

# UNBUNDLING THE INCUMBENT: EVIDENCE FROM UK BROADBAND

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## Abstract

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 data set covering the whole of the United Kingdom, we find that, over the course of time, many entrants have begun to take advantage of unbundling. LLU entry only had a positive effect on broadband penetration in the early years, and no longer in the recent years as the market reached maturity. In contrast, LLU entry continues to have a positive impact on the quality of the service provided, as entrants differentiate their products upwards compared to the incumbent. 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: D22, K23, L43, L51, L96)

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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

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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.<sup>1</sup>

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 opening 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. Regulators respond by arguing that, on the contrary, incumbents have a stronger incentive to invest to fend off competition. New entrants, however, 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 is in fact a highly strategic situation where the investments of all players will determine the degree of product market differentiation.

This variety of views is also reflected in different policies across countries. 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 in all member states.<sup>2</sup> LLU is the process whereby the incumbent makes its local network available to other companies. Entrants are then able to upgrade 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 United States—does not regulate access to broadband networks. While unbundling requirements for the narrowband networks of the incumbent carriers were mandated by the Telecommunications Act of 1996, these were first eliminated from the emerging broadband markets in 2003, and further curtailed in 2004 also in narrowband markets. In the United States, 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

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1. The European Commission estimated that between 181bn and 268bn would be required to achieve the Digital Agenda's broadband goal of guaranteeing a speed of at least 100 Mbps to 50% of all European households by 2020—see COM(2010) 472 final.

2. Regulation (EC) No 2887/2000 of the European Parliament on unbundling.

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 United Kingdom, based on two unique data sets: one concerning broadband penetration, made available to us for the purpose of this study by Ofcom (the United Kingdom's communication regulator); and one regarding broadband speeds, obtained from a private company. The United Kingdom is particularly interesting in that it has both a large traditional telephone network, owned by the British Telecom (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 versus traditional telcos) and intra-platform competition (whereby entrants access BT's network).

The first data set consists of quarterly figures for all broadband lines subscribed to locally by end users in the United Kingdom, between December 2005 and December 2009. The unit of observation is the "local exchange" (LE), also known as "central office" in the United States. 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 dwelling where customers live or work, which tend to be within a few hundred meters of the LE.<sup>3</sup> For each one of the 5,500 plus LEs in the United Kingdom, we observe the number of broadband subscribers per operator, that is: BT, the LLU entrants who rent the lines from the incumbent and may invest in upgrades, and the cable operator who utilizes a different platform without being subject to any access obligations.

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

In the first stage, we estimate an entry model to 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

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

can then install their own particular brand or style of broadband, with differing speeds and download limits to those offered by BT.

Our analysis of entry reveals an interesting, complex picture. We document a strong increase in LLU entry in the United Kingdom 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 the technology exhibits substantial sunk costs.

In the second stage, we study the determinants of broadband penetration. To identify the impact of LLU entry we use two identification approaches. We first use a panel fixed effects estimator, which accounts for unobserved heterogeneity across local markets and can be interpreted as a difference in difference estimator. We subsequently estimate a cross-section model for several periods, and use the entry model estimated in the first stage of our analysis to account for the potential endogeneity of entry. This entry model gives rise to natural exclusion restrictions (which we implement through a control function approach). Both approaches yield similar findings. During the period in which entrants progressively unbundled local loops, broadband penetration more than doubled in the United Kingdom. However, apart from this upward trend, LLU entry only contributed to higher penetration levels in the early years. In the more recent years, when the market matured, LLU entry no longer had a positive impact on total broadband penetration. In contrast, inter-platform competition (from cable) has increased local broadband penetration to a greater degree, and also in more recent years.

The absence of positive effects of LLU entry on broadband penetration levels in recent years could suggest that the competitive effects of LLU entry are outweighed by 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 also have a considerably 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 summarize, our analysis focuses on the effects of LLU entry, which shows useful variation both across local markets and over time. We find that LLU entry drastically increased throughout the period from 2005 to 2009. This in turn led to a faster diffusion of broadband adoption in the early years. It did not imply wider diffusion when the market matured near the end of our sample, but it 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 2006; 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 United States (from 1999 to 2004). Other studies covering similar ground include Hausman, Sidak, and Singer (2001), and Crandall, Ingraham, and Singer (2004).

However, on the empirical side, there are few robust econometric studies quantifying the effect of access regulation on entry and infrastructure 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 data set covering 20 countries over a period of ten years, and in doing so they distinguish between the incumbent's investment and the entrants' investments.<sup>4</sup> 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, Seim, and Viard 2008; Xiao and Orazem 2009, 2011; Goldfarb and Xiao 2011). It is however difficult to rely on such studies when studying broadband markets, as the data employed are usually at least ten 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.

The remainder of the paper is organized as follows. Section 2 provides background information on the UK broadband market and on our data sets. 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.

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4. See also Distaso, Lupi, and Manenti (2006), Wallsten and Hausladen (2009), Bouckaert, Dijk, and Verboven (2010).

## 2. Industry Background

### 2.1. *The UK Broadband Market*

The market for Internet services in the United Kingdom is characterized by the presence of a network, originally deployed by 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.<sup>5</sup> 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. However, LLU 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. By investing more resources, a LLU entrant can use a wider range of frequencies over the copper wire, which allows it to reach higher speeds.

In the United Kingdom, 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.<sup>6</sup> 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 50% of premises in the United Kingdom, concentrating its presence in urban areas and in flat parts of the country. 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. However, the existing network has been quickly upgraded to support voice and broadband services. 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 Virgin has never done so).

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5. Until 2005, BT was a vertically integrated operator, and a number of disputes arose concerning discriminatory and foreclosure conduct with regards to 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.

6. Broadband access via Wi-Fi technologies, however, is included in our data set.

## 2.2. *Data Sets*

We combine three different data sets, available at a highly disaggregated geographical level: two unique data sets with information on the number of broadband lines and on broadband speed, and one census data set containing local demographic information. The first data set is provided by Ofcom, and contains the quarterly data supplied to the regulator by BT and Virgin Media over a five-year period from December 2005 to December 2009. Ofcom collects such data for its analysis of the wholesale broadband market.<sup>7</sup> 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.

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 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 that the three companies within the BT group (BT Retail, BT Wholesale and Openreach) are separated, and constantly monitored, by the regulator.

The second data set 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.<sup>8</sup> In particular, it provided figures for one million speed tests performed throughout the United Kingdom in 2009. For each test, we observe the customer's full (six digit) postcode (and hence the respective LE), the broadband operator, the type of contract purchased, and the time the test took place. The data set 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.

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7. See <http://stakeholders.ofcom.org.uk/binaries/consultations/wba>.

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

The third data set contains demographic and geographic 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 (HH), ethnic group, type of occupation, sector of occupation, number of hours worked per week, and other variables that proxy for social status.<sup>9</sup> In addition, we have income figures from the labor force surveys. These figures are collected periodically at a higher level of aggregation than census data are.<sup>10</sup> Hence, following Smith (2004), we first regress this more aggregate measure of income (which is time varying) 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 time-varying 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).

Using Ofcom's data set and the third data set, we computed two variables that may affect the profitability of broadband investment. First, we computed the distance of the LE to the backbone of the broadband network. This is an important cost factor for LLU operators, because the farther a LE is to the backbone, the larger the costs to provide broadband. Second, we computed the distance of the premises in the catchment area of each LE. This variable is also crucial for broadband operators relying on the telephone network, because the quality of their service (negatively) depends on the length of the copper lines connecting the LE to the homes of the final users.

While the data set is very rich, we acknowledge that we do not have price information. For the purpose of this study this is not a limitation, as we are most interested in entry strategies and the impact of LLU on penetration. Prices do not vary anyway across local markets, only by operator and over the different quarters. However, since we do not incorporate price information, we cannot do a full welfare analysis.

Table 1 provides summary statistics of the main variables. The top panel shows information from the first data set. "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 in the catchment area of a given LE). "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%.<sup>11</sup>

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.

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 also robust to changes in this specific value.

