restricted to enabled exchanges.

significant relationship with the broader ERP software variable in regression 3.3, but it is the wrong sign. Of interest, comparing across the regressions for the different types of PCs in regressions 3.4, 3.5 and 3.6, the results suggest that portable PCs are most strongly affected by ADSL enablement and cable distance.

How large are the effects? According to the estimates from regression 2.1, for a firm that has a local loop distance from the telephone exchange equal to the mean value (median) the ICT capital stock is an estimated 69% (65%) larger for firms within the area of ADSL enabled exchanges compared to a firm connected to a non-enabled exchange. To put the estimated effect on ICT capital within a broader perspective, for the average firm the ICT stock is just under £59,000 in Table 1, with a standard deviation of £71,000. For the number of PCs per employees, regression 2.4 shows that being inside the region of a enabled exchange increases this by approximately one computer for every 8 employees (the ratio increases by 0.128), while regression 2.5 shows the number of portable PCs increases by close to one for every 5 employees (the ratio increases by 0.190).

Given our inability to explain variation in software or VPN use across firms due to ADSL enablement and local loop distance variables, we do not consider the effects of these forms of ICT on the performance of the firm later in the paper. Curious to explain their insignificant relationship with the instrument we do briefly consider whether there might be a sequencing of the ICT adopted by the firm. Initial support for this view can be found from these variables across time. According to the CiTDB data the percentage of firms using ERP and VPN in 2000 is 16% for the narrow definition of ERP (29% for the broader measure) and 6% for VPN. By 2002 these have increased to 31% for ERP (43% for the broad measure) and 36% for VPN, while by 2004 they are 37% (48% for the broad measure of ERP) and 50% respectively. In contrast the PC intensity of the firm is much more stable. We consider this more formally using a regression of the use of ERP or VPN against the number of PCs (Appendix Table A5) we find that the estimated coefficient on PCs increases in magnitude over time. We also find that when we instrument for the number of PCs using the enablement of ADSL and the local loop distance we find a similar positive effect in a pooled regression using wave one data for 2000 to 2002 (Table A6). We take this as evidence that firms that use PC more intensively because of the instrument were more likely to use ERP software or VPNs in subsequent years.

[Table 2] [Table 3]

*Evidence of Instrument Validity*

The exclusion restrictions for the validity of our instrument require that ADSL enablement and the distance from the telephone exchange have no direct effect on our firm performance measures independent of its relationship with ICT. As the previous section demonstrates, instruments based on the telephone network are significantly correlated with the ICT used by firms measured by the total ICT capital stock and the number and type of PCs. That we are unable to explain their choice of software or VPN provide some assurances that the instruments are not correlated directly with firm performance or indirectly because of some omitted variable that is positively correlated with the overall ICT intensity of the firm. Or, at least, describing the potential confounding factor that is capable of mimicking this pattern of a positive correlation with some forms of ICT used by a firm but not others becomes a much more challenging exercise. Nevertheless, it is difficult to claim that objections to the choice of instruments cannot remain. We first lay out the potential causes of these objections before explaining how we deal with these points or provide supporting evidence that they are not a concern.

We have already presented a brief sketch of the ADSL enablement programme by BT above, with further detail in the Appendix to the paper, and made it clear that, while the timing of enablement of the local exchange might be considered outside of the control of an individual firm, it remained a commercial decision for BT. Thus far, we have used a combination of sample restrictions and control variables to account for this. As noted earlier, the timing of enablement of wave two exchanges was explicitly demand-driven. To decide where to break the sample we exploited the exogenous break in the ADSL rollout programme and restricted the sample to include exchanges enabled in wave one up to the end of 2002

However, as we show in the Appendix, the first wave of enablement appears to have been targeted at urban exchanges, which were characterised by shorter local loops and greater numbers of households. Those characteristics of exchanges are likely to be correlated with agglomeration or other geographic factors, raising the possibility that enabled locations were likely to have been already experiencing, or predicted to experience, economic growth and increases in employment. Agglomerations of businesses are typically more productive (Combes et al., 2012), and are more likely to use new technologies, such as ICT, but also possess greater management skills (Glaeser and Resseger, 2010; Puga, 2010). It therefore follows that agglomeration may help predict shorter local loop lengths and ADSL enablement and be correlated with measures of firm performance.

A further potential challenge to validity is an argument of passive sorting. The locations chosen for telephone exchanges were not random; they were sited to be near to commercial centres and concentrations of residential property and, to aid with the laying of cabling, they were often also located near major road junctions. Given that this distance had no bearing on the quality of telephone connections it would seem plausible that firms did not choose their locations to be close to the telephone exchange. However, the local characteristics that helped to determine the commercial decision by BT of where to locate its telephone exchange may be similar to those that affect firm location decisions. Plausibly firms may also wish to be close to commercial centres and major road junctions.

This discussion suggests a need to explore the potential for a correlation between the characteristics of firms and unobserved geographic factors. We do this in four ways. We begin by establishing that the correlation between ADSL enablement and local loop distances with ICT are not explained by a correlation with agglomeration measures such as the number of households and business addresses attached to a telephone exchange. Second, we show that the introduction of RADSL technology by BT weakens the correlation between the cable distance of the firm and ICT in a way that would not be expected if time-invariant (or at least slow changing) factors such as agglomeration are important. Third, we explore the relationship between local loop distances in non-enabled exchanges. Our arguments about the effect of local loop lengths on firms' ICT decisions are specific only to ADSL enabled exchanges and therefore should not be present for firms attached to non-enabled exchanged. Here we exploit the fact that the ONS data are available in the years before ADSL enablement took place and, because the rollout took a number of years to complete, there were firms that were attached to non-enabled exchanges in 2000. Our final approach follows a similar line and exploits the pre-enablement data to test for a correlation between firm performance and future ADSL-broadband enablement. We show that for firms attached to wave one enabled exchanges there are no correlations with firm characteristics in 1998, indicating that we do not capture pre-existing trends.[30]

*Additional Control Variables*

In Table 4 we test the robustness of the model explaining to the inclusion of measures of agglomeration as control variables. We capture agglomerations using the database provided by the telecoms consultancy firm PointTopic which includes information on the number of households and businesses attached to an exchange (labelled exchange size). To conserve space we report only the results for the two instruments and the exchange size variable. In all of the regressions we also include the length of the local loop, firm age, ownership, and multi-plant status and a full set of regional dummies.[31] The results from this table suggest that agglomeration factors do not explain the results we find between the instruments and ICT. There is a positive relationship between the ICT capital stock and the number and type of PCs with the ADSL enablement of the telephone exchange and a negative correlation with the cable distance from the exchange. The measure of exchange size itself has a surprising negative relationship with the measures of ICT.

[Table 4]

*Across Time and Non-Enabled Exchanges*

[30] This result does not hold if we remove the sample restriction on exchanges and include firms attached to any telephone exchange. Here we find strong evidence that firms attached to exchanges enabled early in the rollout programme tended to be larger, more productive and more likely to be foreign owned.

[31] We find identical results if we restrict the sample to ADSL enabled exchanges and use local loop distance as a single instrument.

Table 5 presents the regression results for various ICT measures and local loop distance across later years (2001 to 2003) and for non-enabled exchanges. For brevity, we present data using the ICT capital stock variable from the ONS and report similar results for the CiTDB data in Appendix Table A6. Here we anticipate that the introduction of RADSL technologies in 2001 should weaken the relationship between the firm's local loop distance and ICT for enabled exchanges over time in Table 5. We repeat the result for 2000 for ease of reference. The declining importance of distance on ICT is confirmed by the results in regressions 5.1 to 5.4 in Table 5. In each additional year beyond 2000 we find that the distance has a significant negative relationship with ICT capital but the strength of this relationship falls in value each year.[32] In 2000 the elasticity of distance with respect to ICT capital is -0.336, but has more than halved in magnitude to -0.152 by 2003. It would appear that, as expected, the length of the local loop has a stronger effect on ICT capital before the introduction of RADSL technologies by BT. Geographic factors that cause passive sorting are likely to be time invariant, or at the very least, seem an unlikely explanation for the correlations we find between local loop distance and ICT, unless their effects for some reason decayed in the vicinity of exchanges that BT enabled for ADSL. Akerman et al. (2015) make a similar argument based on a measure of household adoption of broadband during a government-sponsored broadband rollout programme in Norway.

This pattern also holds when we use the CiTDB data and disaggregate the ICT used by firms (Table A6). The declining effect of local loop distance on ICT is similar to that for the IT capital stock when we measure ICT by the number or type of PCs. In every case the relationship with local loop distance weakens, the effect of distance has less of an influence on variation in the number of PCs, portable PCs or Pentium PCs, although the effect of distance remains significant until 2003. In the case of portable and Pentium PCs the estimated elasticity is again half that found for 2000.

Within Table 5 we also present results for two different groups of firms attached to non-enabled exchanges using the ONS data.[33] In regressions 5.5 and 5.6 we present the results for ICT measured in 1998 and 1999 respectively but using firms attached to exchanges that were enabled by the end of 2000 (wave 1 exchanges). These therefore represent the same firms as in regressions 5.1 to 5.4 but for years preceding the ADSL rollout. In regression 5.7 we use data on ICT capital in 2000, the same year as the baseline model, but restrict the sample to include firms attached to exchanges that were enabled later in wave one (i.e. they were enabled between 2001 and the end of 2002) and in regression 5.8 firms attached to exchanges that were enabled in wave two or three (i.e. from 2003 onwards). For these firms the only internet technology available via the telephone network was narrowband, which was much less affected by cable distance. To be

[32] We find no evidence that this change is explained by some change in the relationship between ICT and productivity. In an unreported OLS regression we find that the effects of ICT are identical in the 1999-2002 and 2003-2005 periods.

[33] We do not have pre-rollout data from the CiTDB data and so cannot perform an equivalent exercise using this data. We do of course have data on firms attached to non-enabled exchanges in 2000 and we do include these results in the Table (these are equivalent to regressions 5.7 and 5.8 in Table 5).

clear, in these four regressions we do not interact the local loop distance variable with the ADSL enablement variable (as this is equal to zero i.e. non-enabled, in all cases) but rather just include the local loop distance by itself.

