Broadband Infrastructure, ICT use and Firm Performance: Evidence for UK Firms

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Abstract

The recent economics literature has begun to recognise that ICT is a heterogeneous technology altering information storage, processing and communication in distinct ways. In this paper we use the arrival of a new communication technology, ADSL broadband, to study the effects of heterogeneous types of ICT on firm performance. To do so free from endogeneity bias, we construct instruments using postcode-level geographic variation in 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. We find in turn, that ICT causally affects firm size (captured by either sales or employment) but not productivity.

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1.0 Introduction

Traditionally, ICT is modelled as an aggregated, homogenous capital (Draca et al, 2006). More recently however, greater availability of data on the types of ICT used by firms, has led to the recognition that these technologies provide firms with a variety of ways to store, process and transmit information, which in turn generates new knowledge and improves coordination and communication across production lines and customers. Particular types of ICT may therefore have distinct impacts on the firm (Garicano and Rossi-Hansberg, 2006), which may differentially impact employment, output and/or productivity of the firm.

While the distinction between heterogeneous types of ICT has added new insights, it leaves in place familiar endogeneity concerns. Firms do not randomly select into adopting particular ICT technologies but choose to do so aware of the distinct possibilities they offer. Growing evidence shows that management practices, for example, are both a key determinant and outcome of technology adoption. Firms with sophisticated managerial ability are more likely to adopt new technologies (Bloom et al., 2012). In addition, by facilitating new types of management practices, 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; Garicano and Heaton, 2010; Garicano, 2010; Bloom et al., 2012).

This paper brings together these themes of ICT heterogeneity and causality that have developed largely independently in the literature, using a new instrumental variable to explore the causal effects of heterogeneous types ICT on firm performance. We construct instruments that exploit plausibly exogenous spatial variation in access to broadband connections due to historic differences in firms' access to the infrastructure underlying broadband internet, the telephone network.[1] By using instruments of this type we build on a small number of studies that have also used the constraints that arise from the infrastructure of ICT (Abramovsky and Griffith, 2006; Grimes et al., 2012; Bertschek et al., 2013; Czernich, 2014; Akerman et al. 2015; Haller and Lyons, 2015; Fabling and Grimes, 2016). Most of these papers construct instruments derived from measures of household broadband penetration within a particular region, therefore assuming that the effects of ICT

[1] 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.

infrastructure are the same for all firms within that location. We instead build instruments that vary even amongst firms within the same local geographic area. Using firm-specific instruments is important for two reasons: 1) using time-varying regional instruments amounts to effectively running regressions with data aggregated to the region-time level and is thus vulnerable to shocks affecting ICT decisions at that level; 2) the telecoms engineering literature has shown that within-region variation in broadband speeds is as important as across-regions and hence instruments that vary only at the region level may yield imprecise estimates.

Our instruments exploit the fact that firm broadband speeds depend upon the telephone exchange they are connected to and also on the cable distance between each firm and the local telephone exchange. There are 5,630 telephone exchanges in the UK and we know the date of broadband enablement for each of these. In addition, we collected information on cable distances between the telephone exchange and 1.66 million different postcodes. Engineering tests conducted on the types of internet technologies we consider find that connection speeds deteriorate for cable lengths beyond 2 km. The mean cable distance in our data is a little over 3km, indicating that the spatial variation in connection speeds we can exploit using this information is important and far more disaggregated than regional, local government or even city-level. The mapping of the telephone network in the UK and constructing firm-specific instruments represents a primary contribution of the paper to the broader literature on ICT. These instruments are the focus of the paper and we provide a large number of tests for their reliability.

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, such as through websites, expanding the potential market of the firm. The computing literature indicates that the spread of the internet complemented the diffusion of new forms of ICT, including both hardware, such as Pentium PCs, and software, such as virtual private networks (VPN)[2], e-commerce and

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

enterprise resource planning (ERP)[3] (Forman, 2002). To examine both the possible heterogeneous effects and the complementarities of these various types of IT hardware and software we use a comprehensive dataset on the physical units of ICT used within a firm, known as the Ci Technology Database (CiTDB)[4]. 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.

From this dataset we identify the types of ICT that are affected by the speed of broadband connection, extending the types of ICT that have been previously explored in the literature. To ensure compatibility with the existing literature, to enable the use of a broad range of firm performance measures, and to provide some tests on the reliability of the instrument, we also present a robustness check using aggregate ICT data from the UK Census Bureau, the Office for National Statistics (ONS).[5]

To preview our main findings, when using the CiTDB we find some types of ICT 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 ERP or VPN software use. We find some evidence that the adoption 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.[6]

We find evidence that ICT causally affects firm size, with significant revenue effects from PC hardware. That these effects are somewhat larger than the OLS estimates in both cases indicates strong effects from the instrument on the compliant population. ADSL broadband provided small and medium sized firms low cost access to internet technologies for the first time allowing them create websites, develop e-commerce sales and extend their market reach. Consistent with this we also find evidence of larger effects for small as opposed to large firms.

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[3] 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.

[4] The CiTDB is produced by the Aberdeen Group (formally known as Harte Hanks)

[5] The disadvantage of this data source is that ICT is measured only as an aggregated capital stock measure.

[6] 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 which occurred later into that decade.

We find similar evidence of a statistically significant effect of our instruments on ICT capital in the ONS data and again, evidence that ICT causally affects firm size, with strong positive effects on revenue and employment from the stock of ICT capital. For productivity, we find a positive correlation in the OLS estimates but that this is no longer significant when correcting for endogeneity bias. This holds irrespective of the measure of productivity that we use.[7]

In our data, ICT therefore appears to be associated with increases in the scale of firms rather than their productivity. Digging deeper into the way that ICT is used by the firm we find that the firms that 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, which appears consistent with the scale effect we find.

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' 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. Our approach to this issue draws on the historical accounts of broadband enablement in the UK, and the technology of the internet itself. These insights motivate us to conduct a number of sample restrictions; closely following the predictions from the telecoms engineering literature; 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 just 20% of UK telephone exchanges.[8] 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 indicated by the parameters of the technology infrastructure. Outside of this they have no explanatory power, including for time periods in which exchanges were not yet broadband enabled.

[7] Calculation of productivity is only possible using ONS data (see later data discussion).
[8] Concerns over instrument validity are a further reason for our application of the instrument to just a single year, 2000.

Our use of detailed types of ICT ensures this paper most closely fits with the more recent strand of the literature questioning the treatment of ICT as a composite capital. This relaxes the restriction that its effects are homogenous across different technologies, as had been imposed in the literature (Draca et al, 2006; Cardona et al., 2013).[9] Prominent works here include Garicano and Heaton (2010), Garicano and Rossi-Hansberg (2006) and Bloom et al. (2013). See also Maliranta and Rouvinen (2006) and Capelli (2010) for empirical approaches on this issue and Bertschek et al. (2015) for a recent review of broadband literature.

We are also motivated by the ICT literature to suggest suitable instruments (Abramovsky and Griffith, 2006; Grimes et al., 2012; Czernich, 2014; Akerman et al. 2015; Haller and Lyons, 2015; Fabling and Grimes, 2016). We build on existing studies to examine availability of ICT infrastructure at the level of the firm, arguably improving the reliability of the estimates that we derive. 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 using the timing of ICT adoption as an instrument. 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. More recently Fabling and Grimes (2016) use the rollout of ultrafast broadband to schools in New Zealand, exploiting the fact that these schools were enabled for different political and policy motives. Our approach improves on this by having the date that each telephone exchange becomes ADSL enabled alongside information on the telephone exchange that each firm is connected to. We are also able to show that instruments based on cross-time changes in enablement of all telephone exchanges do not pass tests for its validity. This occurs because ADSL enablement did not occur randomly in the UK and there are unobservable (to us) determinants of ADSL enablement and firm level outcomes[10].

[9] 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) on U.S. firms while Greenan and Mairesse (1996), Greenan et al (2001), Forth & Mason (2003), Bloom et al. (2005, 2012) on European firms.

[10] We also build on DeStefano et al. (2014) who use a cluster of rural and sub-urban telephone exchanges in the North East of England that were enabled for ADSL earlier than neighbouring exchanges to study the effects of broadband use on

In using distance as an instrument we are closest to Bloom et al. (2013), Czernich (2014) and Fabling and Grimes (2016), albeit for very different types of distance to those of the cable distance we use. Bloom et al. (2013) use distance of a firm from the headquarters of SAP, the market leader in ERP software technology, to predict ERP use. Fabling and Grimes (2016) use a variety of measures based on the distance of a firm to the local primary or secondary school, where these schools were the target of a broadband rollout programme in New Zealand. Our instruments capture the strength of the broadband connection as it declines with the cable distance to the telephone exchange, where the siting of these exchanges has no bearing on the location of schools in the UK. In this regard we build more closely on Czernich (2014) who also uses a measure of local loop distance for German municipalities. While the logic for why our instrument has predictive power is the same, we are able to improve on the author's approach by constructing the local loop distance for each firm, rather than as a measure averaged across many firms within a municipality. Arguably, this is likely to improve the precision of the estimates that we derive.

The remainder of the paper is organised as follows. Section 2 describes our firm-level data and empirical methodology. Section 3 discusses the details of the UK rollout of ADSL and the construction and plausibility of our instruments. Section 4 presents our main estimation results, first using more detailed information from the CiTDB data, and then a robustness check using the ONS data. We also consider heterogeneity in the effects of ICT and complementary investments in this section. We use section 5 to draw conclusions from the paper.

2.0 Data, Empirical Specification and ADSL Rollout

2.1 Data

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

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service sector firms. We differ in our use of different types of ICT, include both manufacturing and service sector firms and, because of restrictions we place on the instrument, on firms in urban areas.

Our primary source of ICT data is the Ci Technology Database (CiTDB), produced by the Aberdeen Group (formally known as Harte Hanks). Firms are surveyed annually, providing detailed information on heterogeneous ICT capital, such as the number of computers of various types, various forms of software like business management systems, e-commerce applications, as well as 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, and there postcode. 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).[11]

The hardware and software examined in this paper are guided by the computing literature which discusses the types of ICT firms use 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 of Pentium PCs. To remove differences in size we express these relative to employment within the firm.[12] 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, including e-commerce. All firms who use ERPs also have e-commerce software, for this reason we combine them into a single measure of the use of ERPs and E-commerce. Finally, we also construct a measure for whether the firm has a Virtual Private Network (VPN), which used the internet as a tool to extend the intranet of a firm.

[11] 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 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%.

[12] 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 divide ICT hardware by employment.

As a robustness check, we compare the results for these disaggregated types of ICT to those using homogeneous ICT capital made available is the Annual Business Inquiry (ABI) provided by the Office for National Statistics (ONS) in the UK. This data covers all industrial sectors (aside from finance) from 1997 onwards. We follow the STATA-code provided by Bloom et al. (2012) and construct ICT capital for each firm from IT expenditure data collected by the ONS using a perpetual investment method.[13] This avoids the lumpiness of the various micro-level expenditure data and is more directly comparable with the CiTDB capital stock information. Again we scale this variable by employment to provide a measure of ICT intensity of the firm.