TABLE 1. Descriptive statistics.

| <i>Subscribers and coverage</i>          | 2005Q4                  |           | 2007Q4           | 2009Q4           |                                        |
|------------------------------------------|-------------------------|-----------|------------------|------------------|----------------------------------------|
| No. of lines                             | 27,576,261              |           | 27,658,092       | 28,219,684       |                                        |
| No. of 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%            |                                        |
| No. of LEs                               | 5,587                   |           | 5,587            | 5,587            |                                        |
| LLU entry                                | 695 (12.4%)             |           | 1,733 (31%)      | 2,011 (36%)      |                                        |
| Avg. no. of LLU competitors <sup>a</sup> | 1.79                    |           | 3.44             | 3.31             |                                        |
| Cable coverage $\geq 65\%$               | 953 (17%)               |           | 844 (15.1%)      | 829 (14.8%)      |                                        |
| <i>Speed tests by operator</i>           | Download speed (Mbit/s) |           | Sample Frequency | Distance (miles) |                                        |
|                                          | Mean                    | Std. dev. | (%)              | Mean             | 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                                  |
| <i>Demographics</i>                      | LEs without LLU         |           | Unbundled LEs    |                  |                                        |
|                                          | Mean                    | Std. dev  | Mean             | Std. dev         | Test-Stat <sup>c</sup> <i>p</i> -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 <sup>b</sup>                      | 568.8                   | 110.5     | 514.6            | 126.4            | 15.63 <0.001                           |
| HH occupations                           | 53.5                    | 10.4      | 53.5             | 14.3             | 0 0.99                                 |
| HH 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                              |
| Download speed (Mbit/s)                  | 2.846                   | 2.018     | 3.723            | 2.624            | –126.95 <0.001                         |

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.

The middle panel shows information from the second data set. 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. 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 United Kingdom. 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 data set with this level of detail elsewhere in Europe or the United States. The size of the data set is unusually large for this kind of study, as the core data set assembled by Ofcom comprises 5,587 LEs for 17 quarters, resulting in almost 100,000 observations. However, the analysis is carried out on a subsample of 4,264 LEs, amounting to 72,488 observations. This is because one demographic variable (average income) can only be predicted for the LEs in England and Wales. This leaves out 24% of the LEs, but only 12% of the population, since England and Wales are more densely populated than the rest of the country.<sup>12</sup> 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. However, entrants can decide where to enter, given BT's coverage. Entry through LLU, which would give full control over the service provided to the end customer, implies a considerable sunk entry cost of around £100,000 per LE, according to industry sources.

In principle, all the operators can follow a variety of strategies to differentiate from BT, offering Internet services with different speeds, and bundling them in various ways with other services. Entrants themselves are not a homogeneous group. Concentrating on the main rivals of BT, TalkTalk is a traditional telecom operator that started in voice telephony and then progressed to broadband services. The core business of O2 and Orange is instead mobile services, which they then bundled with broadband Internet. Sky is a satellite TV operator that needs access to BT's network via LLU in those areas that are not covered by its own satellite network.<sup>13</sup>

### *2.3. An Initial Look at the Market*

We use our various data sets 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.

12. As a robustness check, we have also estimated our panel regressions of Section 4.2 for the full sample, excluding the income variable (but retaining the fixed effects for time-invariant heterogeneity). This gave very similar results.

13. See Prince and Greenstein (2014) for a recent empirical analysis of bundling in the United States.

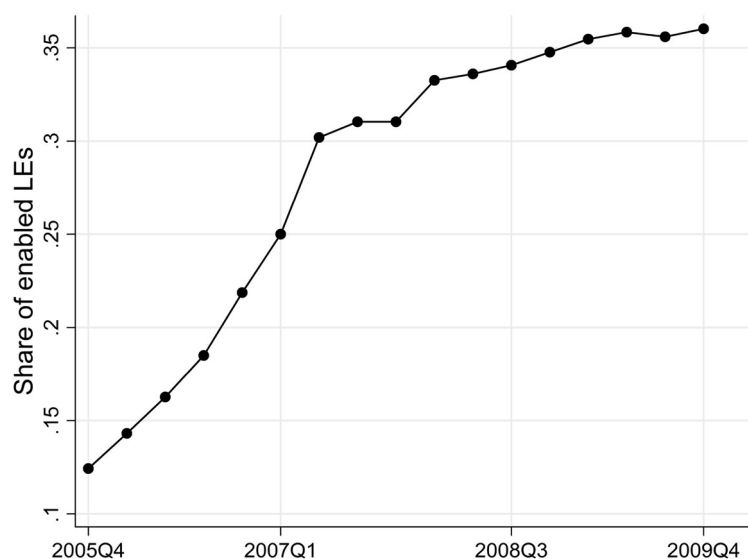


FIGURE 1. Share of unbundled LEs over time.

*Local Loop Unbundling (LLU).* Figure 1 shows the evolution of LLU coverage between 2005Q4 and 2009Q4. The figure portrays LLU entry across LEs, that is, the fraction of LEs where there is at least one LLU entrant. This fraction increased rapidly from 12% in 2005 to about 30% in mid-2007. 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 United Kingdom had access to at least one LLU entrant.

Figure 2 presents two maps of the United Kingdom 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 show the presence of neighborhood effects on LLU. 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. Indeed, 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

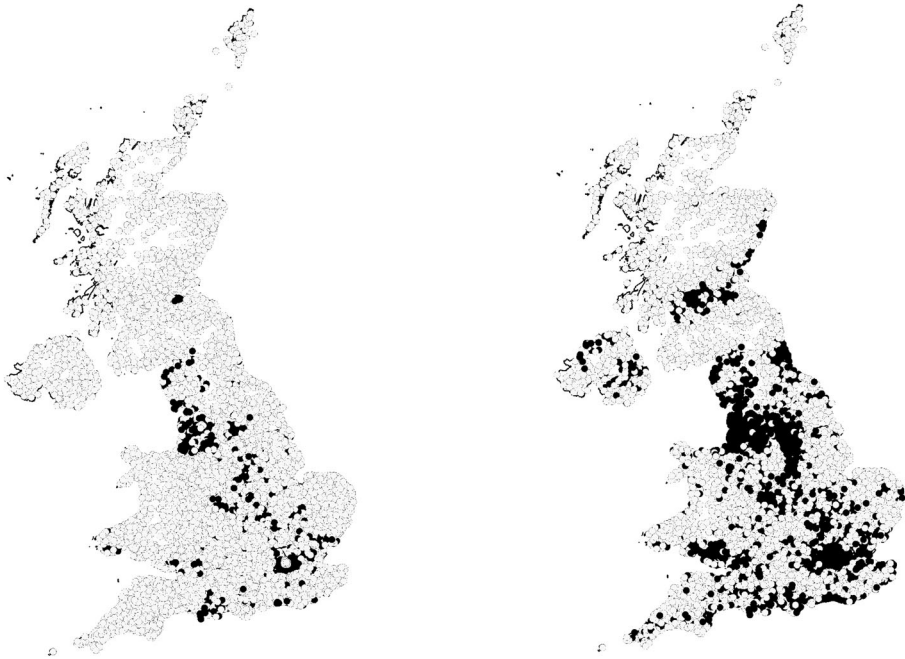


FIGURE 2. LEs without LLU (white) and with at least one LLU operator (black) over time. Left panel: 2005Q4; right panel: 2009Q4.

link distance. Hence, once LLU has been put in place in a LE, the cost of unbundling a neighboring LE will be lower than in nonadjacent areas. These and related features of the entry process will be exploited in the next sections to identify the effects of entry on penetration and quality of service.

*Broadband Penetration and the Quality of Service.* As defined previously, 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 3 shows that broadband penetration almost doubled between the end of 2005 and the end of 2009, from 36% to 62% (and in 2012 it 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 3 shows that the growth of LLU penetration coincides with a parallel fall in Bit-stream penetration at national level. The 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

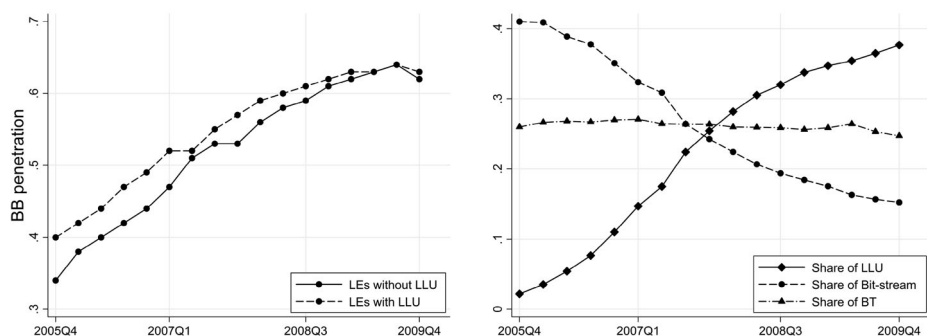


FIGURE 3. Left panel: Penetration in LEs with and without LLU. Right panel: Market shares of BT and of the entrants.

about 26%, while the market share of cable (not shown in the figure) fell from 30.8% to 22.4%.