Our predicted negative relationship between local loop distance and ICT is expected to hold only for firms attached to ADSL enabled exchanges. The results for non-enabled exchanges in the second half suggest this is so, irrespective of whether we use data on firms attached to wave one exchanges before ADSL enablement took place (regressions 5.5 and 5.6) or we use firms attached to exchanges enabled at some point after 2000 (regressions 5.7 and 5.8). In none of these four regressions do we find an effect from cable distance on the IT capital of firms.

To summarise: across these tables in this and the previous section of the paper we have found a negative effect of cable distance on ICT only for the firms attached to enabled exchanges, only for the years in which ADSL was being rolled out, and that this effect weakens as BT rolled out a technology that increased connection speeds for customers with long local loop distances. The cable distance instrument therefore behaves empirically in a manner consistent with the telecoms engineering literature and taken together point strongly to a view that cable distance is a valid instrument for the ICT of firms attached to wave 1 enabled telephone exchanges in the year 2000.

[Table 5]

*Ex-ante Firm Characteristics*

The restrictions that we place on the data limit us to explaining the ICT choices of a cross-section of firms in a single year. While this restriction is used to support the claim for instrument validity, it prevents us from for example, controlling for time-invariant firm characteristics through firm fixed effects and using the within-firm variation in the data to identify the effects of ICT.[34] That is, to follow the approach taken in much of the rest of the literature.

As a reminder the concern here is that there are some unobservable firm characteristics, such as managerial quality, that may vary across time and are correlated with our instruments and firm performance, where the existing literature provides a strong motivation that the latter are important. To judge whether measures of firm performance might be correlated with our instruments through these unobserved managerial differences, we test for a correlation with ex-ante performance characteristics of firms and our instruments. Here the assumption we make is that if managerial quality has a high degree of time persistence, as seems likely, and is positively correlated with the sales, employment, productivity, age or ownership then this will

[34] The lack of time variation in the local loop distance variable represents another reason that we cannot go this path.

show up as a correlation with the instrument set in the periods before ADSL rollout began. A lack of a significant correlation would therefore provide support for the choice of instruments.

The results from this are reported in Table 6, where the first half of the table considers the enablement variable and the second half, the local loop distance enablement interaction. Using data on firm characteristics in 1998 the results indicate that firms connected to exchanges enabled in wave one of the rollout programme in the years 1999 to 2000 were not statistically different to firms attached to exchanges that were enabled in 2001 or 2002 prior to the rollout programme (regressions 6.1 to 6.3).[35] Similarly 1998 firm characteristics do not predict their cable distance from the telephone exchange (regressions 6.4 to 6.6).[36] This suggests that the ordering of ADSL enablement of exchanges (within wave one) was not targeted at firms that were larger, more productive, older or closer to telephone exchanges, despite these areas potentially having higher demand for broadband services. Therefore the relevance of the instruments for firms ICT use in Table 2 and Table 3 are not explained by some pre-existing trend and the instruments are not correlated with ICT use because of a correlation with unobservable managerial quality.

[Table 6]

## 5. Instrumental Variable Results

In Table 7 and Table 8 we report the results from our IV regressions. Table 7 uses the ONS data and Table 8 the CiTDB data. In Table 7 we report results for the effect of ICT capital on output, employment, TFP and labour costs while in Table 8 we consider the effect of the number of PCs, portable PCs and Pentium PCs per employee on firm revenues. In both tables we report regressions using ADSL enablement and local loop distances as instruments for firms attached to exchanges in wave one of BT's ADSL rollout and local loop distance as a single instrument for firms attached to exchanges that were enabled by the end of 2000. We report standard tests on the strength of the instruments, the Cragg-Donald and Kleibergen-Paap F-statistics, and when we use the two instruments the over-identification test, the Hansen J statistic. We begin our discussion with the results in Table 7.

As already discussed in section 4, the instruments are highly significant and have the expected signs in the first-stage regressions, while the diagnostic statistics also reported in Table 7 support the plausibility of the instruments. ICT capital is positively impacted by the ADSL enablement of the telephone exchange to which the firm is connected, where that stock is lower the greater its distance from the local telephone exchange. The F-tests on the excluded instruments provide a clear rejection of the null hypothesis of weak instruments as the F-statistics exceed the Staiger and Stock (1997) critical values for strong instruments. With two

[35] Similar results are obtained using the year 1997, the first year of available data, however the sample sizes are substantially lower.
[36] The same conclusions are reached when consider enablement in 2000 or 2001 in isolation.

instruments and if we are willing to accept an actual rejection rate of 20 (25) per cent when it should be 5 per cent, the critical value is 8.75 (7.25). For one instrument the relevant statistics is 6.66 (5.53). Here we find that the Kleibergergen-Paap F-statistic are greater than this value and provides some confidence that the bias in 2SLS is likely to be small relative to the bias of OLS. The results of the over-identification test (Hansen J-statistic) where there are multiple instruments, also support the view that our instruments are exogenous. We cannot reject the null hypothesis that the instruments are jointly valid, that is, uncorrelated with the residual. This holds whether we measure firm performance by revenue, employment or total factor productivity.

[Table 7] [Table 8]

There is mixed evidence that ICT matters for firm performance however. From the second stage regressions our results indicate a strong significant effect of ICT capital on firm employment and revenues but not TFP.[37] Correcting for the endogeneity bias between ICT capital and TFP indicates that there is no causal effect between these variables.[38] This TFP result holds irrespective of whether we use all firms connected to exchanges enabled for broadband before the end of 2002 (regression 7.5) or those connected to exchanges enabled by the end of 2000 (regression 7.6).[39]

Given that the local loop distance instrument is not far above the accepted boundary for weak instruments in Table 7 we also report in the table results using LIML (Anderson and Rubin, 1949, 1950) and Moreira's conditional likelihood ratio, which have the advantage of being less sensitive than 2SLS to finite sample bias. Both provide a similar conclusion. Even if our instruments are inferred to be weak, the LIML estimates are very similar to those found from 2SLS, with a similar sized standard error, while the confidence regions of Moreira's CLR passes through zero and is also not close to being statistically significant. Irrespective of the method that we use, we continue to find a strong effect on firm performance measures other than TFP.[40]

As a final regression in Table 7 we show how the conclusions reached thus far for TFP do not change dramatically when we include into the analysis firms that were attached to exchanges enabled from 2003 (wave two) onwards, but we now fail the tests for instrument validity. Identification of the effects of IT capital now exploit differences in ADSL enablement and distance as before, but comparing its effects against a much broader cross-section of non-enabled firms. As reported in regression 7.7, the tests for valid instruments indicate that the instruments have explanatory power in the first stage regression. Given the

[37] This result also holds if we follow Bloom et al (2012) and divide ICT capital by the number of employees to derive a measure of ICT intensity. We do find a strong positive effect in the second stage if we use labour productivity.

[38] This conclusion is unchanged if we replace the level of TFP with its growth rate. In this regression we find no significant effect of IT in either the OLS or the IV regressions.

[39] The results are also robust to the inclusion of a measure of agglomeration, measured as the number of businesses and households connected to the exchange.

[40] In Table A7 in the Appendix we consider the possibility that the effects of IT take some time to reveal themselves on IT. Allowing for the possibility of an effect up to five years we continue to find no effect.

earlier correlations found with ex-ante firm characteristics perhaps unsurprising we do find evidence that these are not orthogonal to the error term from the regression. Despite this we note the continued insignificance of the ICT variable in the second stage regression for TFP.

The CiTDB data allows for the possibility of digging deeper into the effects of ICT on one measure of firm performance, its revenue. The results from the instrumental variable regressions are presented in Table 8. Again the Cragg-Donald and Kleibergen-Paap tests for weak instrument are passed, particularly so when we use the cable distance as a single instrument. The exception to this is when we use both instruments and Pentium PCs per employee as the measure of ICT in regressions 8.5. The over-identification test cannot reject the null of jointly valid instruments.

Reassuringly the results are also of a similar direction to those in Table 7. In all cases we find a significant positive effect of ICT on firm revenues, which holds for all of the different types of PCs that we use. The results are consistent with an interpretation that communication-ICT caused an increase in the sales of those firms that had a greater quantity and quality of PC-ICT stock because of the instrument.

Throughout the two tables the estimated effects on employment and revenues are large. IV estimates that are greater than the OLS estimates are not untypical in this literature. Similarly large effects from ICT were found by Brynjolfsson and Hitt (2003) for example. The literature has used this to point to two alternative potential explanations. Firstly, that the availability of these communication technologies were particularly powerful for compliant group of firms affected by the instrument. This is plausible in this setting as ADSL broadband provided small and medium sized firms low cost access to internet technologies for the first time. This allowed them to create websites and develop e-commerce sales extending the market reach for these firms. That is, it lowered communication costs with customers, increasing the scale but not the efficiency of affected firms. Secondly, it might also be because the complementary factors, such as absorptive capacity or management, are abundant in these firms (Akerman et al., 2015). [41] That is the compliant population already displayed characteristics that made them more likely to use this technology. That we found no relationship between the pre-enablement characteristics of firms and the instruments in Table 6 would suggest that the former is the more likely in our case. This is important as it suggests that these results might generalise to the population of firms at large.

As a final exercise we test for the presence of complementary forms of ICT software and human capital as a way of understanding whether large effects for the compliant population are plausible. We measure these complementary investments by whether the firm has a homepage or not and whether it uses web

[41] An alternative explanation might be adjustment costs, which Brynjolfsson and Hitt (2000) and Leung (2004) suggest may even be negative in the short run if firms struggle to maintain output and productivity during the reorganization period. Given that the primary effects of the instrument appear to be in the adoption of new types of PC, we view it as unlikely that these are relevant in our setting.

design/development software and the number of IT employees and programmers. We then regress this against PC intensity, where we instrument for this using ADSL enablement and local loop distance. We anticipate that the effect of PC intensity should be strongest for those firms in which website design/development software is available and the greater is employment of IT workers and programmers.

The results in Table 9 point to the importance of complementary software and human capital within the firm as an explanation for the revenue and employment effects that we find. The firms with greater use of PCs because of broadband communication technologies are more likely to use web-design/development software and have more IT employees and programmers. In contrast, there appears to be no relationship with simply having a homepage. This indicates that firms' who invested in the sales and distribution systems that lie behind the website were the ones that delivered the largest effects of revenues. The complementarity between ICT and the absorptive capacity of the firm, including human capital, is a well-documented feature in the literature (see amongst others Yang and Brynjolfsson, 2001; Brynjolfsson et al., 2002; Brenahan et al, 2002; Bloom et al. 2012), to which we add the complementarity between forms of ICT and ICT-human capital.