From the CiTDB data we measure performance by the sales revenue of the firm. We are able to extend this list when using the ONS data and here we use employment, revenues, as well as TFP to measure firm performance. TFP is estimated using the Ackerberg, Caves and Frazer (ACF) estimator, that deals with the functional dependence problems that arise from the Olley-Pakes and Levinsohn-Petrin (Van Beveren, 2012).[14] To remove the effect of outliers we drop the top and bottom 1% of the distribution. Given the different sampling frames of the CiTDB and ONS data it has not proved possible to merge these data.

To construct our instruments, we draw on 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 *PointTopic* data is available at the postcode level, for which there are 1.66 million in the UK.[15] 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. The *OFCOM* data provides the date of ADSL enablement for each telephone exchange in the UK. We merge the OFCOM and PointTopic data using common exchange

[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] We also constructed a TFP estimate for each 2-digit industry, thereby allowing the elasticities on capital, labour etc. to differ across industries. The results were unchanged from the use of this alternative estimate of TFP. The results are similar using Levinsohn-Petrin and Olly-Pakes estimators.
[15] Postcodes in the UK typically relate to 14 domestic houses or a medium sized firm.

identifiers (exchange codes) and then with the micro data from CiTDB and ONS 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 CiTDB data contains 58,283 firm-year observations for which employment and revenue information is available. Restricting the sample to the year 2000 leaves us with 4,871 observations. We provide summary statistics for the main variables from the CiTDB 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 Table 1 (labelled Estimation Sample) we find 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. The average revenue per firm is £39.4 million. Summary statistics for the ONS are reported within Appendix Table A1.

These various measures of ICT are positively correlated with firm performance in the expected manner (see Table A2 in the Appendix). The different types of software and hardware are correlated with firm revenues from the CiTDB data and ICT capital stock constructed from ONS data is positively and significantly correlated with firm output, employment and productivity.

Table 1: Firm Summary Statistics for year 2000 from the CiTDB database

CiTDB Data	**Estimation Sample (obs. 4,871)**		**Enabled Exchanges (obs. 3,308)**		**Non-enabled exchanges (obs. 1,563)**		**Non-enabled exchanges (obs. 1,898)**	
Exchange Enabled in Wave	**Wave One**		**Wave One**		**Wave One**		**Wave Two & Three**	
Year	**2000**		**2000**		**2000**		**2000**	
Variable	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*
ERP & Ecom. Software	0.108	0.311	0.102	0.303	0.121	0.326	0.124	0.330
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
Employment (Log)	4.837	1.107	4.810	1.129	4.895	1.057	4.995	1.042

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.

2.2 Empirical Specification

To capture the relationship between ICT and firm level outcomes we adopt the regression model set out in equation (1), where Y refers to revenue for firm i. When using the ONS data we use output, employment and TFP to measure firm performance. ict is measured by various components of ICT hardware and software when using the CiTDB data and by the ICT capital stock when using the ONS data. To control for differences in the size of the firm we scale the ICT hardware and capital stock data by the number of employees. 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 include employment, multi-plant status and the local loop distance. When using the ONS data we add the age of the firm as well as foreign ownership.[16] α, β and γ are parameters to be estimated and μ_i is the error term.

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

We are interested in particular in the effects of ICT on the firm, reflected in the model by β. 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. The naïve OLS estimates are likely to be biased downwards if there are adjustment costs to the adoption of technologies. Indeed, there now exists a large literature that explores the relationship

[16] The results remain unchanged when we focus only on single-plant firms. These regressions are available from the authors on request.

between ICT, firm performance and complementary investments as well as their associated adjustment costs (see for example Anderson et al. 2000; Brynjolfsson and Hitt, 2000; Bresnahan et al., 2002; Brynjolfsson et al. 2002; Leung, 2004; 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.[17] To be considered valid requires that our instrument has no direct effect on our firm performance measures independent of its relationship with ICT. We present evidence consistent with this assumption in the next sections of the paper.

3.0 Construction of Instrumental Variables and Tests for Validity

3.1 UK Rollout of ADSL Broadband and Cable Distance

Our instruments are derived from postcode-level differences in access to ADSL broadband infrastructure. The sample period we consider coincides with the rollout of ADSL broadband by BT, which generates spatial variation in the speed of internet that firms can access.[18] ADSL required that the local exchange be equipped with DSL capability and the end-user premises were fitted with a modem, a micro-filter device and ADSL splitter (Guardian, 2002).[19] The large number of telephone exchanges combined with a limited number of BT engineers meant that ADSL was rolled out across exchanges over a time period stretching from November 1999 to September 2007. Broadband services were offered to customers connected to ADSL enabled exchanges from 2000 onwards. BT gave relatively short notice of the start of the programme; as of February 1999, BT still had not informed the public of

[17] A number of alternative approaches have been considered within the existing literature (see the review by Cardona et al., 2013). These include the addition of firm fixed effects and lagged dependent variables (Grimes et al., 2012). The use of a cross-section prevents us from taking the former approach, while in some robustness tests we have added a lagged dependent variable.

[18] 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 for 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).

[19] BT insisted on using its own engineers for line modification and equipment installation (BBC, 1999).

any plans for broadband service and BT only announced exchanges to be enabled in the forthcoming 6 months (BBC, 1999).[20] This would tend to suggest that anticipation effects are unlikely to be present. In Figure 1 to Figure 4 we show the location of enabled exchanges in the UK for the years 1999, 2001, 2003 and 2005.

[20] 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).

Figure 1: Location of BT ADSL Enabled Exchanges by 1999

Figure 2: Location of BT ADSL Enabled Exchanges by 2001

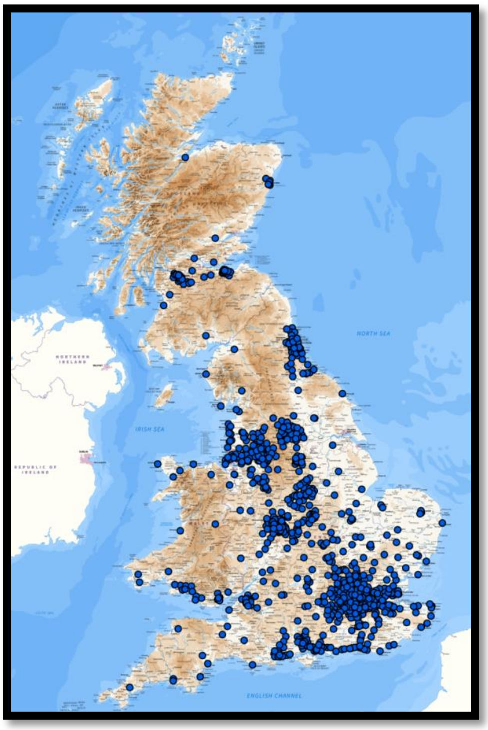


Figure 3: Location of BT ADSL Enabled Exchanges by 2003

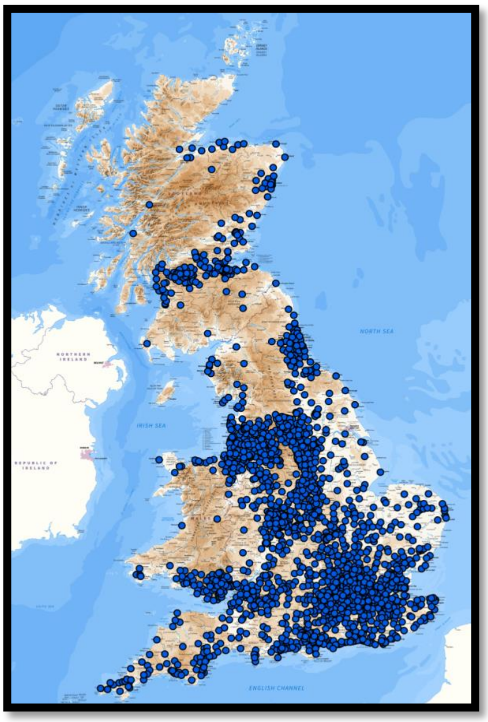
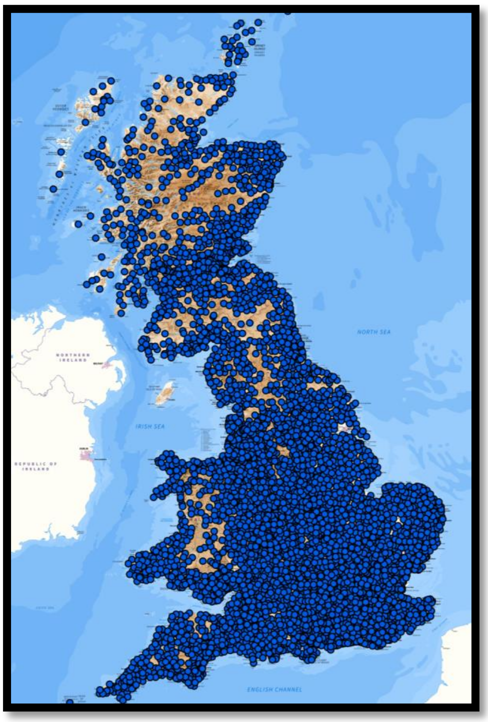


Figure 4: Location of BT ADSL Enabled Exchanges by 2005



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 to maximise their 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 using the entire roll-out programme. 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) (see Figure 5). The first break, announced in November 2001 occurred as a consequence of the poor take-up of broadband internet by households.[21]