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 3 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. Finally, areas receiving LLU are characterized by a larger proportion of the population being of a working age, and working in high-skill sectors in particular.

To sum up, there does not immediately appear to be any strongly positive or negative relationship between LLU entry and broadband penetration. However, to obtain a reliable picture, we need to perform an analysis at the level of the LEs, taking into account the endogeneity of LLU entry and the fact that LLU was first introduced in the more profitable markets, which we shall do in Sections 3 and 4.

Finally, the bottom part of 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.

### 3. LLU Entry

#### 3.1. Entry Model

In this section we estimate several entry models. This is important for two reasons. First, understanding the determinants of LLU entry is of independent interest, as it gives us insights into intra-platform competition. This complements recent studies of inter-platform competition in telecommunications markets, such as Greenstein and Mazzeo (2006) and Xiao and Orazem (2011). Second, the entry model will be a key input to address our main research question, namely the effect of LLU on market performance (broadband penetration and quality). In particular, several variables appear as determinants in the entry model, but do not directly impact the broadband penetration and quality model. This is the case for market size and several fixed cost determinants. These variables thus serve as natural exclusion restrictions to identify the effects of LLU entry. As we discuss in Section 4, we will implement this following a control function approach as in Heckman (1979) and Manuszak and Moul (2008), which is closely linked to the entry model estimated in this section.

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. We extend the static free-entry model of Bresnahan and Reiss (1991; henceforth BR) to a dynamic framework with sunk costs, as in Bresnahan and Reiss (1994) and Xiao and Orazem (2011).<sup>14</sup> Following Aguirregabiria (2012), one may interpret this as a “semi-structural” dynamic model of free entry and exit. On the one hand, it is fully consistent with a dynamic game of entry and exit. On the other hand, it does not explicitly model how the expected future value function depends on sunk costs. As such, the model enables one to account for entry persistence due to sunk costs without a large computational cost. However, it is not immediately possible to use the framework to conduct policy counterfactuals, since the model ignores the relationship between the value function and the structural parameters of the model.

The number of entrants in LE  $i$  at time  $t$  is  $N_{it} = n$ , where  $n = \{0, 1\}$  in the model of LLU coverage, and  $n = \{0, 1, 2, 3+\}$  in the model for the number of LLU entrants (and  $n = 3+$  refers to the situation of at least three entrants). With  $n$  competitors, the discounted value of future profits in LE  $i$  at time  $t$ ,  $\pi_{it}^n$ , is specified as

$$\pi_{it}^n = \bar{\pi}_{it}^n + \varepsilon_{it} \equiv \lambda_t \ln S_{it} + Z_{it} \delta_t - \mu_t^n I(N_{it} = n) + \varepsilon_{it}, \quad (1)$$

where  $S_{it}$  is the potential market size (number of telephone lines, which is approximately equal to the number of households),  $Z_{it}$  is a vector of other profit determinants (such as income, other demographics, and geographic characteristics, such as the distance to the backbone),  $\mu_t^n$  is a fixed effect describing the negative profit

14. Compared with Xiao and Orazem (2011) we can do a richer analysis, since they do not have information on the first three entrants and do not observe broadband penetration per market.

effect from the  $n$ th firm, and  $\varepsilon_{it}$  is an i.i.d. standard normal random variable, capturing unobserved profit determinants.<sup>15</sup> Note that market size  $S_{it}$  and a subset of  $Z_{it}$  (the distance to the backbone) only appear in the entry equation and not in the penetration equation of the next section. They will thus serve as exclusion restrictions to identify the effect of LLU entry.

While  $\pi_{it}^n$  already includes the nonsunk part of fixed costs, firms also incur a sunk cost  $SC$  to enter a market, which cannot be recouped when they exit. Profits are unobserved, so  $\pi_{it}^n$  is a latent variable. It is still possible to draw inferences on the profit determinants by assuming a free-entry equilibrium, where firms enter if and only if such a move is profitable. This implies the following profit inequalities:

$$\begin{aligned} \text{Case 1, net entry: } N_{it} &> N_{it-1} \text{ if } \pi_{it}^n \geq SC \text{ and } \pi_{it}^{n+1} < SC, \\ \text{Case 2, inaction: } N_{it} &= N_{it-1} \text{ if } \pi_{it}^n \geq 0 \text{ and } \pi_{it}^{n+1} < SC, \\ \text{Case 3, net exit: } N_{it} &< N_{it-1} \text{ if } \pi_{it}^n \geq 0 \text{ and } \pi_{it}^{n+1} < 0. \end{aligned}$$

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 nonsunk 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 inaction, then sunk costs will be of importance.

Using the profit specification (1), the previous inequalities can be combined to obtain the following likelihood of observing  $N_{it} = n$  entrants in market  $i$  at time  $t$ :

$$\Pr(N_{it} = n) = \Phi(\bar{\pi}_{it}^n - SC \cdot I_{it}^+) - \Phi(\bar{\pi}_{it}^{n+1} - SC \cdot (I_{it}^+ + I_{it}^0)),$$

where  $\Phi(\cdot)$  denotes the cumulative normal distribution function, and  $I_{it}^+ \equiv I(N_{it} > N_{it-1})$  and  $I_{it}^0 \equiv I(N_{it} = N_{it-1})$  are indicator variables to denote whether entry increased (+) or remained constant (0). Notice that if there are no sunk costs,  $SC = 0$ , then the model is static and reduces to a standard ordered probit.<sup>16</sup> The model can be estimated by maximum likelihood. Standard errors are clustered by LE.<sup>17</sup>

15. We also considered a model where  $\varepsilon_{it}$  is serially correlated. Following Keane (1993) and Collard-Wexler (2014), we estimated this model based on simulated maximum likelihood, using the GHK simulator. The model is very slow to converge on our full sample with more than 4,000 LEs and 17 time periods. For smaller samples of 200 LEs and five periods (i.e., selecting the last quarter of each year), we find moderate serial correlation and otherwise similar parameter estimates (as compared with the model with i.i.d. errors for the same reduced sample). We report these results in the Online Appendix.

16. Otherwise, the model is more complicated since the inaction variable,  $I(N_{it} = N_{it-1})$ , only enters in the lower part of the cumulative distribution function.

17. Collard-Wexler (2014) estimates a dynamic entry model with serial correlation in the unobservable. His model includes a demand variable, which varies over time but does not depend on the number of entrants. This differs from our setup, where the demand variable (broadband penetration) depends on the number of entrants (which is our main interest, as discussed in the next section). In future research, it would be interesting to see how his approach can be extended to accommodate the case where demand depends on the number of entrants.

### 3.2. Empirical Results

Table 2 shows the results. The first column is a static binary probit model for LLU coverage (where  $N_{it}$  is either 0 or 1) as a function of market demographics and geographic variables.

The most important determinant of LLU entry is market size—that is, the number of telephone lines which measures 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 ten regional dummy variables are also jointly significant. In addition to the market demographics, the geographic variables play an important role. As expected, the distance of the LE to the backbone of the broadband network has a strong negative effect on investment in LLU. This reflects the fixed costs that the ISPs must incur to connect the LE to the backbone if they want to provide broadband services in a LE—that is, the costs of deploying fast fiber connections. The positive coefficient for squared distance means that these fixed costs are increasing in distance at a decreasing rate. This indicates that there are some economies of scale in this investment. We also include the average distance of households to the LE. This variable has a positive effect on entry, indicating that, conditional on market size and the other demographic variables, geographically more dispersed markets attract more entrants.<sup>18</sup>

The second column of Table 2 reports results from a dynamic binary probit model with sunk costs. The effects of the market demographics and geographic variables remain very similar and the sunk cost effect is highly significant. Intuitively, this is due to the strong persistence of LLU coverage. Based on these estimates, we compute “entry thresholds”, that is, the minimum market size required to support LLU entry at particular points in time.<sup>19</sup> We report these entry thresholds in the left-hand panel of Figure 4. Consistent with the estimated trend effect (and its interaction with the number of lines), the number of telephone lines required to sustain LLU entry was initially more than 50,000, but this figure quickly dropped to 35,000. 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.