[Table 9]

## 6. Conclusions

Recent extensions of the literature on ICT have highlighted the distinction between the communication versus storage-processing effects on firms of this technology. In this paper we use the arrival of a new communication technology, broadband internet, to study the effects of ICT on the performance of UK firms. To isolate the causal effects of the technology we employ an instrumental variable approach, using an instrument set based on the infrastructure underlying broadband internet - the pre-existing telephone network. We exploit spatial variation in the speed of internet technologies that firms can access that are governed by two exogenous features of the telephone network. Firstly, the telephone exchange that the firm is attached to determines the type of internet technologies that can be accessed. In our time period those differences are large because some exchanges were enabled for ADSL broadband and some were not. Our second instrument occurs within the area of ADSL enabled exchanges and concerns the cable distance between the firm and the telephone exchange. ADSL internet speeds decline quickly as this cable distance increases.

We are able to show that being attached to an ADSL enabled exchanges increases the use of ICT and the distance from the exchange reduces this. A number of additional results support a conclusion that the empirical design has validity. Firstly, we are able to show that these instruments have explanatory power for the types of ICT that the literature suggests were likely to respond initially to the faster internet speeds. That is, our data do not coincide with a general upgrading of the firm's ICT. Second, our cable distance instrument is strongest during the time periods before BT rolled out an alternative form of ADSL, which reduced the importance of cable distance on internet speeds. In addition, it only has power for firms connected to ADSL enabled exchanges, which tends to rule out the possibility of some general feature of distance from the exchange. Third, we find that the instruments are uncorrelated with firm performance in the time periods *before* ADSL broadband became available in the UK. This would tend to rule out uncontrolled firm characteristics as a driver of our results. Finally, we find that the instruments are robust to the inclusion of other characteristics of the locality of the exchange such as the number of households and businesses that are connected to the exchange.

Using these instruments we show that the effect of communication-ICT at this time increased the scale rather than the efficiency of firms. There are large and significant effects on revenue and employment but not TFP. We argue that this is consistent with the idea that ADSL broadband allowed firms to create websites and develop e-commerce sales for the first time extending the market reach for these firms. That is it lowered communication costs with customers. We are also able to show that firms that these effects are strongest when the firm makes complementary investments and has high absorptive capacity.

Given the positive effect of ICT on productivity found in other studies, the evidence we present is suggestive that the effects of ICT are not homogenous. One potential avenue of future research would be to explore whether the productivity effects identified in other studies come from the storage and processing of information. This paper also suggests that the effects of communication-ICT are broader than the impacts on firm organisation or wages that have been identified thus far in the literature. Unpacking further the revenue and employment impacts we report as well as examining the effects of alternative communication technologies represent fruitful avenues for research.

**References**


Abramovsky, L., Griffith, R. (2006). 'Outsourcing and Offshoring of Business Services: How Important is ICT?', *Journal of the European Economic Association*, Vol. 4, pp. 594–601.

Akerman, A., Gaarder, I., Mogstad, M. (2015). 'The skill complementarity of broadband internet'. IZA Discussion Paper.

Anderson, T., and Herman Rubin. (1949). 'Estimation of the Parameters of a Single Equation in a Complete System of Stochastic Equations.' *The Annals of Mathematical Statistics*, 46–63.

Anderson, T., and Herman Rubin. (1950). "The Asymptotic Properties of Estimates of the Parameters of a Single Equation in a Complete System of Stochastic Equations." *The Annals of Mathematical Statistics*, 570–82.

Anderson, P., Kimbel, D. and Stuart Macdonald. (2000). 'Measurement or management?: Revisiting the productivity paradox of information technology', *Quarterly Journal of Economic Research*, Vol. 69. pp. 601-617.

Aral, S., Brynjolfsson, E. and Wu, D. (2007). 'What came first, IT or productivity? The virtuous cycle of investment and use in enterprise systems' mimeo. MIT Sloan School of Management.

Bartelsman, E.J., Gautier, P.A. and Joris de Wind. (2011). 'Employment protection, technology choice, and worker allocation', DNB Working Paper, No. 295, pp. 1-56.

Bartel, A, Ichniowski, C. and Kathryn Shaw. (2007). 'How Does Information Technology Affect Productivity? Plant-Level Comparisons of Product Innovation, Process Improvement, and Worker Skills.' *The Quarterly Journal of Economics* 122 (4): 1721–58.

Basu, S., Fernald, J., Oulton, N. and Sylaja Srinivasan. (2004). 'The case of the missing productivity growth, or does information technology explain why productivity accelerated in the United States but not in the United?' Harvard Institute of Economic Research Working Papers 2021

BBC News (1999a) 'The DSL Dinosaur', Online at: http://news.bbc.co.uk/2/hi/science/nature/284208.stm: Accessed on 3/18/2014

Black, S. E. and Lisa M. Lynch. (2001). 'How to compete: The impact of workplace practices and information technology on productivity', *The Review of Economic Statistics*, Vol. 83(3). pp. 434-445.

Black, S.E. and Lisa M. Lynch. (2004). 'What's driving the new economy?: The benefits of workplace innovation', *The Economic Journal*, Vol. 114. pp. 97-116.

Bloom, N, Draca, M. and John Van Reenen. (2011). 'Trade Induced Technical Change? The Impact of Chinese Imports on Innovation, IT and Productivity'. Working Paper 16717. National Bureau of Economic Research.

Bloom, N., Sadun, R. and John Van Reenen. (2005). 'It ain't what you do it's the way that you do I.T. – testing explanations of productivity growth using U.S. affiliates', Centre for Economic Performance, London School of Economics, September

Bloom, N., Sadun, R., Reenen, J.V., (2012). 'Americans Do IT Better: US Multinationals and the Productivity Miracle', *The American Economic Review*, Vol. 102, pp. 167–201.

Bloom, N., Garicano, L., Sadun, R., Van Reenen, J., (2013). 'The distinct effects of information technology and communication technology on firm organization'. National Bureau of Economic Research.

Bresnahan, T. F., Brynjolfsson, E. and Lorin M. Hitt. (2002). 'Information technology, workplace organization, and the demand for skilled labour: firm-level evidence', *Quarterly Journal of Economics*, pp. 339-376.

British Telecom (1998). 'Annual review and summary financial statement 1998', British Telecom, London.

British Telecom (2015). 'Does My Computer Meet the Minimum Specification for BT Broadband?' Online at: http://bt.custhelp.com/app/answers/detail/a_id/623/~/does-my-computer-meet-the-minimum-specification-for-bt-broadband%3F (Accessed on 34/01/2016).

Broadband4wroxton (2002) 'BT Press Release 1st of July 2002', Online at: http://www.broadband4wroxton.org.uk/2004/BT/BT_231.htm (Accessed on 3/19/2014).

Brynjolfsson, E. and Lorin Hitt. (1995). 'Information Technology as a factor of production: The role of differences among firms', *Economics of Innovation and New Technology*, Vol. 3(4). pp. 183-200.

Brynjolfsson, E. and Lorin M. Hitt. (2000). "Beyond Computation: Information Technology, Organizational Transformation and Business Performance." *Journal of Economic Perspectives* 14(4): 23–48.

Brynjolfsson, E. and Hitt., L.M. (2003). 'Computing productivity: Firm-level evidence', *The Review of Economics and Statistics*, Vol. 85(4). pp. 793-808.

Brynjolfsson, E., Hitt, L. M. and Yang, S. (2002). 'Intangible assets: Computers and organizational capital', Forthcoming in Brookings Papers on Economic Activity, 2002.

Brynjolfsson, E., McAfee, A., Sorell, M., Zhu. F. (2008). 'Scale without Mass: Business Process Replication and Industry Dynamics', *Harvard Business School Technology & Operations Mgt. Unit Research Paper No. 07-016*

Cadman, R. (2005). 'Invention, Innovation and Diffusion of Local Loop Unbundling in the UK.' *CCP Working Paper 12-8*.

Cardona, M., Kretschmer, T. and Strobel, T. (2013). 'ICT and productivity: conclusions from the empirical literature', *Information Economics and Policy*, Vol. 25, pp 109-125.

Combes, P. P., Duranton, G., Gobillon, L., Puga, D., & Roux, S. (2012). The productivity advantages of large cities: Distinguishing agglomeration from firm selection. *Econometrica*, *80*(6), 2543-2594.

Deshpande, A. (2013). 'Broadband Deployment and the Bandwagon Effect in the UK.' *Info* 15 (1): 34–47.

Dewan, S. and Chung-ki Min. (1997). 'The substitution of information technology for other factors of production: a firm level analysis', *Management Science*, Vol. 43(12). pp. 1660-1675.

DeStefano, T., Kneller, R. and Timmis (2014).

Draca, M., Raffaella S., and van Reenen, J. (2006). 'Productivity and IT: a Review of the Evidence', CEP Discussion Paper, 749.

Forman, C. (2002). 'The corporate digital divide: Determinants of internet adoption', WIDER Discussion Papers/World Institute for Development Economics (UNU-WIDER), No. 2002/89.

Forman, C., Goldfarb, A., Greenstein, S. M., (2012). 'The internet and local wages: a puzzle', *American Economic Review*, Vol 102(1), pp.556-575.

Forman, C, Goldfarb, A, and Shane Greenstein. (2014). 'Information Technology and the Distribution of Inventive Activity'. Working Paper 20036. National Bureau of Economic Research.

Forth, J. and Mason, G. (2003). 'Persistence of Skill Deficiencies across Sectors, 1999- 2001', in G. Mason and R. Wilson (eds) Employers Skill Survey: New Analyses and Lessons Learned. Nottingham: Department for Education and Skills, 71-89.

Garicano, L., (2010). 'Policeman, mangers, lawyers: New results on complementarities between organization and information and communication technology'. *International Journal of Industrial Organization*, Vol. 28, pp. 355-358.

Garicano, L., Heaton, P., (2010). 'Information Technology, Organization, and Productivity in the Public Sector: Evidence from Police Departments', *Journal of Labor Economics*, Vol. 28, pp. 167–201.