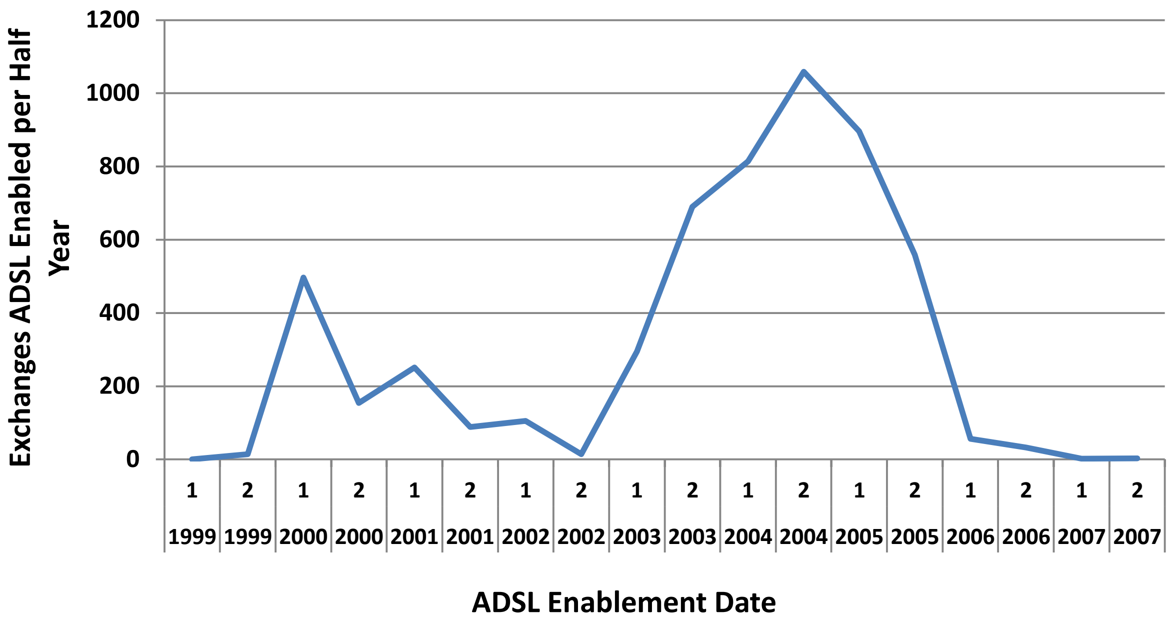
In wave two BT resumed the roll-out with a demand-driven registration system which we describe in more detail in the Appendix. The demand-driven system of wave two makes it highly unlikely that the timing of ADSL enablement within this wave is exogenous, leading to our focus upon firms connected to wave one exchanges (see below). In 2005 (announced April 2004), BT scrapped this and pursued a policy of "universal" access, wave three, meaning a target of access to 99.6% of homes and businesses. We show that within wave two the timing 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 Table A4 in the Appendix).

In the baseline empirical analysis we adopt a cautious approach and focus only on firm observations attached to exchanges enabled in wave one; representing 20% of the UK exchanges, 63% of UK commercial premises and 60% of households. The justification for this is based on the context of the rollout discussed above. Enablement in wave two is demand

[21] Poor take up by households was blamed on ADSL connections being expensive, wholesale prices were £40-£150 per month. At the start of the program such a break was unplanned and therefore unlikely to have been anticipated by customers (households and businesses).

driven and thus potentially endogenous. In addition, firms attached to exchanges enabled after wave one are typically smaller firms, in less urban locations and are thus not an appropriate counterfactual to those in wave one.[22] We return to this point in Section 3.3.

Figure 5: Telephone Exchange Enabled for ADSL by BT per Half Year



Notes: Data are from OFCOM. The time periods relate to the first (1) and second (2) half of the relevant year.

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 (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 inside the customer's premises). Engineering tests showed that when measured in the absence of these additional factors, connection speeds deteriorated for cable lengths beyond 2,000 metres (see Figure A2 in the Appendix).

Importantly, distance from the local telephone exchange had a less important impact on the quality of telephone connections, suggesting that firms' location decision would not be affected by attempts to improve access to this technology. Through the use of a technology called loading coils, the quality of telephone calls could be maintained using copper wiring

[22] See Figure A3 on the relationship (log) number of households and business connected to an exchange against the date of its enablement

for distances up to 16 kilometres and there was no deterioration in quality until 5 kilometres (Macassey 1985). Loading coils are not compatible with ADSL.

3.2 Construction of Instrumental Variables

We identify two potential instruments to explain cross-section variation in firm's ICT capital. The first instrument is constructed only for firms attached to exchanges enabled in wave one, the part of the rollout that is plausibly exogenous (1999-2002). Here we anticipate that the returns to ICT investment are higher for firms connected to an enabled exchange such that they are likely to have greater ICT. 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; is coded as 1 if the exchange that the firm is attached to was enabled by the end of 2000; and is set to missing if the exchange the firm is attached to was enabled in wave two three.[23] 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).

The second instrument uses the length of the local loop made available from the *Point-Topic* database. Here we anticipate that because communication speeds are slower, firms that are further from the telephone exchange are likely to invest in less ICT.[24] In Table 1 the mean (median) cable distance from the telephone exchange is 3.24 (3.18) kilometres with a standard deviation of 1.33 kilometres (see Table 1). Given that firm distance at the 90th (99th) percentile is just 4.98 (5.99) kilometres indicates that we are using relatively small geographic distances within the analysis. The strong negative effects of cable distance on broadband speed were present for a relatively short time period. From June 2001 BT implemented a technology called Rate Adaptive Digital Subscriber Line (RADSL) that reduced the effects of cable length on broadband speeds (further discussion of RADSL is within the Appendix section 6.1).[25] This further underpins our decision to focus on the year 2000.

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[23] Firms connected to exchanges enabled in later waves exhibit significantly different characteristics, so we do not include non-enabled wave two and three exchanges as a counterfactual. Also see Table A4 in Appendix.

[24] We provide further information on local loop distances across firms in Table A4 in the Appendix.

[25] This was managed by adjusting the up-load speed.

In the main regression sample we have 4,871 firm observations. Of these, 3,308 were attached to telephone exchanges enabled in 2000 and 1,563 were attached to exchanges non-enabled in 2000 (but which were enabled before the end of 2002)[26]. According to the information presented in Table 1, in the regression sample 68% of firms are attached to enabled exchanges in the CiTDB data.

3.3 Correlation between the Instruments and ICT

Table 2 provides evidence on the power of our instruments to explain variation in the level of ICT capital across firms. Regressions 2.1 to 2.5 use 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.

We find differences in terms of the power of the instruments to explain variation in ICT use across firms; our instruments seem to strongly predict measures of hardware, but not software. The enablement of the local telephone exchange and the local loop distance of the firm from the exchange are significantly correlated the number of PCs per employee (regressions 2.2 to 2.4 in Table 2). As expected ICT increases with enablement of the local telephone exchange and decreases with the cable distance between the firm and the telephone exchange. They are not significantly correlated with ERP or e-commerce software (regressions 2.1) or the use of a VPN (regression 2.5). These results are consistent with Varian et al (2002) who also finds that users of broadband invest more heavily in ICT. In later robustness analyses we show that our instruments also predict ICT capital stock per employee using ONS data.

[26] The CiTDB contains a total of 6,769 plants in 2000, 1,898 of which are attached to exchanges enabled in wave three.

Table 2: First Stage Regressions of the Instruments on ICT: Enablement and Distance

Regression No.	2.1	2.2	2.3	2.4	2.5
Sample	**Year: 2000; Exchanges Enabled in Wave 1 (1999-2002)**				
ICT Variable	**ERP & E.comm software**	**PCs/ Emp.**	**Portable PCs/ Emp.**	**Pentium PCs/ Emp.**	**VPN**
ADSL Enabled	-0.002	0.513***	0.664***	0.502***	0.002
	(0.03)	(0.07)	(0.12)	(0.09)	(0.01)
*Logged Local Loop dist.*ADSL Enabled*	-0.011	-0.277***	-0.358***	-0.283***	-0.012
	(0.02)	(0.03)	(0.10)	(0.07)	(0.01)
Firm Controls	✓	✓	✓	✓	✓
R^2	0.01	0.12	0.08	0.10	0.01
Observations	4,866	4,866	3,307	4,702	4,866

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 log of the cable distance between the firm and the telephone exchange. Regressions use data from the CiTDB database and include employment, multiplant status and local loop cable distance 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.

The negative relationship between ICT and cable distance to the local telephone exchange remains when we restrict the sample to firms attached to exchanges enabled by the end of 2000 (see 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 intensity was lower the further the firm was located from the telephone exchange. Again, there is no significant relationship with the measures of ERP software or use of VPNs. Of interest, comparing across the regressions for the different types of PCs in regressions 3.2, 3.3 and 3.4, the results suggest that portable PCs are most strongly affected by ADSL enablement and cable distance.

How large are the effects? For the number of PCs per employees, according to the estimates from regression 2.3, being inside the region of an enabled exchange increases this by approximately one computer for every 3 employees (the ratio increases by 0.311), while regression 2.4 shows the number of portable PCs increases by close to one for every 5 employees (the ratio increases by 0.210).

Table 3: First Stage Regressions of the Instruments on ICT: Distance Only

Regression No.	3.1	3.2	3.3	3.4	3.5
Sample	Year: 2000; Exchanges Enabled by End of 2000				
ICT Variable	**ERP & E.comm software**	**PCs/ Emp.**	**Portable PCs/ Emp.**	**Pentium PCs/ Emp.**	**VPN**
*Logged Local Loop dist.*ADSL Enabled*	0.012 (0.01)	-0.290*** (0.03)	-0.356*** (0.05)	-0.270*** (0.04)	-0.010 (0.01)
Firm Controls	✓	✓	✓	✓	✓
R^2	0.01	0.08	0.10	0.07	0.01
Observations	3,304	3,304	2,266	3,197	3,304

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. Regressions use data from the CiTDB database. Local loop distance refers to the log of the cable distance between the firm and the telephone exchange. Regressions include employment and multiplant status 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.

Given our inability to explain variation in ERP and e-commerce software or VPN use across firms due to our instruments, 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. If the timing of software investments follows earlier hardware investments, then Table 2 and 3 may miss these later software effects. Initial support for this view can be found from these variables across time. According to the CiTDB data in 2000 16% of firms used ERP and 6% VPN. By 2002 these have increased to 31% for ERP and 36% for VPN, while by 2004 they are 37% and 50% respectively. In contrast the PC intensity of the firm is much more stable.[27]

So far, we have modelled the local loop as having a (log) linear effect on ICT. Engineering tests on the effects of distance on broadband speed (of the type reported in Figure A2 in the Appendix) suggests a more complicated relationship, albeit one where additional unobserved factors such as the thickness of the copper cabling, quality of joints etc. may also play a role. The engineering tests indicate a weak effect of distance on broadband speeds up to around 2km and then a stronger effect between 2km and 3.5km. Beyond 3.5km ADSL speeds are similar to those available from dial-up technologies. In the first half

[27] We consider this more formally using a regression of the use of ERP or VPN against the number of PCs (Appendix Table A10).

of Table 4 we explore this by using the linear and squared versions of the local loop distance.[28]

We find evidence consistent with the engineering tests. We find in Table 4 that a firm attached to an ADSL enabled exchange in 2000 used more PCs per employee and that this effect declined with the length of the cable between the firm and the local telephone exchange at a decreasing rate (the squared term is positive). According to the results from regression 4.1 the effect of distance is at its minimum at 4.1km, which is reasonably close to that suggested by the engineering tests. In regressions 4.2 and 4.3 the minimum is reached at 4.1km and 4.2km, respectively.

In the second half of the table we use these engineering tests to suggest the form of the non-linearity and place firms attached to an enabled telephone exchange by the end of 2000 into one of three distance bins (<2.0km; 2.0-3.5km; >3.5km). Here we expect the coefficients to be positive, as they also capture the effect of enablement of the exchange, but to step downwards in size as the local loop distance increases.