The third and fourth columns extend the binary probit models of LLU coverage (entry by at least one entrant) to ordered probit models for the number of LLU entrants (0, 1, 2, or 3+): the third column is a static version, while the fourth column is a dynamic version with sunk costs. The results regarding market demographics, geographic characteristics, and sunk costs remain similar. The new finding relates to the “cut-off points” of the ordered probit (the  $\mu^n$ ), which refer to the fixed effects of entry on profits for each market configuration. We find that the effect of the second entrant ( $\mu^2 - \mu^1$ ) and third entrant ( $\mu^3 - \mu^2$ ) are statistically significant. To interpret

18. We also considered an extension which includes cable coverage. The effect of this variable was insignificant and did not affect the other parameters of the model.

19. The entry threshold in LE  $i$  at period  $t$  is obtained by solving for the critical market size that sets the mean profits to zero:  $S_{it}^n = \exp((-z_{it}\delta_t + \mu_t^n + SC_t)/\lambda_t)$ .

TABLE 2. Estimates of the entry models.

| Dependent variable:                     | LLU entry            |                      | No. of competitors   |                      |
|-----------------------------------------|----------------------|----------------------|----------------------|----------------------|
|                                         | (1)                  | (2)                  | (3)                  | (4)                  |
|                                         | BR                   | Sunk cost            | BR                   | Sunk cost            |
| Log(lines) ( $\% \lambda$ )             | 0.508***<br>(0.036)  | 0.587***<br>(0.028)  | 0.537***<br>(0.032)  | 0.719***<br>(0.027)  |
| Log(lines) $\times$ trend               | 0.078***<br>(0.004)  | 0.011***<br>(0.003)  | 0.092***<br>(0.004)  | 0.020***<br>(0.003)  |
| Backbone distance                       | -3.111***<br>(0.243) | -1.297***<br>(0.128) | -3.264***<br>(0.222) | -1.605***<br>(0.136) |
| Backbone distance <sup>2</sup>          | 0.154***<br>(0.014)  | 0.067***<br>(0.007)  | 0.169***<br>(0.013)  | 0.091***<br>(0.008)  |
| Log(income)                             | 0.408**<br>(0.133)   | 0.402**<br>(0.132)   | 0.743***<br>(0.116)  | 0.727***<br>(0.111)  |
| Working age                             | 0.028**<br>(0.009)   | 0.015**<br>(0.006)   | 0.033***<br>(0.007)  | 0.020***<br>(0.005)  |
| Over 60 y.o.                            | 0.023**<br>(0.007)   | 0.015**<br>(0.005)   | 0.029***<br>(0.006)  | 0.022***<br>(0.004)  |
| White                                   | -0.015***<br>(0.004) | -0.003<br>(0.003)    | -0.015***<br>(0.003) | -0.008***<br>(0.002) |
| Black                                   | 0.021<br>(0.020)     | 0.009<br>(0.023)     | 0.042***<br>(0.013)  | 0.047***<br>(0.012)  |
| Student                                 | 0.006<br>(0.005)     | 0.004<br>(0.004)     | 0.004<br>(0.004)     | 0.002<br>(0.003)     |
| HS occupation                           | -0.017***<br>(0.003) | -0.012***<br>(0.002) | -0.023***<br>(0.003) | -0.018***<br>(0.002) |
| HS sector                               | 0.011**<br>(0.004)   | 0.005**<br>(0.003)   | 0.020***<br>(0.004)  | 0.013***<br>(0.003)  |
| Urban                                   | 0.080<br>(0.058)     | 0.060*<br>(0.032)    | 0.075<br>(0.050)     | 0.072**<br>(0.032)   |
| Distance LE-homes                       | 0.171***<br>(0.050)  | 0.039<br>(0.027)     | 0.190***<br>(0.046)  | 0.079**<br>(0.030)   |
| Trend                                   | -0.523***<br>(0.033) | -0.079**<br>(0.025)  | -0.638***<br>(0.033) | -0.136***<br>(0.024) |
| Sunk (SC)                               |                      | 3.313***<br>(0.038)  |                      | 2.894***<br>(0.029)  |
| Fixed effect firm 1 ( $\mu^1$ )         | 8.525***<br>(1.166)  | 6.234***<br>(1.053)  | 11.086***<br>(0.977) | 9.509***<br>(0.890)  |
| Extra-effect firm 2 ( $\mu^2 - \mu^1$ ) |                      |                      | 0.946***<br>(0.022)  | 0.568***<br>(0.012)  |
| Extra-effect firm 3 ( $\mu^3 - \mu^2$ ) |                      |                      | 0.55***<br>(0.019)   | 0.45***<br>(0.011)   |
| Region dummy vars.                      | Yes                  | Yes                  | Yes                  | Yes                  |
| Log-likelihood                          | -16277.689           | -5646.424            | -29824.56            | -13539.71            |
| $\chi^2$                                | 2719.617             | 14863.557            | 4128.015             | 3389.01              |
| Observations                            | 72505                | 68240                | 72505                | 68240                |

Notes: Notes: Cluster-robust standard errors at the LE level. Backbone distance<sup>2</sup> is scaled by a factor 1/1000 for readability.

\*\*\*Significant at 1%; \*\*significant at 5%.

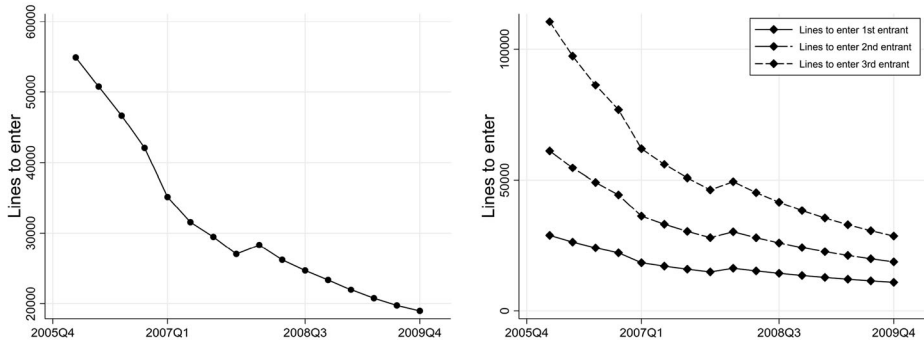


FIGURE 4. Entry thresholds of the dynamic (sunk cost) models. Left panel: estimated entry thresholds where the dependent variable is entry of at least one operator with LLU. Right panel: estimated entry thresholds where the dependent variable is the number of entrants with LLU.

their size, they can be used to compute entry thresholds supporting at least 1, 2, or 3+ LLU entrants. According to the right-hand panel in Figure 4, in 2005 the number of telephone lines required to sustain at least 1, 2 or 3+ entrants was, respectively, 28,944, 61,149, and 110,649. By the end of 2009, these entry thresholds had dropped substantially to 10,986, 18,765, and 28,686 respectively.

In conclusion, these findings suggest that a sufficiently large market size is important to recover fixed investment costs, but also that fixed costs relative to demand have sharply declined in recent years. Furthermore, a large part of the investment costs appear to be sunk. Finally, in addition to market demographics, several geographic variables play an important role in the entry process. These findings will be relevant for identifying the effect of LLU entry on broadband performance. We turn to this question next.

## 4. LLU Entry and Broadband Penetration

### 4.1. Empirical Model

As explained previously, 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 total number of 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:

$$y_{it} = \eta_i + \tau_t + \beta_t N_{it} + \gamma X_{it} + u_{it}. \quad (2)$$

Here,  $y_{it}$  is the relevant performance measure of broadband penetration. We focus on total broadband penetration—that is, total broadband subscribers as a percentage of total telephone lines. Our main interest is in the variable  $N_{it}$ , which is either a dummy variable for LLU coverage (0/1) in the LE, or an ordered variable for the

number of LLU entrants (0, 1, 2, 3+). We first consider  $\beta_t = \beta$ , and subsequently also include an interaction with a time trend to allow for a nonconstant effect of LLU over time. The vector  $X_{it}$  contains control variables, in particular market demographics such as average income in the LE, and the extent to which the LE is also served by an alternative cable network that was built prior to the Internet era. Finally, specification (2) includes individual effects  $\eta_i$  capturing time-invariant characteristics of the LEs (such as urban status), time effects  $\tau_t$  capturing the growth in UK broadband adoption over the 17 quarters during the period 2005–2009, and a residual error term  $u_{it}$ , which captures unobserved factors that affect penetration in a LE and time period, for example stemming from a temporary advertising campaign in a specific LE.