Garicano, L., Rossi-Hansberg, E., (2006). 'Organization and Inequality in a Knowledge Economy', *The Quarterly Journal of Economics*, Vol. 121, pp. 1383–1435.

Glaeser, E. L., & Resseger, M. G. (2010). The complementarity between cities and skills*. *Journal of Regional Science*, *50*(1), 221-244.

Greenan, N. and Mairesse, J. (1996). 'Computers and productivity in France: Some evidence', NBER Working Paper, No. 5836.

Greenan, N., Mairesse, J. and Topiol-Bensaid, A. (2001). 'Information technology and research and development impacts on productivity and skills: Looking for correlations on French firm', NBER Working Paper, No. 8075.

Hammersley, Ben. 2002. 'Bringing the Net to Eden.' *The Guardian*, October 3, sec. Technology. http://www.theguardian.com/technology/2002/oct/03/internetnews.onlinesupplement.

Hendel, I. (1999). 'Estimating multiple-discrete choice models: An application to computerization returns', *Review of Economic Studies*, Vol. 66. pp. 423-446.

Hubbard, T. N. (2003). 'Information, decisions, and productivity: On-board computers and capacity utilization in trucking', American Economic Review, Vol. 93(4). pp. 1328-1353.

Lehr, B. and Lichtenberg, F. (1999). 'Information technology and its impact on productivity: Firm-level evidence from government and private data sources', *Canadian Journal of Economics*, Vol. 32(2). pp. 335-362.

Leung, D. (2004). 'The effect of adjustment costs and organizational change on productivity in Canada: evidence from aggregate data', Bank of Canada Working Paper 2004-1.

Lichtenberg, F. R. (1993). 'The output contributions of computer equipment and personnel: A firm-level analysis', NBER Working Paper, No. 4540.

Macassey, J. (1985). 'Understanding Telephones', Ham Radio Magazine, September 1985.

Murray, M. (2010). 'The bad, the weak and the ugly: Avoiding the pitfalls of instrumental variable estimation', mimeo. Bates College, US.

OECD (2008). 'Broadband and the economy' Ministerial Background Report DSTI/ICCP/IE(2007)/FINAL

Ofcom (2002) 'ADSL Fact Sheet', pp.1-6

Oftel (2001). 'Communications Market Report 2001', Appendix B. Available from: http://www.ofcom.org.uk/static/archive/ra/topics/bfwa/doc28ghz/info-mem-sep2001/bfwaap_b.htm

ONS (2013). 'E-Commerce and ICT Activity'. Online at: http://www.ons.gov.uk/ons/dcp171778_342569.pdf (Accessed on 2012)

Puga, D. (2010). The Magnitude and Causes of Agglomeration Economies. *Journal of Regional Science*, *50*(1), 203-219.

Staiger, D., and Stock, J.H., (1997). 'Instrumental Variables Regression with Weak Instruments'. *Econometrica*, Vol. 65, pp. 57–586.

Stiroh, K. (2002a). 'Information technology and the US productivity revival: what do the industry data say?, American Economic Review, Vol. 92(5). pp. 1559-1576.

Van Ark, B. and Inklaar, R. (2005). 'Catching up or getting stuck? Europe's troubles to exploit IT's productivity potential', Economics Program Working Paper Series.

Van Beveren, I. (2012). 'Total Factor Productivity Estimation: A Practical Review.' *Journal of Economic Surveys* 26 (1): 98–128.

Varian, H., Litan, R.E., Elder, A., Shutter, J., (2002). 'The net impact study'. January. www.netimpactstudy.com.

Wolff, E.N. 2002. "Productivity, Computerization, and Skill Change." National Bureau of Economic Research Working Paper No. 8743.

**Data References**

Office for National Statistics, *Annual Respondent Database, 2000-2005: Secure Data Service Access [computer file].* Colchester, Essex: UK Data Archive [distributor], December 2013.

Office for National Statistics, *Business Structural Database*, *2000-2005: Secure Data Service Access [computer file].* Colchester, Essex: UK Data Archive [distributor], December 2013.

Office for National Statistics, *Capital Stock Database, 2000-2005: Secure Data Service Access [computer file]. Colchester,* Essex: UK Data Archive [distributor], December 2013.

Office if National Statistics, *Postcode Directory*, 2013: *Secure Data Service Access [computer file].* Colchester, Essex: UK Data Archive [distributor], February 2014.

Virtual Microdata Laboratory*, ICT Capital Stock Database*, *2000-*2005: *Secure Data Service Access [computer file].* Colchester, Essex: UK Data Archive [distributor], December 2013.

BBC News (1999b) 'BT to to launch high-speed Internet access', Online at: http://news.bbc.co.uk/2/hi/business/377844.stm: Accessed on 3/18/2014

BBC News (1999c) 'ADSL priced high for consumer', Online at: http://news.bbc.co.uk/2/hi/science/nature/406819.stm: Accessed on 3/18/2014

Brynjolfsson, E. (1992). 'The productivity paradox of information technology: Review and assessment', Center for Coordination Science, September

Forman, C., Goldfarb, A., Greenstein, S. M., (2005). 'Technology adoption in and out of major urban areas: When do internal firm resources matter most?', CSIO working paper, No. 0070.

Hubbard, T. N. (2009).

Ofcom (2004) 'Ofcom's DSL Fact Sheet', pp. 1-9

Oliner, S. D. and Sichel, D.E. (2002). 'Information Technology and productivity: Where are we now and where are we going?', Federal Reserve Bank of Atlanta Economic Review Third Quarter, pp. 15-44.

Stiroh, K. (2002b). 'Are IT spillovers driving the new economy?', Review of Income and Wealth, Series 48(1). pp. 33-57.

Stiroh, K. J. (2004). 'Reassessing the impact of IT in the production function: A meta-analysis and sensitivity tests', Federal Reserve Bank of New York, November 2002.

Stiroh, K. and Botsch (2007).