Again, we find that this is a strong feature of the data. In regressions 4.4 to 4.6 the number of PCs per employee is greatest for firms a short distance from the exchange. In regression 4.4 this effect then halves for firms between 2.0 and 3.5km from the exchange and halves again for firms greater than 3.5km.

[28] We also explored whether higher-order distance terms had any explanatory power. We found in no cases that this held and so we report only results using a linear and squared terms.

Table 4: Non-linear Effect of Instruments on ICT

Regression No.	4.1	4.2	4.3	4.4	4.5	4.6
Sample	Year: 2000; Telephone Exchanges Enabled in Wave 1 (1999-2002)					
ICT Variable	PCs/ Emp.	Portable PCs/ Emp.	Pentium PCs/ Emp.	PCs/ Emp.	Portable PCs/ Emp.	Pentium PCs/ Emp.
ADSL Enabled Exchange	0.985***	1.293***	0.914***			
	(0.130)	(0.200)	(0.150)			
*Local Loop dist. *ADSL Enabled*	-0.442***	-0.584***	-0.402***			
	(0.070)	(0.110)	(0.080)			
*Sq(Local Loop dist.) *ADSL Enabled*	0.054***	0.072***	0.048***			
	(0.010)	(0.010)	(0.010)			
*ADSL Enabled Exch. *Dist<2km*				0.403***	0.546***	0.391***
				(0.050)	(0.090)	(0.060)
*ADSL Enabled Exch. *2km>Dist<3.5km*				0.204***	0.225***	0.166***
				(0.030)	(0.060)	(0.040)
*ADSL Enabled Exch. *Dist>3.5km*				0.121***	0.180***	0.116***
				(0.040)	(0.060)	(0.040)
Firm controls	✓	✓	✓	✓	✓	✓
R^2	0.10	0.13	0.08	0.09	0.12	0.08
Observations	4,866	3,307	4,722	4,866	3,307	4,722

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 log of the cable distance between the firm and the telephone exchange. Regressions use data from the CiTDB database. Regressions include employment, multiplant status and local loop cable distance as controls. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

Thus far our approach to use instruments based on the ADSL rollout period has been cautious and we have only included firms attached to exchanges in wave 1 of the programme. The discussion of the ADSL rollout above would indicate a need to additional geographic controls when including firm attached to exchanges enabled in waves 2 and 3. We perform this exercise in Table A5 in the Appendix where we include firms in all rollout waves and add to the regression regional dummy variables. As shown by the first three regression in the table, the instruments retain their expected relationship with PC capital per employee and pass the over-identification test. This does not hold when we exclude the regional dummies in the next three regressions, where the over-identification test fails.[29] As the results for the main regression sample are not sensitive to the inclusion of regional dummies we retain its use in the rest of the paper.

[29] We also find that it fails if we use data for all time periods (i.e. we no longer restrict the sample to exchanges enabled in 2000 – results are available upon request).

3.4 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. The instruments 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. 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 each of these points.

As discussed above and illustrated in the Appendix (Figure A3), 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.[30] 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

[30] As shown at the end of the previous section, this concern appeared to hold some merit for a sample including firms attached to exchanges enabled under waves 1 to 3.

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 (see Appendix Sections 6.3-6.5 for a more detailed explanation). In this section we begin by establishing that the correlation between ADSL enablement and local loop distances with ICT are not explained the inclusion of agglomeration control variables such as the number of households and business addresses attached to a telephone exchange. Our results are robust to the addition of these controls. Second, we show that the introduction of RADSL technology from 2001 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. Within these regressions we are able to show that, as expected, the relationship between cable distance and ICT weakens over time.

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. This is indeed what we find in the data. 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 in firm characteristics.[31]

The next set of tests for instrument validity focuses on the possibility that the standard errors are being inflated by unobserved influences such as the use of substitute technologies. The rollout of ADSL provided broadband access for small and medium firms in particular, whilst large firms had the pre-existing option of (expensive) leased line connections (see Appendix section 6.2). If the sample includes large firms with leased line

[31] 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.

access, this would tend to weaken the power of our instruments. We undertake three additional validity tests to examine this. Firstly, the CiTDB data contains partial information on leased line connections.[32] As expected we find our instruments have no statistically significant predictive power for those firms using leased lines (see regression 1 of Table 5). Secondly, we exclude large firms (firms with more than 250 employees), representing around a quarter of the firms in our sample, and repeat the first stage estimation with only small firms remaining. We find the instruments remain strong predictors of hardware measures of ICT for smaller firms (see regressions 2 to 3). Finally, we repeat the baseline IV estimation excluding firms with leased lines (see Table A11 in the Appendix) and find very similar results to the main specification. Our identification therefore does not appear to be affected by larger firms or the presence of pre-existing alternative technologies, such as leased lines.

Table 5: First Stage and Leased-Lines or Small Firm Restricted Sample

Regression No.	**5.1**	**5.2**	**5.3**	**5.4**
	2000, Wave 1	**2000, Wave 1, small firms**		
ICT Variable	*Leased Line Internet*	*PCs per employee*	*Portable PCs per employee*	*Pentium PCs per employee*
First Stage				
ADSL Enabled	0.037	0.435***	0.503***	0.384***
	(0.03)	(0.08)	(0.13)	(0.10)
*Logged Local Loop dist.*ADSL Enabled*	-0.020	-0.224***	-0.261**	-0.205***
	(0.03)	(0.07)	(0.10)	(0.08)
Firm Controls	✓	✓	✓	✓
Observations	4,871	3,701	2,435	3,581

Notes: OLS regressions using firm-level data for the year 2000 using CiTDB data. 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 log of the cable distance between the firm and the telephone exchange. Regression 5.1 uses a measure of firm leased-line internet access – reflected as firms having a Wide Area Network with a text description referring to leased lines (this is the only proxy of leased line access available in our data). Regressions 5.2 to 5.4 repeat the baseline first stage estimations of 2.2 to 2.4 (Table 2) but restricting to firms with fewer than 250 employees. Regressions include employment, multiplant status and local loop cable distance as controls. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

4.0 Instrumental Variable Results

4.1 Main Results

[32] We use firm adoption of Wide Area Networks that refer to leased lines in their text descriptions.

In Table 6 and Table 7 we report the results from our IV regressions. Table 6 uses CiTDB data and Table 7 presents robustness analyses using ONS data. In Table 6 we consider the effect of the number of PCs, portable PCs and Pentium PCs per employee on firm revenues. In Table 7 we report results for the effect of ICT capital per employee on output, employment, TFP and labour costs. 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 baseline results in Table 6.

As already discussed in the previous section, the instruments are highly significant and have the expected signs in the first-stage regressions, while the diagnostic statistics also reported in Table 6 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 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) under the Stock-Yogo test. For one instrument the relevant statistics is 6.66 (5.53). Here we find that the Kleibergen-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.

In all cases we find a significant positive effect of ICT hardware 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. They also continue to hold when we replace the log local loop distance variable with the non-linear versions from the previous section. These results are reported in Table A12 in the Appendix.

For robustness, we turn to the ONS data, which has only a homogenous measure of ICT, but additional measures of firm performance. There is mixed evidence that ICT matters for firm performance however. The first stage is weaker when using this aggregate ICT measure, particularly so when relying on the local loop distance as a single instrument but continue to be above the thresholds for weak instruments. This weakening of the power of the instrument for this composite ICT variable is consistent with the mix of significance levels found when using differing types of ICT in the CiTDB data in Section 2.5.

From the second stage regressions our results indicate a strong significant effect of ICT capital on firm employment and revenues but not TFP.[33] Correcting for the endogeneity bias between ICT capital and TFP indicates that there is no causal effect between these variables.[34] 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).[35] It also holds if we alter the measure of TFP from the Ackerberg, Caves and Frazer (ACF) measure that is our benchmark, with one calculated using the Levisohn-Petrin (LP) or Olley-Pakes (OP) methodology (regressions 7.7 and 7.8 respectively). In Table A13 in the Appendix we also 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.

Throughout the two tables the estimated effects on employment and revenues are large. IV estimates that are greater than the OLS estimates are not atypical 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 was 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

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[33] 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.

[34] This conclusion is unchanged if we replace the level of TFP with its growth rate.

[35] 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.

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).[36] 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 the previous section of the paper would suggest that the former is the more likely in our case. This is important as it indicates that these results might generalise to the population of firms at large. We consider the possibility that the internet had stronger effects on smaller firms and led to complementary software and human capital investments further below.

The sizes of the coefficients are somewhat larger for revenue in Table 6, than for output in Table 7. There are several possible reasons for this. Firstly, the ONS ICT capital measure refers to a total, homogenous measure and so corresponds to an average of the estimated effects across each different heterogeneous type of ICT capital. In the estimates on revenue, we report only the 3 measures of PCs from the CiTDB data for which the instruments have strong predictive power. But we found no predictive power for other types of ICT capital, such as ERPs or VPN software (Table 3).

Secondly, the data on total ICT capital and specific ICTs come from two different datasets (ONS vs CiTDB) with somewhat different characteristics of firms. For example, the average employment in the CiTDB data is smaller than ONS data (see Table 1 and Table A1 estimation samples). As we note in the data section, it is unfortunately not possible to merge the two for direct comparison. However, if the estimated effects of ICTs are larger for smaller firms, this might also explain some of the differences between the ONS and CiTDB results. We examine the potential heterogeneity of the effects of ICT in the next table.

[36] 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.

