Unbundling the incumbent and deployment of high-speed internet: Evidence from France

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Unbundling the Incumbent and Deployment of High-Speed Internet: Evidence from France*

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Abstract

In this paper, we study the impact of competition on the legacy copper network on the deployment of high-speed broadband. We first develop a theoretical model, which shows that the relation between the number of competitors and investment in a quality-improving technology can be positive if the quality of the new technology is high enough, and is negative otherwise. We test these theoretical predictions using data on broadband deployments in France in more than 36,000 local municipalities. First, using panel data over the period 2011-2014, we estimate a model of entry into local markets by alternative operators using local loop unbundling (LLU). Second, using cross-sectional data for the year 2015, we estimate how the number of LLU entrants impacts the deployment of high-speed broadband with speed of 30Mbps or more by means of VDSL, cable and fiber technologies, controlling for the endogeneity of LLU entry. We find that a higher number of LLU competitors in a municipality implies lower incentives to deploy and expand coverage of high-speed broadband with speed of 30Mbps or more.

Keywords: High-Speed Broadband; Local Loop Unbundling; Competition; Market Entry.

JEL Classification: K23, L13, L51, L96.

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1 Introduction

The deployment of next-generation broadband access networks, capable of delivering high-speed Internet access, is seen as an important driver of economic and social development. High-speed broadband infrastructures are expected to stimulate growth and job creation, through increased productivity and by stimulating innovation in products and services.[1]

Europe however lags behind other regions, in particular the US, South Korea and Japan, in terms of deployment of next-generation access networks, which has raised concerns from policymakers.[2] Some (incumbent) telecommunications operators blame an overly competitive landscape in Europe, which, they argue, has eroded operators' margins, and as a consequence, their ability to invest in new infrastructures.[3] By contrast, alternative operators contend that it is competition that drives investment.[4]

Competition in broadband markets in Europe has developed via liberalization and the introduction of a specific regulatory provision, "local loop unbundling" (LLU), a policy that enables alternative operators to lease wholesale access to the incumbents' legacy copper networks to offer broadband Internet access services to consumers. LLU aimed at facilitating entry of alternative operators, but is impact on investment has been hotly debated.[5]

While local loop unbundling was abandoned in the US in 2005, in Europe it has been a cornerstone of the regulation of broadband markets over the last ten years. The European local loop unbundling regulation, which was implemented in the early 2000's,[6] eventually led to a wave of entry of alternative operators in local markets, offering broadband services to residential and business consumers through the DSL ('Digital Subscriber Line') technology.[7]

In this paper, we study how the number of LLU entrants in a local market, which has resulted

[1]See Röller and Waverman (2001), Czernich, Falck, Kretschmer and Woessmann (2011) and Ahlfeldt, Koutroumpis and Valletti (2017), among others, for empirical evidence on the positive impact of telecommunications infrastructures, and in particular broadband infrastructures, on growth and jobs.

[2]For a comparative study of broadband deployment in Europe and in the US, see, e.g., Yoo (2014).

[3]For example, in a report for ETNO, the professional association of incumbent (historical) operators, BCG (2013) states that: "network owners are hindered in capturing the fair returns needed to fund investments, primarily because of over- and inconsistent regulation."

[4]For example, ECTA, which is the professional association of alternative (entrant) operators, argues that "sustainable competition is what drives efficient investment" (ECTA, 2017).

[5]For a comprehensive survey on the impact of LLU regulation on investment in broadband markets, see Cambini and Jiang (2009).

[6]Regulation (EC) No 2887/2000 of the European Parliament on unbundling.

[7]Cave (2014) provides descriptive evidence of this wave of LLU entry in European markets, and discusses the role of European LLU regulations.

from this entry wave, affects today the incentives of broadband service providers to roll out next-generation access network infrastructures ('NGA networks'). The impact of the number of local competitors on investment incentives is *a priori* ambiguous. On the one hand, a higher number of LLU operators delivering DSL services, and hence a more competitive local broadband market, reduces the expected profits from offering NGA services, and therefore the incentive to invest (a profitability effect). On the other hand, a higher number of LLU competitors implies lower pre-investment profits from existing broadband operations. The opportunity cost of investment (foregone *ex-ante* profits), which corresponds to Arrow's famous 'replacement effect' (Arrow, 1962), is thus lower, which increases the incentive to invest. Which of these two effects dominates is *a priori* unclear.

We start by developing a simple theoretical model to study the impact of the number of competitors using an old technology (in our context, basic broadband) on a firm's incentive to invest in a quality-improving new technology (the NGA network technology). We show that the relative impact of the number of competitors on the profitability of the investment and on the replacement effect depends on the quality improvement brought by the new technology, compared to the old technology. Using a specific model of quantity competition with quality differentiation, we find that if the quality improvement is sufficiently high, the relation between the number of competitors and the investment incentive is positive, and that otherwise it is negative.

We test these theoretical predictions using a comprehensive data set on the market structure and the deployment of high-speed broadband in local municipalities in France. We adopt a two-step empirical approach, which allows us to estimate the impact of the local market structure on the deployment of high-speed broadband, controlling for the endogeneity of market structure.

In the first step, we build a model of entry of alternative operators in local municipalities via local loop unbundling. We estimate this entry model using panel data on the number of LLU entries and exits in 36,104 municipalities over the period 2011-2014. We find that local market characteristics, such as the size of the market and the density of population, are important determinants of LLU entry. We also find significant sunk costs which represent a barrier to entry, though entry becomes easier over time.

In the second step of our empirical approach, we estimate how the number of LLU operators in a municipality affects the deployment of high-speed broadband. To do so, we use a cross-sectional data set for the second quarter of 2015 on the coverage of different speed tiers in municipalities. We control for the endogeneity of LLU entry by means of a control function approach, using our model of LLU entry estimated at the first step of the analysis. We also take into account local market characteristics such as market size, population density and income, and the heterogeneity in local market conditions. We find that a higher number of LLU competitors in a municipality has a negative impact on the deployment and coverage of fast broadband, delivering speeds of 30Mbps or more by means of VDSL, cable and fiber technologies.

The remainder of the paper is organized as follows. In Section 2, we review the relevant theoretical and empirical literature and discuss our contribution. In Section 3, we present the theoretical model and results. In Section 4, we provide some background on the broadband industry in France and describe our data sets. In Section 5, we introduce the econometric framework, and in Section 6 we present the estimation results. Section 7 concludes.

2 Literature Review

2.1 Theory

Bourreau, Cambini and Doğan (2012) and Inderst and Peitz (2012) analyze the effect of access to the legacy copper network (i.e., local loop unbundling) on the incentives to deploy a fiber network for an incumbent and an entrant operator. They show that access affects both pre- and post-investment profits, and hence, influences investment incentives through different channels. As a consequence, a lower access price for copper implies less investment incentives for the entrant, but has an ambiguous effect on the investment incentives of the incumbent.

Bourreau et al. (2012) and Inderst and Peitz (2012) take market structure (a duopoly) as given, and analyze the effect of access regulation on investment. By contrast, we take access regulation as given, and analyze the impact of the market structure of local markets on investment. Our paper is thus also related to the broad theoretical literature on the impact of market structure on investment and innovation.[8] Since the firms that invest in new broadband infrastructures earn *ex-ante* profits from the old broadband technology, we are more specifically interested in the impact of market structure on the profit incentive, defined as the difference between post- and pre-investment profits. Arrow (1962) shows that the profit incentive under

[8]See Gilbert (2006) for a survey of the theoretical and empirical literature on this topic.

monopoly is lower than under perfect competition, due to a "replacement effect" for the monopolist; as a consequence, the monopolist has less incentives to invest or innovate than firms under competition. Yi (1999) and Belleflamme and Vergari (2011) extend Arrow's analysis to oligopolistic markets, and study how the profit incentive varies with the number of competitors. Yi (1999) considers a homogeneous product market under Cournot competition, and shows that the profit incentive decreases with the number of firms for a large class of demand functions. Belleflamme and Vergari (2011) consider an oligopoly with horizontally differentiated products, and show that the relationship between the profit incentive and the number of firms can be non-monotonic.

We contribute to this literature by studying the relation between the profit incentive and the number of firms for *vertically* differentiated products. In Section 3, we show that the relation between the profit incentive and the number of firms depends on the level of quality differentiation.

2.2 Empirics

Our paper is related to three streams of empirical literature, which study: (i) entry into telecommunications markets, (ii) investments in next-generation broadband networks, and (iii) quality competition between Internet service providers.

First, our paper is related to the literature on entry into local telecommunications markets. This literature was mainly focused on the US market before the Federal Communications Commission (FCC) changed its decision on the open access policy in 2004 (see Greenstein and Mazzeo, 2006; Economides, Seim and Viard, 2008; Xiao and Orazem, 2011; Goldfarb and Xiao, 2011; Wilson, Xiao and Orazem, 2018). Recently, Nardotto, Valletti and Verboven (2015) use UK data in the years 2005-2009 to estimate entry into local markets by alternative LLU operators. In another recent paper, Skiti (2016) uses local market data in New York State to analyze the entry and technology deployment decisions of cable and fiber operators. He provides evidence that cable incumbents made strategic investments in high-speed broadband technology to deter fiber entry. Wilson (2016) uses nationwide US data to estimate a dynamic oligopoly model, and shows that public investment in infrastructure crowds out investment from private firms more than it induces them to invest preemptively. In the first part of our empirical analysis, we use data from France in the years 2011-2014 to estimate a model of entry by LLU operators, which is similar to Nardotto et al. (2015).