## Figures

**Figure 1: Summary of UK Telephone Network**

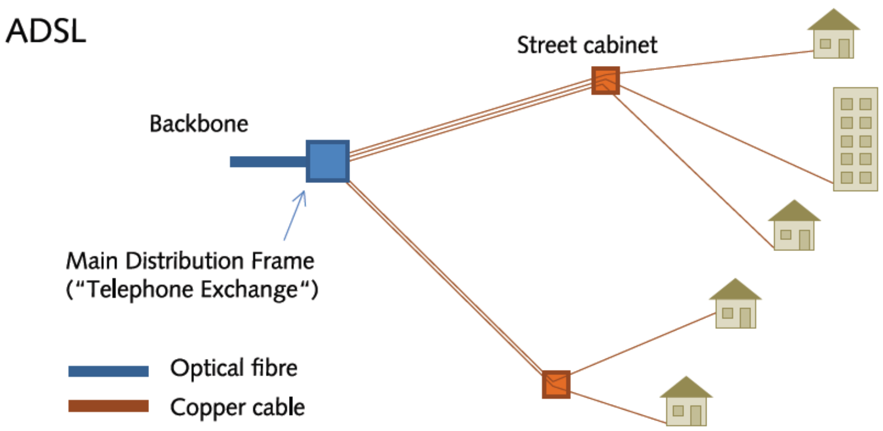


**Figure 2: Engineering Tests of ADSL and RADSL broadband speeds against Local Loop Length**

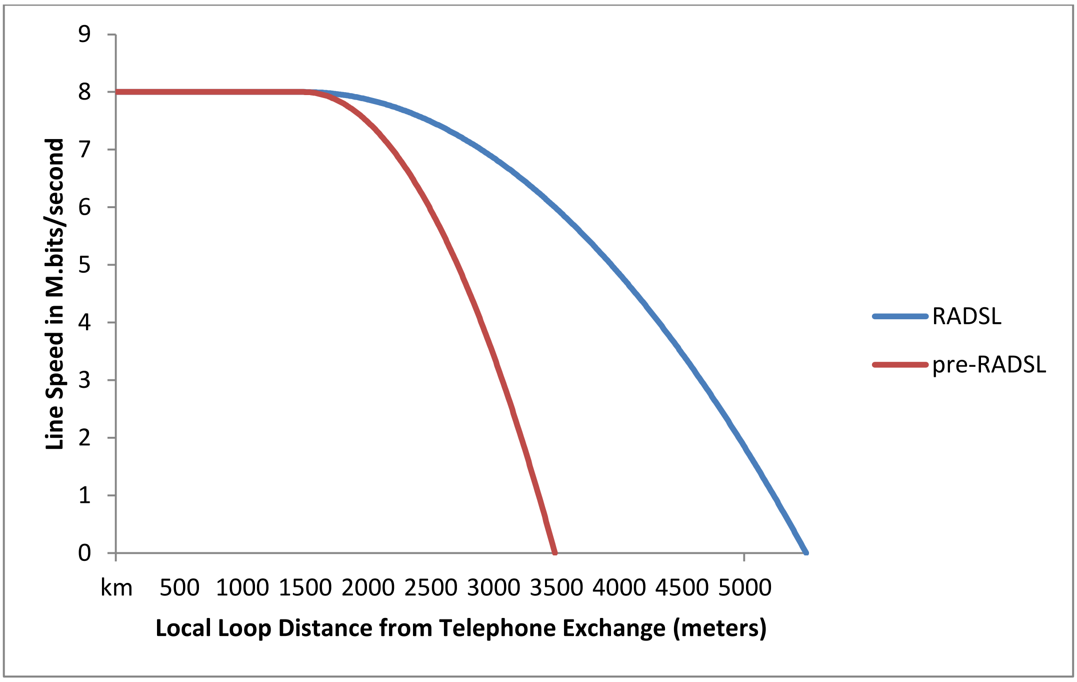



**Figure 3: Location of BT ADSL Enabled Exchanges by 1999**

**Figure 4: Location of BT ADSL Enabled Exchanges by 2001**

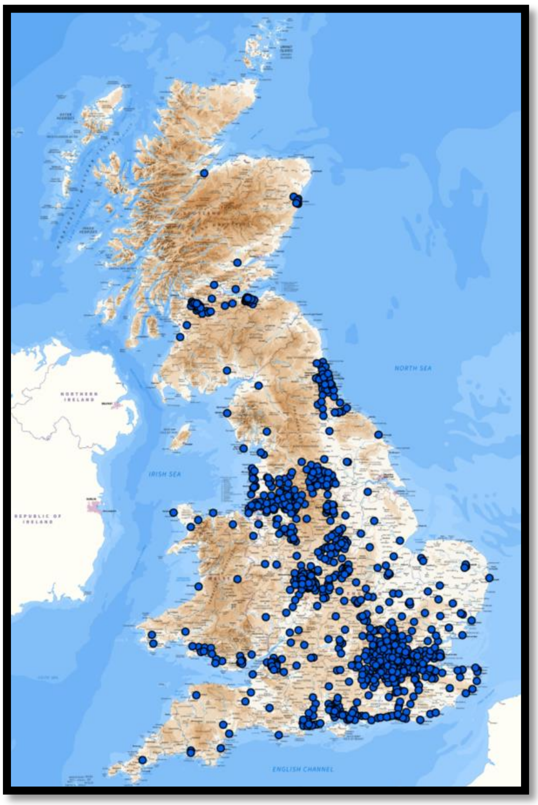



**Figure 5: Location of BT ADSL Enabled Exchanges by 2003**

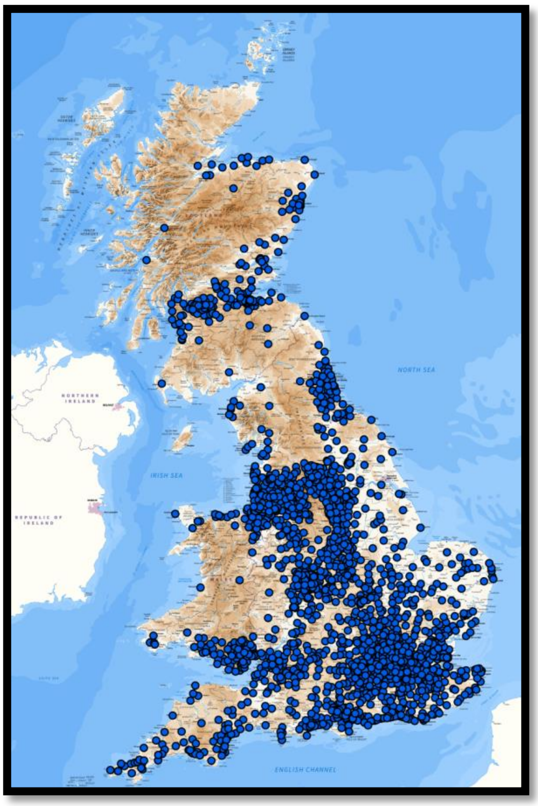


**Figure 6: Location of BT ADSL Enabled Exchanges by 2005**

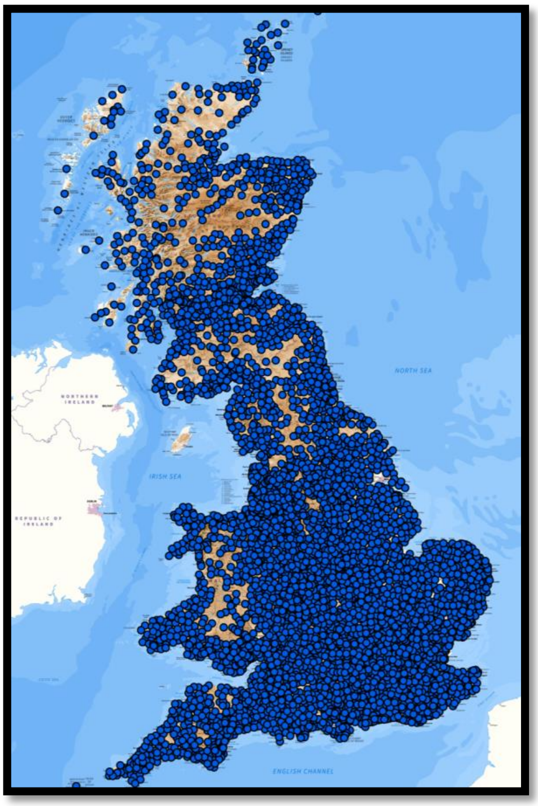


**Figure 7: Telephone Exchange Enabled for ADSL by BT per Half Year**

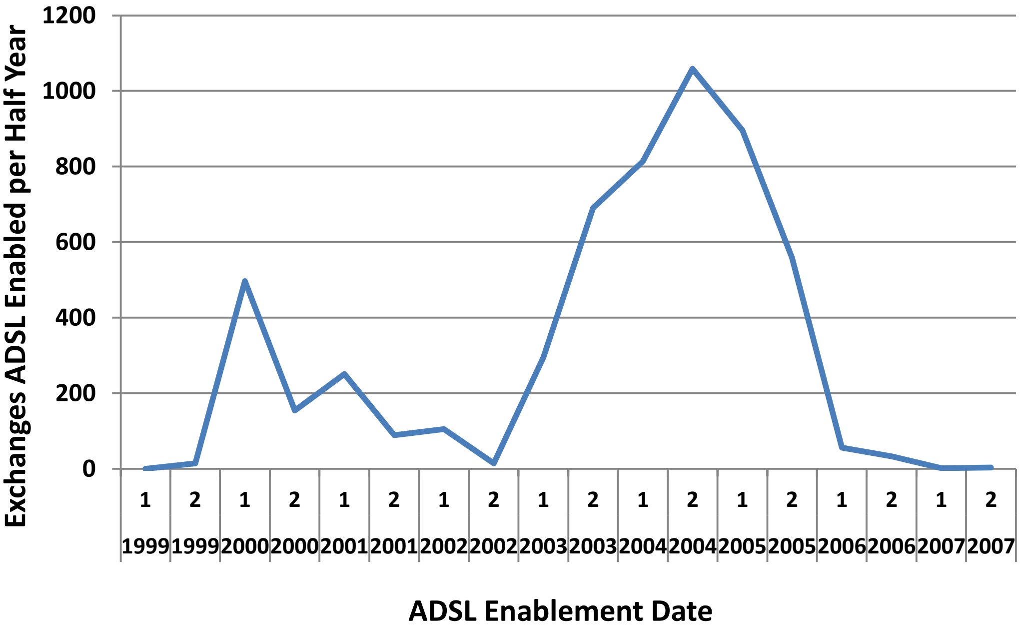


Table 1: Firm Summary Statistics for year 2000 from the ONS data and CiTDB databases

| **ONS Data** | **Estimation Sample (obs. 3,352)** | | **Enabled Exchanges (obs. 2,303)** | | **Non-enabled exchanges (obs. 1,049)** | | **Non-enabled exchanges (obs. 1,496)** | |
|---|---|---|---|---|---|---|---|---|
| **Exchange Enabled in Wave** | **One** | | **One** | | **One** | | **Two & Three** | |
| **Year** | **2000** | | **2000** | | **2000** | | **2000** | |
| *Variable* | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* |
| *ICT Capital Stock (Log)* | 4.093 | 2.371 | 4.273 | 2.404 | 3.705 | 2.250 | 3.630 | 2.174 |
| *Gross Output (Log)* | 8.975 | 1.588 | 9.089 | 1.626 | 8.726 | 1.471 | 8.573 | 1.486 |
| *Employment (Log)* | 5.607 | 1.394 | 5.689 | 1.445 | 5.426 | 1.255 | 5.301 | 1.260 |
| *TFP (Log)* | 0.712 | 0.866 | 0.712 | 0.899 | 0.712 | 0.790 | 0.663 | 0.778 |
| *Exchange ADSL Enabled* | 0.687 | 0.464 | 1 | 0 | 0 | 0 | 0 | 0 |
| *Local Loop Length* | 1.001 | 0.547 | 0.978 | 0.523 | 1.070 | 0.591 | 1.131 | 0.505 |
| **CiTDB Data** | **Estimation Sample (obs. 4,871)** | | **Enabled Exchanges (obs. 3,308)** | | **Non-enabled exchanges (obs. 1,563)** | | **Non-enabled exchanges (obs. 1,898)** | |
| *Variable* | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* |
| *ERP Software* | 0.104 | 0.305 | 0.097 | 0.296 | 0.118 | 0.322 | 0.121 | 0.326 |
| *ERP & Sales Software* | 0.225 | 0.418 | 0.213 | 0.409 | 0.250 | 0.433 | 0.250 | 0.433 |
| *PCs per employee (Log)* | -0.663 | 0.935 | -0.583 | 0.935 | -0.834 | 0.912 | -0.994 | 0.939 |
| *Portable PCs per employee (Log)* | -2.665 | 1.246 | -2.557 | 1.252 | -2.902 | 1.198 | -3.109 | 1.201 |
| *Pentium PCs per employee (log)* | -0.955 | 1.056 | -0.880 | 1.053 | -1.112 | 1.044 | -1.280 | 1.072 |
| *VPN* | 0.034 | 0.180 | 0.030 | 0.171 | 0.042 | 0.200 | 0.033 | 0.178 |
| *Revenue (Log)* | 3.679 | 1.815 | 3.750 | 1.876 | 3.513 | 1.668 | 3.476 | 1.552 |
| *Exchange ADSL Enabled* | 0.679 | 0.467 | 1 | 0 | 0 | 0 | 0 | 0 |
| *Local Loop Length* | 1.075 | 0.4818 | 1.019 | 0.491 | 1.192 | 0.439 | 1.147 | 0.479 |

Note: Employment represents employee headcount. Wave one relates to telephone exchanges enabled by British Telecom between 1999 and the end of 2002. Wave two and three exchanges are those enabled from 2003 to 2007.

