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Mattia Nardotto, University of Cologne
Tommaso Valletti, Imperial College London
Frank Verboven, University of Leuven and CEPR

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Centre for Economic Policy Research
77 Bastwick Street, London EC1V 3PZ, UK
Tel: (44 20) 7183 8801, Fax: (44 20) 7183 8820
Email: cepr@cepr.org, Website: www.cepr.org

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ABSTRACT

Unbundling the incumbent: Evidence from UK broadband*

We consider the impact of a regulatory process forcing an incumbent telecom operator to make its local broadband network available to other companies (local loop unbundling, or LLU). Entrants are then able to upgrade their individual lines and offer Internet services directly to customers. Employing a very detailed dataset covering the whole of the UK, we find that over the course of time, many entrants have begun to take advantage of LLU. However, unbundling has little or no effect on broadband penetration, compared to those areas where the loops are not unbundled. LLU entry instead has a strongly positive impact on the quality of the service provided. We also assess the impact of competition from an alternative form of technology (cable) which is not subject to regulation, and what we discover is that inter-platform competition has a positive impact on both penetration and quality.

JEL Classification: L51
Keywords: broadband, competition, entry, local loop unbundling, regulation and telecommunications

Mattia Nardotto
Department of Economics
University of Cologne
Albertus-Magnus-Platz
50923 Cologne
Germany

Email: mattia.nardotto@uni-koeln.de

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Tommaso Valletti
Imperial College London
South Kensington Campus
London
SW7 2AZ

Email: t.valletti@imperial.ac.uk

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Frank Verboven
Department of Economics
University of Leuven
Naamsestraat 69
B-3000 Leuven
BELGIUM

Email:
frank.verboven@econ.kuleuven.be

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1 Introduction

A broadband infrastructure is needed to deliver high-speed Internet access. Like other communication networks, broadband is seen as a driver of economic activity and growth (Röller and Waverman, 2001; Czernich et al., 2011). The potential benefits of broadband are considerable, but so are its rollout costs. Although cost estimates vary widely from country to country, the order of magnitude of the required investment is of several billions of dollars.[1]

Large, sunk infrastructure investments also create market power. Thus the telecom industry has traditionally been subject to some form of regulation, just like other network industries exhibiting features of natural monopoly. While in the past regulation would typically concern final (retail) prices to end-users, over the last two decades its focus has shifted towards the regulation of (wholesale) access, in order to let other operators use the vertically-integrated incumbent's facilities, and as a result, compete in the final market.

This view that incumbents should be "opened up" to entrants is not shared by all. Incumbents generally oppose to open themselves to competition, arguing that forced access to essential business inputs amounts to a regulatory taking that stifles infrastructure-based competition and technological innovation, because new entrants prefer to use the incumbent's network instead of creating their own. New entrants, on the other hand, argue that since they cannot afford to duplicate the incumbent's infrastructure, they cannot actually provide certain services, with the consequent likelihood that a "closed" incumbent could monopolize the market.

This variety of views is also reflected in different policies across countries.[2] European countries do regulate the incumbent telecom operator, and they do let entrants access its network. In particular, the implementation of so-called "local loop unbundling" (henceforth, LLU) is a requirement of the European Union policy on competition in the telecommunications sector, and is at various stages of development in all member states.[3] LLU is the process whereby the incumbent makes its local network available to other companies. Entrants are then able to upgrade

[1] For example, NBN Co, a government-owned corporation, was established in 2010 in Australia to design, build and operate a national broadband network. Construction began in 2011 and the estimated cost of the network was $40bn spread over a 10-year period. The European Commission estimated that between €38bn and €58bn would be required to achieve the Digital Agenda's broadband goal of guaranteeing all European households a speed of at least 30 Mbps by 2020 (these estimates increase to €181-€268bn to ensure at least 100 Mbps to 50% of all European households) - see COM(2010) 472 final.

[2] We should point out that programs aimed at opening up networks in vertically-integrated monopolies are also present in industries other than telecoms. Access requirements are found, for example, in the 1992 U.S. Energy Policy Act, or in the railways sector in many countries.

[3] Regulation (EC) No 2887/2000 of the European Parliament on unbundled access to the local loop.

individual lines to offer services, such as high-speed Internet, directly to customers.

In stark contrast with the EU approach, the FCC – the federal regulator in the US – does not regulate access to broadband networks. While unbundling requirements for the narrowband networks of the incumbent local exchange carriers were mandated by the Telecommunications Act of 1996, these were first eliminated from the emerging broadband markets in 2003, and further drastically curtailed in 2004 also in narrowband markets. In the US, the incumbents' platforms are therefore considered to be "closed", as opposed to the "open" approach endorsed by the EU.

The traditional debate over unbundling concerns whether the benefits of promoting intra-platform competition outweigh a possible reduction in investment incentives when incumbents are required to share their infrastructures. Although the questions tackled in this debate are of key importance to academics, policy makers and market regulators, there has not been much sound empirical analysis by the academic world. The lack of reliable studies is largely due to the paucity of data released by companies and regulators.

In this paper, we propose an analysis of the unbundling experience in the UK, based on two unique datasets: one concerning broadband penetration, made available to us for the purpose of this study by Ofcom (the UK's communication regulator); and one regarding broadband speeds, obtained from a private company. The UK is particularly interesting in that it has both a large traditional telephone network (owned by the BT group), which is subject to access regulation, and a well-established cable network that has never been required to offer its facilities to competitors. We can thus analyze both the impact of inter-platform competition (cable vs. traditional telcos) and intra-platform competition (whereby entrants access BT's network).

The first dataset consists of quarterly figures for all broadband lines subscribed to locally by end-users in the UK, between December 2005 and December 2009. The unit of observation is the "local exchange" (LE), also known as "central office" in the US. Each LE is a node of BT's local distribution network, and is the physical building used to house internal plant and equipment. From the LE, lines are then further distributed locally to each building where customers live or work, which tend to be within a few hundred meters of the LE.[4] For each one of the 5,000 plus LEs in the UK, we observe the number of local broadband subscribers per operator, that

[4] "Local loop" is another term for the actual cable through which customers receive broadband and telephone calls. LEs aggregate local traffic, and then connect up to the network's higher levels to ensure world-wide connectivity.

is: the incumbent operator BT, the LLU entrants who rent the lines from the incumbent and may invest in quality upgrades, and the cable operator who utilizes a different platform without being subject to any access obligations.

The second dataset contains information on broadband speed tests carried out by individuals in 2009. For each individual/speed test, we observe the operator, the contract option chosen by the user, and the location (post code) – and thus the distance from the relevant LE. We combine both datasets with a third dataset on the demographic characteristics by local exchange. Our data enable us to obtain a substantial understanding of the unbundling process in the UK, and of its effects on broadband penetration and quality (as measured by speed). Our empirical analysis comprises three stages.

Firstly, we analyze the unbundling process at the level of the LEs. Unbundling refers to the entry of other operators who use their own facilities together with BT's network infrastructure (at a regulated access price). Since the process began, hundreds of thousands of local loops have been unbundled from BT, freeing them up for use by other operators. With unbundling, entrants literally put their equipment inside BT's exchanges (paying the corresponding fixed costs). They can then install their own particular brand or style of broadband, with differing speeds and download limits to those offered by BT, thus potentially offering faster, cheaper deals.

Our analysis of entry reveals an interesting, complex picture. We document a strong increase in LLU entry in the UK over the period 2005-2009, albeit characterized by considerable heterogeneity across local markets. Larger markets support a greater number of entrants, thus confirming the importance of high fixed investment costs. Entry is highly persistent over time, implying that technology exhibits substantial sunk costs. Finally, entry is more likely in adjacent areas where there is already LLU coverage, which shows there are agglomeration advantages or "economies of density" at play here.

In the second step, we study broadband penetration and its determinants, and in particular the role of LLU entry. We utilize our findings from the first stage in order to obtain a number of reasonable identification strategies. We find that, during the period in which entrants progressively unbundled local loops, broadband penetration more than doubled in the UK. However, apart from this upward trend, those areas with LLU do not seem to obtain higher penetration levels than those without. On the other hand, inter-platform competition (from cable) has increased local broadband penetration to a greater degree.

The absence of any strong positive effects on broadband penetration levels would seem to suggest that the competitive effects of LLU entry are outweighed by the adverse effects of lower investment incentives. Before drawing such a conclusion, however, we need to consider how LLU entry has affected the quality of the service offered, through our measure of broadband speed.

This brings us to the third stage of our analysis. As expected, LEs characterized by inter-platform competition are the ones boasting the highest average speed. More interestingly, we find that the LEs that have experienced LLU entry have a higher average broadband speed than those that have not experienced LLU entry. Remarkably, this higher speed is entirely due to the LLU entrants; there is no significantly higher average speed for BT customers' lines. To fully understand this phenomenon, we investigate the average speed by contract offered by two of the main LLU entrants, O2 and Sky. These two LLU entrants turn out to have a disproportionately large fraction of high-speed contracts, compared with the incumbent BT. This could be seen as evidence of the fact that the LLU entrants mainly compete by offering comparatively better conditions for their fastest connections.

Summing up then, while LLU entry has not raised total broadband penetration across different local markets, it has increased the quality of the service as measured by average broadband speed.