Second, our paper contributes to the literature on investment in next-generation access (NGA) fiber networks. In this stream of literature, a few papers have studied the effect of access regulation on the migration from copper to fiber networks (see, e.g., Bacache, Bourreau and Gaudin, 2014; Briglauer, 2015; Briglauer, Cambini and Grajek, 2018). In particular, Briglauer et al. (2018) use data on incumbent telecom operators and cable players for 27 European member states for the period 2004-2014, and show that more stringent regulation of access to legacy or fiber networks harms investment by incumbent telecom operators. However, these studies use country-level data, and as such they cannot account for the large within-country differences in market structure and NGA investments that we observe in our micro-level data.

Only two papers in this strand of literature rely on local market information. Minamihashi (2012) uses municipal-level data for Japan in years 2005-2009 and finds that the LLU regulation imposed on the Japanese incumbent operator has discouraged entrants to deploy new broadband infrastructures. According to his counter-factual exercise, LLU regulation led to a 24% decrease in the roll-out of new fiber infrastructures. However, the incumbent's NGA investments were not hindered by LLU regulation. Fabritz and Falck (2013) use data on local exchange areas in the UK for the years 2007-2013 to analyze how the introduction of geographically differentiated regulation of wholesale broadband access has influenced investment in NGA networks by the incumbent. They find that deregulation had a positive effect on the roll-out of fiber. All these papers study the impact of access regulation on NGA investments, whereas our focus is different: we study the impact of market structure and competition on investments in NGA networks.

Finally, our paper is related to the literature on the impact of market structure on quality competition between Internet Service Providers. Nardotto et al. (2015) show that LLU entry had a positive impact on the quality of the DSL services provided by entrants (i.e., download speed) in the UK, because of their efforts to differentiate from the incumbent. Prieger, Molnar and Savage (2015) study how DSL firms respond to increased competition in terms of quality of broadband (speed) in a thousand local markets in California in years 2011-2013. They show that incumbent DSL firms increase the quality of their products when a cable operator enters a local market and starts offering fast broadband, or when a competing operator deploys fiber in the market. Wallsten and Mallahan (2013) use data on US residential broadband subscriptions and speeds, and find that broadband speed in a census area is significantly higher with a higher number of fixed broadband providers. In a similar vein, Molnar and Savage (2017) show that competition has a positive effect on broadband speed. Based on data for a sample of 5,281 census block groups (CBGs) in the US in 2011, they analyze the relationship between market structure and product quality, and show that the broadband speed is higher in markets with two or more competing firms, compared to markets with a single firm.

We contribute to this literature by using a comprehensive data set on the market structure and the provision of fast and ultra-fast broadband at the municipality level in France, and by offering evidence on the impact of LLU competition on the provision of high-speed broadband in a municipality.

3 A Model of Investment in Network Quality

In this section, we develop a stylized model of investment in network quality, which allows us to derive theoretical predictions on the impact of the number of LLU competitors on quality investment by network operators.

Model. A network operator, firm 0, contemplates upgrading its network in a given municipality with a new technology (e.g., next-generation broadband access), which offers a higher quality of service compared to the old technology (e.g., DSL broadband), for an investment cost of C.

Prior to investment, firm 0 operates an old-technology network, and faces competition from $n \geq 1$ identical firms, indexed with $i = 1, ..., n$, which also use the same old technology. In the context of the broadband market, we can interpret the n rival firms as LLU competitors. We denote the quality of the old technology by s_O, and the quality of the new technology by s_N, with $s_N > s_O$. We assume that the new technology is not a "drastic" innovation that replaces the old technology, which is consistent with what we observe in the broadband market.

For a given number of competitors n, let $\pi^O_{\text{pre}}(n, s_O)$ denote firm 0's pre-investment profit with the old technology O, and $\pi^N_{\text{post}}(n, s_N, s_O)$ its post-investment profit with the new technology N. We assume that firm 0's post-investment profit increases with the quality of the new technology, that is, $\partial\pi^N_{\text{post}}/\partial s_N \geq 0$. We assume furthermore that a higher number of firms in the market intensifies competition and lowers profits, that is, $\partial\pi^O_{\text{pre}}/\partial n \leq 0$ and $\partial\pi^N_{\text{post}}/\partial n \leq 0$.

Impact of market structure on investment. Firm 0's incentive to invest in the new technology is given by the difference in profit that the firm can earn if it invests in the new technology compared to the profit it would earn if it did not invest, which we refer to as the firm's *profit incentive*. Formally, firm 0's profit incentive is $PI \equiv \pi^N_{\text{post}}(n, s_N, s_O) - \pi^O_{\text{pre}}(n, s_O)$. Firm 0 decides to deploy the new network technology in the municipality if and only if $PI \geq C$.

We are interested in how the number of local competitors affects firm 0's incentive to invest in the new network technology. We thus study how the number of rivals affects its profit incentive:

$$\frac{\partial PI}{\partial n} = \underbrace{\frac{\partial \pi^N_{\text{post}}}{\partial n}}_{\text{(-)}} - \underbrace{\frac{\partial \pi^O_{\text{pre}}}{\partial n}}_{\text{(-)}}. \tag{1}$$

Equation (1) shows that the effect of the number of competitors on firm 0's profit incentive depends on two opposite effects. First, more intense competition reduces the profitability of the investment ($\partial \pi^N_{\text{post}}/\partial n \leq 0$), and therefore reduces investment incentives. Second, when the local market is more competitive, the opportunity cost of investment in terms of foregone (pre-investment) profits is reduced ($\partial \pi^O_{\text{pre}}/\partial n \leq 0$), which increases firm 0's investment incentive.

The impact of the local market structure on firm 0's investment incentive is thus *a priori* ambiguous. Which effect dominates is going to depend in particular on the quality of the new technology, s_N, and on the variation of the marginal effect of the number of firms on the profit incentive, $\partial PI/\partial n$, with respect to the level of quality s_N, i.e., $\partial^2 PI/\partial n \partial s_N = \partial^2 \pi^N_{\text{post}}/\partial n \partial s_N$.

If $\partial^2 \pi^N_{\text{post}}/\partial n \partial s_N \leq 0$ for all n and s_N, then $\partial PI/\partial n \leq 0$ for all n and s_N. Indeed, at $s_N = s_O$, we have $PI = 0$ and thus $\partial PI/\partial n = 0$. Since $\partial PI/\partial n$ decreases with s_N, the profit incentive is always (weakly) decreasing in the number of firms.

By contrast, if $\partial^2 \pi^N_{\text{post}}/\partial n \partial s_N \geq 0$ for some n and s_N, then we can have $\partial PI/\partial n \geq 0$ for some n and s_N, in which case the profit incentive increases with the number of firms. For example, at the extreme, if the new technology replaces the old one (i.e., it is "drastic"), then we have $\partial^2 \pi^N_{\text{post}}/\partial n \partial s_N = 0$ and the profit incentive increases with the number of competitors.

This discussion suggests that the number of competitors may have a positive effect on the incentive to invest if the quality of the new technology is sufficiently high. We propose below an illustrative model where this is indeed the case.

An illustrative model. We adopt the model of quantity competition with quality differentiation of Katz and Shapiro (1985), which has often been used in the literature to model competition in the broadband market.[9]

Consumers buy at most one product from one of the firms. The indirect utility of a consumer of type τ buying the product of firm $i = 0, ..., n$ is $U_i = \tau + s_i - p_i$, where s_i and p_i denote the quality and price of firm i. Consumers' types are uniformly distributed over $(-\infty, 1]$ with density one.[10] Firms compete in quantities and their marginal cost is normalized to zero. Firms $i = 1, ..., n$ offer quality $s_i = s_O$, whereas firm 0 offers quality $s_0 = s_O$ before investing and $s_0 = s_N$ after investing. We assume that $s_N < 1 + 2s_O$, which ensures that the firms that use the old technology remain active when the new technology is deployed.

Assuming that all firms are active in equilibrium (i.e., have positive sales), their quality-adjusted prices must be the same, that is, we have $p_i - s_i = p_j - s_j = \hat{p}$, for all i and j. The type of the marginal consumer is thus $\tau = \hat{p}$, and from the uniform distribution, the total demand is then equal to $1 - \hat{p}$. Since demand should be equal to supply, we have $Q = \sum_{i=0}^{n} q_i = 1 - \hat{p}$, where q_i denotes the quantity of firm i. The inverse demand faced by firm i is therefore given by $p_i = 1 + s_i - Q$.

Firms compete *à la Cournot*. Each firm i maximizes its profit $\pi_i = p_i q_i$ with respect to its quantity q_i, with a price p_i given by the inverse demand above. We solve for the equilibrium quantities pre- and post-investment. The pre-investment equilibrium profits are:

$$\pi^O_{\text{pre}}(n, s_O) = \left(\frac{1 + s_O}{n + 2}\right)^2.$$

The post-investment equilibrium profits are:

$$\pi^O_{\text{post}}(n, s_N, s_O) = \left(\frac{1 + 2s_O - s_N}{n + 2}\right)^2$$

for firms $i = 1, ...n$ and

$$\pi^N_{\text{post}}(n, s_N, s_O) = \left(\frac{1 + s_N + n(s_N - s_O)}{n + 2}\right)^2$$

[9] See, for example, Foros (2004) and Bourreau et al. (2012).

[10] Allowing for negative values of τ with no finite lower bound avoids corner solutions where all consumers purchase one of the firms' products.

for firm 0. In equilibrium, all firms are active under our assumptions. Firms' profits decrease with the number of competitors, and firm 0's post-investment profit increases with the level of quality s_N, as assumed in the general model.

The following proposition characterizes the impact of the number of competitors on firm 0's incentive to invest in the new technology.

Proposition 1. *In the Katz & Shapiro illustrative model, firm 0's incentive to invest in the new technology increases with the number of competitors in the market if the quality of the new technology is high enough, relative to the old technology; otherwise, it decreases with the number of competitors.*

Proof. We have $\partial PI/\partial n \geq 0$ if and only if

$$s_N \geq 1 + 2s_O - \frac{1 + s_O}{n + 1}. \tag{2}$$

Note that condition (2) is compatible with our assumption that $s_N < 1 + 2s_O$.

For a given number of competitors n, if s_N is sufficiently high to that (2) holds strictly, a small increase in the number of competitors leads to higher investment incentives. Note though that when n becomes large, (2) may not hold. If (2) does not hold for a given number of competitors n, an increase in the number of competitors leads to lower investment incentives. □

In our framework, this result suggests that if the new high-speed broadband technology brings a sufficiently high quality improvement for consumers over the old broadband technology (i.e., DSL), then we might expect a *positive* relationship between the number of LLU competitors and investment in high-speed broadband. Otherwise, if the quality improvement is less significant, we should expect a *negative* relationship. The intuition is that a high level of quality improvement softens the impact of local competition on post-investment profits (when (2) holds, we have indeed $\partial^2\pi^N_{\text{post}}/\partial n \partial s_N > 0$), due the strong vertical differentiation between the old and the new technologies.

To test these theoretical predictions, we use micro-level data on competition and investment in the broadband market in France, as we explain below.

4 Industry Background

4.1 The Broadband Market in France

Broadband connections provide consumers with high-speed access to the Internet.[11] In France, four main wireline technologies are used to deliver broadband: digital subscriber line (DSL), very-high-bit-rate digital subscriber line (VDSL), cable modem, and optical fiber. In 2014, DSL represented 88% of all broadband connections (with some of these connections being VDSL), cable modem 6.6%, and optical fiber 3.6%.[12]

DSL is a family of technologies used to transmit data over traditional copper telephone wires, which connect customer premises to the main distribution frames (MDFs) of the historical incumbent operator (France Telecom/Orange in France). The asymmetric version of the DSL technology ('ADSL') was first introduced in France in 1999 by Orange. To allow entry and competition in the broadband market, the French regulator (ARCEP) quickly mandated Orange to provide access to its MDFs and copper lines to competitors, a policy known as 'Local Loop Unbundling' or LLU.[13] To provide DSL services to consumers, an operator wishing to use LLU ('LLU operator' hereafter) has to build a backhaul network down to the MDFs, and then install its DSL equipment in the MDFs to deliver broadband over copper lines.

The LLU regulation led to a wave of entry of operators in various local municipalities. Table A.1 in the Appendix shows the number of municipalities in which operators have LLU presence for the years 2011-2014. Free and SFR are the most active LLU operators, and therefore the main competitors to Orange in the DSL market, with a presence in 19,488 and 14,140 municipalities, respectively, as of 2014. There is also a competitive fringe of smaller LLU operators with presence in 8,610 municipalities as of 2014.[14]

VDSL is a DSL technology providing faster transmission speeds than standard DSL, but

[11] The European Commission defines broadband as Internet connections with speed of at least 144 kbps.

[12] Other broadband technologies such as WiFi or satellite represented only 1.8% of broadband connections in 2014. Source: ARCEP observatory – High and very-high-speed Internet – Retail market.

[13] Discussions between Orange and the regulator about LLU started in December 1999, and LLU experiments were launched in July 2000. In December 2000, the European Commission published its Regulation No. 2887/2000 on unbundled access to the local loop.

[14] The two next largest LLU operators are Axione (2,236 municipalities covered with LLU) and Bouygues Telecom (2,070 municipalities covered with LLU). The other LLU operators have mainly a regional presence and include Teloise, Moselle Telecom, Manche Telecom, Iris 64, Alsace Connexia, Medialys, Ovh, Armor Connectique, Herault Telecom, Ariege Telecom, Haut Rhin Telecom, Colt, Rennes Metropole Telecom, Alliance Connectic and a number of other very small operators.

only for short copper lines.[15] The deployment of VDSL was authorized by the French regulator, ARCEP, in October 2013.[16] VDSL is deployed by the main DSL operators, Orange, Free and SFR. They are upgrading their DSL networks to VDSL progressively, as consumers switch to VDSL commercial offers.

Cable modem is a technology that enables broadband over coaxial cables, which were originally developed to carry television signals. There is only one cable operator in France, Numericable, which covers about 30% of the population, mainly in urban areas. In 2007, Numericable started to upgrade its cable network using the DOCSIS 3.0 standard, which permits high-bandwidth data transfers substantially exceeding those of DSL connections. Since 2007, Numericable has not deployed new cable infrastructure.

Finally, optical fiber is a technology that converts electrical signals carrying data into light, and transmits it over fibers. It can provide speeds that exceed by far those achievable with the DSL or cable modem technologies. In France, from 2010 onwards, the main DSL operators (Orange, SFR and Free) started to roll out fiber-to-the-home (FTTH) networks.[17] Fiber networks are expected to replace copper networks at least in densely populated areas.[18] They rely on a different architecture than copper networks, with new main distribution frames (the NROs, "noeuds de raccordement optiques").

We adopt the European Commission's definitions for the different broadband speed tiers: *basic broadband* refers to a connection with download speed below 30Mbps, *fast broadband* to a connection of 30Mbps or more, and *ultra-fast broadband* to a connection of 100Mbps or more. In France, basic broadband is provided using the DSL technology by the incumbent Orange and LLU entrants (SFR, Free and a competitive fringe). Fast broadband is available on the FTTH networks of the main operators (Orange, SFR and Free), on the VDSL lines of the same operators, and in the areas where the cable operator, Numericable, has upgraded its network. Finally, ultra-fast broadband is available in the areas where DOCSIS 3.0 and/or FTTH has been deployed.

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[15] In France, operators are deploying the second generation of VDSL, called VDSL2. With VDSL2, the maximum speed is achieved for lines of up to 300 meters. The connection speed decreases sharply for longer copper lines.

[16] In 2013, the authorization to implement VDSL concerned only lines in direct distribution, i.e, lines directly connected to an MDF. In October 2014, ARCEP authorized the deployment of VDSL to all eligible lines, i.e., including lines connected to a street cabinet.

[17] The FTTH technology is also called fiber-to-the-premises (FTTP).

[18] Note that currently in France there is no regulation imposing access to fiber infrastructure, i.e., there is no unbundled or bitstream access to fiber networks.

Table 1 summarizes the definitions of basic, fast and ultra-fast broadband. In the paper, we define *high-speed broadband* as fast or ultra-fast connections.[19]

Broadband category	Speed	Technology
Basic	< 30Mbps	DSL, cable modem, VDSL, fiber
Fast	≥ 30Mbps	Cable modem, VDSL, fiber
Ultra-fast	≥ 100Mbps	Cable modem, fiber

Table 1: Definition of basic, fast and ultra-fast broadband.

4.2 Data Sets

We use three data sets, which are available at the municipal level: (i) a data set on the identity and the number of active LLU operators in municipalities; (ii) a data set on the share of the households with access to Internet speeds of at least 3Mbps, 8Mbps, 30Mbps and 100Mbps; and (iii) a data set with socio-economic information on municipalities.

The first data set, which we received from the fixed copper-line incumbent operator Orange, contains information on the presence of LLU operators at the municipality level. For each municipality in Mainland France and each year between 2011-2014, we observe the presence and identity of LLU operators. In the municipalities where the local loop has been unbundled, there are between one and five LLU operators. Table A.6 in Appendix shows that there is a large number of entries and exits by LLU firms in France in the time period considered.

Our second data set provides information on the share of households in every municipality in Mainland France with access to Internet connections with speeds of at least 3Mbps, 8Mbps, 30Mbps and 100Mbps, based on different technologies: DSL (including VDSL), cable modem and fiber. We obtained this information from the Observatory of High-Speed Internet in France, which is a government initiative collecting broadband coverage information from local authorities and operators at the municipal level and on a quarterly basis. The objective of the Observatory is to track the development of high-speed Internet in France. The data set is publicly available,

[19] This is consistent with the focus in the European Union on fast and ultra-fast broadband. This is also consistent with the current definition by the FCC of high-speed broadband, that is, fixed broadband connections delivering speeds of at least 25Mbps download and 3Mbps upload. See Federal Communications Commission, "2018 Broadband Deployment Report", FCC 18-10.

and the first period is the second quarter of 2015.[20] The information on speed represents the maximum download speed that the line can actually reach, and was computed using data provided by network operators. As a result, the information provided may differ from the speeds reported by different Internet service providers in the context of their business practices. In addition, the actual speed depends on other factors, such as modem, traffic congestion, etc.

Our third data set contains socio-economic information at the municipality level, and was obtained from the French National Institute for Statistics and Economic Studies (INSEE). We have municipal-level data on the population size (defined as the number of households), population density (defined as the number of households divided by the geographic area of the municipality), and the number of flats and houses. This information is published with a two-year delay and available only until 2012. Since firms also do not have access to recent statistics, we consider that they make their entry decisions based on demographic information with a two-year lag. In addition, we have information on the average household income per municipality in the years 2010-2014, which was retrieved from the website of the General Direction of Public Finance (DGFIP). Table A.4 in the Appendix describes the variables used in the analysis.

These different data sets were merged using the unique INSEE code for each municipality. After merging, we have information on 36,104 municipalities in France for the years 2011-2014, resulting in a total of 144,416 observations.[21] The statistics on coverage by broadband speed is available only from 2015 onwards. Thus, we merge the coverage data in 2015 with the other information in 2014. There should be no drastic difference in coverage between the end of 2014 and the second quarter of 2015. We lose 78 municipalities when merging the coverage data with LLU entry data, and end up with 36,026 observations for 2015. Table A.5 reports summary statistics for the variables used in the analysis. The availability of detailed local data on LLU operators and coverage with high-speed broadband allows us to estimate the models at the municipality level.

[20] Source: `http://www.francethd.fr/`.

[21] There were 36,192 municipalities in France in the year 2014. Due to administrative changes in the years 2011-2014, we removed from the data 88 small municipalities. Some municipalities were also split into two and others merged, which led to changes in their names and INSEE codes.

5 Econometric Models

In this section, we present the econometric models. First, we set up a model of LLU entry, which allows us to estimate the determinants of the LLU entry decision together with the sunk entry costs. Next, we introduce a reduced-form model of broadband coverage, in which we take into account the endogeneity of LLU entry through a control function approach. Finally, we extend the model of broadband coverage to account for sample selection.

5.1 LLU Entry

To begin with, we set up a model of LLU entry to analyze the demand-side and supply-side factors that influence entry. A firm is going to enter a given local market via LLU to offer DSL broadband services to residential and/or business consumers. The firm enters the local market if, and only if, its expected gross profits in the area outweigh the entry costs. There are substantial fixed costs of entry into local markets. As discussed in Section 4, a firm wishing to enter a local market via LLU has to build a backhaul network down to the incumbent's MDF, and then co-locate its DSL equipment in the MDF.

In the previous literature on entry into broadband markets, both Xiao and Orazem (2011) for the US and Nardotto et al. (2015) for the UK consider the investments made by LLU operators to be mostly sunk. The identification of sunk costs is based on a comparison of entry thresholds for markets where entry took place with thresholds for markets where there was no entry. The sunk costs imply that less demand is needed for an incumbent to continue operations than is needed to support a new entrant.

We assume that at the end of each time period firms decide whether to enter into 'new' local markets in the next period and whether to continue their operations in the 'old' local markets where entry had already occurred in the previous periods. Firms form expectations about market demand, costs and competition with other firms. These expectations are fulfilled in equilibrium, and the marginal firm enters or exits the market. We draw inferences on the profit determinants assuming a free entry equilibrium, where firms enter a local market if and only if it is profitable for them to do so. The model that we consider does not allow for simultaneous entry and exit.

The number of LLU entrants in municipality i at time t is denoted as $N_{it} = n \in \{0, 1, 2, 3+\}$, where 3+ refers to three entrants or more.[22] The discounted future profits of a firm facing n

[22] Since there is only a small number of markets with more than three entrants, we truncate the number of

competitors in market i at time t can be written as:

$$\bar{\pi}_{it}^{n} = \alpha_t lnS_{it} + X_{it}\beta - \mu^n + \epsilon_{it} \equiv \pi_{it}^{n} + \epsilon_{it}, \quad (3)$$

where S_{it} is the market size approximated by the number of households and X_{it} is a vector of other characteristics of municipalities, which are potential determinants of profits (including income, population density, and the share of flats in the total number of premises). We also consider that firms' profits may differ across geographic regions due to other factors, which we approximate by a set of regional dummy variables.[23] In addition, we include a set of dummy variables for the year in which ADSL was deployed in a municipality for the first time, since municipalities in which ADSL was deployed earlier were open to LLU entry for a longer period of time. Finally, μ^n represents the negative effect on profits from the n^{th} firm, and ϵ_{it} is the error term which has a standard normal distribution. This reduced-form profit specification is similar to the specifications proposed by Xiao and Orazem (2011) and Nardotto et al. (2015), and does not distinguish between variable profits and fixed costs of production, as in Bresnahan and Reiss (1991).

Profits, π_{it}^{n}, are not observed and represent a latent variable. They include the non-sunk part of fixed costs. Apart from that, firms have sunk costs, SC, which cannot be recovered when they exit. The model of entry that we consider does not account for heterogeneity between firms, which is problematic because firms may have different cost structures. There are firms of different size and different geographic presence. Moreover, the main LLU operators, SFR and Free, deploy fiber networks and provide mobile services, which cannot be offered by smaller LLU entrants.

There are three different cases in which we may observe that at time t in market i there are $N_{it} = n$ active firms. In the first case, there were fewer than n firms in period $t-1$ and one or more firms have entered in period t, so that $N_{it} > N_{it-1}$. In this case, for the n^{th} marginal firm, the gross profits from entry must exceed the sunk cost of entry. But for the $(n+1)^{th}$ marginal firm, the gross profits must be lower than the sunk cost, which can be expressed as follows:

$$\textbf{Case 1, net entry: } N_{it} > N_{it-1} \text{ if } \bar{\pi}_{it}^{n} \geq SC \text{ and } \bar{\pi}_{it}^{n+1} < SC. \quad (4)$$

entrants to three.

[23]Until 1 January 2016, there were 22 regions in France. In 2014, the French parliament passed a law reducing the number of metropolitan regions to 13; it has been effective since 1 January 2016.

In the second case, no firm has entered or exited the market in period t, which means that there were n firms in period $t-1$ and $N_{it} = N_{it-1}$. The n^{th} marginal firm stays in the market, because its expected discounted profits from continuation exceed 0. But for the $(n+1)^{th}$ marginal firm, the benefit from entry is lower than the sunk cost, which can be specified as:

$$\textbf{Case 2, inaction: } N_{it} = N_{it-1} \text{ if } \bar{\pi}_{it}^{n} \geq 0 \text{ and } \bar{\pi}_{it}^{n+1} < SC. \tag{5}$$

Finally, in the third case, there were more than n firms in period $t-1$ and one or more firms have exited the market in period t, which implies that $N_{it} < N_{it-1}$. In this case, the market becomes unprofitable when more than n firms stay in operation. The $(n+1)^{th}$ marginal firm expects that it would be unprofitable to remain in the market, and decides to exit. Once this firm has exited the market, the n^{th} marginal firm expects positive profits, which can be expressed as:

$$\textbf{Case 3, net exit: } N_{it} < N_{it-1} \text{ if } \bar{\pi}_{it}^{n} \geq 0 \text{ and } \bar{\pi}_{it}^{n+1} < 0. \tag{6}$$

Using the profit specification (3), the above inequalities can be combined to derive the probability of observing $N_{it} = n$ entrants in market i at time t:

$$Pr(N_{it} = n) = \Phi(\pi_{it}^{n} - SC \cdot I_{it}^{+}) - \Phi(\pi_{it}^{n+1} - SC \cdot (I_{it}^{+} + I_{it}^{0})), \tag{7}$$

where $\Phi(.)$ 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 which show whether the number of firms increased (subscript +) or remained constant (subscript 0). The parameter vector $\theta = (\alpha, \beta, \mu, SC)$ is estimated by maximizing the following log-likelihood function:

$$\hat{\theta} = \arg\max \sum_{i=1}^{M} \sum_{t=1}^{T} \sum_{n=0}^{N} y_{it}^{n} \ln(Pr(N_{it} = n|\theta)), \tag{8}$$

where y_{it}^{n} takes value of 1 if $N_{it} = n \in \{0, 1, 2, 3+\}$, and 0 otherwise.

5.2 Deployment of High-Speed Broadband

We now introduce the model of deployment of high-speed Internet access. As mentioned in Section 4, we define basic broadband as a connection with download speed below 30Mbps, fast broadband as a connection of 30Mbps or more, and ultra-fast broadband as a connection of 100Mbps or more. We then define high-speed broadband as a fast or ultra-fast connection. To deliver high-speed broadband, operators have to upgrade their networks. DSL operators upgrade their networks to VDSL and/or fiber, while the cable operator, Numericable, upgrades its network to the DOCSIS 3.0 technology. The deployment of new broadband technologies takes place in parallel and is endogenously determined. First, the three operators deploying fiber (Orange, SFR and Free) can strategically respond to upgrades of the cable network to high-speed broadband. They may also decide to deploy VDSL instead of fiber. At the same time, Numericable can decide to upgrade its network as a strategic response to fiber or VDSL deployment by Orange, SFR and Free. The deployment of high-speed broadband is also affected by competition from LLU operators offering slower DSL services based on the copper network.

We abstract from modeling the strategic decisions of operators in this complex environment, and estimate a reduced-form equation for the share of households in a given municipality with access to high-speed (i.e., fast) broadband:

$$y_i = \delta N_i + \gamma Z_i + u_i, \tag{9}$$

where y_i denotes the share of households in municipality i with access to a connection with speed of at least 30Mbps; N_i denotes the number of LLU entrants in the municipality; and Z_i is a set of control variables that may determine coverage, including demand and cost shifters. Since the information on coverage starts in the second quarter of 2015, we estimate the model for a single cross-section of municipalities in this year, with the right-hand side variables for the end of 2014. The municipality characteristics included in the estimation are the same as in the model of LLU entry, except for the set of dummy variables for the year of launching DSL in a municipality. These dummy variables are our exclusion restrictions discussed below.

Model (9) is first estimated using ordinary least squares (OLS), with a set of municipality characteristics and dummy variables for regions. In this regression, the LLU entry variable may be correlated with the error term u_i. If there is a persistent shock in the municipality with a positive impact on high-speed broadband coverage, it may also positively impact LLU entry. For instance, local authorities may decide to reduce administrative costs and burdens to stimulate LLU competition and foster the deployment of high-speed broadband. We account for this using our model of LLU entry, which we discussed above. More specifically, we account for endogeneity of the number of LLU entrants, N_i, using the control function approach proposed by Manuszak and Moul (2008). This approach was also used by Nardotto et al. (2015) to estimate the impact of LLU on broadband penetration in the UK.

Assuming that the error terms of the LLU entry and high-speed broadband coverage models (ϵ_{it} and u_i) are multivariate normally distributed, one can show that:

$$\begin{aligned} E(y_i|X_i, N_i, S_i, Z_i) &= \delta N_i + \gamma Z_i + E(u_i|N_i = n, S_i, X_i), \\ &= \delta N_i + \gamma Z_i + \sigma_{u\epsilon} h(N_i, S_i, X_i; \theta), \end{aligned} \tag{10}$$

where $\theta = (\alpha, \beta, \mu^n)$ is the parameter vector from the entry model, $\sigma_{u\epsilon}$ is the covariance between u_i and ϵ_i, and $h(N_i, S_i, X_i; \theta)$ is the inverse Mills ratio (see Nardotto et al. (2015)):

$$\begin{aligned} h(N_i, S_i, X_i; \hat{\theta}) &\equiv E(\epsilon_i|\hat{\pi}_i^n - \hat{SC} \cdot I_i^+ < \epsilon_i < \hat{\pi}_i^{n+1} - \hat{SC} \cdot (I_i^+ + I_i^0)) \\ &= \frac{\phi(\hat{\pi}_i^n - \hat{SC} \cdot I_i^+) - \phi(\hat{\pi}_i^{n+1} - \hat{SC} \cdot (I_i^+ + I_i^0))}{\Phi(\hat{\pi}_i^n - \hat{SC} \cdot I_i^+) - \Phi(\hat{\pi}_i^{n+1} - \hat{SC} \cdot (I_i^+ + I_i^0))}. \end{aligned} \tag{11}$$

The error term u_i in the coverage equation (9) can be decomposed into the sum of two terms and written as $u_i = \sigma_{u\epsilon} h(N_i, S_i, X_i; \hat{\theta}) + \varepsilon_i$, where by construction ε_i is mean zero conditional on N_i , S_i, X_i and Z_i. The coverage equation (9) can be then rewritten as follows:

$$y_i = \delta N_i + \gamma Z_i + \sigma_{u\epsilon} h(N_i, S_i, X_i; \hat{\theta}) + \varepsilon_i. \tag{12}$$

First, we estimate the model of LLU entry using the maximum likelihood estimator (8). Then, we use the estimates to compute the correction term $h(N_i, S_i, X_i; \hat{\theta})$, which is used as an additional variable in the coverage regression (12).

The control function approach needs exclusion restrictions. We need at least one variable which determines entry of LLU operators, but is not correlated with the error term in the coverage equation for high-speed broadband. As we discussed above, the set of dummy variables for the year of launching DSL services in a municipality should satisfy this condition. The early launch of DSL in more attractive municipalities led to a higher number of LLU entrants, but there should not be a direct impact on the deployment of high-speed broadband. Table A.7 shows the average number of LLU operators in 2014 for different years of launching DSL services in a municipality. However, even though DSL launch in a municipality should not directly impact the deployment of high-speed broadband, it may be correlated with omitted municipality-specific characteristics. To mitigate this issue, we use in the estimation a set of municipality characteristics and regional dummy variables.

Our modeling approach has certain limitations. In particular, it does not allow us to evaluate the impact of LLU competition separately for fast and ultra-fast broadband, for reasons that we explain now. We therefore cannot test all the predictions of the theoretical model of Section 3. Table A.3 shows for the second quarter of 2015 the share of total population in France, computed from municipality-level data, with access to speeds above 3Mbps, 8Mbps, 30Mbps and 100Mbps, using DSL (including VDSL), cable and fiber networks. In the case of fiber, eligibility implies access to speeds of 100Mbps or more. In the case of cable, eligibility implies access to 30Mbps or more, but there are cable households that cannot achieve speeds of 100Mbps or more according to the data. In the case of DSL, there is no household which can achieve 100Mbps or more, but 30-100Mbps is achievable when DSL is upgraded to the VDSL technology. Speed of 8Mbps and more can be achieved on DSL or VDSL networks, depending on the distance between the household and MDF.

If we analyze the impact of LLU competition on coverage with speeds of 100Mbps or more (i.e., ultra-fast broadband), we *de facto* study the impact on the deployment of cable or fiber. If we analyze the impact on coverage with speeds of 30Mbps or more (i.e., fast broadband), we study how LLU competition affects the deployment of cable, fiber and VDSL. Firms which provide high-speed broadband in France strategically decide whether to invest in fiber, VDSL or not at all. The decisions to deploy VDSL and fiber are interdependent and the share of households covered with speed of 100Mbps or more via fiber is affected by VDSL deployment. Conversely, the share of households covered with speeds of 30-100Mbps, possibly via VDSL, depends on fiber deployment. The model developed in this section cannot take this interdependence into account. Our analysis is therefore primarily focused on coverage with speeds of 30Mbps or more, by means of any technology, VDSL, cable and fiber, for which the interdependence between technologies is not an issue.[24] With this model, we evaluate an average effect of LLU competition on fast and ultra-fast broadband deployment.

[24] In many municipalities, fiber was deployed and cable upgraded before 2013, and hence independently from VDSL. In particular, we observe that that fiber was deployed in 307 municipalities before 2013; the number of municipalities covered with fiber increased to 465 in 2013 and 596 in 2014. Cable was upgraded in 329 municipalities before 2013, and this number increased to 700 in 2013 and 1,068 in 2014.

5.3 Heckman's sample selection model

When estimating equation (12), we need to take into account a potential sample selection problem. In the majority of municipalities (24,830 municipalities out of 36,026), fast and ultra-fast broadband is not deployed at all, and hence there is no broadband coverage with speed of at least 30Mbps. We take this into account by estimating Heckman's sample selection model in two stages (see Heckman (1979)). In the first stage, we estimate a sample selection equation by means of a probit model:

$$y_i^* = \delta_s N_i + \gamma_s W_i + \sigma_{u\epsilon} h(N_i, S_i, X_i; \hat{\theta}) + \upsilon_i, \tag{13}$$

where y_i^* takes value of 1 for municipalities with some coverage, and 0 otherwise. The vector of estimated parameters is denoted by $\varphi = (\delta_s, \gamma_s, \sigma_{u\epsilon})$. In the second stage, the modified coverage equation is estimated for the sample of municipalities with positive coverage:

$$y_i = \delta_c N_i + \gamma_c Z_i + \sigma_{u\epsilon} h(N_i, S_i, X_i; \hat{\theta}) + \sigma_{\upsilon\varepsilon} \lambda(N_i, W_i, h_i; \hat{\varphi}) + e_i. \tag{14}$$

In equation (14), we use the fact that the error term ε_i in equation (12) can be decomposed into the sum of two terms, $\varepsilon_i = \sigma_{\varepsilon\upsilon} \lambda(N_i, W_i, h_i; \hat{\varphi}) + e_i$, where by construction e_i is mean zero conditional on N_i, S_i, X_i, Z_i and W_i. The hazard function (inverse Mills ratio), denoted by $\lambda(N_i, W_i, h_i; \hat{\varphi})$, is computed using the first-stage probit estimates:

$$\lambda_i(N_i, W_i, h_i; \hat{\varphi}) = \frac{\phi(\hat{\delta} N_i + \hat{\gamma} W_i + \hat{\sigma}_{u\epsilon} h(N_i, S_i, X_i; \hat{\theta}))}{\Phi(\hat{\delta} N_i + \hat{\gamma} W_i + \hat{\sigma}_{u\epsilon} h(N_i, S_i, X_i; \hat{\theta}))}. \tag{15}$$

Heckman's selection model also needs to satisfy the exclusion restrictions. We need at least one variable which determines the presence of high-speed broadband in a municipality and is included in W_i, but which does not impact coverage and is not correlated with the error term e_i in the coverage equation (14). In the probit estimation, we include the number of households in the municipality and the total population in the department to which this municipality belongs. More populous municipalities are more attractive for deploying high-speed broadband, but these variables should not affect the share of population covered. In other words, the share of population covered with high-speed broadband may be comparable in smaller and larger municipalities, conditional on the presence of high-speed broadband operators in these municipalities.

6 Estimation Results

Our estimation is done in the following steps. First, we estimate the LLU entry model using the maximum likelihood estimator (8) for panel data of 36,104 municipalities over the period 2011-2014. Second, we use the estimates to compute the correction term (11). Third, for a cross-section of 36,026 municipalities we estimate a probit model for the presence of high-speed broadband, including the number of LLU entrants and the correction term (11) among regressors. Fourth, we compute the inverse Mills ratio (15). Fifth, we use ordinary least squares to estimate the coverage equation (14) for uncensored observations. This equation includes the number of LLU entrants, the correction term from the entry model (11) and the inverse Mills ratio (15). We use two sets of exclusion restrictions in the estimation as discussed above.

6.1 LLU Entry

Table A.8 shows the estimation results for the model of LLU entry using panel data for 36,104 municipalities over the period 2011-2014. Model I is estimated without sunk costs (the ordered probit model), while Model II allows for non-zero sunk costs. Based on the much lower value of the log-likelihood function, the preferred model is Model II. The estimation results show the presence of significant sunk costs, which represent a barrier to entry and play an important role in broadband markets.[25]

We find that the market size and the density of the population significantly and positively affect LLU entry. In the estimation, we also use time dummies which are significant and increase over time. Thus, entry becomes easier over time and we observe more entry in smaller municipalities. This may be due to technological progress and declining costs of equipment, and/or to the introduction of specific regulations, which reduced the wholesale costs of LLU for alternative operators.[26] Furthermore, we find that a higher level of income has a positive impact on LLU entry, indicating a higher demand for broadband in richer municipalities. The

[25]Xiao and Orazem (2011) and Nardotto et al. (2015) also find significant sunk costs in the US and UK markets, respectively.

[26]For example, in January 2012, the LLU wholesale price was slightly reduced by ARCEP from €9 to €8.80. In 2011, there was also a change in the regulation of bitstream access (the removal of the obligation of cost orientation for bitstream access in areas with wholesale competition), after which operators may have favored LLU over bitstream access.

share of flats in the total number of residences is significant and negative, which implies that there is less LLU entry in markets with a larger share of flats. Since the costs of LLU entry should not depend on the share of flats,[27] we expect this variable to capture demand-side factors influencing LLU entry. It may in particular capture income effects, due to the fact that in municipalities with a high share of social housing, there is also a high share of flats. Apart from that, municipalities in which DSL was launched earlier experience more LLU entry, which is also shown in Table A.7. These variables are our exclusion restrictions which impact LLU entry but do not impact coverage with fast and ultra-fast broadband. Finally, we include in the estimation a set of regional dummy variables which are highly significant. They control for other factors determining the attractiveness of municipalities which belong to the same regions.

To sum up, our estimation results confirm the role of market size and other local market characteristics in determining the number of LLU entrants. We use the estimates from Model II to compute the correction term given by equation (11), which we use in the second-stage regressions for high-speed broadband coverage.

6.2 Deployment of High-Speed Broadband

Table A.9 shows the estimation results for the share of households with access to high-speed broadband (i.e., at least 30Mbps), based on any technology that can deliver these speed levels (i.e., VDSL, cable or fiber). The model is estimated using a cross-section of 36,026 municipalities in the second quarter of 2015. We estimate six regressions for each speed level: (i) the OLS model given by equation (12), with and without the correction term for the number of LLU entrants; (ii) Heckman's sample selection model given by equations (13) and (14), with and without LLU correction term.

In the OLS regressions, the number of LLU operators has a significant and negative impact on the share of households in a municipality with access to broadband speeds of 30Mbps and more (OLS I). When the correction term from the LLU model is included in the estimation, the magnitude of the impact increases (OLS II). Thus, competition on the copper network reduces the incentives to deploy high-speed broadband. The significant and positive estimate of the covariance between the error terms, $\sigma_{u\epsilon}$, indicates that, conditional on other market character-

[27] As discussed in Section 4, a firm who wants to enter a local market via LLU has to build a backhaul network down to the incumbent's MDF, and then co-locate its DSL equipment (the DSLAMs) in the MDF. These costs are mainly fixed and independent of the type of housing.

istics, high broadband coverage is observed in markets that are more likely to support a greater number of LLU operators. Thus, unusually attractive demand conditions in a municipality encourage both LLU entry and higher broadband coverage, and consequently, the estimates of the impact of LLU competition on broadband coverage in model (OLS I) suffer from an omitted variable bias. To correct for this bias, we need to include in the regression the correction term, $h(N_i, S_i, X_i; \hat{\theta})$, as in model (OLS II).

However, in the majority of municipalities fast or ultra-fast broadband is not deployed at all, which we need to take into account by estimating Heckman's sample selection model. First, we estimate how the number of LLU operators impacts the presence in a municipality of technologies which offer speeds of at least 30Mbps by means of a probit model (selection equation). Then, we use 11,196 uncensored observations and include the inverse Mills ratio computed from the probit model in an OLS regression to estimate how the number of LLU operators impacts the share of households in a municipality with access to speeds of 30Mbps or more (coverage equation). The first model that we estimate does not include the LLU correction term (Heckman I), while the second model includes it (Heckman II). The results for Heckman's sample selection models are similar to those obtained in the OLS regressions. The number of LLU entrants is significant and negative in coverage equations, with and without LLU correction terms. In the presence equation, LLU competition is insignificant in the estimation without correction term (Heckman I), but significant and negative when the correction term is included (Heckman II). The LLU correction term is significant and positive in both coverage and presence equations, which indicates that not accounting for the LLU correction term results in an omitted variable bias. We thus focus our discussion on the results for Heckman's model with the LLU correction term included (Heckman II).

We include in the models a number of socio-economic variables to account for the heterogeneity of local markets, which have a significant impact on the deployment of high-speed broadband. In Heckman's model, high-speed broadband is more likely to be present in more populous municipalities. Both the presence and the coverage of broadband is greater in municipalities with a higher density of population. This is consistent with the idea that in general, it is cheaper and more profitable to deploy high-speed broadband in densely populated areas. The share of flats in the total number of residences has also a positive impact on coverage. We indeed expect that a higher share of flats in a municipality implies lower costs of extending coverage with high-speed broadband due to more dense housing. The same income effects that we discussed for LLU entry may be at play, but the positive impact that we find seems to suggest that these income effects are dominated by the cost effects. Furthermore, we find that a higher level of income has a positive impact on the presence of high-speed broadband in municipalities. We also include in the estimations a set of regional dummy variables to control for differences in attractiveness of municipalities which belong to them, which are in general significant. The estimates of municipality characteristics in Heckman's and OLS models are comparable, with some differences with respect to the significance and sign of income and share of flats.

As an alternative approach, we use observations on all municipalities to estimate a Tobit model with and without LLU correction term, where the high-speed coverage variable y_i is censored at zero for municipalities without coverage and at one for municipalities with full coverage. The estimation results are shown in Table B.3 in the Appendix. Results are comparable to the ones obtained with Heckman's sample selection model: we find a significant and negative impact of LLU competition on coverage with speeds of at least 30Mbps or more. The LLU correction term is also significant and positive. The remaining socio-economic variables have similar impact on coverage as in Heckman's model.[28]

We also estimated the same models for the share of households with access to speeds of 8Mbps or more and to speeds of 100Mbps or more (i.e., ultra-fast broadband). The estimation results are shown in Tables B.1 and B.2 in the Appendix, respectively. The estimation results for speeds of 8Mbps and more show the impact of LLU competition on the incentives to deploy *any* broadband technology in municipalities, because these speed levels can be delivered with the "old" DSL technology, and not only with the "new" VDSL, upgraded cable and fiber technologies. This is because households which are located close to a MDF can achieve broadband speeds in the range 8-30Mbps with a standard DSL connection.

The second regression for ultra-fast broadband shows the impact of LLU competition on the deployment of cable and fiber technologies. But fiber operators can choose whether to invest in fiber or VDSL, which implies that the deployment of these technologies is determined at the same time. In other words, there is interdependence between coverage with technologies

[28]Heckman's sample selection and Tobit models are closely related. The first model is less restrictive in that the parameters explaining the censoring are not constrained to equal those explaining the variation in the observed dependent variable. Furthermore, Heckman's model depends on the assumed normal distribution of the error terms in the first stage regression, while Tobit model also relies on normality assumption of the error term. Both methods are inconsistent when this assumption is violated.

delivering speeds of 100Mbps and more and coverage with technologies offering speeds in the range 30-100Mbps. Thus, our regression suffers from an omitted variable bias. The assessment of the impact of LLU competition on the deployment of ultra-fast broadband would require a different modeling approach than the one adopted in this paper.

The estimation results for speeds of 8Mbps or more are very similar to those obtained for speeds of 30Mbps or more, as shown in Table B.1 in the Appendix. In Heckman's sample selection model (Heckman I), we find a negative impact of LLU competition on both market presence and coverage by technologies which offer such speed levels. The inclusion of the LLU correction term leads to a larger (negative) impact of LLU competition on both market presence and coverage (Heckman II). We obtain similar results with the Tobit model (see Table B.3).

The estimation results for speeds of 100Mbps and more are shown in Table B.2 in the Appendix. In Heckman's sample selection model (Heckman I), the number of LLU entrants is insignificant in the coverage equation, but significant and positive in the selection equation. The inverse Mills ratio is positive and significant at the 10% significance level, which indicates that the error terms in both equations are correlated, and so unusually attractive demand conditions in a municipality encourage both the presence of ultra-fast broadband providers and greater coverage. After inclusion of both correction terms, $h(N_i, S_i, X_i; \hat{\theta})$ and $\lambda(N_i, W_i, h_i; \hat{\varphi})$, we find that the number of LLU competitors does not have any significant impact on coverage of ultra-fast broadband (Heckman II). By contrast, the market presence of ultra-fast broadband is positively stimulated by competition on the copper network. These results contrast with our results for the OLS regressions, with and without LLU correction term, in which we found a significant and negative effect. But the number of 1,322 observations used in the second stage regression is rather small. Moreover, as mentioned above, our estimates may be biased because the share of households with ultra-fast broadband is determined simultaneously with coverage in the range 30-100Mbps. Note that in the Tobit model, we also find a positive impact of LLU competition on coverage with speeds of 100Mbps or more (see Table B.3).

To sum up, our estimation results suggest that the number of LLU entrants in a municipality has a negative effect on investment in high-speed broadband (30Mbps or more) by means of VDSL, cable and fiber. These technologies are less likely to be deployed by operators, and their coverage is also lower, when the local market is very competitive. We find the same results for speeds of 8Mbps or more. By contrast, for high levels of quality (100Mbps or more), we find a positive relationship between the number of LLU competitors and the presence of the new (ultra-fast broadband) technology, but there is no significant effect on coverage. However, as mentioned above, the results for ultra-fast broadband should be treated with caution.

Our empirical findings are consistent with the model developed in Section 3. First, we showed that when the quality improvement brought by a new technology is limited, we should expect a negative impact of the number of competitors on the deployment of the new technology. Our results obtained for fast broadband are in line with this model prediction: we find a negative impact of the number of LLU competitors on the diffusion of fast broadband. Second, the model predicts that for a quality improvement significant enough, there can be a positive relation between the number of competitors and the deployment of the new technology. The results obtained for ultra-fast broadband, which should be seen as speculative due to the possible omitted variable bias, seem to fit with this second prediction. The intuition would be that the strong vertical differentiation between ultra-fast and basic broadband softens the impact of LLU competition on the profits of ultra-fast broadband providers, while at the same time intense LLU competition decreases the opportunity cost of investment. As the profitability of ultra-fast broadband operations is hardly affected by the number of LLU competitors, there can be a positive relation between the number of LLU competitors and investment incentives.

7 Conclusion

In this paper, we analyze the impact of local market competition on the legacy copper network on the deployment of high-speed broadband. We develop a theoretical model and show that the relation between the number of local competitors and investment in a quality-improving technology such as high-speed broadband can be positive if the quality of the new technology is high enough, and is negative otherwise. We test these theoretical predictions using data on broadband deployment in local municipalities in France. First, we use panel data on 36,104 municipalities in France over the period 2011-2014 to estimate a model of entry into local markets by alternative operators via local loop unbundling (LLU). Second, we use cross-sectional data on 36,026 municipalities in year 2015, and controlling for the endogeneity of LLU entry, estimate how the number of operators that have entered a local market via LLU impacts the deployment of broadband access with speed of 30Mbps and more with the VDSL, cable and fiber technologies.

Our empirical results suggest that there is negative relation between the degree of competition in local markets (approximated by the number of LLU competitors) and investment in high-speed broadband with speeds of 30Mbps or more, by means of VDSL, fiber and cable technologies. We find the same results for connection speeds of 8Mbps and more, which can also be achieved with the DSL technology for households located close to MDFs. By contrast, we find a positive relation between the number of local competitors and the incentive to deploy ultra-fast broadband, that is, broadband with speed of 100Mbps or more. However, we find no significant relation between the number of competitors and the coverage of ultra-fast broadband in the municipality. The results for ultra-fast broadband should however be treated with caution because of possible omitted variable bias. This may be the case because the share of households with ultra-fast broadband is determined simultaneously with coverage in the range 30-100Mbps.

We find that local market characteristics also affect investment incentives. The presence of high-speed broadband in a municipality is positively influenced by its market size, population density and the income level, while coverage is positively influenced by the density of population and the level of income. Thus, investment in high-speed broadband is also driven by demand factors and declining costs of deployment.

From a policy perspective, our results show that LLU has been successful in stimulating entry in local markets in France. However, in local markets which experienced a lot of entry and are now competitive, operators are less likely to deploy high-speed broadband. In sum, while LLU has had positive short-term effects via entry and intensified local competition, its long-term impact in terms of investment may be negative.

Since the merger between one of the fiber operators, SFR, and the only cable operator, Numericable, there are now three firms deploying ultra-fast broadband in France. In each municipality, they can choose between investing in fiber and upgrading their DSL network to VDSL. These firms thus play a strategic investment game, and in some municipalities they can also decide to deploy fiber in co-investment. In this paper, we are not able to model this investment game, because we do not have information about which firms upgraded to VDSL in a given municipality. Instead, we adopted a simpler reduced-form approach to study how LLU competition impacts incentives to deploy fast and ultra-fast broadband by all technologies and firms. In future research, when the broadband industry in France develops further and more detailed information becomes available we may attempt to model a more advanced discrete entry game.

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Appendix A

Table A.1: LLU entry in municipalities by SFR, Free and other operators.

Year	SFR	Free	Other	Total
2011	7,739	10,727	7,435	15,295
2012	9,586	12,894	7,922	17,367
2013	13,025	16,103	8,219	20,876
2014	14,140	19,488	8,610	23,215

Number of municipalities in which SFR, Free and other operators entered via LLU out of a total of 36,104 municipalities.

Table A.2: Number of LLU entries in municipalities by year.

Nb LLU	2011	2012	2013	2014
0	20,809	18,737	15,228	12,889
1	6,750	6,503	6,662	6,687
2	6,441	8,624	11,885	13,941
3	1,766	1,829	1,731	1,941
4	336	407	569	617
5	2	4	29	29
Total	36,104	36,104	36,104	36,104

Table A.3: Total coverage in France in Q2 2015.

	All	DSL	Cable	Fiber
Eligible	99.2%	99.2%	27.2%	11.3%
Speed >3Mbps	87.4%	85.2%	27.2%	11.3%
Speed >8Mbps	77.2%	71.3%	27.2%	11.3%
Speed >30Mbps	44.5%	20.7%	27.1%	11.3%
Speed >100Mbps	24.6%	0.0%	19.9%	11.3%

Table A.4: Description of variables.

Variable Name	Description	Years	Source
Coverage	Share of population covered with		
	3Mbps+, 8Mbps+, 30Mbps+, 100Mbps+	Q2 2015	France THD
Nb LLU	Number of LLU operators in municipality	2010-2014	Orange
ADSL launch year	ADSL launch year in municipality	2010-2014	Orange
Households	Number of households (in thousand)	2008-2012	INSEE
Population department	Population in department (local authority) (in thsd hh)	2008-2012	INSEE
Population density	Number of households per km^2 (thousand/km^2)	2008-2012	INSEE
Share flats	Percentage of flats (%)	2008-2012	INSEE
Income	Average annual income (in thousand Euros)	2010-2014	DGFIP

Table A.5: Summary statistics for 2010-2014.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Nb LLU	144,416	0.96	1.04	0	5
LLU	144,416	0.53	0.50	0	1
Households (tsd)	144,416	0.75	3.53	0	100
Population department (tsd)	144,416	668	478	77	2,834
Population density per km2	144,416	76	464	0	21,835
Share flats	144,416	0.09	0.14	0.00	1.00
Income (Euros)	144,416	19,497	3,090	4,815	45,463
ADSL after 2005	144,416	0.12	0.32	0	1
ADSL 2005	144,416	0.20	0.40	0	1
ADSL 2004	144,416	0.25	0.43	0	1
ADSL 2003	144,416	0.14	0.35	0	1
ADSL 2002	144,416	0.07	0.26	0	1
ADSL 2001	144,416	0.15	0.36	0	1
ADSL before 2000	144,416	0.07	0.26	0	1
Coverage 3Mbps	36,026	0.61	0.40	0	1
Coverage 8Mbps	36,026	0.45	0.41	0	1
Coverage 30Mbps	36,026	0.14	0.26	0	1
Coverage 100Mbps	36,026	0.02	0.13	0	1
Presence 3Mbps	36,026	0.83	0.38	0	1
Presence 8Mbps	36,026	0.71	0.45	0	1
Presence 30Mbps	36,026	0.31	0.46	0	1
Presence 100Mbps	36,026	0.04	0.19	0	1

The number of households in a municipality was truncated to one hundred thousand due to a few extreme cases.

Table A.6: LLU new entrants and exits between periods.

	Nb LLU_t					
Nb LLU_{t-1}	0	1	2	3	4	5
0	67,092	509	61	1	0	0
1	8,820	17,210	561	13	0	0
2	2,121	8,228	30,298	240	4	0
3	19	95	806	6,268	79	0
4	0	1	10	426	1,488	4
5	0	0	0	2	30	32

Change in the number of LLU operators in municipalities between two consecutive periods for all observations in years 2010-2014. The total number of observations is 144,416. Observations on the diagonal represent no change in the number of operators between two periods, observations above the diagonal represent entries and below the diagonal are exits.

Table A.7: Number of LLU new entrants in 2014 by year of launching ADSL services in a municipality.

ADSL launch	Mean	Std. Dev.	Min	Max	N
1999	3.22	0.86	0	4	171
2000	2.56	0.96	0	5	2331
2001	1.90	0.86	0	5	5391
2002	1.63	0.74	0	5	2675
2003	1.57	0.75	0	4	5036
2004	1.04	0.87	0	4	9062
2005	0.45	0.71	0	4	7210
2006	0.24	0.59	0	5	3034
2007	0.33	0.62	0	4	475
2008	0.63	0.86	0	2	96
2009	0.22	0.52	0	2	105
2010	0.31	0.62	0	2	155
2011	0.34	0.54	0	2	285
All	1.19	1.04	0	5	36,026

Based on the sample of 36,019 municipalities.

Table A.8: LLU entry in municipalities.

Variables	Model I	Model II
Log households	0.145***	0.119***
	(0.005)	(0.007)
Log density	0.441***	0.305***
	(0.006)	(0.007)
Log income	0.662***	0.522***
	(0.018)	(0.023)
Share flats	-0.238***	-0.442***
	(0.036)	(0.049)
ADSL after 2005	-1.963***	-1.261***
	(0.020)	(0.028)
ADSL 2005	-1.849***	-1.007***
	(0.018)	(0.024)
ADSL 2004	-1.347***	-0.520***
	(0.016)	(0.023)
ADSL 2003	-0.837***	-0.162***
	(0.016)	(0.023)
ADSL 2002	-0.741***	-0.159***
	(0.018)	(0.025)
ADSL 2001	-0.475***	-0.123***
	(0.015)	(0.022)
Year 2012	0.198***	0.122***
	(0.010)	(0.013)
Year 2013	0.530***	0.458***
	(0.010)	(0.012)
Year 2014	0.758***	0.522***
	(0.010)	(0.013)
Cut_1	-0.825***	-2.491***
	(0.071)	(0.093)
Cut_2	-0.005	-1.858***
	(0.071)	(0.093)
Cut_3	2.084***	-0.167*
	(0.071)	(0.093)
Sunk cost		3.011***
		(0.013)
Regional dummies	Yes	Yes
Observations	144,416	144,146
LL	-115,783	-61,503

Model I: without sunk costs. Model II: with sunk costs.
Significance at * 10%, ** 5%, *** 1% level. t statistics are in parentheses.

Table A.9: Coverage with high-speed broadband: speed of 30Mbps and above.

	OLS I	OLS II	Heckman I		Heckman II	
Variables			Coverage	Presence	Coverage	Presence
Nb LLU	-0.010***	-0.016***	-0.044***	0.005	-0.053***	-0.047***
	(0.002)	(0.002)	(0.004)	(0.011)	(0.005)	(0.014)
Log households	0.059***	0.061***		0.730***		0.742***
	(0.002)	(0.002)		(0.014)		(0.014)
Log density	0.025***	0.027***	0.045***	0.032**	0.048***	0.048***
	(0.002)	(0.002)	(0.004)	(0.014)	(0.004)	(0.014)
Log pop department	0.010***	0.010***		0.030		0.026
	(0.003)	(0.003)		(0.019)		(0.019)
Log income	-0.019***	-0.014**	-0.005	0.053	0.003	0.103**
	(0.006)	(0.006)	(0.013)	(0.046)	(0.014)	(0.047)
Share flats	0.189***	0.186***	0.075***	0.857***	0.072***	0.832***
	(0.013)	(0.013)	(0.021)	(0.094)	(0.021)	(0.094)
Correction term LLU		0.013***			0.020***	0.110***
		(0.003)			(0.005)	(0.017)
Mills ratio				0.080***		0.076***
				(0.008)		(0.008)
Constant	0.337***	0.339***	0.578***	0.497**	0.580***	0.499**
	(0.028)	(0.028)	(0.050)	(0.202)	(0.050)	(0.202)
Regional dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	36,026	36,026	36,026	36,026	36,026	36,026

Significance at * 10%, ** 5%, *** 1% level. t statistics are in parentheses.

Appendix B

Table B.1: Coverage with high-speed broadband: speed of 8Mbps and above.

	OLS I	OLS II	Heckman I		Heckman II	
Variables			Coverage	Presence	Coverage	Presence
Nb LLU	-0.074***	-0.089***	-0.083***	-0.061***	-0.092***	-0.061***
	(0.003)	(0.003)	(0.003)	(0.011)	(0.003)	(0.011)
Log households	0.112***	0.115***		0.535***		0.535***
	(0.003)	(0.003)		(0.013)		(0.013)
Log density	0.065***	0.070***	0.078***	0.112***	0.081***	0.112***
	(0.003)	(0.003)	(0.003)	(0.014)	(0.003)	(0.014)
Log pop department	0.005	0.004		-0.019		-0.019
	(0.004)	(0.004)		(0.017)		(0.017)
Log income	0.019*	0.032***	-0.015	0.121***	-0.008	0.121***
	(0.010)	(0.010)	(0.011)	(0.043)	(0.011)	(0.043)
Share flats	0.089***	0.081***	0.245***	0.488***	0.244***	0.488***
	(0.020)	(0.020)	(0.019)	(0.109)	(0.019)	(0.109)
Correction term LLU		0.034***			0.020***	
		(0.004)			(0.004)	
Mills ratio				-0.098***		-0.098***
				(0.012)		(0.012)
Constant	0.888***	0.893***	1.122***	1.766***	1.123***	1.766***
	(0.045)	(0.045)	(0.042)	(0.188)	(0.042)	(0.188)
Regional dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	36,026	36,026	36,026	36,026	36,026	36,026

Significance at * 10%, ** 5%, *** 1% level. *t* statistics are in parentheses.

Table B.2: Coverage with high-speed broadband: speed of 100Mbps and above.

	OLS I	OLS II	Heckman I		Heckman II	
Variables			Coverage	Presence	Coverage	Presence
Nb LLU	-0.003***	-0.003***	-0.023	0.065**	-0.012	0.070**
	(0.001)	(0.001)	(0.015)	(0.027)	(0.017)	(0.032)
Log households	-0.002	-0.001		0.248***		0.247***
	(0.001)	(0.001)		(0.026)		(0.027)
Log density	0.015***	0.015***	0.056***	0.167***	0.051***	0.166***
	(0.001)	(0.001)	(0.015)	(0.026)	(0.015)	(0.026)
Log pop department	0.017***	0.017***		0.500***		0.501***
	(0.001)	(0.001)		(0.041)		(0.041)
Log income	0.017***	0.018***	0.168***	0.503***	0.160***	0.499***
	(0.003)	(0.003)	(0.034)	(0.078)	(0.035)	(0.080)
Share flats	0.174***	0.173***	-0.046	0.713***	-0.042	0.717***
	(0.007)	(0.007)	(0.064)	(0.130)	(0.064)	(0.130)
Correction term LLU		0.001			-0.027	-0.011
		(0.001)			(0.020)	(0.039)
Mills ratio				0.065*		0.065*
				(0.037)		(0.037)
Constant	-0.121***	-0.121***	-0.066	-6.816***	-0.077	-6.819***
	(0.015)	(0.015)	(0.167)	(0.416)	(0.168)	(0.416)
Regional dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	36,026	36,026	36,026	36,026	36,026	36,026

Significance at * 10%, ** 5%, *** 1% level. t statistics are in parentheses.

Table B.3: Tobit regressions.

Variables	>30Mbps	>8Mbps	>100Mbps
Nb LLU	-0.038***	-0.129***	0.067**
	(0.006)	(0.005)	(0.029)
Log households	0.263***	0.167***	0.192***
	(0.006)	(0.005)	(0.024)
Log density	0.049***	0.114***	0.163***
	(0.006)	(0.005)	(0.024)
Log pop department	0.009	-0.003	0.457***
	(0.008)	(0.006)	(0.037)
Log income	0.061***	0.076***	0.469***
	(0.020)	(0.016)	(0.069)
Share flats	-0.091***	-0.020	0.507***
	(0.035)	(0.030)	(0.116)
Correction term LLU	0.047***	0.055***	-0.027
	(0.008)	(0.006)	(0.035)
Constant	0.179**	1.016***	-6.231***
	(0.086)	(0.068)	(0.382)
Sigma	0.525***	0.514***	0.935***
	(0.004)	(0.003)	(0.022)
Regional dummies	Yes	Yes	Yes
Observations	36,026	36,026	36,026
Left-censored	11,049	10,349	34,673
Uncensored	24,830	23,023	1,322
Right-censored	147	2,654	31

Significance at * 10%, ** 5%, *** 1% level. *t* statistics are in parentheses.