**Table 2: First Stage Regressions of the Instruments on Software ICT capital**

| Regression No. | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 |
|---|---|---|---|---|---|---|---|
| Sample | Year: 2000; Telephone Exchanges Enabled in Wave 1 (1999-2002) | | | | | | |
| ICT Variable | ICT Capital Stock | ERP software | ERP & Sales Software | PCs/ Emp. | Portable PCs/ Emp. | Pentium PCs/ Emp. | VPN |
| *ADSL Enabled* | 0.908*** | -0.004 | -0.049 | 0.347*** | 0.494*** | 0.323*** | -0.004 |
| *Exchange* | (0.171) | (0.030) | (0.040) | (0.080) | (0.120) | (0.090) | (0.010) |
| *Local Loop dist.** | -0.382*** | -0.013 | 0.034 | -0.201*** | -0.298*** | -0.199*** | -0.011 |
| *ADSL Enabled* | (0.142) | (0.020) | (0.030) | (0.060) | (0.100) | (0.070) | (0.010) |
| *Firm controls* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Observations* | 3,331 | 4,830 | 4,831 | 4,830 | 3,281 | 4,686 | 4,830 |

Notes: OLS regressions using firm-level data for the year 2000. The sample of firms is restricted to those that are connected to telephone exchanges that were ADSL enabled under wave 1 of the BT rollout programme (1999-2002). Local loop distance refers to the cable distance between the firm and the telephone exchange. Regression 2.1 uses firm level data from the ONS and regressions 2.2 to 2.7 use data from the CiTDB database. Regression 2.1 includes a measure of age, ownership, multiplant status, local loop cable distance and region fixed effects as control variables. Regressions 2.2. to 2.7 include firm size (log employment), multiplant status, local loop cable distance and region fixed effects as controls. ERP denotes enterprise resource planning software; PCs denote personal computers; VPN denote virtual private networks. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 3: First Stage Regressions of the Instruments on Software ICT capital**

| Regression No. | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 | 3.7 |
|---|---|---|---|---|---|---|---|
| Sample | Year: 2000; Exchanges Enabled by End of 2000 | | | | | | |
| ICT Variable | ICT Capital Stock | ERP software | ERP & Sales Software | PCs/ Emp. | Portable PCs/ Emp. | Pentium PCs/ Emp. | VPN |
| *Local Loop dist.** | -0.336*** | 0.008 | 0.072*** | -0.225*** | -0.305*** | -0.203*** | -0.010 |
| *ADSL Enabled* | (0.093) | (0.010) | (0.010) | (0.030) | (0.050) | (0.040) | (0.010) |
| *Firm Controls* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Observations* | 2,290 | 3,276 | 3,277 | 3,276 | 2,246 | 3,169 | 3,276 |

Notes: OLS regressions using firm-level data for the year 2000. The sample of firms is restricted to those that are connected to telephone exchanges that were ADSL enabled by the end of 2000. Regression 3.1 uses firm level data from the ONS and regressions 3.2 to 3.7 use data from the CiTDB database. Local loop distance refers to the cable distance between the firm and the telephone exchange. Regression 3.1 includes a measure of age, ownership, multiplant status and region fixed effects as control variables. Regressions 3.2. to 3.7 include firm size (log employment), multiplant status and region fixed effects as controls. ERP denotes enterprise resource planning software; PCs denote personal computers; VPN denote virtual private networks. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 4: Adding Exchange Size as a Control Variable**

| Regression No. | 4.1 | 4.2 | 4.3 | 4.4 |
|---|---|---|---|---|
| **ICT Variable** | **ICT Capital Stock** | **PCs/ Employment** | **Portable PCs/ Employment** | **Pentium PCs/ Employment** |
| *ADSL Enabled Exchange* | 0.875*** | 0.348*** | 0.493*** | 0.323*** |
| | (0.173) | (0.080) | (0.120) | (0.090) |
| *Local Loop dist.* ADSL Enabled* | -0.310*** | -0.202*** | -0.298*** | -0.200*** |
| | (0.209) | (0.060) | (0.100) | (0.070) |
| *Exchange Size* | -0.222*** | -0.031*** | -0.019 | -0.029** |
| | (0.063) | (0.010) | (0.020) | (0.010) |
| *Firm Controls* | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ |
| *Observations* | 3,331 | 4,830 | 3,281 | 4,686 |

Notes: OLS regressions using firm-level data for the year 2000. The sample of firms is restricted to those that are connected to telephone exchanges that were ADSL enabled under wave 1 of the BT rollout programme (1999-2002). Regression 4.1 uses firm level data from the ONS and regressions 4.2 to 4.4 use data from the CiTDB database. Local loop distance refers to the cable distance between the firm and the telephone exchange. Exchange size is the (log) sum of the number households and businesses connected to a telephone, the data for which is from PointTopic. Regression 4.1 includes a measure of age, ownership, multiplant status and region fixed effects as control variables. Regressions 4.2. to 4.4 include firm size (log employment), multiplant status and region fixed effects as controls. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 5: First Stage Regressions of Local Loop Distance as a Single Instrument on ICT capital Over Time and for non-enabled Exchanges**

| **Regression No.** | **5.1** | **5.2** | **5.3** | **5.4** | **5.5** | **5.6** | **5.7** | **5.8** |
|---|---|---|---|---|---|---|---|---|
| **Exchanges** | **ADSL Enabled Exchanges** | | | | **Non-Enabled Exchanges** | | | |
| **Exchange enabled in** | **Wave 1** | **Wave 1** | **Wave 1** | **Wave 1** | **Wave 1** | **Wave 1** | **Wave 1** | **Wave 2&3** |
| **Year of ICT data** | **2000** | **2001** | **2002** | **2003** | **1998** | **1999** | **2000** | **2000** |
| **ICT Variable** | **ICT Capital Stock** | | | | **ICT Capital Stock** | | | |
| *Local Loop Distance * ADSL enabled* | -0.336*** | -0.250*** | -0.169*** | -0.151*** | -0.129 | 0.184 | 0.065 | 0.159 |
| | (0.093) | (0.063) | (0.057) | (0.053) | (0.352) | (0.171) | (0.106) | (0.110) |
| *Firm Controls* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Observations* | 925 | 4816 | 5317 | 5317 | 122 | 961 | 1041 | 1478 |

Notes: OLS regressions using firm-level data for various years. The sample of firms in regressions 5.1 to 5.4 is restricted to those that are connected to telephone exchanges that were ADSL enabled by the end of the year indicated. Regressions 5.5 and 5.6 use firm level data for the years 1998 and 1999 respectively. In both regressions the sample of firms is restricted to those that were connected to telephone exchanges that were ADSL enabled in 2000. Regressions 5.7 and 5.8 use firm level data for the year 2000. In regression 5.7 the sample of firms is restricted to those that were connected to telephone exchanges that were not ADSL enabled by the end of 2000, but were enabled by the end of 2002 (wave 1). In regression 5.8 the sample of firms is restricted to those that were connected to telephone exchanges that were not ADSL enabled by the end of 2000, but were enabled between 2003 and 2007 (wave 2 and 3). Local loop distance refers to the cable distance between the firm and the telephone exchange. Regression 5.1 and 5.5 uses firm level data from the ONS and regressions 5.2 to 5.4 and 5.6 to 5.8 use data from the CiTDB database. All control variables are as in Tables 3 and 4. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 6: Correlation between Timing of Wave 1 ADSL Enablement and Ex-ante Firm Characteristics**

| **Regression No.** | **6.1** | **6.2** | **6.3** | **6.4** | **6.5** | **6.6** |
|---|---|---|---|---|---|---|
| **Dependent Variable:** | **Probability of ADSL Enablement** | | | **ADSL Enablement* Local Loop Distance** | | |
| *Employment in 1998* | 0.001 | | | 0.002 | | |
| | (0.003) | | | (0.012) | | |
| *Gross Output in 1998* | | 0.003 | | | -0.002 | |
| | | (0.003) | | | (0.009) | |
| *TFP in 1998* | | | 0.005 | | | 0.026 |
| | | | (0.007) | | | (0.019) |
| *Foreign in 1998* | 0.007 | 0.004 | 0.004 | 0.002 | 0.005 | -0.035 |
| | (0.015) | (0.015) | (0.016) | (0.045) | (0.046) | (0.052) |
| *USA in 1998* | -0.012 | -0.011 | -0.017 | -0.007 | -0.007 | 0.012 |
| | (0.023) | (0.023) | (0.025) | (0.077) | (0.077) | (0.088) |
| *Firm Age* | 0.007 | 0.007 | 0.002 | -0.036 | -0.036 | -0.015 |
| | (0.008) | (0.008) | (0.009) | (0.022) | (0.022) | (0.026) |
| *Local Loop Length* | -0.004 | -0.004 | 0.001 | | | |
| | (0.005) | (0.005) | (0.005) | | | |
| *3digit Industry FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Regional FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Year FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Observations* | 7,681 | 7,681 | 5,758 | 7,681 | 7,681 | 5,758 |

Notes: OLS regressions using firm-level data for the year 1998. All regressions uses firm level data from the ONS. Local loop distance refers to the cable distance between the firm and the telephone exchange. Firm age is in years. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 7: Baseline IV Regressions using ONS data (Year: 2000)**

| **Regression No.** | **7.1** | **7.2** | **7.3** | **7.4** | **7.5** | **7.6** | **7.7** |
|---|---|---|---|---|---|---|---|
| **Dependent Variable** | **Output** | | **Employment** | | **TFP** | | |
| **Telephone Exchanges** | **All Wave 1** | **Enabled By 2000** | **All Wave 1** | **Enabled By 2000** | **All Wave 1** | **Enabled By 2000** | **All** |
| **Second Stage** | | | | | | | |
| *ICT Capital Stock* | 0.605*** | 0.471*** | 0.399*** | 0.399** | 0.014 | -0.158 | 0.058 |
| | (0.072) | (0.115) | (0.065) | (0.120) | (0.092) | (0.107) | (0.042) |
| **First Stage** | | | | | | | |
| *ADSL Enabled Exchange* | 0.908*** | | 0.908*** | | 0.908*** | | 0.969*** |
| | (0.171) | | (0.171) | | (0.171) | | (0.143) |
| *Local Loop dist. *ADSL Enabled* | -0.382*** | -0.336*** | -0.382*** | -0.336*** | -0.382*** | -0.336*** | -0.414*** |
| | (0.142) | (0.093) | (0.142) | (0.093) | (0.142) | (0.093) | (0.122) |
| *Firm Controls* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Cragg-Donald F Test* | 21.883 | 13.688 | 21.883 | 13.688 | 21.883 | 13.688 | 41.786 |
| *Kleibergen-Paap F Test* | 22.249 | 12.926 | 22.249 | 12.926 | 22.249 | 12.926 | 40.503 |
| *Hansen J Statistic* | 0.504 | | 0.604 | | 0.545 | | 0.083 |
| *LIML* | 0.606*** | 0.471*** | 0.399*** | 0.399** | 0.014 | -0.158 | 0.060** |
| *(std. error)* | (0.073) | (0.115) | (0.065) | (0.120) | (0.056) | (0.107) | (0.117) |
| *Moreira's CLR (p-value)* | 0.47, 0.77 (0.00)*** | 0.29, 0.76 (0.00)*** | 0.26, 0.55 (0.00)** | 0.27, 0.75 (0.00)** | -0.11, 0.13 (0.82) | -0.45, -0.00 (0.05) | -0.02, 0.15 (0.16) |
| *Observations* | 3331 | 2290 | 3331 | 2290 | 3331 | 2290 | 4807 |