Previous literature From a theoretical point of view, a wealth of studies have analyzed access charges in telecommunications networks (see, for example, Armstrong, 2002; Vogelsang, 2003; Guthrie, 2006), some of which have also gone on to account for investment dynamics (Bourreau and Dogan, 2005; Klumpp and Su, 2010). Given the high interests at stake, it is not surprising to also find a considerable number of policy papers regarding the question. Hausman and Sidak (2005) offered an empirical review of unbundling experiences in five countries, while Hazlett and Bazelon (2005) examined two natural experiments in the US (from 1999 to 2004). Other studies covering similar ground include Hausman et al. (2001), and Crandall et al. (2004).

However, on the empirical side, there are few robust econometric studies quantifying the effect of access regulation on entry and infrastructural investment. The main reason for this is the lack of suitable microdata, which has meant that researchers have had to rely on aggregate, country-level data, when examining the impact of the different regulatory paths taken by national authorities with regard to access policies. Grajek and Röller (2012) study a comprehensive dataset covering 20 countries over a period of 10 years, and in doing so they distinguish between the incumbent's investment and the entrants' investments. The specificity of their paper lies in their use of a regulatory index and to account for the possible endogeneity of regulation.[5] These studies have good external validity due to their cross-country nature, although they do suffer from one serious shortcoming in terms of the data used, as telecom investment tends to occur at the micro level, that is, within a given area of a certain country. Therefore, macro-level studies aggregating all investments in a given country, tend to lose their appeal, as they confound too many effects. Indeed, one of the findings of this paper is the considerable within-country heterogeneity of entry into local broadband markets.

Empirical work based on micro-data, at the level of local markets, is even scarcer. A few papers consider entry at the local area level, based on US data prior to the FCC's decision in 2004 to reverse its "open" access policy (Greenstein and Mazzeo, 2006; Economides et al., 2008; Xiao and Orazem, 2009; Xiao and Orazem, 2011; Goldfarb and Xiao, 2011). These studies are based on FCC data that are rather coarse, as they do not disclose the identity of firms, and they group together, for confidentiality reasons, all markets with 1-3 entrants, which is where most of the interesting action takes place. It is also difficult to rely on such studies when studying broadband markets, as the data employed are usually 10 years old, whereas the diffusion of broadband is a more recent phenomenon. Compared with these papers, we can offer a more complete analysis of the entry process in recent years, at a time when the diffusion of broadband has reached levels closer to maturity.

Two interesting recent papers consider broadband performance at the local area level. Firstly, Fevrier et al. (2011) have data on the number of broadband lines by operator for 1,500 LEs in France in 2005. They have access to a cross-section which, however, limits any possible dynamic analysis. A unique feature of the penetration data analyzed in our paper is their panel structure, as we have quarterly figures for the universe of the LEs in the UK over a period of five years. This enables us to better identify the effect of LLU entry and competition on broadband penetration. Secondly, Wallsten and Mallahan (2010) focus on broadband speed, based on cross-section data per census tract for the US. They find a positive relationship between broadband speed and the number of wireline providers, but they do not address the question of how unbundling the incumbent can affect speed, simply because there is no unbundling in the US. The data in our paper enable us to directly relate broadband speed, at a detailed micro-level, to LLU competition, and compare it with our other measure of local performance, namely broadband penetration.

[5] See also Distaso et al. (2006), Wallsten and Hausladen (2009), Bouckaert et al. (2010), and Gruber and Koutroumpis (2012).

The remainder of the paper is organized as follows. Section 2 provides background information on the UK broadband market and on our datasets. In Section 3 we take an initial look at the data, and in particular we focus on the determinants of LLU entry. Section 4 estimates the impact of unbundling on broadband penetration across LEs, while Section 5 analyzes the impact on the quality of service (broadband speed). In Section 6 we present our conclusions.

2 Industry background

2.1 The UK broadband market

The market for Internet services in the UK is characterized by the presence of a network, originally deployed by British Telecom (BT) during the 20th century to provide telephony services. BT was state-owned until its privatization in 1984. This network consists of 5,587 nodes, called Local Exchanges (LEs hereafter), each of which is connected to the others by means of high-capacity (fiber) lines, and this network is linked to 28 million premises throughout the country by means of copper lines. One of the most important factors contributing towards the rapid diffusion of Internet services has been the possibility to adapt voice telephone technology to the high-speed Internet by installing DSL equipment in the LEs.

Given the substantial market power that the traditional telephone incumbent could transfer to this new market, Ofcom, like many other regulators in Europe, decided to regulate access in the LEs. Until 2005, BT was a vertically-integrated operator, and a number of disputes arose concerning discriminatory and foreclosure conduct vis-à-vis new entrants. In 2005, the regulator accepted BT's undertaking to create separate wholesale divisions – Openreach and BT Wholesale. The former was created to invest in the maintenance and upgrading of the local network, while the latter aimed to deal with the leasing of lines to entrants. A third division, BT Retail, was created to sell to end users. This separation has been successful in ensuring equal access to the "economic bottlenecks", and no claims of discrimination have been submitted since 2005.

Entrants relying on BT's network can choose between two options in order to provide, and brand, Internet services: Bit-stream or LLU. Bit-stream requires limited investment by the entrant, since the connection is still managed by BT, and hence the procedure constitutes a form of re-branding. LLU, on the other hand, requires a much greater level of investment, since control over the local connection is transferred from BT to the entrant, which has to install and maintain its own equipment in the LE.

In the UK, the main broadband alternative to the traditional telephony network is cable.

There has been little investment in fiber within the local loop, and during the period we consider here, there has been limited take up of high-speed connections based on 3G cellular technology.[6] The cable operator Virgin Media deployed its own network during the 1990s, primarily for the purpose of selling cable TV. The topology of this network is very different from BT's. It covers roughly 60% of premises in the UK, concentrating its presence in urban areas and in flat parts of the country. Moreover, the network can only be upgraded to support broadband if an area is already covered by cable. However, it has not expanded since the 1990s, that is, ten years prior to the start date of our sample. It is too costly to extend the reach of the cable network into areas which are not covered. Given that it is a private company, and a later entrant, the telephony business of Virgin Media has never been subject to regulation. Virgin is not forced by the regulator to let entrants access its network (and in fact Virgin has never done so).

2.2 Datasets

We combine three different datasets, available at a highly disaggregated geographical level: two unique datasets with information on the number of broadband lines and on broadband speed, and one census dataset containing local demographic information. The first dataset is provided by Ofcom, and contains the quarterly data supplied to the regulator by BT and Virgin Media over a 5-year period from December 2005 to December 2009. Ofcom collects such data for its analysis of the wholesale broadband market.[7] BT is asked to provide, for each LE, all relevant information regarding the wholesale market, that is, the exact number of connections leased to each LLU entrant. Virgin Media is also required to provide figures for the number of subscribers for each of its central offices (the equivalent of LEs in the cable network). Given that the two networks do not perfectly overlap, Ofcom bases its wholesale market analysis on BT's network. Within the area covered by each LE, it then determines the share of households that are potentially served also by the cable operator.

Hence, for each LE, we are able to observe: the number of premises connected to the telephone network (that is, the potential subscribers for BT and for the entrants), the number of premises covered by the cable network (that is, the potential cable market), the actual number of cable subscribers, the number of subscribers actually served by BT (either directly or by entrants by

[6]Broadband access via Wi–Fi technologies, on the other hand, is included in our dataset.

[7]In this review, the regulator makes an assessment of the relevant market for broadband services in the UK, together with the presence of market power. For an example, see: http://stakeholders.ofcom.org.uk/binaries/consultations/wba

means of Bit-stream technology), and finally, the number of actual subscribers served by each entrant by means of LLU. This information enables us to measure broadband penetration over 17 quarters for all LEs, and for the following operators: BT (including Bit-stream entry), all LLU entrants and the cable operator (Virgin Media). One limitation is that we can only observe BT's total Bit-stream wholesale business; we cannot distinguish, in each LE, between BT's own retail business and the business catered for using Bit-stream technologies. It should be pointed out, nevertheless, that the three companies within the BT group (BT Retail/BT Wholesale and Openreach) are separated, and constantly monitored, by the regulator.

The second dataset consists of information about the quality of broadband services sold across markets. The locus of competition might not be just price, but could also include product improvements, such as increased broadband speed. We therefore supplemented Ofcom's broadband penetration data with information about the characteristics and performances of those broadband packages offered by the incumbent, by the main entrants, and by the cable operator. This information was supplied by a private company specialized in connection speed tests.[8] In particular, it provided figures for 1 million speed tests performed throughout the UK in 2009. For each test, we observe the customer's postcode (and hence the respective LE), the broadband operator, the type of contract purchased, and the time the test took place. The dataset contemplates two measures of performance: download speed and upload speed. We focus on the former, which is by far the most important feature for household users.

The third dataset contains demographic information. The main difficulty encountered here was to find time-varying demographic information at the level of the LE, and in particular a measure of income. In order to estimate this variable, we proceed as follows. First of all, we use census data to obtain a highly detailed cross-section of demographic characteristics. Variables collected include ages, size of the household, ethnic group, type of occupation, sector of occupation, number of hours worked per week, and other variables that proxy for social status.[9] In addition, we have income figures collected periodically by the labor force surveys (LFS). These figures are collected at a higher level of aggregation than census data are.[10] Hence, following Smith (2004), we first regress this more aggregate measure of income (which is time varying)

[8]See http://www.broadbandspeedchecker.co.uk/

[9]See http://www.neighbourhood.statistics.gov.uk/

[10]Income is reported by the Office of National Statistics (ONS) at the middle layer super output area (MSOA), while census data are available at the level of lower layer super output area (LSOA). These two geographical units are such that the territory of England and Wales is divided into 7,193 MSOAs and 34,378 LSOAs.

on our set of demographics, and then use the estimated coefficients to predict the evolution of income at the lowest census level. Finally, we reconstruct the predicted income at the level of the LE, based on the list of post codes served by each LE contained in the sample (as provided by Ofcom).

Table 1 provides summary statistics of the main variables. The top panel shows information from the first dataset. “Broadband penetration” is defined as the ratio of the number of actual subscribers to the number of potential subscribers (which is equal to the number of telephone lines). “LLU entry” is a dummy equal to one if there is at least one LLU entrant in the LE. “LLU competitors” refers to the number of LLU entrants present in a given LE. Finally, “Cable coverage” is the fraction of local lines in the LE that can be potentially served by the cable operator as well. In Table 1 we report the number of LEs such that this variable is above 65%.[11] The middle panel shows information from the second dataset. The columns show, respectively and by technology, the average download speed measured in the tests, the relative frequency of these technological options in the sample (this frequency reflects their respective market shares), and the average distance in miles between the place where the test is run (the premises) and the LE.[12] Finally, the bottom panel shows summary statistics on the demographics. The most important variable is income in the LE, which is time-varying. Time-invariant control variables are a dummy for urban status, age, occupation and ethnic group (the latter is not reported in the table).

Summarizing, then, our data provide a precise portrait of the wholesale broadband market in the UK. They contain information at the geographic level required to study the effects of LLU entry, and cover the period during which investments were made. We are not aware of any other dataset with this level of detail elsewhere in Europe or the US. The size of the dataset is unusually large for this kind of study, as the core dataset assembled by Ofcom comprises approximately 100,000 observations. However, the analysis is carried out on a subsample of the universe of LEs. This is because demographic characteristics at the LE level (in particular average income) can only be predicted in a consistent way for England and Wales. This restricts the cross-section

[11] This number is not chosen at random. Indeed, the regulator uses this threshold when conducting its market review, since it has been estimated as the minimum size constituting a competitive constraint for the incumbent. Our results are robust to the inclusion of a dummy variable for this threshold, instead of the continuous variable. Our results are also robust to changes in this specific value.

[12] As pointed out above, we know both the location of the premises and the location of the LE in question, and thus we can calculate the distance between the two.

Table 1: Descriptive statistics

Subscribers and coverage	2005Q4	2007Q4	2009Q4
Num. lines	27,576,261	27,658,092	28,219,684
Num. subscribers	10,052,446	15,624,059	17,664,344
- *BT*	*26%*	*26.3%*	*24.7%*
- *Bit-Stream*	*41%*	*24.2%*	*15.3%*
- *LLU*	*2.2%*	*25.4%*	*37.7%*
- *Cable*	*30.8%*	*24%*	*22.4%*
Broadband penetration	36.5%	56.5%	62.6%
Num. of LEs	5,587	5,587	5,587
LLU entry	695 (12.4%)	1,733 (31%)	2,011 (36%)
Avg. num. of LLU competitors[a]	1.79	3.44	3.31
Cable coverage ≥65%	953 (17%)	844 (15.1%)	829 (14.8%)

Speed tests by operator	Download Speed (Mbit/s.) Mean	Download Speed (Mbit/s.) Std. dev.	Sample Frequency (%)	Distance (miles) Mean	Distance (miles) Std. dev.
BT	2,887	2,002	29.9	2.057	9.135
LLU entrants	3,221	2,339	51.5	1.823	6.973
Virgin Cable	5,351	3,301	18.6	1.574	5.066

Demographics	LEs without LLU Mean	LEs without LLU Std. dev	Unbundled LEs Mean	Unbundled LEs Std. dev	Test–Stat[c]	P-value
Urban (%)	13	33.6	77.4	41.8	-47.85	<0.001
Lines	1,243	1,463	12,135	8,444	-57.56	<0.001
Income[b]	568.8	110.5	514.6	126.4	15.63	<0.001
HS occupations	53.5	10.4	53.5	14.3	0	0.99
HS occupations sectors	26.5	8	29.9	11.6	-2.39	0.017
Pop. 0-14 y.o.	17.4	2.7	16.8	4.5	.47	0.64
Pop. 15-60 y.o.	57.6	4.3	60	7.2	-1.51	0.13
Pop. more 60 y.o.	25	5.7	23.2	7.6	1.32	0.19

[a]: considering the LEs where at least one operator has invested in LLU

[b]: average weekly household total income estimate

[c]: Wilcoxon-Mann-Whitney test is run on continuous variables, proportion test on dummy variables

dimension of the LE to 4,265 (out of a total of 5,587). The overall number of observations contained in our panel dataset amounts to 72,505. One important feature of these data is that relevant geographical markets are almost perfectly identified: buildings are served by only one network (or two, should cable also be present), and customers cannot move to a neighboring LE in order to benefit from lower prices or better quality (in order to do so they would have to move house). We observe the identity of each operator for each LE, so that we can track the process of entry and exit over time. As we have already mentioned, the network topologies of

BT and its main cable rival were decided decades ago. These networks have been upgraded over the years (e.g., from copper to DSL for BT; coaxial TV cables can also be upgraded). However, they have not been extended to cover a greater area; the fixed infrastructural costs (digging up existing roads) would be too high. Hence, the cable operator had already decided the areas it was to cover back in the 1990s: within such areas, it could further choose to serve buildings and make additional investments, but it could not extend its reach. Entrants, on the other hand, can decide where to enter, given BT's coverage. Should they decide to enter via LLU, which would give them full control over the service provided to the end customer, they have to sink costs. According to industry sources, the average LLU entry cost per LE is around £100,000: thus if an entrant wanted to enter all the UK's LEs, it would have to spend the considerable sum of £500 million.

3 An initial look at the market

We use our various datasets to take an initial look at the market. We first consider the trend in LLU entry over the sample period. We then look at broadband penetration, and compare the evolution of markets both with and without LLU coverage.

LLU entry. Figure 1 shows the evolution of LLU entry between 2005Q4 and 2009Q4. The Figure portrays LLU entry across LEs, that is, the fraction of LEs where LLU has been enabled so that there is at least one LLU entrant. The fraction of LEs offering LLU entry increased rapidly from 12% in 2005 to about 30% in mid-2008. After that, the unbundling process slowed down somewhat, resulting in a fraction of unbundled LEs of 36% at the end of 2009. This fraction may not appear that high at first; however, it should be remarked that unbundling typically takes place in those LEs with a large number of premises (and thus telephone lines), as shown in the lower panel of Table 1, where we compare the average number of lines potentially served in unbundled LEs, with the average number of lines in the remaining non-unbundled LEs. Hence, the total percentage of lines that can be served by LLU entrants was actually much higher than 36% in 2009: about 85% of telephone lines in the UK had access to at least one LLU entrant.

Figure 2 presents two maps of the UK to show how LLU expanded geographically. In the figure, each little circle represents a LE. In 2005, LLU coverage was limited to those LEs serving London and other selected city centers. By the end of 2009, LLU had spread substantially: the number of LEs covered by unbundling had tripled. The maps clearly show the importance of

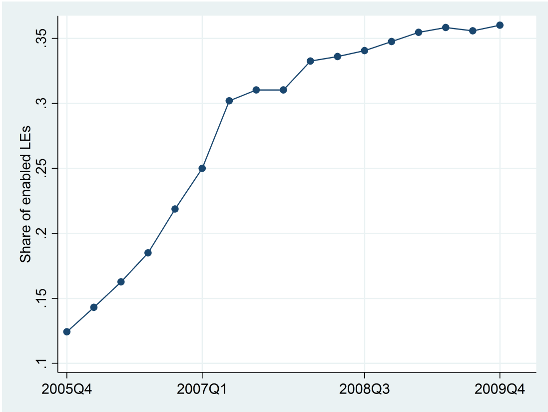

Figure 1: Share of unbundled LEs over time.

neighborhood effects on LLU coverage and growth. This may be due to the fact that neighboring areas are demographically similar (urbanized, high income, etc.). There may also be a number of real agglomeration effects, in particular stemming from economies of density in LLU investment.[13]

To further understand LLU entry, we estimated several simple entry models, keeping with Bresnahan and Reiss (1991; henceforth BR). We extend their static model to allow for entry persistence because of sunk costs, as in Bresnahan and Reiss (1994) and Xiao and Orazem (2011). We also account for a spatial entry effect because of possible economies of density. We describe these entry models in more detail in the Appendix. Here, we simply provide an intuitive overview of the determinants of LLU entry, based on the pooled dataset of 4,265 LEs and 17 quarters.

Table 2 shows the results. The first column is a static probit model for LLU entry as a function of market demographics. The most important determinant of LLU entry is the number of telephone lines, that is, the potential number of subscribers within a given LE. Furthermore, LLU entry is more likely in LEs situated in urban areas, where average income is high, and a large proportion of the population are of a working age. The model includes a trend as a main effect and interacted with the number of telephone lines. Based on these estimates, we compute "entry thresholds", that is, the minimum market size required to support LLU entry at particular points in time (see once again the Appendix for details). According to the left-hand panel in Figure 3, the number of telephone lines required to sustain LLU entry was initially more than

[13]Entrants must build or purchase a network backhaul link (that is, a leased line) to connect each LE where they are present back to their core network. Leased line costs increase proportionally with the link distance, and so once LLU has been put in place in a LE, the cost of unbundling a neighbouring LE will be lower than in non-adjacent areas (which will be further away from the core network, and thus more costly to serve).

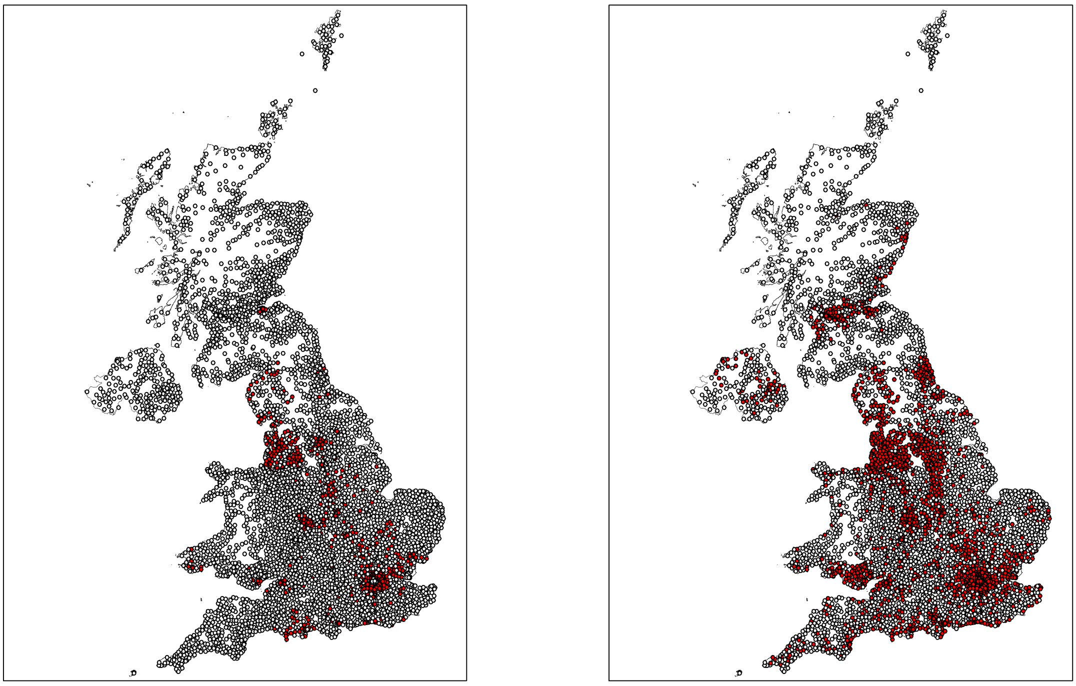

Figure 2: LEs without LLU (white) and with at least one LLU operator (red) over time. Left panel: 2005Q4; right panel: 2009Q4.

25,000, but this figure quickly dropped dramatically to about 4,000. As in Xiao and Orazem (2011), these falling entry thresholds may either stem from declining investment costs, or from an increase in demand, or indeed from a combination of both.

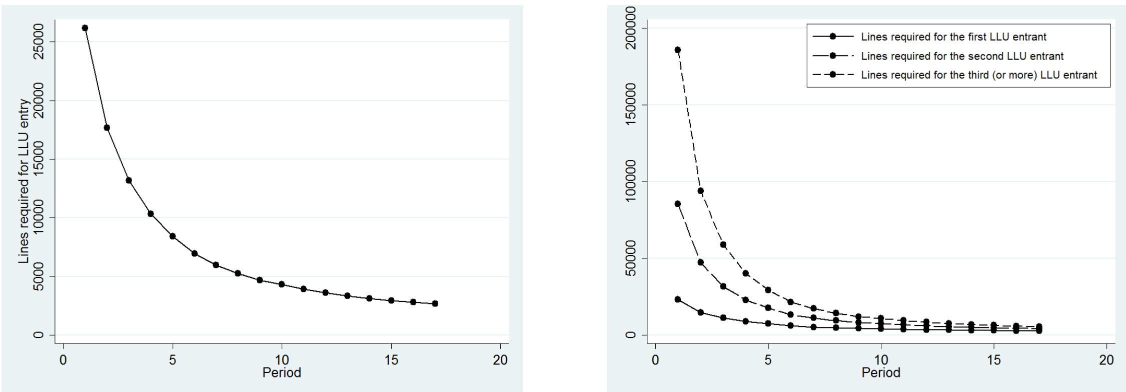

Figure 3: Entry thresholds BR model. Left panel: estimated entry thresholds BR model where the dependent variable is entry of at least 1 operator with LLU. Right panel: estimated entry thresholds BR model where the dependent variable is the number of entrants with LLU (limited to 3).

Table 2: Estimates of the entry models

Dependent Variable:	**LLU entry**			**Num. of competitors**	
	BR	BR spatial	Sunk cost	BR	Sunk cost – spatial
Log(lines)	0.519***	0.463***	0.578***	0.567***	0.742***
	(0.016)	(0.016)	(0.030)	(0.014)	(0.022)
Log(lines) × Trend	0.067***	0.065***	0.011***	0.082***	0.032***
	(0.002)	(0.002)	(0.003)	(0.001)	(0.002)
Log(income)	0.106	0.172**	0.095	0.393***	0.694***
	(0.056)	(0.057)	(0.109)	(0.048)	(0.070)
Working age	0.029***	0.032***	0.017**	0.028***	0.030***
	(0.003)	(0.003)	(0.005)	(0.002)	(0.003)
Over 60 y.o.	0.012***	0.019***	0.010*	0.014***	0.024***
	(0.002)	(0.002)	(0.005)	(0.002)	(0.003)
White	-0.018***	-0.013***	-0.004	-0.019***	-0.013***
	(0.002)	(0.002)	(0.003)	(0.001)	(0.001)
Black	0.054***	0.045***	0.025	0.073***	0.080***
	(0.010)	(0.009)	(0.019)	(0.006)	(0.009)
HS occupation	-0.009***	-0.010***	-0.005	-0.014***	-0.016***
	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)
HS sector	0.019***	0.012***	0.008**	0.026***	0.014***
	(0.001)	(0.001)	(0.003)	(0.001)	(0.002)
Urban	0.080***	0.103***	0.077*	0.062***	0.065**
	(0.018)	(0.019)	(0.033)	(0.016)	(0.023)
Trend	-0.449***	-0.440***	-0.068**	-0.569***	-0.217***
	(0.014)	(0.014)	(0.025)	(0.012)	(0.019)
LLU within 5 miles		0.555***			0.440***
		(0.016)			(0.020)
Sunk cost			3.679***		3.045***
			(0.035)		(0.026)
Fixed effect firm 1	6.380***	7.206***	4.252***	8.494***	9.900***
	(0.494)	(0.499)	(0.936)	(0.410)	(0.596)
Fixed effect firm 2				9.349***	10.414***
				(0.410)	(0.596)
Fixed effect firm 3				9.853***	10.758***
				(0.411)	(0.597)
Pseudo R-squared	0.593	0.606	0.878	0.522	
Model chi-square	54,481.065	55,678.629	76,880.746	71,327.260	10,952.368
Observations	72,505	72,505	68,240	72,505	68,240

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

The next two columns of Table 2 report results from a dynamic probit model with spatial effects and with sunk costs. The effects of the market demographics remain very similar. In the second column, the dummy variable for LLU coverage in a neighboring LE (within 5 miles) has a positive and significant coefficient. This is consistent with the earlier maps in Figure 2, and suggests there are indeed important economies of density associated with LLU investment. Besides the costs associated with the network backhaul link (see footnote 13), such economies of density may stem from the lower cost of maintenance by engineers, reduced equipment costs, or reduced marketing costs for LLU in neighboring LEs. In the third column, the sunk cost effect is highly significant. Intuitively, this would seem to be due to the strong persistence of LLU coverage. The estimates imply a large gap between the entry and exit thresholds. For example, by the end of 2009, the estimated entry threshold was 14,673 lines, while the exit threshold was only about 150 lines.

The fourth and fifth columns extend the probit models of LLU coverage by at least one entrant to ordered probit models for the number of LLU entrants (0, 1, 2 or 3+): the fourth column is a static version, while the fifth column is a dynamic version with spatial effects. The results regarding market demographics, sunk costs and economies of density remain similar. The new finding relates to the "cut-off points" of the ordered probit, referring as it does to fixed effects for each market configuration. These can be used to compute entry thresholds supporting at least 1, 2 or 3+ LLU entrants. According to the right-hand panel in Figure 2, in 2005 the number of telephone lines required to sustain at least 1, 2 or 3+ entrants was, respectively, 22,928, 85,389 and 185,607. The latter figure is extremely high, but it fell rapidly. By the end of 2009, these entry thresholds had dropped to 2,687, 4,148 and 5,361 respectively.

In conclusion, these findings would suggest that a sufficiently large market size is important if fixed investment costs are to be covered, but also that these fixed costs have sharply declined in recent years. Furthermore, a large part of the investment costs appears to be sunk, and there are benefits to be gained from economies of density. We will take these findings into account when suggesting various identification strategies to estimate the impact of LLU investment on broadband penetration.

Broadband penetration and the quality of service. As defined above, total broadband penetration is the sum of subscribers of the incumbent, the LLU entrants and the cable operator, expressed as a percentage of the number of potential subscribers (that is, the number of telephone lines). The left-hand panel in Figure 4 shows that broadband penetration almost doubled between the end of 2005 and the end of 2009, from 36% to 62% (and in 2012 it has reached 66%). During the same period, LLU broadband penetration increased from a negligible 0.8% to a much more substantial 24% of potential subscribers. The right-hand panel in Figure 4 shows that the growth of LLU penetration coincides with a parallel fall in Bit-stream penetration at national level. The

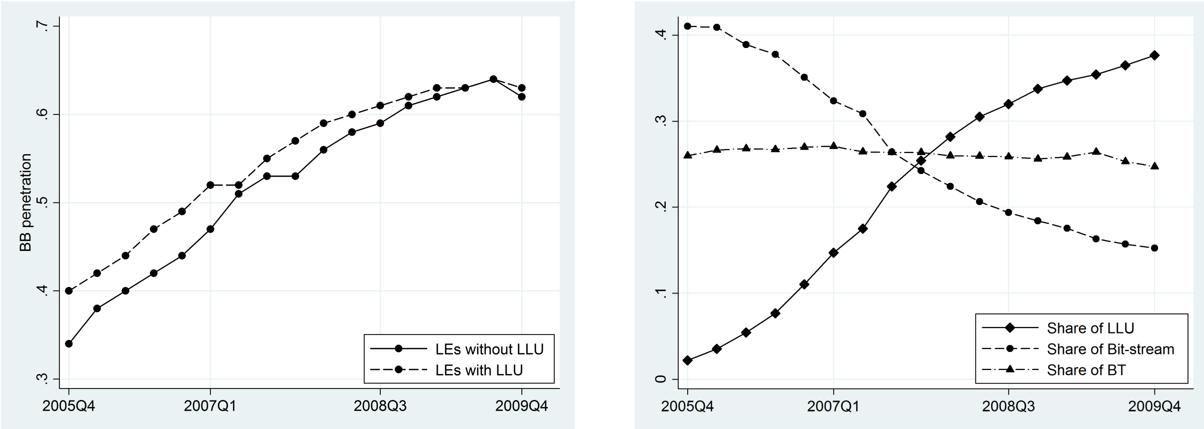

Figure 4: Left panel: Penetration in LEs with and without LLU. Right panel: Market shares of BT and the entrants.

market share of LLU (as a fraction of the overall market) increased from 2% to 38%, while the market share of Bit-stream fell from 41% to 15%. Hence, the entrants to BT's network have essentially moved from providing broadband services through Bit-stream, to LLU. The retail market share of the incumbent BT remained largely unchanged at about 26%, meaning its penetration rate essentially followed market growth, while the market share of cable (not shown in the figure) fell slightly.

One of the main questions we seek to answer is whether broadband penetration increased more rapidly in those LEs where LLU investments were made, than in those where this was not the case. The left-hand panel in Figure 4 is overall rather inconclusive. On the one hand, at the end of 2005 broadband penetration was almost 10% higher in those LEs with LLU entry (dashed line) than in those LEs without LLU entry (solid line). On the other hand, by the end of 2009 broadband penetration was roughly comparable across markets with or without LLU entry.

This indicates that LLU was first introduced in the more profitable markets. Table 1 confirms this hypothesis. Markets with LLU entry tend to be more urban (77.4% versus 13% for other markets), and more densely populated (the average number of lines in unbundled areas is tenfold the number in those areas that did not receive LLU investments). However, average income is lower in unbundled areas. This is in line with the fact that once having started unbundling the central, densely populated areas, operators then move to adjoining neighborhoods, even if the average income is lower than in other, more distant areas that have not received LLU investment for some time.[14] Finally, areas receiving LLU are characterized by a greater proportion of people working in high-skill sectors, and by a larger proportion of the population being of a working age (16-60).

To sum up, there does not appear to be any strongly positive or negative relationship between LLU entry and broadband penetration. However, in order to obtain a reliable picture, we need to perform an analysis at the level of the LEs, taking account of the endogeneity of LLU entry and of the fact that LLU was first introduced in the more profitable markets, which we shall do in Section 4.

Finally, Table 1 reveals that the quality of services (measured by the download speed) is higher in unbundled LEs. As we will show in Section 5, this is due to the presence of LLU entrants, leading to an improvement in quality compared with BT.

4 LLU entry and broadband penetration

4.1 Empirical model

As already explained, we make use of data on 4,265 LEs, indexed by i, observed over 17 time periods, t. For each LE i and time period t, we observe the broadband lines of the incumbent, of the LLU entrants, and of cable. We also observe market demographics, including income. The basic specification takes the following form:

$$y_{it} = \eta_i + \tau_t + \beta LLU_{it} + \gamma x_{it} + \varepsilon_{it}. \tag{1}$$

Here, y_{it} is the relevant performance measure of broadband penetration. We first focus on total broadband penetration, that is, total broadband subscribers as a percentage of total telephone lines. Later, we also look at one component of total penetration, namely the alternative wholesale technology of the incumbent (Bit-stream) as a percentage of total telephone lines. LLU_{it} is our main variable of interest relating to the presence of LLU entry. The vector x_{it} contains time-varying control variables, such as average income in the LE. Finally, specification (1) includes individual effects η_i capturing time-invariant characteristics of the LEs (such as urban status), time effects τ_t capturing the growth in UK broadband adoption over the 17 quarters during the period 2005–2009, and a residual error term ε_{it}, specific to each LE/time period.

[14]Indeed, as Table 2 shows, it turns out from the estimates of the entry models that, after controlling for spatial proximity and for the number of lines, the effect of income on the probability of LLU entry is positive.

We consider several ways of estimating the effect of LLU on broadband penetration, based on (1). Our benchmark approach is a within-groups estimator, which conditions the 4,265 fixed effects η_i.This estimator accounts for the possibility that LLU investment is more likely in LEs with high time-invariant shocks η_i (positive correlation between LLU_{it} and η_i). This avoids overestimating the effect of LLU investment on broadband penetration under a simpler random effects estimator. Since (1) does not only include the LE fixed effects η_i but also time effects τ_t, one may also interpret the within-groups estimator as a difference-in-difference estimator. This means that the estimated coefficient of LLU entry measures the effect of LLU investment net of the common growth in penetration experienced by all LEs during the period under examination.

Although the within-groups estimator is a useful first approach to identify the effect of LLU on broadband performance, it is still possible that LLU_{it} is correlated with the remaining error term ε_{it}, conditional on the fixed effects η_i. To account for this possibility we consider three alternative identification strategies, based on the entry models we estimated earlier.

As a first alternative, we instrument LLU investment by a dummy variable for LLU investment within a radius of 5 miles of an LE. As in Nevo (2001), the identification assumption is that shocks in broadband performance ε_{it} are uncorrelated across LEs, conditional on the time-invariant shocks and control variables. Under this assumption, a shock in ε_{it} will be uncorrelated with LLU investment in neighboring areas. Furthermore, because of economies of density, LLU investment in the LE will be correlated with LLU investment in neighboring areas, so that this can be used as an instrument.

As a second alternative, we instrument LLU investment by a lagged dummy variable. The identification assumption here is that of no serial correlation in broadband performance ε_{it}, conditional on the time effects and control variables. A current shock in an LE is then uncorrelated with past LLU investment, while due to sunk costs, current LLU investment is correlated with past LLU investment.

Finally, the third identification strategy is a more refined approach of the previous one. We specify a dynamic version of (1) with a lagged dependent variable y_{it-1} (which essentially allows for an autoregressive component in ε_{it}). Following Blundell and Bond (1998) and Blundell et al. (2000), we estimate this model by adopting a system GMM approach, using lags of the differences as instruments for the endogenous variables in levels. This estimator has been shown to be an improvement on the one proposed by Arellano and Bond (1991) when series display some persistence, as in our case. We also considered a constrained version of this model with no persistence (no lagged dependent variable).

To summarize, we use a variety of alternative identification strategies to estimate the impact of LLU entry on performance. We will pay particular attention to a comparison with the estimated impact of cable coverage (a variable in x_{it}), to contrast the impact of intra-platform competition with that of inter-platform competition.

4.2 Empirical results

Table 3 reports the empirical results of estimating (1), where the performance measure y_{it} is total broadband penetration (as a percentage of the total number of telephone lines) and LLU_{it} is a dummy for whether there is at least one LLU entrant. Income has a positive and significant effect on penetration. The effects of the demographics are absorbed into the LE fixed effects, since they are time-invariant. A second-stage regression of the fixed effects on the demographics (not reported) shows that broadband penetration is significantly higher in urban LE areas, in areas with a large proportion of highly skilled workers, of whites (compared to people of Asian or Afro-Caribbean origin), and of people under the age of 16 (compared to those of a working age and the elderly).

Our main interest is in the impact of LLU entry on broadband penetration. The first column, based on the within-groups estimator, suggests a very limited negative impact of LLU coverage on broadband penetration, of about 1 percentage point. The second column, using LLU coverage in a neighboring area as an instrument, suggests a more negative impact. The third column, using lagged LLU coverage, confirms the result of the first column, that is, a slightly negative impact. Finally, the last two columns, where we employ a system GMM estimator suggest a very small positive impact. In the static version (fourth column), the coefficient is very small (+0.2%) and not significantly different from zero, while in the dynamic version (last column) the estimated long-term effect amounts to a significant, albeit modest, +1.4%. Overall, we conclude that LLU coverage has at most a small effect on broadband penetration. This contrasts with the estimated impact of cable coverage, which has a significantly positive and larger effect on penetration. In fact, according to the dynamic GMM model, the long-term impact of cable coverage on broadband penetration is +3.4%.[15]

[15] In the static GMM model, the effect of cable is estimated to be even larger, i.e., +6.8%. However, in the static model the results should be taken with more caution, since the null hypothesis of zero second-order serial correlation is rejected. This contrasts with the dynamic model with two lags, where the null hypothesis of zero serial correlation is not rejected.

Table 3: Estimates of the total penetration models

Dependent Variable: Total Broadband Penetration	Panel FE	Panel IV (Spatial lag)	Panel IV (Time lag)	GMM (static)	GMM (dynamic)
LLU entry	-0.009***	-0.056***	-0.008***	0.002	0.007***
	(0.001)	(0.003)	(0.001)	(0.002)	(0.001)
Cable Coverage	0.02***	0.017***	0.019***	0.068***	0.018***
	(0.003)	(0.001)	(0.001)	(0.009)	(0.005)
Log(income)	0.052***	0.064***	0.04***	0.054***	0.035***
	(0.007)	(0.004)	(0.004)	(0.000)	(0.002)
Tot Penetration_{t-1}					0.437***
					(0.038)
Tot Penetration_{t-2}					0.044***
					(0.007)
Constant	0.011	-0.052**	-0.118***		
	(0.042)	(0.027)	(0.026)		
AR(1) p-value				<0.000	<0.000
AR(2) p-value				0.0002	0.048
Long run coefficients:					
LLU entry					0.014***
					(0.003)
Cable Coverage					0.034***
					(0.009)
Observations	72,505	72,505	68,240	72,505	68,240
Period FE	YES	YES	YES	YES	YES
Number of LEs	4,265	4,265	4,265	4,265	4,265
R-squared	0.57	0.51	0.53		

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

As a sensitivity check, we also estimated equation (1), where LLU_{it} is now the number of LLU entrants, instead of a dummy for at least one entrant. The results (not reported) reveal a consistent picture. For all estimators, the number of LLU competitors has a small negative impact on broadband penetration, whereas cable coverage has a significant positive effect.

To summarize, Table 3 shows that intra-platform competition through LLU entry has not significantly raised total broadband penetration. In contrast, inter-platform competition through cable has had a more significant impact. Our finding regarding LLU entry can be interpreted in several ways. Firstly, it may be that the UK regulator, Ofcom, has done a good job in regulating wholesale Bit-stream prices and ensuring competition in smaller markets where there is no LLU entry. Secondly, it is possible that LLU entry has impacted performance in areas other than price competition, for instance, with regard to the quality of service. We will explore the impact of LLU on the quality of service in the next section.

Before addressing this question, however, we examine how LLU has affected Bit-stream broadband penetration, defined as the sum of BT's own retail business and Bit-stream supplied by entrants. Table 4 shows the results, based on specification (1), where the performance measure y_{it} now refers to broadband penetration of Bit-stream. The results show that LLU entry in

Table 4: Estimates of the Bit-stream penetration models

Dependent Variable: Total Bit-stream Penetration					
	Panel FE	Panel IV (Spatial lag)	Panel IV (Time lag)	GMM (static)	GMM (dynamic)
LLU entry	-0.110***	-0.157***	-0.374***	-0.157***	-0.03***
	(0.003)	(0.002)	(0.007)	(0.006)	(0.002)
Cable Coverage	-0.093***	-0.085***	-0.086***	-0.191***	-0.039***
	(0.025)	(0.007)	(0.009)	(0.015)	(0.005)
Log(income)	0.013	0.027***	0.076***	0.062***	0.014***
	(0.019)	(0.008)	(0.010)	(0.001)	(0.001)
Bit-stream penetration$_{t-1}$					0.737***
					(0.03)
Bit-stream penetration$_{t-2}$					0.143***
					(0.024)
Constant	0.243**	0.203***	-0.108*		
	(0.115)	(0.053)	(0.064)		
AR(1) p-value				<0.000	<0.000
AR(2) p-value				<0.000	0.221
Long run coefficients:					
LLU entry					-0.248***
					(0.014)
Cable Coverage					-0.324***
					(0.034)
Observations	72,505	72,505	68,240	72,505	68,240
Period FE	YES	YES	YES	YES	YES
R-squared	0.55	0.54	0.57		
Number of LEs	4,265	4,265	4,265	4,265	4,265

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

an LE has a strong negative effect on Bit-stream. Hence, while LLU entry does not affect total broadband penetration, it clearly shifts the composition of those technologies adopted. This shift is somehow consistent with the "ladder of investment" hypothesis: entrants first use the incumbent's network through Bit-stream access, with few or no investment costs, and subsequently make their own equipment investments through LLU entry (Cave 2006). As such, the regulator appears to have achieved its goal of switching from Bit-stream to LLU competition, although, as reported above, this resulted in no difference in the impact on penetration, between Bit-stream areas and LLU areas. The effect of the presence of cable is negative, as expected, given that this is a strong competitor of both BT and entrant ISPs. Other that this direct effect, cable is likely to have fostered the process of migration to LLU by determining an incentive to differentiate with respect to BT. In fact, as we shall see in the next Section, entrants are able to increase the quality of their Internet services only upon switching to LLU.

5 LLU entry and the quality of service

One explanation for the limited effect of LLU on broadband penetration, lies with the product differentiation pursued by entrants when investing in LLU. In this section we assess whether entrants, once they have obtained control over the last mile, invest by offering higher broadband quality. To explore this question, we make use of the dataset regarding the quality of connections. As reported above, this dataset contains information from one million individual speed tests run by end-users.[16] For each test, we observe the measured speed of the connection, the geographic location of the user (at postcode level), the time of the day when the test was carried out, the operator providing the service (BT, cable, or one of the entrants to BT's network), and the specific contract stipulated between the user and the operator (e.g., "Sky Base", "Sky Unlimited", etc.). We restrict the sample to those tests run in 2009 on the main operators in the market: BT, Virgin Media (the cable operator) and the main LLU entrants: O2, TalkTalk, Sky and Orange.[17]

The location of end-users, and the time of day the test is carried out, are very important factors affecting the speed of the connection. As Ofcom's reviews on broadband speed show,[18] the distance between the user's premises and the LE is the most important factor affecting the performance of a given connection. As a proxy for the distance between the premises and the LE, we use the distance between the geographic center of the postcode area where the test is run, and the exact location of the LE. The time of the day is also important, since the Internet

[16] To assess the representativeness of this sample, we looked at the market shares of BT, Virgin Media and the entrants at the level of the LE. We found that the market shares as computed from Ofcom's detailed subscriber dataset and the currently used speed test dataset display a correlation very close to 1.

[17] Despite many other brands being present in the market, these four groups account for 94% of the entrants' market alone.

[18] See for instance: http://stakeholders.ofcom.org.uk/market-data-research/other/telecoms-research/broadband-speeds

is more congested at certain times than at others. While the latter element is less of a concern if the aim is to compare the speed of connections provided by different operators in the same area, the former factor is very important. This is because, due to the entrants' choice of location, there is a significant difference between the average distance of BT's customers and of its rivals' customers. Since BT is covering all areas, and in particular rural areas that are not covered by entrants, the average speed of BT suffers from the fact that, on average, it is serving more distant consumers. This can be clearly seen in the lower panel of Table 1. The average distance (not reported) between a user and the corresponding LE in the whole sample is 1.84 miles. BT has the highest average distance, 2.06 miles, and, more importantly, the greatest standard deviation, 9.14 miles. LLU entrants on average have their end-users within a range of 1.82 miles from the LE, with a standard deviation of 6.97 miles. This situation is explained by the fact that the incumbent, subject to Universal Service Obligations for voice telephony, which uses the same infrastructure, is providing Internet services throughout rural areas, which are much larger than urban sites.

Table 1 also reveals that the average speed is heterogeneous across operators. Part of this variability is due to the conditions under which speed tests are carried out, as has just been explained. However, part of it is related to the intrinsic quality that each operator can offer. To measure the difference in quality between operators, we first estimate the following model for the (log of) speed of a test j in LE i:

$$\ln speed_{ij} = \gamma_1 LLU\_OP_{ij} + \gamma_2 Bitstream\_OP_{ij} + \gamma_3 Cable\_OP_{ij} + \beta x_{ij} + \eta_i + \varepsilon_{ij}. \quad (2)$$

Here, LLU_OP_{ij}, $Bitstream\_OP_{ij}$ and $Cable\_OP_{ij}$ are dummy variables equal to 1 if the test was run, respectively, on a line served by an LLU entrant, by a Bit-stream entrant, or by the cable operator. If all technology dummies are equal to zero, this means that the test is run by BT. Hence, the coefficients γ_1, γ_2 and γ_3 measure the percentage extra speed for the different technologies, compared to the BT base. The vector x_j contains control variables: the *urban* dummy variable, the log of *income*, *distance* and $distance^2$, a set of dummy variables for the hour at which the test is carried out, and a set of dummy variables for the day of the week on which it is carried out. Finally, we include LE fixed effects η_i to control for unobserved factors that may affect the speed of all operators in the same way in a LE (e.g., the distance from the LE to the backbone, which has the same effect on the speed of connections of all operators in the LE).

Table 5 reports the results. The first column shows the estimates of specification (2). We start with the control variables (x_{ij}). As expected, the distance between the user and the LE has a strong and highly significant negative effect on speed. Furthermore, the time of the day plays an important role (not reported in table). The average connection speed reaches its peak at 6 a.m. It then gradually declines, with speed 10% lower at noon, 21% lower at 6 p.m. and indeed 32% lower at 9 p.m. From then on, the average speed of a connection gradually increases until 6 a.m. The day of the week also determines average speed: it is lowest over the weekend, when residential users tend to be at home.

We now move to the technology dummy variables, which represent our main item of interest. Users who subscribed to an LLU operator have a connection speed that is about 20.1% higher than that provided by BT (equal to $e^{0.183} - 1$). On the other hand, subscribers to a Bit-stream service have a significantly lower connection speed than BT subscribers, the difference between the two being roughly 18.5%. This may be due to coordination difficulties when the entrant and the incumbent have to share a line. Finally, users of cable (Virgin) have a much higher broadband speed (about 78% faster) than that of BT. To summarize, these findings show that the LLU regulation designed to grant full control of the connection to entrants, has been highly successful. This success is not the result of an increase in total broadband penetration, but of a substantial increase in the quality of the service provided: LLU entrants invested in order to make their broadband connections faster than that of the incumbent and on average 47.3%[19] faster than when they operated using Bit-stream technology. This substantial improvement in speed achieved by LLU operators constitutes a valid explanation for the decreasing market share of the cable operator. LLU operators, by getting increasingly closer to the speed of cable, have become a viable alternative both to BT (for end-users looking for a speed higher than the incumbent's) and to cable (for end-users looking for intermediate/high speed).

Is the higher speed of service uniform across LLU entrants, or are there important differences between them? To address this question, we extend specification (2) to allow the effect of LLU_OP_{ij} to differ across the four entrants. The second column of Table 5 shows that there is in fact considerable heterogeneity between entrants. Two LLU operators achieve a slightly higher speed than BT, while the other two operators clearly outperform BT: TalkTalk is on average 23.9% faster than BT, while O2 is up to 65.9% faster, and almost reaches the speed of the cable operator.[20]

[19] This is calculated from $e^{0.183+0.204} - 1$.

[20] This is entirely consistent with reports from the specialized press showing that these Internet Service Providers

Table 5: Regressions on the (log of) speed of connection

Dependent Variables:	Log of download speed (all ISPs)				Log of download speed (BT only)	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
LLU	0.183***	(0.007)			0.115	(0.072)
TalkTalk			0.214***	(0.009)		
O2			0.506***	(0.011)		
Orange			0.068***	(0.013)		
Sky			0.084***	(0.009)		
Bit-stream	-0.204***	(0.009)	-0.200***	(0.009)		
Cable	0.577***	(0.011)	0.575***	(0.010)	-0.189	(0.154)
Constant	8.143***	(0.013)	8.140***	(0.013)	8.242***	(0.072)
Dist. and dist.^{2}	YES		YES		YES	
Hours & Day	YES		YES		YES	
Observations	985,590		985,590		358,849	
R-squared	0.195		0.204		0.199	

Robust standard errors in parentheses, fixed effects at the LE level, *** p<0.01, ** p<0.05, * p<0.1

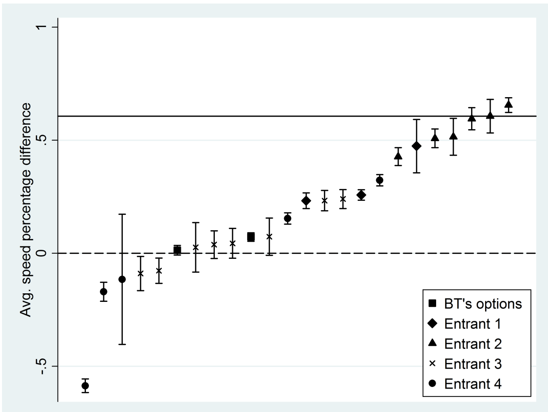

Figure 5: Entrants' relative performance compared to BT's base option.

Do all subscribers to an LLU operator obtain the same quality of service, or do operators offer substantial differences in speed depending on the type of contract? To address these questions, we further extend specification (2). We now allow the speed effect of each operator (BT, the four LLU entrants and the cable operator Virgin) to differ by contract option. In total, there are 29 contract options: 3 offered by BT, 4 offered by Virgin, and the remaining 22 offered by the LLU operators. Since this regression has several variables, we do not present the results in the table.

were the first to deploy the ADSL2+ technology, which is capable of doubling the frequency band of typical ADSL connections, and achieve higher speeds.

Instead, we plot the 29 estimated speed effects in Figure 5. The dashed horizontal line refers to the speed of BT's baseline contract (normalized at zero). The solid line, above the dashed one, depicts the average speed of the cable operator. The squares identify the two options, other than the baseline contract, sold by BT. Diamonds, triangles, crosses and dots refer to the LLU options of TalkTalk, O2, Orange and Sky, respectively. The vertical lines are the 95% confidence intervals of the speed effects. Figure 5 reveals an interesting picture: LLU entrants also sell a few contract options with an average speed below those of BT's options. However, the majority of LLU contract options have higher speeds than BT's products, and all operators offer at least two options with an average speed that is 12% higher than BT's baseline option.

Are subscribers more likely to choose high speed contracts from an operator that has invested in LLU, than when that operator only has Bit-stream? Figure 6 sheds some light on this question in the case of two operators: O2 (left-hand panel) and Sky (right-hand panel).[21] The figure shows

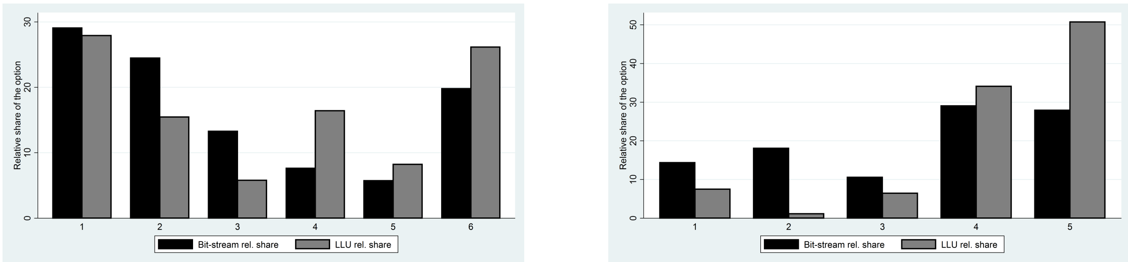

Figure 6: Left panel: relative shares of contract options for O2; Right panel: relative shares of contract options for Sky.

the market share of each contract option offered by a given operator, measured in terms of the number of observed tests in the dataset. The contract options are ordered by speed, from the slowest to the fastest. The gray bars show the market shares of the options in those LEs where the operator offers LLU; the black bars show the market shares of the options in areas where the operator was still providing broadband through Bit-stream. We can draw the same conclusions for both operators: in areas with LLU (gray bars), the distribution of market shares has more mass to the right, that is, towards the faster contractual options.[22] For both operators, we run

[21]To save space, we focus on O2, the fastest, with the 6 options that we labeled with triangles in Figure 5; and on Sky, the operator with the highest speed dispersion, with the 5 options that we labeled with dots in Figure 5. Similar results also hold for the other two LLU operators.

[22]This applies, not surprisingly, to the fastest LLU operator O2 (left panel of Figure 6). But the same holds for Sky, which is offering the 3 slowest contracts but also two fast contracts, which outperform BT's base option by 15% and 32% respectively. In this case the relative shares of the two slowest options drop substantially when the ISP adopts LLU whereas the two fastest options (and especially the best one) gain a large share of sales.

a non-parametric test for the equality of distributions, leading to strong rejection of the null. This means that subscribers are more likely to choose the high speed contracts in areas where the operator has already adopted LLU. This suggests that operators indeed tend to encourage take up of high speed connections when they are in a better position to provide that speed, that is, when they are in full control of the connection and can invest in it. This finding is also in line with the possibility that, in those markets where they can differentiate their products from those offered by BT, they tend to offer different prices for higher quality and lower quality services.

Before concluding, we would like to address the following question: did the incumbent (BT) react to other companies' entry by changing the speed of its services? This question is of relevance in the policy debate, as incumbents often argue that forced access is a regulatory undertaking that tends to curb own investments. Regulators, on the other hand, argue that entrants' investments can force the incumbent to match them with its own investments. Our answer to this question can be found in the last column of Table 5, where we limit the sample to the set of tests run on BT's users. In this case, the *LLU* dummy variable takes a value of 1 if at least one LLU operator is present in the LE, while the *Cable* dummy variable is the cable operator's coverage within the LE.[23] Results show that BT is not significantly reacting to entry by increasing its speed selectively in those areas with LLU. Instead, the incumbent provides quality uniformly throughout the country. This finding is consistent with regulatory documents, and with BT's own documents, stating that BT maintains a national pricing policy for all of its packages.[24]

6 Conclusion

In this paper we have used a rich dataset regarding the demand for Internet services, and the investments made by telecom operators, in the UK, in order to study the impact of access regulation on two market outcomes: total demand (penetration rate) and the quality of the service provided. The economic implications of access regulation are of great importance, given the relevance of this sector for the overall performance of the economy. However, the scarcity of detailed data sources has so far prevented any definitive empirical conclusions being drawn regarding the economic effects of such policies. Our findings are not confined to the market under

[23]Notice that in this last regression about BT, *LLU* and *Cable* are different variables than in the previous two columns. They instead are the very same variables employed in the previous section. We labeled them in the same way in the Table simply for the sake of space.

[24]See, e.g., http://stakeholders.ofcom.org.uk/binaries/consultations/wba/statement/wbastatement.pdf

analysis, but contribute more widely to the regulatory and policy debate in other markets where vertically-integrated monopolies can exercise their market power. Indeed, the presence of a non-replicable infrastructure giving incumbents market power, represents a distinctive feature of all network industries that have been subject to access regulation on the basis of similar principles.

Our dataset spans 5 years, up to December 2009. During this period of time, Local Loop Unbundling has been introduced and rapidly developed, to become the most important technological option adopted by entrants. It has replaced Bit-stream, which is an entry option close to simple resale. Regulators still consider LLU the best way to encourage competition among operators, and to achieve a significant degree of market expansion. This is because entrants, through LLU, can effectively enter the "last mile" in the downstream market, providing the service to final users without having to rely on the incumbent to take care of the connection.

The empirical evidence we have presented challenges a prevalent policy view on unbundling. While unbundling is often described as a policy tool designed to increase adoption, we have found no strong evidence of this happening. Despite its widespread take up by entrants, the observed effect of LLU on total penetration turns out to be extremely limited. This is a remarkable result, and one which runs counter to many policy statements. The data reveal instead that inter-platform competition from cable always leads to market expansion.

While the minimal impact of LLU on total penetration may be surprising, we also show that any accurate assessment of unbundling must also cover investment in the quality of the service provided. LLU entrants have focused on the high-end of the market, drawing high-speed users away from the incumbent by offering them a better quality service. They have also increased their marked shares at the expense of the cable operator, which still offers the highest speed. On the other hand, in those areas where entry via LLU has not occurred, entrants were nonetheless able to use the incumbent's network (Bit-stream), although they could not differentiate themselves in terms of the service provided, and thus could compete only along the price dimension. The combination of regulated Bit-stream access prices with a relatively homogeneous product, has meant that penetration in non-LLU areas has not suffered particularly compared to those areas with LLU entry, despite the former being typically rural and scarcely inhabited. To sum up, then, our final assessment of unbundling is positive when we consider the non-price aspects of the question. LLU adoption has not created any digital divide, in terms of penetration, between urban and rural areas. Instead, it has led to a shift in the locus of competition, from the price to the quality dimension, with a resulting increase in product differentiation.

7 Appendix: Models of LLU entry

This Appendix provides background to the estimated models of LLU entry, as presented in Section 3. Estimating these models is important for two reasons. First of all, understanding LLU entry is in itself of interest, as it gives us an insight into intra-platform competition, which complements recent studies of inter-platform competition in telecommunications markets, such as those by Greenstein and Mazzeo (2006) and by Xiao and Orazem (2011). Secondly, a more thorough understanding of the entry process can serve as a guide for identification strategies to address our main research question, namely the way in which LLU has affected performance in the UK broadband market. We are interested in two aspects of the entry process across LEs: the question of whether there will be LLU coverage (at least one entrant), and the question of how many LLU competitors will enter the incumbent's network across LEs. The following framework covers both cases.

Bresnahan and Reiss (1991) propose a static entry model which enables them to understand the profit determinants of entry, and to compute "entry thresholds", that is, the minimum market size required to profitably enter and to cover fixed costs. Bresnahan and Reiss (1994) show how to extend this to a dynamic setting where firms have sunk costs. This implies a distinction between "entry thresholds"– the market size required to cover total fixed costs – and "exit thresholds"– the market size required to cover only the non-sunk part of fixed costs. Intuitively, entry and exit thresholds will differ in particular when the number of entrants shows persistence over time. We will closely follow a variant of Xiao and Orazem's (2011) sunk cost entry model. Furthermore, we show how to extend this approach so as to also account for economies of density, that is, the fixed costs that are common to areas within a given geographic distance from one another.

The number of entrants in LE i at time t is $N_{i,t} = n$. To model LLU coverage, we simply let $n = \{0, 1\}$, i.e., there is either no LLU entrant, or at least one LLU entrant. To model the number of LLU entrants, we model $n = \{0, 1, 2, 3\}$, i.e., there is either no entrant, one entrant, two entrants or at least three entrants. When there are n competitors, the discounted value of future profits in LE i at time t, $\overline{\pi}^n_{i,t}$, is specified as:

$$\overline{\pi}^n_{i,t} = \lambda_t \ln S_{i,t} + X_{i,t}\beta_t - \mu^n_t + \varepsilon_{i,t}, \quad (3)$$

where $X_{i,t}$ includes potential market size (number of telephone lines), income and other, time-invariant characteristics; μ^n_t is a fixed effect describing the negative profit effect from the n-th firm; and $\varepsilon_{i,t}$ is an i.i.d. standard normal random variable.

Profit specification (3) already includes the non-sunk part of fixed costs. In addition, we model two other important fixed costs when entering a market. Firstly, there may be economies of density, ED_t, when entering a market. These are fixed cost savings when there is already LLU-entry in the neighborhood of market i, i.e., $N_{-i,t} \geq 1$ for at least one market in a close radius of i. Second, following Bresnahan and Reiss (1994) and Xiao and Orazem (2011), firms must incur a sunk cost SC_t to enter a market, a cost that cannot be recouped when leaving the market.

The central point of departure in entry models is that profits are unobserved, so $\overline{\pi}_{i,t}^{n}$ is a latent variable. It is still possible to draw inferences on the profit determinants by assuming an entry equilibrium, whereby firms enter if, and only if, such a move is profitable. Profits, including economies of density, are defined by:

$$\pi_{i,t}^{n} \equiv \overline{\pi}_{i,t}^{n} + ED_t \cdot I\left(N_{-i,t} \geq 1\right), \tag{4}$$

where $I(\cdot)$ is an indicator function equal to 1 if the expression in brackets is true. In the dynamic entry model, this implies the following profit inequalities:

Case 1: net entry, $N_{i,t} > N_{i,t-1}$

$$\pi_{i,t}^{n} \geq SC_t \quad \text{and} \quad \pi_{i,t}^{n+1} < SC_t.$$

Case 2: no change or stasis, $N_{i,t} = N_{i,t-1}$

$$\pi_{i,t}^{n} \geq 0 \quad \text{and} \quad \pi_{i,t}^{n+1} < SC_t.$$

Case 3: net exit $N_{i,t} < N_{i,t-1}$

$$\pi_{i,t}^{n} \geq 0 \quad \text{and} \quad \pi_{i,t}^{n+1} < 0.$$

To interpret this, suppose we observe a LE with two LLU entrants. If there was only one LLU entrant in the previous period (case 1), we can infer bounds on the total entry costs, including the sunk costs. In contrast, if there were three LLU entrants in the previous period (case 3), we can infer bounds on the non-sunk cost part of the entry costs. Intuitively, if LEs experience both net entry and net exit over time, sunk costs tend to be small. In contrast, if there is a lot of stasis, then sunk costs will be of importance.

Using the profit specification (3)-(4), the above inequalities can be combined to obtain the following likelihood of observing $N_{i,t} = n$ entrants in market i at time t:

$$\Pr(N_{i,t} = n) = \Phi\left(\lambda_t \ln S_{i,t} + X_{i,t}\beta_t - \mu_t^n + ED_t \cdot I\left(N_{-i,t} \geq 1\right) - SC_t \cdot I\left(N_{i,t} > N_{i,t-1}\right)\right)$$

$$-\Phi\left(\lambda_t \ln S_{i,t} + X_{i,t}\beta_t - \mu_t^{n+1} + ED_t \cdot I\left(N_{-i,t} \geq 1\right) - SC_t \cdot I\left(N_{i,t} > N_{i,t-1}\right) - SC_t \cdot I\left(N_{i,t} = N_{i,t-1}\right)\right)$$

where $\Phi(\cdot)$ denotes the cumulative normal distribution function. If there are no sunk costs, $SC_t = 0$, the model reduces to a standard ordered probit. Otherwise, the model is more complicated since the stasis variable, $I(N_{i,t} = N_{i,t-1})$, only enters in the lower part of the cumulative distribution function.

The model can be estimated by maximum likelihood. One can then compute the entry and exit thresholds by solving for the critical market size that sets profits to zero:

$$\begin{aligned} S\_Entry_{i,t}^n &= \exp\left(\frac{-X_{i,t}\beta_t + \mu_t^n - ED_t \cdot I\left(N_{-i,t} \geq 1\right) + SC_t}{\lambda_t}\right) \\ S\_Exit_{i,t}^n &= \exp\left(\frac{-X_{i,t}\beta_t + \mu_t^n - ED_t \cdot I\left(N_{-i,t} \geq 1\right)}{\lambda_t}\right). \end{aligned}$$

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