We consider two ways of estimating the effect of LLU on broadband penetration, based on equation (2). As a point of reference, we first estimate the model with pooled OLS, so we omit the LE fixed effects  $\eta_i$ . We subsequently compare these estimates with those obtained from a within-groups estimator, which conditions on the fixed effects  $\eta_i$ . This estimator accounts for the possibility that LLU entry is more likely in LEs with high time-invariant shocks  $\eta_i$  (positive correlation between  $N_{it}$  and  $\eta_i$ ). This avoids overestimating the effect of LLU entry on broadband penetration under pooled OLS or a simpler random effects estimator. Since (2) does not only include the LE fixed effects  $\eta_i$  but also time effects  $\tau_t$ , one may in fact 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 the LLU entry variable  $N_{it}$  is correlated with the remaining error term  $u_{it}$ , conditional on the fixed effects  $\eta_i$ .<sup>20</sup> To account for this possibility, we make explicit use of the entry model estimated in the previous section. For several relevant quarters of our sample we estimate a cross-section version of the penetration equation (2), where we account for the potential endogeneity of LLU entry. More specifically, we follow a control function approach, as in Heckman (1979) for a dummy endogenous variable (where  $N_{it}$  indicates LLU coverage) and the extension by Manuszak and Moul (2008) for an ordered endogenous variable (where  $N_{it}$  is the number of LLU entrants). The penetration equation (2) for a cross-section of LEs in a certain period is

$$y_i = \beta N_i + \gamma X_i + u_i, \quad (3)$$

where we have omitted the subscript  $t$  from all variables and parameters for notational simplicity. The main issue with this regression is that  $N_i$  may be endogenous, and thus correlated with the error term  $u_i$ . To account for this, we make use of the entry

20. The within-groups estimator also serves to identify the effect of cable coverage, as it controls for time-invariant shocks that were also likely to be relevant several decades ago when the cable network was introduced. Furthermore, since cable broadband has been introduced in all locations where the cable network is available, it is reasonable to assume that the cable coverage variable is uncorrelated with  $u_{it}$ , conditional on the fixed effects  $\eta_i$ .

model discussed in the previous section. Assuming that the error terms of the entry and penetration model ( $\varepsilon_i$  and  $u_i$ ) are multivariate normally distributed, it is possible to show that

$$\begin{aligned} E(y_i | X_i, N_i, S_i, Z_i) &= \beta N_i + \gamma X_i + E(u_i | N_i = n, S_i, Z_i) \\ &= \beta N_i + \gamma X_i + \sigma_{u\varepsilon} h(N_i, S_i, Z_i; \theta), \end{aligned}$$

where  $\theta = (\lambda, \delta, \mu^n)$  is the parameter vector from the entry model,  $\sigma_{u\varepsilon}$  is the covariance between  $u_i$  and  $\varepsilon_i$ , and  $h(N_i, S_i, Z_i; \theta)$  is the inverse Mills ratio:

$$\begin{aligned} h(N_i, S_i, Z_i; \theta) &\equiv E(\varepsilon_i | \bar{\pi}_i^n - SC \cdot I_i^+ < \varepsilon_i < \bar{\pi}_i^{n+1} - SC \cdot (I_i^+ + I_i^0)) \\ &= \frac{\phi(\bar{\pi}_i^n - SC \cdot I_i^+) - \phi(\bar{\pi}_i^{n+1} - SC \cdot (I_i^+ + I_i^0))}{\Phi(\bar{\pi}_i^n - SC \cdot I_i^+) - \Phi(\bar{\pi}_i^{n+1} - SC \cdot (I_i^+ + I_i^0))}, \end{aligned}$$

that is, the mean of a doubly truncated standard normal variable  $\varepsilon_i$ .<sup>21</sup> We can then decompose the error term  $u_i$  in the penetration equation (3) into the sum of two terms—that is,  $u_i = \sigma_{u\varepsilon} h(N_i, S_i, Z_i; \theta) + e_i$ , where  $e_i$  is by construction mean zero conditional on  $X_i, N_i, S_i$  and  $Z_i$ . The penetration equation (3) can then be written as

$$y_i = \beta N_i + \gamma X_i + \sigma_{u\varepsilon} h(N_i, S_i, Z_i; \theta) + e_i. \quad (4)$$

This implies a two-step estimation procedure. First, the entry model is estimated to compute the correction term  $h(N_i, S_i, Z_i; \theta)$ . Second, this correction term enters as an additional control variable in the second-stage regression (4). Note that this control function approach is essentially an instrumental variable estimator with a direct link to the entry model. It recognizes that total penetration  $y_i$  is an equilibrium outcome which depends on demand and marginal cost shifters (in  $X_i$ ), and on the number of firms  $N_i$ . Instruments for  $N_i$  in the penetration regression are given by several exclusion restrictions—that is, exogenous variables that only enter in the entry model. These variables are market size  $S_i$  and other instruments  $Z_i$ —that is, the distance of the LE to the backbone. These variables affect total profitability through the entry model, but presumably do not directly affect total penetration. First, market size  $S_i$  affects the profitability of entry, as firms are more likely to enter in larger markets because of fixed costs. At the same time, market size is not a direct determinant of total penetration. In principle, there is a possibility that market size is correlated with the unobservable  $u_i$  in the penetration equation—for example, if market size is correlated with omitted city specific characteristics. For this reason, we include a rich set of controls in the penetration model, including proxies for city characteristics, such as an urban dummy variable, regional dummy variables, income, the fraction of students,

21. This expression holds for  $N_i < N^{\max}$ . For  $N_i = N^{\max}$ , the term reduces to a single truncated normal variable as in Heckman (1979). For a detailed derivation of the Mills ratio in the ordered probit model, see Idson and Feaster (1990).

TABLE 3. Estimates of the total penetration model.

| <b>Dependent variable: total broadband penetration</b> |                      |                      |                      |                      |                      |                     |
|--------------------------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|---------------------|
|                                                        | (1)                  | (2)                  | (3)                  | (4)                  | (5) Panel FE         |                     |
|                                                        | OLS                  | Panel FE             | OLS                  | Panel FE             | No Cable             | Cable               |
| $N_{it}$ (LLU coverage 0/1)                            | 0.021***<br>(0.002)  | -0.010***<br>(0.001) | 0.058***<br>(0.003)  | 0.025***<br>(0.001)  | 0.017***<br>(0.002)  | 0.011***<br>(0.002) |
| $N_{it} \times \text{trend}$                           |                      |                      | -0.004***<br>(0.000) | -0.004***<br>(0.000) | -0.003***<br>(0.000) | -0.001*<br>(0.000)  |
| Cable coverage                                         | 0.048***<br>(0.003)  | 0.019***<br>(0.002)  | 0.047***<br>(0.003)  | 0.017***<br>(0.002)  |                      |                     |
| Log(income)                                            | 0.279***<br>(0.005)  | 0.060***<br>(0.008)  | 0.278***<br>(0.005)  | 0.065***<br>(0.007)  | 0.083***<br>(0.009)  | 0.007<br>(0.009)    |
| Constant                                               | -1.402***<br>(0.028) | -0.033<br>(0.048)    | -1.400***<br>(0.028) | -0.074*<br>(0.044)   | -0.195***<br>(0.055) | 0.360***<br>(0.056) |
| Time effects                                           | Yes                  | Yes                  | Yes                  | Yes                  | Yes                  | Yes                 |
| $R^2$                                                  | 0.717                | 0.893                | 0.720                | 0.898                | 0.895                | 0.945               |
| Observations                                           | 72505                | 72505                | 72505                | 72505                | 59448                | 13057               |

Notes: Notes: Cluster-robust standard errors at the LE level. Columns (1) and (3) are pooled OLS regressions for the panel of 4,265 LEs during 17 periods. Columns (2) and (4) include a full set of fixed effects for the LEs. Columns (5) and (6) extend specification (4), and split the sample in LEs without and with a cable operator. The variable  $N_{it}$  is a dummy variable referring to the presence of at least one LLU entrant.

\*\*\*Significant at 1%; \*significant at 10%.

and other demographic variables, as well as measures of density such as the average distance between the LE and the buildings in its catchment area. Second, distance to the backbone is a fixed cost determinant and not a marginal cost determinant so it qualifies as an additional exclusion restriction. Marginal costs are relatively small and mainly depend on the cost of billing and servicing consumers, so that distance to the backbone does not directly affect equilibrium penetration but only indirectly through LLU entry.<sup>22</sup> Note that the control function approach depends on the assumed normal distribution for the error terms in the entry and penetration model. As a robustness check, we have therefore also implemented a linear two-stage least squares estimator (with the same exclusion restrictions) and this gave similar results.

#### 4.2. Empirical Results

*Panel Data Results.* Table 3 reports the empirical results for the panel data specification (2), where  $y_{it}$  is total broadband penetration (as a percentage of the total number of telephone lines in a given LE) and  $N_{it}$  is a dummy for LLU coverage

22. In addition to distance to the backbone, we also considered other geographic variables in  $Z_i$ : the elevation level of the LE, and the relative elevation position of the LE compared to the surrounding area. Both have the expected effects in the entry model and give similar results when used in the control function. Results and further discussion are available in our working paper.

(i.e.,  $N_{it} = 1$  if there is at least one LLU entrant, and zero otherwise). We first consider a specification where the effect of LLU coverage is constant (first two columns), and then consider a specification where the effect of LLU coverage is interacted with a trend (third and fourth columns). As discussed previously, in each case we compare the results from a simple OLS estimator with those of a fixed effects (or difference-in-difference) estimator. The simple OLS estimator only includes the variable income, while the fixed effects estimator also controls for time-invariant LE characteristics  $\eta_i$ . Income generally has a positive impact on broadband penetration, though the magnitude of its impact is smaller in the fixed effects estimator (as it controls for LE characteristics that may be correlated with income). A 10% increase in income raises total broadband penetration by approximately 0.6 percentage points (second and fourth columns). The effects of other, time-invariant demographics are absorbed in the LE fixed effects, but a second-stage regression of the fixed effects on these demographics gives intuitive findings. We do not report results as they are consistent with those arising from the cross-section analysis shown in Table 4. Total broadband penetration is, for instance, significantly higher in areas with a large proportion of highly skilled workers, and lower where there is a large proportion of elderly people.

Our main interest is in the impact of LLU entry on total broadband penetration. The pooled OLS estimator (first column) suggests a positive impact of LLU coverage on broadband penetration, of about 2.1 percentage points. However, this is no longer the case when we consider the fixed effects estimator. As expected, the OLS estimator thus overestimates the effect of LLU entry, since it does not control for the LE characteristics  $\eta_i$ , which imply both a higher broadband penetration and more likely LLU entry. In fact, the fixed effects estimator suggests that LLU coverage has a modest negative impact on broadband penetration. It is possible that the modest negative impact of LLU is only a recent phenomenon, and that it was not present in the early years when LLU was introduced and most needed.

To explore this possibility, the third and fourth columns of Table 3 present the results from specifications where the LLU coverage variable is interacted with a time trend. Consistent with the earlier results, the OLS estimator again overestimates the effect of LLU because it does not control for the LE characteristics  $\eta_i$ . Interestingly, according to the fixed effects estimator (fourth column), the effect of LLU on broadband penetration is now positive in the early years (+2.5%, down from +5.8% under OLS). At the same time, the interaction term is negative and significant. This implies that the beneficial impact of LLU is declining over time, and ultimately becomes negative. Put differently, LLU has mainly led to faster diffusion of broadband instead of a wider diffusion. Under this interpretation, broadband seems to have reached a natural saturation level of about 2/3 of the households, both with and without LLU.

The results also show that cable coverage, which is an example of inter-platform competition, has a stronger beneficial impact on total broadband penetration by, on average, roughly 2 percentage points according to the fixed effects estimator.<sup>23</sup> This

23. Under OLS, the estimated effect of cable is again larger, about 5%. This indicates the role of time-invariant heterogeneity across LEs, which attracted the cable investments decades ago in the most profitable markets.

TABLE 4. Estimates of the total penetration model—selected periods.

| Dependent variable: total broadband penetration |                      |                      |                      |                      |
|-------------------------------------------------|----------------------|----------------------|----------------------|----------------------|
|                                                 | (1)<br>2007Q4        | (2)<br>2009Q4        | (3)<br>2007Q4        | (4)<br>2009Q4        |
| $N_{it}$ (LLU coverage 0/1)                     | 0.017***<br>(0.004)  | -0.042***<br>(0.004) |                      |                      |
| No. of LLU entrants                             |                      |                      | 0.009***<br>(0.002)  | -0.015***<br>(0.003) |
| Cable coverage                                  | 0.022***<br>(0.003)  | 0.030***<br>(0.003)  | 0.019***<br>(0.003)  | 0.027***<br>(0.004)  |
| Log(income)                                     | 0.078***<br>(0.012)  | 0.130***<br>(0.019)  | 0.083***<br>(0.012)  | 0.136***<br>(0.019)  |
| Working age                                     | -0.069<br>(0.043)    | -0.004<br>(0.052)    | -0.079*<br>(0.047)   | -0.022<br>(0.053)    |
| Over 60 y.o.                                    | -0.357***<br>(0.039) | -0.214***<br>(0.049) | -0.357***<br>(0.039) | -0.217***<br>(0.052) |
| White                                           | 0.038**<br>(0.019)   | 0.009<br>(0.023)     | 0.045**<br>(0.019)   | 0.013<br>(0.023)     |
| Black                                           | 0.043<br>(0.119)     | -0.055<br>(0.124)    | 0.042<br>(0.102)     | -0.051<br>(0.111)    |
| Student                                         | -0.035<br>(0.030)    | -0.025<br>(0.037)    | -0.031<br>(0.037)    | -0.014<br>(0.037)    |
| HS occupation                                   | 0.215***<br>(0.026)  | 0.128***<br>(0.029)  | 0.213***<br>(0.031)  | 0.119***<br>(0.029)  |
| HS sector                                       | 0.115***<br>(0.034)  | 0.106***<br>(0.025)  | 0.104***<br>(0.037)  | 0.108***<br>(0.028)  |
| Urban                                           | -0.006**<br>(0.003)  | 0.000<br>(0.004)     | -0.007*<br>(0.004)   | -0.001<br>(0.005)    |
| Distance LE-homes                               | -0.005<br>(0.003)    | 0.003<br>(0.003)     | -0.006*<br>(0.003)   | 0.006<br>(0.004)     |
| Constant                                        | -0.031<br>(0.082)    | -0.284**<br>(0.116)  | -0.060<br>(0.084)    | -0.305**<br>(0.122)  |
| Region dummy vars.                              | Yes                  | Yes                  | Yes                  | Yes                  |
| correction term ( $h(\cdot)$ )                  | -0.000<br>(0.004)    | 0.057***<br>(0.004)  | -0.000<br>(0.002)    | 0.022***<br>(0.003)  |
| Observations                                    | 4265                 | 4265                 | 4265                 | 4265                 |
| $R^2$                                           | 0.565                | 0.465                | 0.566                | 0.446                |

Notes: Notes: Robust standard errors in parentheses. Standard errors corrected to account for the two-stage procedure using bootstrap. Columns (1) and (2) are cross-section regressions for the LEs in Q4 in 2007, while columns (3) and (4) are cross-section regressions for the LEs in Q4 of 2009. The model is estimated using a control function approach, where  $h(\cdot)$  is the correction term from the ordered probit entry model to account for selection and endogeneity of  $N_{it}$ . The variable  $N_{it}$  is a dummy variable for at least one entrant in columns (1) and (3), and a discrete ordered variable for the number of entrants in columns (2) and (4).

\*\*\*Significant at 1%; \*\*significant at 5%; \*significant at 10%.

is consistent with the view that inter-platform competition gives higher benefits than intra-platform competition.

Finally, we asked whether the impact of LLU investment on penetration is larger in areas without a strong presence of the cable than in areas with competition from this alternative technology. To assess this, we split the sample into two parts: LEs with and without cable coverage. The findings, reported in the fifth and sixth columns of Table 3, confirm our expectations. The earlier documented positive (and declining) impact of LLU on penetration can be mainly attributed to areas where cable is not present. In areas with cable, the impact of LLU is smaller, and it declines less rapidly over time compared with areas without cable.

The declining effect of LLU on broadband penetration over time can also be linked to supply-side phenomena. As more entrants use LLU in a given LE, especially when there is no strong competition from the cable company, local congestion effects upon new entry become more likely, having a negative impact on demand. Likewise there is evidence from the specialized press that one large entrant (Orange) had operational problems with LLU, and eventually handed back the service to BT in 2010. Operators can also have followed various strategies of price and product differentiation in areas with and without LLU. Although we do not have price data, we further investigate these questions in Section 5.<sup>24</sup>

*Cross-section Results with Endogenous LLU Entry.* Our fixed effects estimator accounts for time-invariant sources of unobservables across LEs, but it is still possible that there are unobserved market specific shocks at specific points in time that are correlated with the LLU entry decision. For this reason we now turn to our control function approach, where we use instruments that naturally arise from the entry model (namely market size and geographic variables). We focus our analysis on cross-sections for the following periods: 2007Q4 and 2009Q4 (and briefly comment on the results for other periods). Results are reported in Table 4.

The first two columns of the table report the estimates of the model where the entry variable  $N_{it}$  is a dummy variable for LLU coverage as in the panel data model (0 if there is no entry, and 1 if at least one entrant has invested in LLU). Several market demographics have a significant impact on total broadband penetration. In particular, the penetration rate tends to be larger in LEs with a high income, a large proportion of high-skilled workers, and a large proportion of people of working age, and it tends to be lower in LEs with a large proportion of elderly (over 60). The effect of LLU coverage on broadband penetration is consistent with the findings from our panel data approach. LLU coverage had a positive effect of +1.78% in the earlier periods (2007Q4), while

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24. We performed further robustness checks (see Online Appendix). First, we estimated a panel fixed effects regression, where we weigh the observations by the size of the LE. This gives comparable results. Second, we replace the interaction between the dummy for LLU investments and the trend with a set of interactions between the former variable and a dummy variable for each year. Results are consistent with a steady declining trend of the effect of LLU over time. Third, we run a panel fixed effects regression employing the full sample of LEs (i.e., we drop income to include also observations from Scotland and North Ireland). Results again do not change.

it had a negative effect of  $-4.2\%$  at the end of our sample (2009Q4). We also estimated the model for other periods, and found a consistently declining effect of LLU coverage over time.<sup>25</sup>

The third and fourth columns extend the analysis to a model where  $N_{it}$  is no longer a dummy for LLU coverage, but rather an ordered variable for the number of entrants (0, 1, 2, or 3+) (so that the first-stage entry model is now an ordered probit instead of a binary probit). This gives a picture that is consistent with our earlier findings. In the beginning (2007Q4) every additional entrant tended to raise total broadband penetration by 1%, while at the end of the sample additional LLU entry reduced broadband penetration.

In contrast with LLU, the effect of inter-platform competition through cable is stable over time, and similar in magnitude as in our panel data analysis. Cable coverage in the LE tends to increase broadband penetration by, on average, over 2 percentage points.<sup>26</sup>

To summarize, both Table 3 and Table 4 show that intra-platform competition through LLU entry had an initially positive effect on penetration, but this effect vanished over time. On balance, the conclusion is that LLU entry mainly led to a faster broadband adoption, but did not affect in any sizable way final total broadband penetration when the market matured. This may be interpreted in several ways. First, 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. Second, it is possible that LLU entry has impacted performance in dimensions 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.

25. We considered several other specifications as a robustness analysis, which we present in the Online Appendix. First, we estimated a specification where the entry model for LLU coverage does not include the sunk cost term. The results confirm our finding of a positive effect of LLU coverage in the first period, a smaller effect in the middle period, and a negative effect in the final period. Second, we estimated a long-run difference model between mid-2006 and mid-2009. This model regresses the change in broadband penetration across LEs on the change in the number of LLU entrants and cable coverage during the considered period. We instrument the change in the number of LLU entrants with distance to the backbone and number of lines. The results again confirm the negative effect of LLU on penetration for the second part of the sample period (estimated effect of  $-1.8\%$ ). Finally, we estimate the same model as in columns (1) and (2) of Table 4, where the first-stage entry model is now a simple linear regression instead of an ordered probit. This amounts to a standard linear IV regression with the same instruments as in our control function approach. The results are again close to those reported in Table 4: the estimated effect of LLU on penetration is  $+2.6\%$  in 2007Q4, while it is  $-4.1\%$  at the end of the sample in 2009Q4.

26. The coefficient for the correction term  $h(\cdot)$  (i.e.,  $\sigma_{ue}$ ) shows the same pattern for both the model with LLU coverage and the model with the number of LLU entrants as an explanatory variable: the coefficient is insignificant in the early period (2007Q4) and highly significant at the end of our sample (2009Q4). This indicates that the unobservables in the penetration and entry model show significant covariance in 2009, while this was not the case in 2007. One possible interpretation is that the observable entry determinants were more important in the first years, while the unobservable factors became more relevant in recent years.

## 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 data set regarding the quality of connections. As reported previously, this data set contains information from one million individual speed tests run by end users.<sup>27</sup> 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.<sup>28</sup>

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,<sup>29</sup> the distance between the user's premises and the LE is the most important factor affecting the performance of a given connection. As a very good proxy for the distance between the premises and the LE, we use the distance between the geographic center of the six-digit 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 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 subject to Universal Service Obligations for voice telephony, which uses the same infrastructure, it covers all areas, and in particular wider rural areas that are not covered by entrants. Thus the average speed of BT suffers from the fact that, on average, it is serving more distant consumers.

The lower panel of Table 1 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  $j$

27. Tests have been performed in 97.6% of the LEs. To further assess the representativeness of this sample, we looked at the operators' market shares at the level of the LEs. We found that the market shares as computed from Ofcom's detailed subscriber data set and the currently used speed test data set display a correlation very close to 1.

28. These four operators account for 94% of the entrants' market alone.

29. <http://stakeholders.ofcom.org.uk/market-data-research/other/telecoms-research/broadband-speeds>.

in LE  $i$ :

$$\ln speed_{ij} = \gamma_1 LLU\_OP_{ij} + \gamma_2 Bitstream\_OP_{ij} + \gamma_3 Cable\_OP_{ij} + \beta x_{ij} + v_{ij}. \quad (5)$$

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 these dummies are equal to zero, this means that the test is run by BT. Hence, the coefficients  $\gamma_1$ ,  $\gamma_2$ , and  $\gamma_3$  measure the additional speed for the different technologies, compared to the BT base. The vector  $x_{ij}$  contains several control variables. This includes variables that only vary by LE  $i$ —that is, the *urban* dummy variable, the log of *income*, and other market demographics; and variables that vary both by LE  $i$  and test  $j$ —that is, *distance* and *distance*<sup>2</sup>, 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. As in our analysis of broadband penetration, it is possible that the different forms of entry are correlated with the error term  $v_{ij}$ . We therefore again instrumented for sources of endogeneity through a control function approach: we first estimate a probit entry model for each form of entry (with the same profit determinants as before), and subsequently use the implied correction terms as controls in equation (5).<sup>30</sup>

Table 5 reports the results. The first column shows the estimates of equation (5). 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 16% lower at noon, 28% lower at 6 p.m. and indeed 45% 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 on Sundays, 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 18.6% higher than that provided by BT (equal to  $e^{0.175} - 1$ ). However, subscribers to a Bit-stream service have a significantly lower connection speed than BT subscribers, the difference between the two being roughly 16.9%. This may be due to coordination difficulties when the Bit-stream entrant and the incumbent have to share a line. Since BT is in full control of Bit-stream, there have also been allegations that BT might have strategically slowed down the connection of its competitors' lines. (This is not possible under LLU entry, since the entrant then manages directly its own lines.) Finally, users of cable (Virgin) have a much higher broadband speed (about 76% faster) than those of BT.

We also extended the specification to estimate the effects of additional entrants beyond the first. We find that the effect of the first entrant is the largest (+30%), and

30. Note that the correction terms also pick up 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 that LE). As an alternative, we also estimated a version of equation (5) with fixed effects  $\eta_i$  and this gave similar results.

TABLE 5. Regressions on the (log of) speed of connection.

| Dep. var: Log of download speed  | All ISPs  |          |           |          | BT only   |          |
|----------------------------------|-----------|----------|-----------|----------|-----------|----------|
|                                  | (1)       |          | (2)       |          | (3)       |          |
|                                  | Coeff.    | Std Err. | Coeff.    | Std Err. | Coeff.    | Std Err. |
| LLU                              | 0.171***  | (0.009)  |           |          | -0.008    | (0.015)  |
| TalkTalk                         |           |          | 0.202***  | (0.003)  |           |          |
| O2                               |           |          | 0.508***  | (0.004)  |           |          |
| Orange                           |           |          | 0.057***  | (0.004)  |           |          |
| Sky                              |           |          | 0.074***  | (0.003)  |           |          |
| Bit-stream                       | -0.185*** | (0.013)  | -0.186*** | (0.003)  |           |          |
| Cable                            | 0.567***  | (0.012)  | 0.567***  | (0.002)  | 0.022     | (0.014)  |
| Distance LE–homes                | -0.263*** | (0.018)  | -0.262*** | (0.002)  | -0.350*** | (0.020)  |
| (Distance LE–homes) <sup>2</sup> | 0.332     | (5.126)  | 0.422     | (0.537)  | 12.121**  | (5.417)  |
| Log(income)                      | 5.725**   | (2.044)  | 5.032***  | (0.418)  | 6.383**   | (3.052)  |
| Working age                      | -0.163    | (0.110)  | -0.183*** | (0.027)  | -0.260    | (0.173)  |
| Over 60 y.o.                     | 0.091     | (0.085)  | 0.062**   | (0.021)  | 0.046     | (0.135)  |
| White                            | -0.012    | (0.038)  | 0.003     | (0.010)  | -0.109    | (0.090)  |
| Black                            | 0.363*    | (0.191)  | 0.273***  | (0.038)  | 0.244     | (0.380)  |
| Student                          | -0.351**  | (0.134)  | -0.380*** | (0.019)  | -0.007    | (0.215)  |
| HS occupation                    | -0.258*** | (0.056)  | -0.272*** | (0.011)  | -0.039    | (0.085)  |
| HS sector                        | 0.132     | (0.087)  | 0.126***  | (0.014)  | -0.139    | (0.119)  |
| Urban                            | 0.015*    | (0.009)  | 0.019***  | (0.002)  | 0.006     | (0.013)  |
| Monday                           | 0.019***  | (0.005)  | 0.018***  | (0.003)  | 0.014**   | (0.007)  |
| Tuesday                          | 0.039***  | (0.005)  | 0.039***  | (0.003)  | 0.045***  | (0.007)  |
| Wednesday                        | 0.055***  | (0.005)  | 0.055***  | (0.003)  | 0.066***  | (0.007)  |
| Thursday                         | 0.057***  | (0.005)  | 0.056***  | (0.003)  | 0.071***  | (0.007)  |
| Friday                           | 0.078***  | (0.005)  | 0.077***  | (0.003)  | 0.099***  | (0.007)  |
| Saturday                         | 0.064***  | (0.005)  | 0.065***  | (0.003)  | 0.106***  | (0.007)  |
| correction term ( $h(\cdot)$ )   | 0.009     | (0.007)  |           |          | 0.001     | (0.010)  |
| correction term for TalkTalk     |           |          | -0.010*** | (0.002)  |           |          |
| correction term for O2           |           |          | -0.006**  | (0.002)  |           |          |
| correction term for Orange       |           |          | -0.008*** | (0.002)  |           |          |
| correction term for ISP Sky      |           |          | 0.006**   | (0.002)  |           |          |
| Constant                         | 8.018***  | (0.150)  | 8.068***  | (0.034)  | 8.231***  | (0.246)  |
| Hours                            | Yes       |          | Yes       |          | Yes       |          |
| Region dummy variables           | Yes       |          | Yes       |          | Yes       |          |
| $R^2$                            | 0.199     |          | 0.209     |          | 0.202     |          |
| Observations                     | 922603    |          | 922603    |          | 335082    |          |

Notes: Notes: Cluster-robust standard errors at the LE level. Standard errors corrected to account for the two-stage procedure using bootstrap. (Distance LE–homes)<sup>2</sup> is scaled by a factor 1/1000 for readability.

\*\*\* Significant at 1%; \*\* significant at 5%; \* significant at 10%.

then gradually declines for each additional entrant. This may be due to congestion or lower quality brought by additional entrants. This finding contributes to understanding why penetration decreased with LLU in 2009.<sup>31</sup>

31. This is consistent with a regulatory price revision of wholesale prices that became operational in 2008 which made LLU relatively cheaper compared to Bit-stream, possibly inducing excessive entry.

To summarize, these findings show that the LLU regulation designed to grant full control of the connection to entrants has been 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 those of the incumbent, and on average 42.8% faster than when they operated using Bit-stream technology.<sup>32</sup> 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 or 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 the specification given by equation (5) 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 22.4% faster than BT, while O2 is up to 66.2% faster, and almost reaches the speed of the cable operator.<sup>33</sup>

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 equation (5). 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. 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 average speeds 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.<sup>34</sup>

32. This is calculated from  $e^{0.171+0.185} - 1$ .

33. This is entirely consistent with reports from the specialized press showing that these Internet Service Providers were the first to deploy the ADSL2+ technology, which is capable of doubling the frequency band of typical ADSL connections, and achieving higher speeds. Notice that our data refer to the retail market for "residential and small business fixed internet connections", as defined by the regulator. Hence our results might suggest that LLU entrants manage to cater to small businesses that typically need higher Internet speed for their operations.

34. In the Online Appendix we give additional evidence that subscribers are more likely to choose the entrants' high speed contracts in areas where the operator has already adopted LLU.

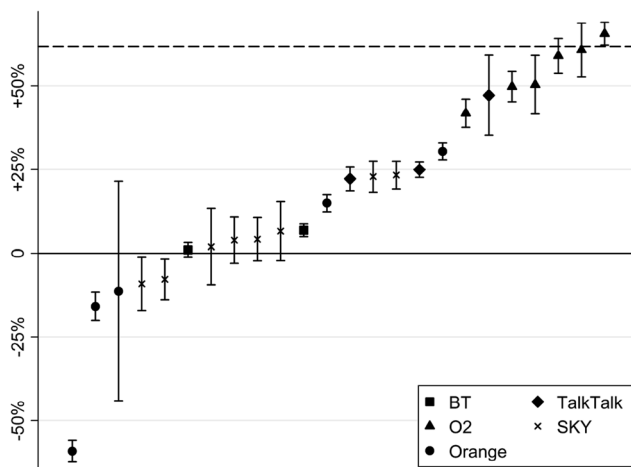


FIGURE 5. Entrants' relative performance compared to BT's base option.

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. However, regulators 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, we estimate a specification similar to equation (2), where 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.<sup>35</sup> 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.<sup>36</sup>

The findings in this section shed additional light on the impact of LLU on competition in the broadband market. Broadband speed is an important strategic variable of vertical product differentiation that becomes particularly prominent when the local loop is unbundled. Once they get control of the last mile via LLU, entrants have been successful in targeting customers with a high willingness to pay for speed. In particular, they have attracted inframarginal customers "at the top" of the distribution of preferences in those areas where cable is not present, and inframarginal customers "in

35. 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.

36. See, for example, <http://stakeholders.ofcom.org.uk/binaries/consultations/wba/statement/wbastatement.pdf>.

the middle” where cable (the fastest operator) is present. Instead, marginal customers “at the bottom” of the preference distribution are typically catered for by BT. Since it is the marginal customer that ultimately determines penetration in a given area, and BT does not seem to have differentiated much between areas with and without LLU, these results are useful to understand why LLU did not play a prominent role in expanding penetration in the broadband market.

## 6. Conclusion

In this paper we have used a rich data set regarding the demand for Internet services, and the investments made by telecom operators in the United Kingdom, 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 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 nonreplicable infrastructure giving incumbents market power, represents a distinctive feature of all network industries that have been subject to access regulation.

Our data set spans five 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 limited to the early years, and vanished as the market reached maturity. This is a remarkable result, and one which runs counter to many policy statements. The data instead reveal that inter-platform competition from cable always leads to market expansion.

While the small impact of LLU on total broadband penetration may be surprising, we also show that any assessment of unbundling must 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 market shares at the expense of the cable operator, which still offers the highest speed. However, 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.

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. 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. The lesson to be learnt is that unbundling incumbents makes sense when it provides ground for differentiation strategies.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Online Appendix to Evidence from UK Broadband