Notes: 2SLS regressions using firm-level data for 2000 from the ONS. 'All wave 1 exchanges' refers restricts the sample of to those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). 'Enabled by 2000 exchanges restricts the sample of firms to those that were connected to telephone exchanges that were ADSL enabled in 2000. 'All exchanges' restricts the sample of firms to those connected to BT telephone exchanges enabled between 1999-2007. Regressions include a measure of age, ownership, multiplant status and region fixed effects as control variables. Regressions 7.1, 7.3, 7.5 and 7.7 additionally include local loop cable distance. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 8: IV Regressions using CiTDB (Year: 2000)**

| **Regression No.** | **8.1** | **8.2** | **8.3** | **8.4** | **8.5** | **8.6** |
|---|---|---|---|---|---|---|
| **Dependent Variable** | **Revenue** | | | | | |
| **Telephone Exchanges** | **All Wave 1** | **Enabled By 2000** | **All Wave 1** | **Enabled By 2000** | **All Wave 1** | **Enabled By 2000** |
| **Second Stage** | | | | | | |
| *PCs per employee* | 1.425*** | 1.904*** | | | | |
| | (0.424) | (0.402) | | | | |
| *Portable PCs* | | | 1.137*** | 1.186*** | | |
| *per employee* | | | (0.342) | (0.275) | | |
| *Pentium PCs* | | | | | 1.740*** | 2.181*** |
| *per employee* | | | | | (0.569) | (0.527) |
| **First Stage** | | | | | | |
| *ADSL Enabled* | 0.347*** | | 0.494*** | | 0.323*** | |
| *Exchange* | (0.078) | | (0.123) | | (0.089) | |
| *Local Loop Distance* | -0.201*** | -0.225*** | -0.298*** | -0.305*** | -0.199*** | -0.203*** |
| **ADSL Enabled* | (0.061) | (0.033) | (0.097) | (0.053) | (0.070) | (0.038) |
| *Firm Controls* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Cragg-Donald F Test* | 12.948 | 47.418 | 9.067 | 33.619 | 7.55 | 28.544 |
| *Kleibergen-Paap F Test* | 12.339 | 46.588 | 9.382 | 33.332 | 7.318 | 28.313 |
| *Hansen J Statistic* | 0.166 | | 0.346 | | 0.335 | |
| *Observations* | 4,830 | 3,276 | 3,281 | 2,246 | 4,686 | 3,169 |

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database. 'All wave 1 exchanges' refers restricts the sample of to those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). 'Enabled by 2000 exchanges restricts the sample of firms to those that were connected to telephone exchanges that were ADSL enabled in 2000. Local loop distance refers to the cable distance between the firm and the telephone exchange. All regression include firm size (log employment), multiplant status and region fixed as controls. Regressions 8.1, 8.3 and 8.5 additionally include local loop cable distance. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table 9: Complementary Factors IV Regressions (Year: 2000)**

| Regression No. | 9.1 | 9.2 | 9.3 | 9.4 |
|---|---|---|---|---|
| **Dependent Variable** | **Homepage** | **Web design software** | **IT employees/ total employment** | **Programmers/ total employment** |
| **Second Stage** | | | | |
| *PCs per employee* | 0.095 | 0.013* | 0.084*** | 0.036*** |
| | (0.088) | (0.007) | (0.028) | (0.012) |
| **First Stage** | | | | |
| *ADSL Enabled* | 0.345*** | 0.345*** | 0.345*** | 0.345*** |
| *Exchange* | (0.073) | (0.073) | (0.073) | (0.073) |
| *Local Loop Distance* | -0.201*** | -0.201*** | -0.201*** | -0.201*** |
| **ADSL Enabled* | (0.058) | (0.058) | (0.058) | (0.058) |
| *Firm Controls* | ✓ | ✓ | ✓ | ✓ |
| *Region FE* | ✓ | ✓ | ✓ | ✓ |
| *Cragg-Donald F Test* | 14.076 | 14.076 | 14.054 | 14.076 |
| *Kleibergen-Paap F Test* | 13.24 | 13.24 | 13.22 | 13.24 |
| *Hansen J Statistic* | 0.518 | 0.468 | 0.052 | 0.997 |
| *Observations* | 7095 | 7095 | 7094 | 7095 |

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database. 'All wave 1 exchanges' refers restricts the sample of to those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). 'Enabled by 2000 exchanges restricts the sample of firms to those that were connected to telephone exchanges that were ADSL enabled in 2000. All regression include firm size (log employment), multiplant status and region fixed as controls. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

## Appendix

**Table A1: OLS Estimates of ICT and Firm Performance**

| Data Source | ONS | | | CiTDB | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Firm Performance Indicator** | **Revenue** | **Employment** | **TFP** | **Revenue** | **Revenue** | **Revenue** | **Revenue** | **Revenue** | **Revenue** |
| *ICT Capital Stock* | 0.498*** | 0.390*** | 0.021* | | | | | | |
| | (0.009) | (0.009) | (0.012) | | | | | | |
| *ERP Software* | | | | 0.723*** | | | | | |
| | | | | (0.110) | | | | | |
| *ERP & Sales Software* | | | | | 0.115* | | | | |
| | | | | | (0.070) | | | | |
| *No. PCs per* | | | | | | 0.184*** | | | |
| *per employee* | | | | | | (0.030) | | | |
| *Pentium PCs* | | | | | | | 0.185*** | | |
| *per employee* | | | | | | | (0.020) | | |
| *Portable PCs* | | | | | | | | 0.134*** | |
| *per employee* | | | | | | | | (0.030) | |
| *VPN* | | | | | | | | | 0.598*** |
| | | | | | | | | | (0.130) |
| *Observations* | 3352 | 3352 | 3352 | 4866 | 4866 | 4866 | 3307 | 4722 | 4866 |

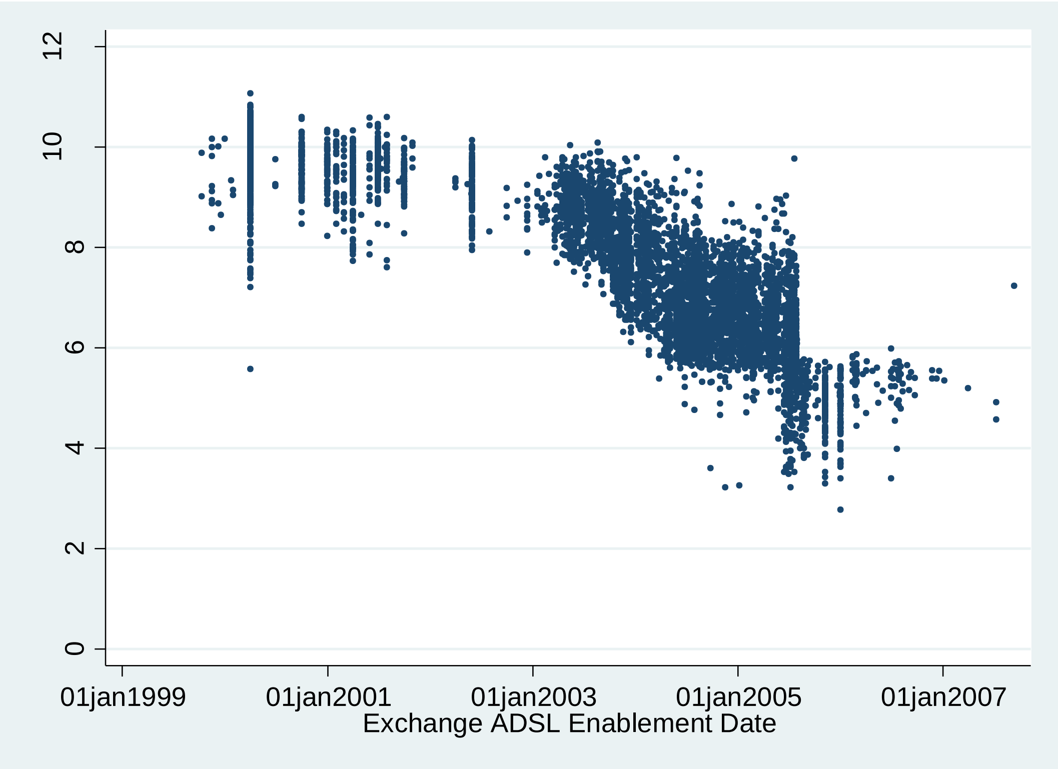
Notes: All regressions are OLS estimates using data for the year 2000. The sample of firms is restricted to those that are connected to telephone exchanges that were ADSL enabled under wave 1 of the BT rollout programme (1999-2002). Regressions 2.1 to 2.3 use firm level data from the ONS and regressions 2.4 to 2.8 use data from the CiTDB database. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table A2: ADSL Telephone Exchange Enablement per Year**

| Year | Number of Exchanges Enabled | Percentage | Accumulated Enablement |
|---|---|---|---|
| *1999* | 14 | 0.3 | 0.3 |
| *2000* | 651 | 11.8 | 12.0 |
| *2001* | 340 | 6.2 | 18.2 |
| *2002* | 119 | 2.2 | 20.3 |
| *2003* | 985 | 17.8 | 38.2 |
| *2004* | 1,873 | 33.9 | 72.1 |
| *2005* | 1,451 | 26.3 | 98.3 |
| *2006* | 89 | 1.6 | 99.9 |
| *2007* | 5 | 0.1 | 100.0 |
| *Total* | 5,527 | 100.0 | |

The following table excludes 37 Kingston communication exchanges. Northern Ireland exchanges are also excluded due to data issues. Another 9 exchanges are excluded due to incomplete activation dates

**Figure A1: Exchange Size against ADSL Enablement Date**




Note: Exchange Size measured by the sum of households and businesses attached to a telephone exchange. Data source: PointTopic.