Table 6: Baseline IV Regressions using CiTDB (Year: 2000)

Regression No.	**6.1**	**6.2**	**6.3**	**6.4**	**6.5**	**6.6**
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	1.365***	1.744***				
	(0.245)	(0.283)				
Portable PCs per employee			1.012***	1.200***		
			(0.208)	(0.232)		
Pentium PCs per employee					1.505***	1.917***
					(0.291)	(0.349)
First Stage						
ADSL Enabled Exchange	0.513***		0.664***		0.502***	
	(0.074)		(0.119)		(0.085)	
*Logged Local Loop dist.*ADSL Enabled*	-0.277***	-0.290***	-0.358***	-0.356***	-0.283***	-0.270***
	(0.060)	(0.031)	(0.096)	(0.050)	(0.068)	(0.036)
Firm Controls	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	35.481	83.51	22.27	49.342	23.726	54.433
Kleibergen-Paap F Test	35.436	86.46	23.715	50.041	23.357	54.777
Hansen J Statistic	0.292		0.317		0.438	
Observations	4,866	3,304	3,307	2,266	4,722	3,197

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database. 'All wave 1 exchanges' 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) and multiplant status as controls. Regressions 6.1, 6.3 and 6.5 additionally include local loop cable distance. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

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

Regression No.	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8
Dependent Variable	**Output**		**Employment**		**ACF TFP**		**LP TFP**	**OP TFP**
Telephone Exchanges	**All Wave 1**	**Enabled By 2000**	**All Wave 1**	**Enabled By 2000**	**All Wave 1**	**Enabled By 2000**	**Enabled By 2000**	**Enabled By 2000**
Second Stage								
ICT Capital Stock	0.856***	0.699***	0.878***	0.722***	0.081	-0.144	-0.080	-0.326
	(0.21)	(0.31)	(0.23)	(0.35)	(0.05)	(0.16)	(0.15)	(0.57)
First Stage								
ADSL Enabled Exchange	0.528***		0.541***		0.528***			
	(0.13)		(0.13)		(0.13)			
*Log Local Loop dist.*ADSL Enab.*	-0.251***	-0.194***	-0.256***	-0.195***	-0.251***	-0.194***	-0.194***	-0.194***
	(0.11)	(0.07)	(0.11)	(0.07)	(0.11)	(0.07)	(0.07)	(0.07)
Firm Controls	✓	✓	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	10.794	7.725	11.432	7.845	10.794	7.725	7.725	7.725
Kleibergen-Paap F Test	10.985	8.131	11.620	8.244	10.985	8.131	8.131	8.131
Hansen J Statistic	0.532		0.532		0.532			
Observations	3,268	2,242	3,268	2,242	3,268	2,242	2,242	2,242

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 employment, age, ownership and multiplant status as control variables except regression 7.3 and 7.4 which do not control for employment. Regressions 7.1, 7.3 and 7.5 additionally include local loop cable distance. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

4.2 Heterogeneity

It is unclear a priori whether the impact of ICT should be greater for smaller or larger firms. On the one hand, ICT can present new business models, that smaller firms may be more able to take advantage of, without incurring many of the sunk restructuring costs. On the other hand, ICT requires complementary investments in skills and organisational capital (see next section), many of these are sunk and so only feasible for larger firms.

We assess potential heterogeneity by firm size by repeating the baseline regressions from Table 6, but interacting both the ICT treatment and the two instruments with a small firm dummy - reflecting employment less than 250. In the second stage, the coefficient on the (non-interacted) ICT term shows the estimated impact of ICT on revenues for larger firms, and the ICT interaction term then shows the additional effect of ICTs on revenue for small firms.

The first stage identification is somewhat weaker than the baseline, as is expected by doubling the number of endogeneous variables through the interaction, but remains reasonably strong with F statistics in the range of 9 to 33 (see Table 8). Note that for brevity we have moved the first-stage estimates to section 6.9 in the Appendix. In the second stage, we find a substantial positive impact of ICT on the revenues of both smaller and larger firms. However, we find a larger impact of ICT on the scale of small firms, the interaction term is positive and significant for PCs, Pentium PCs or Portable PCs (all with the exception of regression 1). Also the estimated coefficients for larger firms (the non-interacted variables) are much closer to that of total ICT capital stock per employee using the ONS data (7.1 and 7.2).

In terms of firm sector, ICT forms a crucial role in modern manufacturing, which is increasingly an interconnected activity with firms using the inputs crossing borders and firms many times along the way to a finished product. Whilst some services continue to rely heavily on face-to-face contact and networks of customers or potential employees, ICT has enabled firms to trade business service activities (Kneller and Timmis, 2016).

Table 8: IV Regressions using CiTDB (Year: 2000) – Heterogeneity by Firm Size

Regression No.	**8.1**	**8.2**	**8.3**	**8.4**	**8.5**	**8.6**
Dependent Variable				**Revenue**		
Second Stage						
PCs per employee	0.893***	0.981***				
	(0.31)	(0.37)				
PCs per employee - small firm	0.601	1.150**				
	(0.37)	(0.53)				
Portable PCs per Employee			0.494***	0.503**		
			(0.19)	(0.23)		
Portable PCs per Employee – small firm			0.794**	1.200**		
			(0.31)	(0.48)		
Pentium PCs per Employee					0.902***	0.970**
					(0.32)	(0.40)
Pentium PCs per Employee – small firm					0.894**	1.494**
					(0.44)	(0.65)
Firm Controls	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	16.496	32.579	8.942	14.991	9.711	19.514
Kleibergen-Paap F Test	15.605	26.216	8.804	11.582	9.522	15.636
Hansen J Statistic	0.207		0.390		0.338	
Observations	4,866	3,304	3,307	2,266	4,722	3,197

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database for wave 1 exchanges - those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). Local loop distance refers to the cable distance between the firm and the telephone exchange. All regression include employment, multiplant status and local loop cable distance as controls. First stage results for each of the endogenous variables are relegated to section 6.9 in the Appendix for brevity. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

Again, we assess potential heterogeneity by firm sector by repeating the baseline regressions from Table 6, but interacting both the ICT treatment and the two instruments with a service sector. In the second stage, the coefficient on the (non-interacted) ICT term shows the estimated impact of ICT on revenues for services firms, and the ICT interaction term then shows the additional effect of ICTs on revenue for services firms.

As before first stage identification is somewhat weaker than the baseline as expected, but remains reasonably strong with F statistics in the range of 8 to 35 (see Table 8, and section 6.10 in the Appendix for the first stage estimates). In the second stage, we find a substantial positive impact of ICT on the revenues of both services and manufacturing firms. However, there is some evidence of heterogeneity across sectors, but it depends upon the type of ICT capital measure. For instance, there is no statistically significant difference in the effect of portable PCs on the revenue of services and manufacturing firms. However, for PCs or Pentium PCs we find weaker effects for services compared to manufacturing firms.

Table 9: IV Regressions using CiTDB (Year: 2000) – Heterogeneity by Firm Sector

Regression No.	**9.1**	**9.2**	**9.3**	**9.4**	**9.5**	**9.6**
Dependent Variable	**Revenue**					
Second Stage						
PCs per employee	1.413***	1.814***				
	(0.23)	(0.26)				
PCs per employee	-0.616***	-0.490***				
- services	(0.16)	(0.18)				
Portable PCs per			1.022***	1.244***		
Employee			(0.23)	(0.28)		
Portable PCs per			0.025	0.050		
Employee – services			(0.05)	(0.06)		
Pentium PCs per					1.421***	1.890***
Employee					(0.28)	(0.34)
Pentium PCs per					-0.419***	-0.329**
Employee – services					(0.11)	(0.13)
Firm Controls	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	13.956	34.682	8.259	16.602	9.243	22.474
Kleibergen-Paap F Test	14.203	31.887	9.154	15.923	9.419	21.304
Hansen J Statistic	0.242		0.529		0.405	
Observations	4,866	3,304	3,307	2,266	4,722	3,197

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database for wave 1 exchanges - those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). Local loop distance refers to the cable distance between the firm and the telephone exchange. All regression include employment, multiplant status and local loop cable distance as controls. First stage results for each of the endogenous variables are relegated to section 6.10 in the Appendix for brevity. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

4.3 Complementary Investments

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 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 10 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. From regression 10.1 there also appears to be a weakly significant relationship with having a homepage. This suggests that investment in the sales and distribution systems that lie behind the website, is complementary to the ICT capital investments we observe. 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 10: Complementary Factors IV Regressions (Year: 2000)

Regression No.	**10.1**	**10.2**	**10.3**	**10.4**
Dependent Variable	**Homepage**	**Web design software**	**IT employees/ total employment**	**Programmers/ total employment**
Second Stage				
PCs per employee	0.089*	0.011***	0.061***	0.021***
	(0.050)	(0.004)	(0.015)	(0.006)
First Stage				
ADSL Enabled Exchange	0.540***	0.540***	0.540***	0.540***
	(0.070)	(0.070)	(0.070)	(0.070)
*Logged Local Loop dist.*ADSL Enabled*	-0.298***	-0.298***	-0.299***	-0.298***
	(0.056)	(0.056)	(0.056)	(0.056)
Firm Controls	✓	✓	✓	✓
Cragg-Donald F Test	42.902	42.902	42.858	42.902
Kleibergen-Paap F Test	40.73	40.73	40.69	40.73
Hansen J Statistic	0.540	0.684	0.097	0.636
Observations	7,095	7,095	7,094	7,095

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 regressions include firm size (log employment) and multiplant status as controls (firm age and foreign ownership are not available in CiTDB data). * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

5.0 Conclusions

Recent extensions of the literature on ICT have highlighted the importance of unbundling information and communication technologies in order to understand their heterogeneous effects. In this paper we use the arrival of a new technology, broadband internet, to study the effects of ICT on the performance of UK firms in urban regions. To isolate the causal effects of the technology we employ an instrumental variable approach, using firm-specific instruments 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 broadband speeds decline quickly as this cable distance increases.

We show that being attached to an ADSL enabled exchanges increases the use of ICT and the distance from the exchange reduces this. Several additional results support a conclusion that the empirical design has validity. For example, our instruments only have predictive power for the set of firms connected to enabled exchanges and are uncorrelated with ex-ante firm characteristics.

Using these instruments we show that the effect of 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. We are also able to show that the effects are strongest when the firm makes complementary investments and has high absorptive capacity. One reason for why our results differ from previous paper may be explained by the ability of the instrument to control for endogeneity bias. Another reason may also be the fact that the types of ICTs relevant to faster broadband access are more scale enhancing (such as through PCs, websites and online advertising software) rather than technologies which may allow firms to be more efficient (like potentially ERP software and database management systems).

The following results are likely to be of interest to policy makers for several reasons. We find that both access to and expected speed (via local loop distance) matter for firm scale, and so policies aimed at deploying high-speed broadband infrastructure should consider both access and also the speed of these services. However, access to broadband alone is not a silver bullet. The paper also suggests the importance of having the necessary complementary inputs in place such as such as software and skills (such IT employees and programmers) in order to leverage the potential from ICT. That we find stronger impacts for smaller firms raises further policy challenges, since these firms often face more constraints, in terms of skills, access to finance, information and so on, which highlights the importance of improving these framework conditions to maximise the impact of broadband access policies.

The outcome of this research also suggests that policy makers may want to consider the potential heterogeneous effects of different types of ICT use on various economic outcomes. Until recently much of the policy and economic literature assumed homogenous effects from many types ICTs on economic outcomes such as productivity. Similar to Bloom et al (2015) we find that such assumptions may not be correct. Thus, while broadband and complementary investments in ICTs are important for scale, their impact on firm productivity is less evident.

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Data References

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6.0 Appendix

Table A1: Firm Summary Statistics for year 2000 from the ONS database

ONS Data	**Estimation Sample (obs. 3,289)** **Wave One**		**Enabled Exchanges (obs. 2,255)** **Wave One**		**Non-enabled exchanges (obs. 1,034)** **Wave One**		**Non-enabled exchanges (obs. 1,478)** **Wave Two & Three**	
Variable	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*
ICT Capital Stock (Log)	4.088	2.360	4.256	2.391	3.722	2.247	3.628	2.176
Gross Output (Log)	8.972	1.546	9.072	1.589	8.754	1.424	8.577	1.465
Employment (Log)	5.612	1.389	5.694	1.442	5.434	1.245	5.297	1.256
TFP (Log)	2.182	0.579	2.189	0.706	2.167	0.622	2.101	0.481
Exchange ADSL Enabled	0.686	0.464	1	0	0	0	0	0
Local Loop Length	1.010	0.548	0.981	0.524	1.073	0.592	1.130	0.504

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 A2: OLS Estimates of ICT and Firm Performance

Regression No.	1	2	3	4	5	6	7	8
Data Source			**CiTDB**				**ONS**	
Firm Performance Indicator	**Revenue**	**Revenue**	**Revenue**	**Revenue**	**Revenue**	**Gross Output**	**Employment**	**TFP**
ICT Capital Stock						0.280***	0.095***	0.121***
per employee						(0.02)	(0.01)	(0.01)
ERP & E-comm	0.723***							
Software	(0.110)							
PCs		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	4,866	4,866	3,307	4,722	4,866	3,289	3,289	3,289

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). TFP is estimated using the Ackerberg Caves and Frazer method. * p<0.10, ** p<0.05, *** p<0.01 . Robust standard errors in parentheses

6.1 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).[37] ADSL offers considerably faster internet connection speeds (up to 8mpbs) compared to narrowband (up to 64kbps). 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 Public Switched Telephone Network (PSTN). 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.

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 a 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 around 4,700 households and 250 businesses. These exchanges are geographically dispersed and are unequal distances apart. 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).

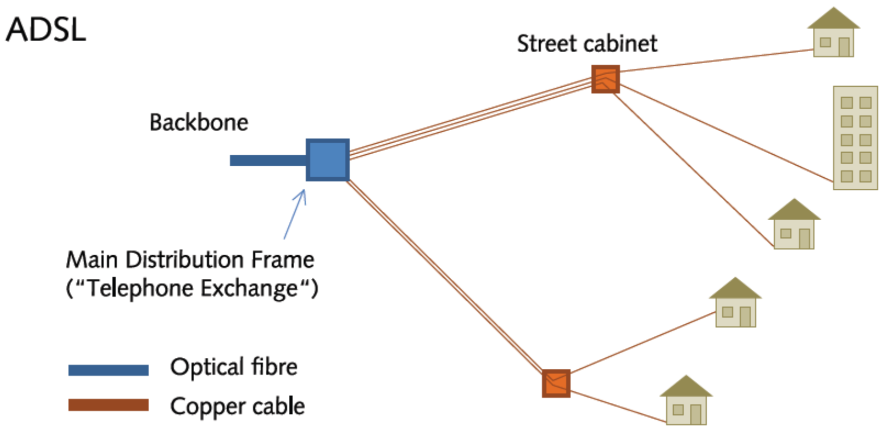
All exchanges can provide narrowband (dial-up) internet connections to customers but required some investment to deliver ADSL broadband. ADSL was used in many countries as a lower-cost solution for telecommunications companies to provide broadband internet access, in particular for its household customers.[38] 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, predominately in residential settings.[39]

[37] 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.

[38] 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.

[39] 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%).

Figure A1: Summary of UK Telephone Network



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 (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 inside the customer's 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 kilometres (see Figure A2). Accordingly, at the start of the ADSL enablement programme, BT would not connect customers with a cable-distance greater than about 3.5 kilometres. 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.[40] We use the log of the cable distance as an instrumental variable.

[40] Using fibre optic wiring to connect homes to local exchanges did not occur in the UK until 2009.

Table A3: Distribution of Local Loop Lengths by Firms

Data Source	ONS	CiTDB
Frequency	Local loop length (km.)	
1%	0.74	0.78
5%	1.04	1.11
10%	1.34	1.46
25%	2.06	2.18
50%	2.93	3.18
75%	4.12	4.31
90%	4.98	5.04
95%	5.34	5.35
99%	5.99	5.95
Mean	3.07	3.24
Standard Deviation	1.34	1.33

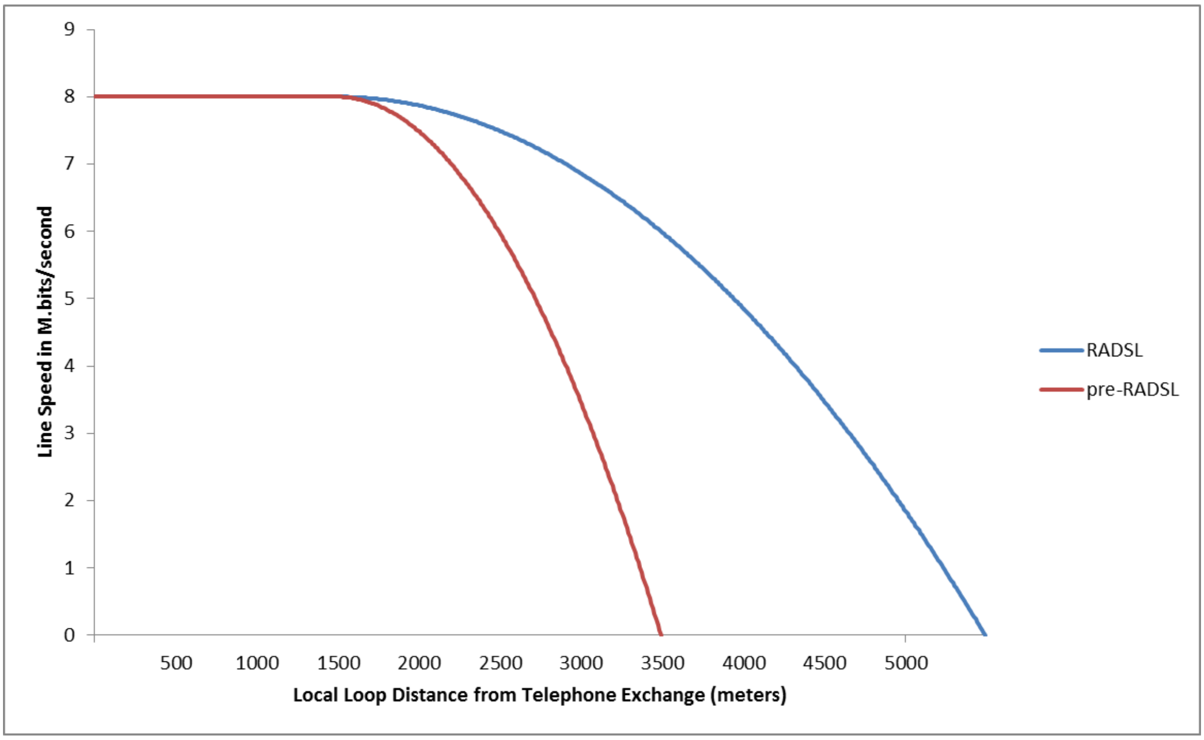
Notes: Local loop distance for firms attached to exchanges enabled for ADSL broadband under wave 1 of the BT rollout programme (1999-2002). Cable distances are from Point-Topic

Distance from the local exchange was of much less importance for pre-existing technologies, such as telephone 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.

The strong negative effects of cable distance on broadband speed were present for a relatively short time period. 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 (see Figure A2).[41] A disadvantage that this raises for our research is that we must restrict the data period severely as a consequence of RADSL and we can therefore claim to capture only the short-run effects of ICT. We balance this against the advantage that it allows us to demonstrate that the effect of cable distance falls across time in the manner expected, enhancing its credibility as a plausible instrument.

[41] This was managed by adjusting the up-load speed.

Figure A2: Engineering Tests of ADSL and RADSL broadband speeds against Local Loop Length



6.2 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).

6.3 The ADSL rollout

In Table A4 we explore the differences in location characteristics by their timing of enablement. We estimate 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 A4: 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***
	(0.21)	(0.35)	(0.17)	(0.17)
Ln (no. of businesses)	-2.219***	-0.389	-0.341**	-0.21
	(0.21)	(0.27)	(0.17)	(0.16)
Ln (average local loop)	0.635	3.896***	2.701***	0.48
	(0.53)	(0.26)	(0.42)	(0.35)
R^2	0.725	0.238	0.463	0.212
Observations.	5,520	1,123	3,022	1,375

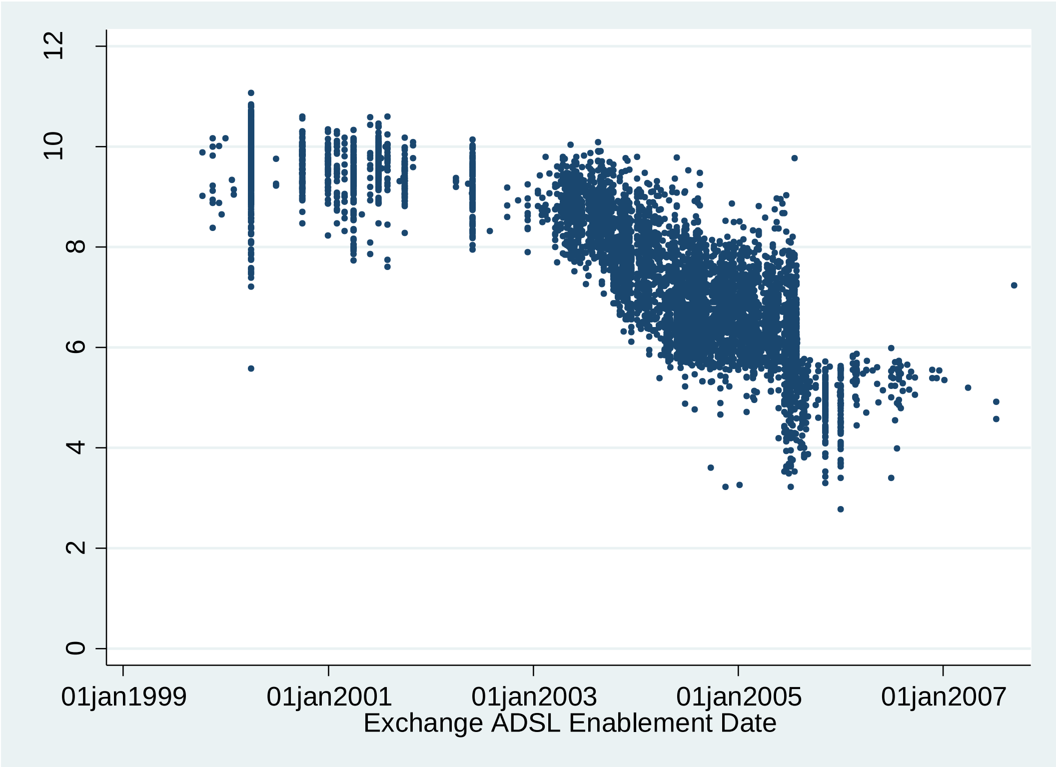
Notes: OLS regressions of the month-year in which ADSL enablement occurred (1= November-1999; 40=September-2007). Data on date of enablement and exchanges characteristics is from OFCOM. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

The differences between the phases of the rollout programme are evident from Figure A3 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 Table A4. The correlation in Figure A3 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.[42] The regressions in Table A4 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 Table A4). 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

[42] 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.

between the number of households and the length of the local loop. For this reason we include these as control variables in the regressions.

Figure A3: Exchange Size against ADSL Enablement Date



Note: Exchange Size measured by the sum of households and businesses attached to a telephone exchange. Data source: *OFCOM ADSL Broadband Database*.

In Table A5 we repeat the baseline estimations in Table 6 but now including firms attached to telephone exchanges enabled in waves 2 and 3. In regressions 1 to 3 in Table A5 we add region dummies to remove the effect of time invariant regional characteristics that might help to explain differences in ICT use across firms. We show the importance of the inclusion of these region dummies in regression 4 to 6, where we report a rejection of the overidentification test for regressions 4 and 5 involving PCs or Portable PCs per employee.

Table A5: Validity of Including non-Enabled Exchanges from All Waves

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**
	2000, All Waves + Region Dummies			**2000, All Waves**		
ICT Variable	*PCs per employee*	*Portable PCs per employee*	*Pentium PCs per employee*	*PCs per employee*	*Portable PCs per employee*	*Pentium PCs per employee*
First Stage						
ADSL Enabled	0.504***	0.631***	0.491***	0.674***	0.800***	0.664***
	(0.06)	(0.09)	(0.07)	(0.06)	(0.09)	(0.06)
*Logged Local Loop dist.*ADSL Enabled*	-0.290***	-0.357***	-0.291***	-0.351***	-0.394***	-0.356***
	(0.05)	(0.07)	(0.05)	(0.05)	(0.07)	(0.05)
Firm Controls	✓	✓	✓	✓	✓	✓
Region Dummies	✓	✓	✓			
Cragg-Donald F Test	47.870	30.388	32.340	115.657	70.686	80.413
Kleibergen-Paap F Test	45.010	29.289	30.734	111.152	70.592	78.253
Hansen J Statistic	0.174	0.222	0.286	0.072	0.039	0.143
Observations	6,721	4,572	6,520	6,762	4,599	6,561

Notes: We report the first stage from 2SLS regressions using firm-level data for 2000 from the CiTDB database. ‘All wave 1 exchanges’ restricts the sample to those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). ‘All waves’ includes non-enabled exchanges from all waves (i.e. also waves 2 and wave 3). Local loop distance refers to the cable distance between the firm and the telephone exchange. All regressions include firm size (log employment), multiplant status and local loop cable distance as controls (firm age and foreign ownership are not available in CiTDB data). * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

6.4 Additional Control Variables

In Table A6 we test the robustness of the model 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.[43] 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 negative relationship with some measures of ICT.

The negative correlation of ICT with our agglomeration measure could reflect sectoral differences in the importance of agglomeration. To examine this introduce a services dummy and interact this with the exchange size measure. We find a negative coefficient for both manufacturing and services firms, although it is more negative for services firms, perhaps suggesting that face-to-face and other forms of communication are more important for such firms. Therefore, it does not seem to be simply reflecting sectoral differences.

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

However, it is not clear a priori the expected sign on our agglomeration measure. On the one hand, agglomerations tend to be positively correlated with productivity that also tend to correlate with ICT use. On the other hand, this may reflect the importance of other forms or communication such as face-to-face contact. Indeed, Torre (2008) finds that even long-distance research collaborations often begin through and continue to require temporary face-to-face contact. In our case it suggests the latter may dominate.

Table A6: Adding Exchange Size as a Control Variable

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**
ICT Variable	**PCs/ Emp.**	**Portable PCs/ Emp.**	**Pentium PCs/ Emp.**	**PCs/ Emp.**	**Portable PCs/ Emp.**	**Pentium PCs/ Emp.**
ADSL Enabled	0.491***	0.629***	0.483***	0.452***	0.549***	0.445***
	(0.07)	(0.12)	(0.08)	(0.07)	(0.12)	(0.08)
*Logged Local Loop dist.*ADSL Enabled*	-0.225***	-0.293***	-0.236***	-0.209***	-0.256***	-0.221***
	(0.06)	(0.10)	(0.07)	(0.06)	(0.09)	(0.07)
Exchange Size	-0.114***	-0.127***	-0.103***	-0.116***	-0.131***	-0.104***
	(0.01)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)
*Exchange Size * Services Dummy*				-0.095***	-0.091***	-0.085***
				(0.01)	(0.02)	(0.02)
Firm Controls	✓	✓	✓	✓	✓	✓
Observations	4,866	3,307	4,722	4,866	3,307	4,722

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). Regressions 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 OFCOM. Regressions include firm size (log employment), multi-plant status and local loop distance as controls (firm age and foreign ownership are not available in CiTDB data). * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses

6.4 Across Time and Non-Enabled Exchanges

Table A7 presents the regression results for various ICT measures and local loop distance across later years (2001 to 2003) and for non-enabled exchanges. 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 6. We repeat the result for 2000 for ease of reference. The declining importance of distance on ICT is confirmed by the results in regressions 1 to 4 in Table A7. In each additional year beyond 2000 we find that distance has a significant negative relationship with ICT capital but the strength of this relationship falls in value each year.[44] 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. This pattern also holds when we use the CiTDB data and disaggregate the ICT used by firms (Table A8). 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.

[44] 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.

Within Table A7 we also examine whether ICT is correlated with local-loop distance for non-enabled exchanges using the ONS data.[45] In regressions 5 and 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 6.1 to 6.4 but for years preceding the ADSL rollout. In regression 6.7 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 8 firms attached to exchanges that were enabled in wave two or three (i.e. from 2003 onwards).

The 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 and 6) or we use firms attached to exchanges enabled at some point after 2000 (regressions 7 and 8). In the first three regressions we find no effect from cable distance on the IT capital of firms, while in the final regression we find a positive rather than a negative effect that is statistically different from zero at the 10% level of significance.[46]

[45] 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 Table A8.
[46] This is mirrored by results found in Table A8 when using the CiTDB data.

Table A7: First Stage Regressions of Local Loop Distance as a Single Instrument on ICT capital Over Time and for non-enabled Exchanges

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**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**			
*Logged Local Loop dist.*ADSL Enabled*	-0.336***	-0.267***	-0.173***	-0.163***	-0.629	-0.201	0.057	0.199*
	(0.09)	(0.06)	(0.06)	(0.05)	(0.39)	(0.24)	(0.11)	(0.11)
Firm Controls	✓	✓	✓	✓	✓	✓	✓	✓
Observations	2,246	4,710	5,238	5,240	94	485	1,020	1,460

Notes: OLS regressions using firm-level data for various years. The sample of firms in regressions 1 to 4 is 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 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 7 and 8 use firm level data for the year 2000. In regression 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 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 1 to 8 uses firm level data from the ONS. Regressions include a measure of age, ownership and multiplant status as control variables. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

Table A8: 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	-0.290***	-0.298***	-0.238***	-0.234***	-0.006	0.116***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.05)	(0.05)
Obs.	3304	5396	5372	5206	1562	1896
Portable PCs/Emp	-0.356***	-0.290***	-0.223***	-0.243***	0.015	0.071
	(0.05)	(0.04)	(0.04)	(0.04)	(0.08)	(0.07)
Obs.	2266	3814	3973	3913	1041	1292
Pentium PCs/Emp	-0.270***	-0.277***	-0.232***	-0.194***	0.02	0.142***
	(0.04)	(0.03)	(0.03)	(0.03)	(0.06)	(0.05)
Obs.	3,197	5,278	5,238	5,068	1,525	1,839

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.

6.5 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.[47] That is, to follow the approach taken in much of the rest of the literature. [48]

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. We include observable characteristics such as age and size as an attempt to control for such factors. 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 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 and the idea that unobserved managerial ability does not explain our findings.

The results from this are reported in Table A9, 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 1 to 3). [49] To put this differently, the characteristics of the firm in 1998 do not predict future ADSL enablement of the telephone to which they are attached. Similarly 1998 firm characteristics do not predict their cable distance from the telephone exchange (regressions 4 to 6).[50] This suggests that the ordering of ADSL enablement of exchanges (within wave one) was not targeted at firms that were larger, more productive or older, despite these areas potentially having higher demand for broadband services. This strongly indicates that the instruments do not capture some pre-existing trend and are not correlated with ICT use because of a correlation with persistent, unobservable managerial quality.

We find that firms that had shorter local loops were more likely to be attached to enabled exchanges. This is expected given the way that BT rolled out ADSL to exchanges with shorter local loops first and suggests the importance of including local loop distance as a control

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

[48] When using the ONS data we are able to follow Grimes et al. (2012) and include lags of the dependent variable (we choose 3 years prior) as a control, which they include as an alternative method to capture time-invariant firm characteristics. The results from the paper are unchanged when we do this. As our CiTDB data period starts in 1999 that approach is not possible when using that data. We try instead the inclusion of the lag of employment in our regressions for firm revenue. Again the results are robust to their inclusion.

[49] Similar results are obtained using year 1997, the first year of available data, however the sample size is substantially smaller.

[50] The same conclusions are reached when consider enablement in 2000 or 2001 in isolation.

variable in those regressions where we compare across enabled and non-enabled exchanges.

Table A9: Correlation between Timing of Wave 1 Enablement and Ex-ante Firm Characteristics

Regression No.	1	2	3	4	5	6
Dependent Variable:	Probability of ADSL Enablement			ADSL Enablement* Local Loop Distance		
Employment in 1998	0.006			0.002		
	(0.00)			(0.00)		
Gross Output in		0.003			-0.002	
		(0.00)			(0.00)	
TFP in 1998			0.000			0.001
			(0.00)			(0.00)
Foreign in 1998	-0.011	-0.012	-0.01	-0.012	-0.011	-0.012
	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
USA in 1998	-0.006	-0.006	-0.005	-0.018	-0.017	-0.017
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)
Firm Age	-0.005	-0.006	-0.005	0.001	0.001	0.001
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Log Local Loop Distance	-0.023***	-0.024***	-0.024***	0.794**	0.794**	0.794**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Observations	7,779	7,779	7,779	7,779	7,779	7,779

Notes: OLS regressions using firm-level data for the year 1998. All regressions use 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 A10: 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***
	(0.00)	(0.00)	(0.00)	(0.07)	(0.07)	(0.07)
Obs.	16,087	16,087	16,087	21,402	21,402	21,402

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 regressions include firm size (log employment) and multiplant status as controls (firm age and foreign ownership are not available in CiTDB data). * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

6.6 IV Estimation Excluding Firms with Leased Line Connections

The rollout of ADSL provided broadband access for small and medium firms in particular, whilst large firms had the pre-existing option of (expensive) leased line connections. The CiTDB data contains partial information on leased line connections - as a proxy we use firm adoption of Wide Area Networks that refer to leased lines in their text descriptions. We demonstrated in Section 2 that our instruments had no predictive power of this leased line proxy. Here we undertake an additional robustness check, by repeating the baseline IV estimation (of Table 6), but excluding firms with leased line connections. The results are presented in Table A11.

We find that the first stage identification remains strong, with F statistics above 10 in all specifications. The identification is somewhat weaker than the baseline, mainly for portable PCs, but to some extent this is expected as we have reduced the sample size by around 20%. In the second stage we find similar estimated coefficients to the baseline specification.

Table A11: IV Regressions using CiTDB – Excluding Firms with Leased Lines (Year: 2000)

Regression No.	**1**	**2**	**3**
Dependent Variable		**Revenue**	
Second Stage			
PCs per employee	1.231***		
	(0.26)		
Portable PCs per Employee		1.041***	
		(0.31)	
Pentium PCs per Employee			1.349***
			(0.30)
First Stage			
ADSL Enabled	0.479***	0.428***	0.488***
	(0.08)	(0.14)	(0.10)
*Logged Local Loop dist.*ADSL Enabled*	-0.253***	-0.182	-0.273***
	(0.07)	(0.11)	(0.08)
Firm Controls	✓	✓	✓
Cragg-Donald F Test	25.092	10.434	17.277
Kleibergen-Paap F Test	25.748	10.994	17.297
Hansen J Statistic	0.103	0.048	0.232
Observations	3,889	2,548	3,764

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database for wave 1 exchanges - those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). We further exclude firms with leased-line internet access – reflected as firms having a Wide Area Network with a text description referring to leased lines (this is the only proxy of leased line access available in our data). 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 local loop cable distance as controls (firm age and foreign ownership are not available in CiTDB data). * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

6.7 Non-Linear First Stage IV Estimation

In Table A12, we repeat the baseline IV estimation of Table 6, but with a non-linear measure of local loop distance in the first stage. In earlier first stage analyses, we had showed that the predictive power of distance on ICT decays non-linearly, consistent with the expected decay of ADSL broadband speeds with distance from the exchange, suggested by engineering tests (see Table 4). We find with a non-linear distance instrument, the predictive power of the first stage remains strong, with F statistics in the range 15 to 31. In the second stage, the results closely mirror the baseline, see Table 6.

Table A12: Non-linear IV Regressions using CiTDB (Year: 2000)

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**
Dependent Variable			**Revenue**			
Telephone Exchanges	**All Wave 1**	**All Wave 1**	**All Wave 1**	**All Wave 1**	**All Wave 1**	**All Wave 1**
Second Stage						
PCs per employee	1.329***			1.372***		
	(0.22)			(0.25)		
Portable PCs		0.941***			0.957***	
per employee		(0.18)			(0.20)	
Pentium PCs			1.531***			1.507***
per employee			(0.28)			(0.30)
First Stage						
ADSL Enabled	0.985***	1.293***	0.914***			
Exchange	(0.13)	(0.20)	(0.15)			
Local Loop dist.	-0.442***	-0.584***	-0.402***			
**ADSL Enabled*	(0.07)	(0.11)	(0.08)			
Sq(Local Loop dist.)	0.054***	0.072***	0.048***			
**ADSL Enabled*	(0.01)	(0.01)	(0.01)			
ADSL Enabled Exch.				0.403***	0.546***	0.391***
**Dist<2k.m*				(0.06)	(0.09)	(0.06)
ADSL Enabled Exch.				0.204***	0.225***	0.166***
**2km>Dist<3.5k.m*				(0.04)	(0.06)	(0.04)
ADSL Enabled Exch.				0.121***	0.180***	0.116***
**Dist>3.5k.m*				(0.04)	(0.06)	(0.04)
Firm Controls	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	30.348	19.494	19.031	23.201	15.88	15.627
Kleibergen-Paap F Test	31.1	21.117	18.672	23.093	16.811	15.457
Hansen J Statistic	0.505	0.386	0.686	0.525	0.609	0.66
Observations	4,866	3,307	3,197	4,866	3,307	3,197

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database. 'All wave 1 exchanges' restricts the sample of to those that are connected to telephone exchanges that were ADSL enabled by the end of 2002 (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) and multiplant status as controls. Regressions 1, 3 and 5 additionally include local loop cable distance (firm age and foreign ownership are not available in CiTDB data). * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses

6.8 Longer run effects on productivity

In Table A13 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 A13: 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 per worker	-0.143	-0.01	0.108	0.069	0.147
	(0.16)	(0.11)	(0.10)	(0.12)	(0.10)
First Stage					
*Logged Local Loop dist.*ADSL Enabled*	-0.195***	-0.274**	-0.348***	-0.321**	-0.455***
	(0.07)	(0.11)	(0.13)	(0.15)	(0.18)
Cragg-Donald F Test	7.845	7.261	7.898	5.399	8.531
Kleibergen-Paap F Test	8.244	6.433	6.782	4.458	6.672
Observations	2242	1630	1263	1040	830

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 employment, age, ownership, multiplant status and local loop cable distance as controls. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

6.9 First Stage of IV Regressions – Heterogeneity by Firm Size

Below we show the first stage estimates that mirror Table 8. Here we examine heterogeneous impacts by firm size, through interacting the ICT treatment and instruments with a small firm dummy – reflecting firms with fewer than 250 employees. In the main body of the text we omitted the first stage estimate for brevity, since with two endogenous variables now (due to the interaction) and four instruments, these become somewhat long. For each endogeneous variable we show its corresponding first stage regression below, firstly for the ICT variable and then for the small firm interaction with the ICT variable. As noted in the main text, identification remains quite strong with F statistics in the range 9 to 33 and over-identification tests do not reject the null of jointly valid instruments.

Table A14: IV Regressions using CiTDB (Year: 2000) – Heterogeneity by Firm Size

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**
Dependent Variable	**Revenue**					
First Stage – ICT Variable						
ADSL Enabled	0.663***		1.049***		0.694***	
	(0.11)		(0.18)		(0.13)	
Logged Local Loop	-0.385***	-0.396***	-0.607***	-0.597***	-0.397***	-0.379***
*dist.*ADSL Enabled*	(0.09)	(0.07)	(0.14)	(0.11)	(0.10)	(0.08)
ADSL Enabled – small firm	-0.208**		-0.526***		-0.262**	
	(0.10)		(0.16)		(0.12)	
Logged Local Loop	0.149*	0.146*	0.337***	0.334***	0.156*	0.153*
*dist.*ADSL Enabled - small*	(0.08)	(0.08)	(0.13)	(0.13)	(0.09)	(0.09)
First Stage – ICT Variable-small firm						
ADSL Enabled	-0.018		0.030		-0.016	
	(0.06)		(0.09)		(0.07)	
Logged Local Loop	0.028	0.014	-0.018	-0.008	0.027	0.017
*dist.*ADSL Enabled*	(0.05)	(0.01)	(0.07)	(0.02)	(0.05)	(0.01)
ADSL Enabled – small firm	0.467***		0.490***		0.414***	
	(0.05)		(0.08)		(0.06)	
Logged Local Loop	-0.260***	-0.264***	-0.250***	-0.257***	-0.239***	-0.243***
*dist.*ADSL Enabled - small*	(0.04)	(0.04)	(0.06)	(0.06)	(0.04)	(0.04)
Firm Controls	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	16.496	32.579	8.942	14.991	9.711	19.514
Kleibergen-Paap F Test	15.605	26.216	8.804	11.582	9.522	15.636
Hansen J Statistic	0.207		0.390		0.338	
Observations	4,866	3,304	3,307	2,266	4,722	3,197

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database for wave 1 exchanges - those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). 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 local loop cable distance as controls (firm age and foreign ownership are not available in CiTDB data). First stage results for each of the endogenous variables are presented here, which accompany the second stage results in Table 8. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

6.10 First Stage of IV Regressions – Heterogeneity by Firm Sector

Below we show the first stage estimates that mirror Table 9. Here we examine heterogeneous impacts by firm sector, through interacting the ICT treatment and instruments with a services sector dummy. In the main body of the text we omitted the first stage estimate for brevity. For each endogeneous variable we show its corresponding first stage regression below, firstly for the ICT variable and then for the small firm interaction with the ICT variable. As noted in the main text, identification remains quite strong with F statistics in the range 8 to 35 and over-identification tests do not reject the null of jointly valid instruments.

Table A15: IV Regressions using CiTDB (Year: 2000) – Heterogeneity by Firm Sector

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**
Dependent Variable	**Revenue**					
First Stage – ICT Variable						
ADSL Enabled	0.399***		0.464***		0.428***	
	(0.08)		(0.13)		(0.10)	
*Logged Local Loop dist.*ADSL Enabled*	-0.233***	-0.330***	-0.285***	-0.428***	-0.263***	-0.304***
	(0.07)	(0.03)	(0.11)	(0.05)	(0.08)	(0.04)
ADSL Enabled – services	0.215***		0.354***		0.137*	
	(0.07)		(0.11)		(0.08)	
*Logged Local Loop dist.*ADSL Enabled - small*	-0.037	0.137***	-0.02	0.267***	0.005	0.116***
	(0.06)	(0.03)	(0.10)	(0.05)	(0.08)	(0.03)
First Stage – ICT Variable-services						
ADSL Enabled	0.162***		0.797***		0.246***	
	(0.04)		(0.12)		(0.05)	
*Logged Local Loop dist.*ADSL Enabled*	-0.012	0.081***	-0.155*	0.827***	-0.032	0.220***
	(0.04)	(0.02)	(0.09)	(0.05)	(0.04)	(0.02)
ADSL Enabled – services	-0.175***		-2.023***		-0.533***	
	(0.05)		(0.08)		(0.06)	
*Logged Local Loop dist.*ADSL Enabled - services*	-0.289***	-0.430***	-0.304***	-1.930***	-0.251***	-0.681***
	(0.05)	(0.03)	(0.08)	(0.04)	(0.06)	(0.03)
Firm Controls	✓	✓	✓	✓	✓	✓
Cragg-Donald F Test	13.956	34.682	8.259	16.602	9.243	22.474
Kleibergen-Paap F Test	14.203	31.887	9.154	15.923	9.419	21.304
Hansen J Statistic	0.242		0.529		0.405	
Observations	4,866	3,304	3,307	2,266	4,722	3,197

Notes: 2SLS regressions using firm-level data for 2000 from the CiTDB database for wave 1 exchanges - those that are connected to telephone exchanges that were ADSL enabled by the end of 2001 (wave 1). 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 local loop cable distance as controls (firm age and foreign ownership are not available in CiTDB data). First stage results for each of the endogenous variables are presented here, which accompany the second stage results in Table 9. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.