### The ADSL rollout in Wave 2

The enablement of an exchange was undertaken only upon completing a number of steps. Firstly, households and businesses had to confirm their willingness to purchase a broadband connection by subscribing interest on BT's website (Ofcom, 2002).[42] In order for installation to take place, the number of potential subscribers needed to reach a particular threshold, which differed across exchanges.[43] Once the threshold was met and customers had confirmed their willingness to purchase a broadband connection, then the exchange was enabled (broadband4wroxton, 2002). In 2002 BT reduced the wholesale price 40% and also removed the need for engineers to visit the customer's premises, allowing self-connection of ADSL modems.

In Table A3 we explore this further by estimating a regression of the number of months since the start of the ADSL rollout began (November 1999) using the (log) average length of the local loop for customers connected to that exchange, the (log) number of households, the (log) number of business premises and region dummies as explanatory variables. We report regressions for the full time period (1999 to 2007), the first wave (1999 to 2002), the second wave (2003 to 2005) and the third wave (2006-2007). All of the regressions show that an exchange was more likely to be enabled by BT later in the programme if the exchange had fewer households connected to it and the average cable distance to the exchange was longer (the local loop was longer). There are a number of differences across the regressions that are also revealing however. Firstly, the parameter on the number of households is much larger for the regression of the second wave (regression 3) compared to the first (regression 2) and the third wave (regression 4), consistent with the demand-driven focus in the second wave. The adjusted-$R^2$ also suggests that this small number of explanatory variables explains a greater proportion of the variation in the data in this second wave. Secondly, the measure of the number of business is significant only when we use data for the entire rollout period (regression 1) and wave 2 (regression 3). This is likely explained by the targeting of major conurbations in wave 1, and mainly rural areas in wave 3, which may also explain why the average local loop variable has a larger elasticity in the regression for wave 1 (regression 2) compared to wave 2 (regression 3).

**Table A3: Timing of Enablement**

| **Regression No.** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| **Sample** | **All exchanges** | **Wave 1 exchanges** | **Wave 2 exchanges** | **Wave 3 exchanges** |
| *Ln (no. of households)* | -6.286*** | -2.826*** | -3.324*** | -1.087*** |
| | (0.214) | (0.348) | (0.171) | (0.174) |
| *Ln (no. of businesses)* | -2.219*** | -0.389 | -0.341** | -0.210 |
| | (0.213) | (0.268) | (0.166) | (0.160) |
| *Ln (average local loop)* | 0.635 | 3.896*** | 2.701*** | 0.480 |
| | (0.532) | (0.259) | (0.422) | (0.346) |
| *Region FE* | ✓ | ✓ | ✓ | ✓ |
| *$R^2$* | 0.725 | 0.238 | 0.463 | 0.212 |
| *Observations.* | 5520 | 1123 | 3022 | 1375 |

[42] Each firm or household counted as a single registration.

[43] This step was introduced by BT due to manipulation of the register of interest with 'bogus' claims (According to some sources 'M. Mouse' was a frequently used name on these lists). The subscription threshold was determined by the cost of upgrading a particular exchange box.

Notes: OLS regressions of the month-year in which ADSL enablement occurred (1= November-1999; 40=September-2007). Data on date of enablement is from OFCOM and exchanges characteristics from PointTopic. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

*UK Rollout of Alternative Broadband Technologies*

We consider a time period where there are no other substantial contemporaneous changes in UK broadband technology that may contaminate the analysis. The main alternative technologies for high-speed broadband access at this time were cable and, for businesses, leased line connections. Cable broadband utilises the network originally installed for cable television, which in the UK was installed before the roll out of ADSL took place. The cable network was rolled out in the UK in the early 1990s and ending by 1998. Thereafter, the number of premises eligible for cable broadband has remained broadly constant (OCOM, 2004). Leased line access requires a permanent, dedicated fibre-optic connection between the customer and the local exchange. These differ from ADSL primarily in that they do not rely on the pre-existing telephone copper wiring to connect the premises to the exchange and offer higher connection speeds, however the high cost of installation makes this an option only for the largest firms. Leased line connections have been available since the 1990s and also do not overlap with the timing of ADSL roll out (OFCOM, 2004).

**Table A4: Distribution of Local Loop Lengths by Firms**

| **Data Source** | **ONS** | **CiTDB** |
|---|---|---|
| **Frequency** | **Local loop length (km.)** | |
| 1% | 0.74 | 0.78 |
| 5% | 1.05 | 1.11 |
| 10% | 1.34 | 1.46 |
| 25% | 2.01 | 2.18 |
| 50% | 2.92 | 3.18 |
| 75% | 4.10 | 4.31 |
| 90% | 4.97 | 5.04 |
| 95% | 5.34 | 5.35 |
| 99% | 6.02 | 5.95 |
| Mean | 2.71 | 3.24 |
| Standard Deviation | 1.75 | 1.33 |

Notes: Local loop distance for firms attached to exchanges enabled for ADSL broadband under wave 1 of the BT rollout programme (1999-2002). Cable distances are from Point-Topic

**Table A5: Use of ERP and VPN by PC intensive firms (Years: 2000 to 2003)**

| Regression No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Estimation method | OLS | | | Instrumental Variable | | |
| ICT type: | ERP software | ERP & Sales Software | VPN | ERP software | ERP & Sales Software | VPN |
| *PCs/Employment* | 0.022*** | 0.012*** | 0.071*** | 0.272*** | 0.191*** | 0.436*** |
| | (0.000) | (0.000) | (0.000) | -(0.070) | -(0.070) | -(0.070) |
| *Obs.* | 16087 | 16087 | 16087 | 21402 | 21402 | 21402 |

Notes: Regressions 1-3 are estimated by OLS. Regressions 4-6 are 2SLS regressions. All use firm-level data for 2000 to 2003 from the CiTDB database and are for firms attached to wave 1 exchanges (enabled: 1999-2002). All regression include firm size (log employment), multiplant status and region fixed as controls. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Table A6: Across Time and Non-enabled Exchanges: Additional Results using CiTDB data**

| Regression No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Sample | Exchanges Enabled by | | | | Exchanges not enabled by | |
| | 2000 | 2001 | 2002 | 2003 | 2000 Wave 1 | 2000 Wave 2 & 3 |
| | | | | | | |
| *PCs/employment* | -0.225*** | -0.207*** | -0.154*** | -0.148*** | -0.012 | 0.143** |
| | (0.030) | (0.030) | (0.030) | (0.030) | (0.050) | (0.050) |
| *Obs.* | 3,276 | 5,347 | 5,325 | 5,166 | 1,554 | 1,891 |
| Portable PCs/Emp | -0.305*** | -0.201*** | -0.131*** | -0.153*** | -0.001 | 0.111* |
| | (0.050) | (0.040) | (0.040) | (0.040) | (0.080) | (0.070) |
| *Obs.* | 2,246 | 3,779 | 3,940 | 3,884 | 1,035 | 1,291 |
| Portable PCs/Emp | -0.203*** | -0.192*** | -0.149*** | -0.106*** | 0.009 | 0.168*** |
| | (0.040) | (0.030) | (0.030) | (0.030) | (0.060) | (0.050) |
| *Obs.* | 3,169 | 5,231 | 5,192 | 5,029 | 1,517 | 1,834 |

Notes: OLS regressions using firm-level data for various years. The sample of firms in regressions 1 to 4 are restricted to those that are connected to telephone exchanges that were ADSL enabled by the end of the year indicated. Regressions 5 and 6 use firm level data for the year 2000. In regression 5 the sample of firms is restricted to those that were connected to telephone exchanges that were not ADSL enabled by the end of 2000, but were enabled by the end of 2002 (wave 1). In regression 6 the sample of firms is restricted to those that were connected to telephone exchanges that were not ADSL enabled by the end of 2000, but were enabled between 2003 and 2007 (wave 2 and 3). Local loop distance refers to the cable distance between the firm and the telephone exchange. All regression use data from the CiTDB database. All control variables are as in Tables 3 and 4. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.

**Longer run effects on productivity**

In Table A7 we consider the possibility that the effects of software take some time to reveal themselves on TFP. The instrument for ICT that we have constructed in the paper has internal and external validity only for the year 2000. To explore the long-run effects of ICT we therefore focus on those firms that were attached to telephone exchanges that were enabled by the end of 2000 and thus use the local loop length as a single instrument. Exploiting the variation in the cable distance of firms from the telephone exchange we then consider the effects of ICT in the year 2000 as a determinant of TFP in subsequent years (2001, 2002, 2003 etc.). A downside to this approach is that we lose observations from the sample which tends to weaken with it the power of the instrument which strongly affects the conclusions that might be reached. Taken together, there is some evidence that the effects of ICT become more positive over time, although at no point can we conclude that the effect is statistically significant on TFP.

**Table A7: Lagged Effects on TFP**

| **Regression No.** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Periods since enablement** | **current** | **t-1** | **t-2** | **t-3** | **t-4** |
| **Second Stage** | | | | | |
| *ICT capital* | -0.158 | -0.164 | 0.020 | 0.061 | 0.176 |
| | (0.107) | (0.151) | (0.131) | (0.158) | (0.157) |
| **First Stage** | | | | | |
| *Local Loop Length* | -0.336*** | -0.271** | -0.354*** | -0.311** | -0.422** |
| **ADSL Enabled* | (0.093) | (0.107) | (0.133) | (0.151) | (0.174) |
| *Cragg-Donald F Test* | 13.688 | 7.125 | 8.176 | 5.100 | 7.359 |
| *Kleibergen-Paap F Test* | 12.926 | 6.454 | 7.145 | 4.276 | 5.841 |
| *Observations* | 2290 | 1676 | 1296 | 1064 | 850 |

Notes: 2SLS regressions using firm-level data for from the ONS. The current year refers to 2000, t-1 to 2001 data, t-2 to 2002 data; t-3 to 2003 data; t-4 to 2004 data. All regressions restricts the sample of to those that are connected to telephone exchanges that were ADSL enabled by the end of 2002 (wave 1). Regressions include a measure of age, ownership, multiplant status, local loop cable distance and region fixed effects as controls. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses.