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Speeding Up the Internet: Regulation and Investment in the European Fiber Optic Infrastructure*

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Abstract

In this paper, we study how the coexistence of access regulations for legacy (copper) and fiber networks shapes the incentives to invest in fiber-based network infrastructures. To this end, we first develop a theoretical model that extends the existing literature by, among other things, considering alternative firms with proprietary legacy network (e.g., cable operators) and the presence of asymmetric mandated access to networks. In the empirical part, we test the theoretical predictions using a novel panel data from 27 EU member states pertaining to the last decade. Our main finding is that, in line with the theoretical results, stricter access regulations (i.e., a decrease in access price to legacy network and the adoption of fiber regulation) decrease the incumbent operators' fiber investments. The estimated magnitude of these effects is economically significant. On the other hand, cable operators, who are responsible for the largest share of investments in fiber, are not affected by access regulation. Our paper thus provides policy insights for the on-going revision of the EU regulation framework for the electronic communications industry.

Keywords: Internet access market, Access regulation, Investment, Infrastructure, Next Generation Networks, Broadband, Telecom, Cable operators and EU regulatory framework.

JEL Classification Numbers: L96; L51.

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1 Introduction

Next Generation Access (NGA) networks are based, in part or entirely, on fiber-optic technologies that provide radically improved quality, in terms of high-speed broadband Internet access, to residential or business customers. In view of their generic all-IP technology and enormous bandwidth capacities, these new internet access networks represent a general purpose technology, and are expected to induce significant productivity improvements and growth across major economic sectors (Bresnahan and Trajtenberg, 1995), over and above the impact of existing telecommunication networks (see e.g. Röller and Waverman, 2001; Czernich et al., 2011).[1]

Even though some European Union (EU) member states do particularly well in terms of NGA deployment, Europe overall lags behind a number of non-European nations, including Japan, Korea, Taiwan and the United States (FTTH Council Europe, 2015; Yoo, 2014; OECD, 2013; Briglauer and Gugler, 2013). Accordingly, the aim of the European Commission is to strengthen the competitiveness of Europe's economy with explicit focus on digital communication technologies. In light of this, the European Commissions' Digital Agenda Europe strategy, which is one of the seven flagship initiatives under Europe 2020, specified ambitious NGA deployment targets already back in 2010 (European Commission, 2010).

Although the economic importance of new internet access infrastructures is widely recognized, various approaches exist to promote the deployment of NGA networks via competition, sector-specific regulation and public subsidies. Compared to the US and the leading East-Asian fiber nations, the EU regulatory framework imposes rather comprehensive and strict access obligations on incumbent operators. Furthermore, the EU's access obligations cover not only legacy (copper-based), but also NGA (fiber-based) infrastructures. In fact, the recent regulatory proposals for incentivizing infrastructure investments in very-high capacity NGA networks—in particular, the European Commission's (2016a) review on the eCommunication framework—are mainly related to modifying these access regulations.

In this paper, we shed light on how the existence of parallel regulations for copper and NGA infrastructures shapes the incentives for the two main NGA network operators, that

[1]Ahlfeldt et al. (2017) show that even the most immediate benefits of enabling fast broadband internet access that manifest through increased property prices outweigh the cost in urban and some sub-urban areas of the UK.

is cable TV and incumbent telecom operators, to invest. Over the last decade, the EU broadband market has drastically changed, with the emergence of relevant new players, that is the cable TV operators, who enjoy substantial cost advantages over telecom firms in terms of NGA infrastructure deployment (Taga et al., 2009; European Commission, 2016b, p. 19). In fact, the former accounted for 43% and the latter for 42.8% of the EU's fiber lines at the end of 2014, the last year of our data set. Moreover, cable operators have reached a prominent role in the broadband market, as they provide bundles of TV content, fast internet access and basic telecom services. Their position on the retail broadband market has been improving over time in many EU countries, such as the UK (with Sky), Germany (with Vodafone Kabel Deutschland), Belgium (with Telenet), the Netherlands (with Ziggo) and Portugal (with ZON Optimus), where cable operators are essentially the largest competitors to incumbent telecom operators. However, unlike telecom incumbents, cable operators are not subject to any regulatory obligations pertaining to their networks.

Given the importance of these competitors in the telecom industry, we extend the existing theoretical literature on transition from old to new network infrastructures (Bourreau, Cambini and Dogan, 2012, 2014; Inderst and Peitz, 2012) by accounting for the presence of a competitor with a legacy infrastructure (with full or partial coverage). Thus, our model accommodates cable operators, who have different footprints across EU member states and face lower investment costs to upgrade their networks, and telecom entrants, who have followed different NGA investment patterns to cable operators and relied above all on incumbents' infrastructures, and incumbent telecom operators. We further extend the literature on transition from copper to fiber by considering an asymmetric NGA regulation regime, in which only the telecom incumbent operator's fiber infrastructure is *ex ante* regulated. These extensions allow us to derive testable predictions and policy implications, that fit the differential competitive and regulatory conditions across the EU's internet access markets, in particular with respect to the presence of cable operators.

Our empirical results complement existing evidence on the effect of access regulation on infrastructure investment (e.g. Grajek, Röller, 2012; Nardotto et al., 2015; Bourreau et al., 2017). We use a novel panel data set on incumbent telecom operators and cable operators from 27 EU member states over the last decade. The advantage of our data set is that it includes information on physical NGA network investments rather than the less direct accounting measures that have been used in other studies.[2] We also use direct measures of regulation—the mandated access price to the legacy infrastructure and the presence of mandated access to the NGA infrastructure—rather than regulation-aided market outcomes, such as the number of unbundled lines. Moreover, to the best of our knowledge, the joint impact of these coexisting regulations on firm-level investment incentives has not yet been studied empirically.

Our results indicate that a 1% increase in the regulated access price to legacy network increases the number of telecom incumbents' fiber lines by as much as 8.4% to 10.6%. However, this apparently strong effect is achieved at a relatively low base, because the telecom incumbents had virtually no fiber lines in the initial years of our sample. We also find that the adoption of fiber access regulation has a profound effect, as it largely eliminates the telecom incumbents' incentives to invest in fiber lines. On the other hand, we have not found that cable operators are affected by either of the regulatory obligations. As we show in our theoretical model, there can be various reasons for this neutrality result.

The rest of the paper is organized as follows: Section 2 briefly describes the relevant EU regulatory framework and the theoretical and empirical work most closely related to ours. Section 3 develops an analytical model to analyze the effects of legacy and NGA regulations on investments in fiber networks. Section 4 provides some stylized facts about the European NGA market and empirically tests the predictions of our analytical model using data from the EU member states. Finally, Section 5 concludes the paper by discussing the policy implications of our results.

2 Transition from copper to fiber: EU regulations and the related literature

Within the EU, electronic communication network and service markets have been regulated according to the 2002 eCommunications framework.[3] Among its main provisions is

[2]Our measure of investment is an indirect (and imperfect) measure of speed available on a network. In fact, there are differences in terms of speed both within NGA technologies—for instance, VDSL technology can facilitate download speeds of between 50 Mbit/s and 200 Mbit/s, depending on the proximity of the local switch to the consumer premises—and across NGA technologies.

[3]For an overview of the relevant directives, regulations and recommendations of the EU regulatory framework, the reader can refer to the Commission's website available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3Al24216a. The framework directive (European Commission, 2002a) and the access directive (European Commission, 2002b) are of particular relevance for sector-specific ex

the mandatory multiple access to network infrastructure of the incumbent operators—known as "resale", "bitstream access" and "local loop unbundling" (LLU)—which allows entrants to compete with incumbent operators, that are mostly successors of state-owned monopolistic owners of copper-based (legacy) communication networks.[4] The most relevant mandated sharing provisions imposed on legacy networks is LLU, which specifies, among others, more technical access conditions and the access price that an entrant must pay to the network/local loop owner.

The eCommunications regulatory framework was initially designed for the copper-based networks of incumbent operators, but has been extended to cover fiber-based NGA networks. In particular, the directives of the eCommunications framework have been supplemented by European Commission recommendations on regulated and non-discriminatory access to NGA networks (European Commission, 2010; European Commission, 2013) to form the relevant EU regulatory framework for the emerging NGA infrastructure.

The objectives of the eCommunications regulatory framework were to assure a rapid roll-out of new access networks as well as affordable prices for European Internet users. Thus, the European Commission, in its Digital Agenda Europe strategy (European Commission, 2010), defined the coverage and adoption targets that require at least a partial fiber infrastructure in the access networks. This, in particular, pertains to the minimum target speed levels (>30 Mbit/s) necessary for ubiquitous household coverage by 2020. This target cannot be reached by basic xDSL or non-DOCSIS cable technologies. However, DOCSIS and VDSL technologies, which are based on hybrid fiber-coaxial and fiber-copper access infrastructures, respectively, can easily deliver this speed level. Hence, the definition of the European Commission's broadband target basically coincides with the investments in NGA fiber infrastructures.[5] Recent regulatory proposals for incentivizing these infrastructure investments—in particular, the European Commission's (2016a) review of the eCommunications framework—are mostly related to modifying the existing

ante access obligations asymmetrically imposed on dominant operators.

[4]"Resale" and "bitstream access" requires a small up-front investment, while LLU requires a larger up-front investment. It should be noted that only LLU allows the alternative operators to differentiate their broadband service from that of the incumbent operator.

[5]When we consider higher than the minimum target speed levels, pure fiber infrastructures (e.g., fiber to the home) offer much higher speed levels than hybrid infrastructures (e.g. fiber to the cabinet). However, in practice both the incumbent and cable operators' NGA infrastructures up until 2014, the last period of our empirical analysis, are largely based on hybrid access infrastructures. These infrastructures are capable of providing rather similar maximum speed levels of up to 200 Mbit/s.

access regulations.

The intended dynamics resulting from the mandatory access obligations have been studied by Cave et al. (2001) and by Cave and Vogelsang (2003), and have been popularized in the EU as the "ladder of investment" hypothesis. Although there exists partial confirmation of this hypothesis at lower rungs of the ladder, such as moving from bitstream-based to LLU-based access, the mandatory access obligations have not yielded the intended infrastructure-based competition in the EU (Bacache et al., 2014). Vogelsang (2013, p. 212) refers to this result as a 'natural outcome of the economics of fixed broadband access'. In its current telecom review, the European Commission (2016a) does not refer to the ladder of investment hypothesis, even though it has been considered as a guiding principle since the introduction of the 2002 regulatory framework. At the same time, the goal of the recent EU regulatory framework review is the provision of sufficient incentives for infrastructure investments in NGA networks and the implementation of "reasonable" ex ante obligations.

The experience of leading countries in NGA deployment shows that fiber-based infrastructures do not immediately replace the existing copper or cable legacy networks and that these different infrastructures co-exist during a transition phase. Threrefore, the incentives to invest in NGA infrastructures will not only be influenced by the terms of the mandated access to NGA networks, but also by those pertaining to legacy copper networks.[6]

The existing economic literature provides theoretical models and some empirical evidence on the effect of access regulation on the deployment of fiber-based infrastructures. In a similar setup to ours, Bourreau, Cambini and Dogan (2012) and Inderst and Peitz (2012) show that, depending on the market demand characteristics, the mandated access to a copper network may have a positive or a negative impact on the incumbent operator's investment in fiber networks. These models also predict that higher access fees unambiguously incentivize the entrants to invest in NGA. Bourreau, Cambini and Dogan (2014) extend these models on the presence of access regulation to fiber networks and find that NGA regulation dilutes the incentive to invest. However, this strand of literature assumes that entrants use the copper network managed by the incumbent operator

[6]In the remaining part of the text, we use the terms NGA network and fiber network interchangeably. Moreover, we do not address the problem of legacy-network switch-off since there is no empirical case of this regulatory intervention in Europe; for a theoretical investigation of this topic, see Bourreau, Lupi and Manenti (2014).

to compete on the downstream market for internet service provision. We also consider those cable operators who can provide internet services via their own legacy cable TV infrastructure and have in fact led the NGA infrastructure deployment in the EU.

The early empirical literature on telecom and on the basic (or "old") broadband infrastructure investment and access regulation imposed on those networks has been comprehensively surveyed in Cambini and Jiang (2009). They conclude that the literature by and large points out that LLU, as implemented by many national regulators, discourages both incumbent and alternative telecom operators from investing in communication networks.[7]

Two important contributions related to our work are those of Bouckaert et al. (2010) and Nardotto et al. (2015). Bouckaert et al. (2010) find that the most important driver of total (basic) broadband penetration into the EU member states is competition from cable and other alternative (to the telecom incumbent) broadband providers. Nardotto et al. (2015) use a detailed data set from the UK and find that LLU entry has a positive impact on the quality of the internet service of broadband providers, and that inter-platform competition from cable has a positive impact on both penetration and quality. Our approach differs from that of these two papers over several dimensions. First, Bouckaert et al. (2010) and Nardotto et al. (2015) control for the presence of cable operators in their empirical models, but do not estimate how access regulation affects cable operators' investments, which we instead do. Second, they use data related to basic, i.e. non fiber-based, broadband penetration, whereas we use data on NGA investments. Third, they do not account for the presence of NGA regulation, which we instead do. Furthermore, Nardotto et al. (2015) document that cable operators offer higher broadband speed than other operators in the UK, but they are not able to estimate the impact of access regulation on broadband speeds, because in their data, which stem from a single country, there is no cross-sectional variation of regulatory intensity.[8]

The work by Grajek and Röller (2012), who also use data from EU countries and investigate the relationship between access regulation for legacy networks and investment in the telecommunications industry, is more closely related to our empirical analysis.

[7]For theoretical investigations on the interplay between access regulation and investment in old broadband networks, see Foros (2004), Kotakorpi (2006) and Hori and Mizuno (2006).

[8]It is very difficult, if not impossible, to find a causal effect of regulation based on intertemporal variations in regulation alone, because many other variables, which cannot be observed by an econometrician, but are likely to affect investments, such as specific investment costs, consumer tastes for speed, etc., also vary over time.

They find that access regulation negatively affects both total industry and individual operators' investments, but they focus on the telecom entrants and incumbents, and thus neglect cable operators, who have found to be very important for NGA deployment in the EU. Moreover, in this paper, we use physical NGA lines, a more accurate measure of infrastructure investment than that of Grajek and Röller (2012), who use an accounting measure of investment based on fixed assets.

A number of studies have recently investigated the role of access regulation, and LLU prices in particular, for the investments in NGA networks that are surveyed in Briglauer et al. (2016). These studies generally find a negative impact of regulation on investment (e.g. Bacache et al., 2014; Briglauer et al., 2013; Briglauer 2015), but because they use more aggregated data than ours, they are not able to investigate the impact of LLU or fiber regulations on incumbent telecom operators and cable operators, separately. Briglauer et al. (2013) and Briglauer (2015) control for the presence of regulation and cable competition using a model of aggregate investments in NGA networks. However, they do not test the impact of the intensity of regulation (in terms of LLU access prices and the presence of NGA regulation) on individual operator's investments. More importantly, they do not study the strategic interaction between cable operators' and incumbent operators' investments, both of which we do. Finally, Bourreau et al. (2017) find that the local market presence of entrants using LLU positively influence fiber network deployment in French metropolitan municipalities. However, similarly to Nardotto et al. (2015), they have not been able to assess the effects of the stringency of LLU regulation—as measured by LLU prices, for instance—on the quality of service or fiber network deployment, because they use data from a single EU country.

3 A model of investment in NGA networks

We develop a model of investment in new technologies that complements and extends the Bourreau et al. (2012) model in several ways. The aim of our extension is to account for a number of stylized facts about the European NGA infrastructure investment patterns and dominant regulatory approaches, as well as to derive testable hypotheses about the role of access regulations for NGA investments. We empirically evaluate these hypotheses in section 4.

3.1 The benchmark case

We consider a country as being composed of a continuum of areas with a total size $\overline{z}$. The fixed cost of deploying an NGA (i.e. fiber) network varies across areas, which we order (from 0 to $\overline{z}$) to reflect the investment costs (from the cheapest to the most expensive). Three firms compete on the market: a fixed telecom incumbent operator (firm 1), who manages a legacy copper network and it has a mandatory obligation to grant access at a regulated price ($a \geq 0$); a cable operator (firm 2), who owns a legacy cable network and never seeks access to the incumbent firm's infrastructure to provide the final service; moreover, this operator is not subject to any regulatory obligations concerning the provision of access services; a telecom entrant (firm 3), who does not own any legacy network and seeks access to the incumbent firm's legacy network at the regulated price a.[9]

A new fiber-based network, the NGA network, allows the firms to provide higher quality internet access, but it requires investments. In our main model (i.e. the benchmark model in section 3.1, and the extensions thereof in sections 3.2 and 3.3), we impose the condition that the telecom entrant does not invest in any fiber infrastructure. In other words, all three firms compete at the retail level, but only the incumbent and the cable operator invest in a fiber infrastructure.[10] In this case, for each firm $i = 1, 2$, the decision to invest in fiber involves setting the areas $[0, z_i]$ in which its fiber network will be rolled out, with $[0, z_i] \subset [0, \overline{z}]$.

The fixed cost of covering an area at a given location $x \in [0, \overline{z}]$ is denoted by $c(x)$, with $c(x) > 0$ and $c'(x) > 0$, thus implying that the total cost of covering the area $[0, z_i]$ for firm i is $C(z_i) = \int_0^{z_i} c(x)\,dx$, with $C'(z_i) = c(z_i) > 0$ and $C''(z_i) = c'(z_i) > 0$. To simplify the analysis, but without any loss of generality, we assume that $C(z_i) = \frac{z_i^2}{2}$ and $C'(z_i) = c(z_i) = z_i$. Finally, we assume that all the firms have the same marginal (wholesale and retail) costs in all the areas, which we normalize to zero.

In each area z, we use the superscripts "O" and "N" for the old/legacy (copper or

[9] The telecom incumbent and the cable operator do not compete for the provision of access to the entrant telecom firm. In fact, cable operators in Europe do not provide access to third parties because of a lack of any legal obligations. In view of the technical difficulties, there is also no evidence of any voluntary access agreements. Hence, in the current EU market situation, only the telecom incumbents provide access to their networks.

[10] This is realistic in Europe, where incumbent and cable operators invest by far the most in the new fiber-based infrastructures. We relax this assumption in Appendix A and show that it does not alter the results derived from the main model.

cable) and new (fiber) networks, respectively. The profit of firm $i = 1, 2, 3$ in a given area, gross of the investment costs, is denoted by $\pi_i^{k,l,j}(.)$, where $k, l, j = O, N$ refers to the network infrastructure of the incumbent operator (k), the cable operator (l) and the telecom entrant (j), respectively. The telecom entrant does not invest in fiber (i.e. $z_3 = 0$), and instead relies on access to the incumbent operator's legacy network (i.e. $j = O$).

We make the following key assumptions regarding the ordering of profits and the expected impact of the access charge a:

Assumption 1 For $k = O, N$, $\pi_1^{k,O,O}(.) \geq \pi_1^{k,N,O}(.)$, and $\pi_2^{O,k,O}(.) \geq \pi_2^{N,k,O}(.)$.

This assumption implies that, given its network infrastructure, firm i, $i = 1, 2$, makes more profit when its rival uses an old rather than a new network. Firm 3 does not invest in the new infrastructure, and its profits threfore depend on the conditions of access to the incumbent's legacy network.

Assumption 2 For $k, l = O, N, \pi_i^{k,l,O}(.) > 0$, $i = 1, 2, 3$.

This assumption implies that an old and a new network can profitably coexist in any given area.

Assumption 3 For $k, l = O, N$, there exists $\widehat{a}^k > 0$, so that, for all $a \leq \widehat{a}^k$, we obtain: (i) $d\pi_1^{k,l,O}(a)/da \geq 0$, and $d\pi_1^{k,l,O}(a)/da \leq 0$ otherwise; moreover,
(ii) $d\pi_3^{k,l,O}(a)/da \leq 0$, for all $a \leq \widehat{a}^k$;(iii) $d\pi_2^{k,l,O}(a)/da \geq 0$, for all $a \leq \widehat{a}^k$.

Assumption 3(i) implies that, regardless of its network infrastructure, the incumbent's profit increases with the access price a up to a certain threshold $\widehat{a}^k$, which corresponds to the monopoly access price. In fact, when a is low, an increase in a both increases the incumbent operator's wholesale revenues (a direct effect) and dilutes the competition between the incumbent operator and the telecom entrant (a strategic effect). When a is high enough, increasing it further reduces wholesale revenues and may therefore decrease the incumbent's profit.

Assumption 3(ii) implies that, when the telecom entrant relies on an old network managed by the incumbent, its profit decreases with the access price, a.

Assumption 3(*iii*) is related to the behavior of the cable operator, who never seeks access to the incumbent operator's legacy network, because the operator either invests in its own fiber network or uses its own legacy network. However, an increase in the access price a creates a cost disadvantage, at the retail level, for the telecom entrant and, indirectly, a cost advantage for the cable operator; hence, a higher a softens retail competition and in turn increases the cable operator's profit.

The timing of the game is as follows: The regulator sets the access price of the copper network, a (and of the fiber network, $\tilde{a}$, if the fiber network is also regulated; see extension 2 in section 3.3). Then, the incumbent and the cable operators simultaneously decide on the areas in which to roll-out their fiber networks, z_1 and z_2, respectively (if the telecom entrant is active, it may also decide on z_3; see Appendix A). Finally, all three firms compete in the provision of internet services at the retail level.[11]

Depending on the decisions of the investment-active firms and the access price set by the regulator, the competitive environment in any given geographical area is defined by one of the following three regimes:

1. *Infrastructure-based competition between existing legacy networks (i.e., the copper and the cable networks).*[12] In this case, none of the firms invests in fiber, and the profits are $\pi_i^{O,O,O}(a), i = 1, 2, 3$.

2. *Infrastructure-based competition between the legacy (copper or cable) network and the fiber network.* This can happen under two different scenarios: (i) the incumbent operator uses its copper network, while the cable operator deploys a fiber network; the firms obtain gross profits $\pi_i^{O,N,O}(a), i = 1, 2, 3$; and (ii) the incumbent operator deploys a fiber network, while the cable operator relies on the old cable TV network; the firms obtain gross profits $\pi_i^{N,O,O}(a), i = 1, 2, 3$.

3. *Infrastructure-based competition between the fiber networks.* Both the incumbent

[11] We opt for a simultaneous rather than a sequential game, as in Bourreau et al. (2012), in order to avoid exogenous scenarios (cable moves first vs. incumbent moves first). In an unreported annex, we also developed our benchmark model using a sequential game, as in Bourreau et al. (2012). Though more complex, the results remain the same as those reported in the next paragraphs and, more importantly, the impact of regulation on the firms' incentive to invest remains the same.

[12] In the case where the basic broadband connections that use the copper and the cable networks lead to different levels of service quality, the profit of the incumbent operator, the cable operator and the telecom entrant may differ. In what follows, we assume that the quality of connections in both of the standard legacy networks is the same, but the model could also fit in the case of differentiated per area profits. In section 3.2 and Appendix C, we allow for asymmetry across firms in terms of the infrastructure deployment costs.

and the cable operators deploy their own fiber networks, while the telecom entrant still continues to use mandated access to the old network; the gross profits are thus $\pi_i^{N,N,O}(a), i = 1, 2, 3$.

Depending on the incumbent operator's coverage $[0, z_1]$ and its own coverage $[0, z_2]$, the cable operator's profit is:

$$\Pi_2(z_1, z_2) = -\frac{z_2^2}{2} + \begin{cases} z_2\pi_2^{N,N,O}(a) + (z_1 - z_2)\,\pi_2^{N,O,O}(a) + (\overline{z} - z_1)\,\pi_2^{O,O,O}(a) \\ \text{if } z_2 \leq z_1 \\ z_1\pi_2^{N,N,O}(a) + (z_2 - z_1)\,\pi_2^{O,N,O}(a) + (\overline{z} - z_2)\,\pi_2^{O,O,O}(a) \\ \text{if } z_2 > z_1 \end{cases}.$$

In order to determine the optimal investment of the cable operator, it is necessary to first consider the case in which the cable firm covers an area where the telecom incumbent operator has already rolled out its NGA network (i.e., $z_2 \leq z_1$). It is profitable for the cable operator to invest in its own NGA network in the area $z_2 \in [0, z_1]$, if the additional gross profit it earns by investing is higher than the investment cost in this area, that is, if

$$\pi_2^{N,N,O}(a) - \pi_2^{N,O,O}(a) \geq z_2. \tag{1}$$

A similar reasoning applies when the cable operator considers covering an area z_2, where the incumbent operator has not rolled-out its NGA network (i.e., $z_2 > z_1$). It is profitable for the cable operator to invest in this area if

$$\pi_2^{O,N,O}(a) - \pi_2^{O,O,O}(a) \geq z_2. \tag{2}$$

Let z_2^c and z_2^m be defined as the highest value of z_2 that satisfies inequalities (1) and (2), respectively. We thus obtain $z_2^c = \left(\pi_2^{N,N,O}(a) - \pi_2^{N,O,O}(a)\right)$ and $z_2^m = \left(\pi_2^{O,N,O}(a) - \pi_2^{O,O,O}(a)\right)$. In each respective case, z_2^c and z_2^m represent the largest area in which the cable operator invests.

Assume that firm 2 (i.e. the cable operator) has covered the areas $[0, z_2]$. Firm 1's (i.e. the telecom incumbent operator's) profit is therefore given by

$$\Pi_1(z_1, z_2) = -\frac{z_1^2}{2} + \begin{cases} z_1\pi_1^{N,N,O}(a) + (z_2 - z_1)\,\pi_1^{O,N,O}(a) + (\overline{z} - z_2)\,\pi_1^{O,O,O}(a) \\ \text{if } z_1 \leq z_2 \\ z_2\pi_1^{N,N,O}(a) + (z_1 - z_2)\,\pi_1^{N,O,O}(a) + (\overline{z} - z_1)\,\pi_1^{O,O,O}(a) \\ \text{if } z_1 > z_2 \end{cases}. \tag{3}$$

In order to determine firm 1's optimal investment, first consider the case where firm 1 covers an area in which firm 2 has already rolled out a fiber network (i.e., $z_1 \leq z_2$). It is profitable for firm 1 to invest in such an area $z_1 \in [0, z_2]$ iff $\pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a) \geq z_1$. The same reasoning applies when firm 1 decides to cover an area z_1 in which firm 2 has not rolled out any fiber network (i.e., $z_1 > z_2$). It is profitable for firm 1 to invest in this area iff $\pi_1^{N,O,O}(a) - \pi_1^{O,O,O}(a) \geq z_1$. Let z_1^c and z_1^m be defined as the highest value of z_1 that satisfies these two inequalities, respectively. We thus obtain $z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a)\right)$ and $z_1^m = \left(\pi_1^{N,O,O}(a) - \pi_1^{O,O,O}(a)\right)$.

Given the profit functions of firms 1 and 2, firm 2's reaction function is:[13]

$$z_2^{\mathrm{BR}}(z_1) = \begin{cases} z_2^m & \text{if} \quad z_1 \leq \widehat{z}_1 \\ z_2^c & \text{if} \quad z_1 > \widehat{z}_1 \end{cases}, \tag{4}$$

where the threshold $\widehat{z}_1$, with $\widehat{z}_1 \in [z_2^c, z_2^m]$, is defined as the lowest z_1 so that $\Pi_2(z_1, z_2^c) \geq \Pi_2(z_1, z_2^m)$, i.e. the lowest level of the incumbent's coverage that makes the cable operator's profit in the areas with competing NGA infrastructures equal to or larger than the cable operator's profit in monopoly NGA areas. Hence, $\widehat{z}_1$ is the incumbent's coverage above which it is no longer profitable for the rival cable firm to continue to invest in competing NGA networks.[14]

Considering that $z_1^m > z_1^c$, firm 1's best response function is:

$$z_1^{\mathrm{BR}}(z_2) = \begin{cases} z_1^m & \text{if} \quad z_2 \leq \widehat{z}_2 \\ z_1^c & \text{if} \quad z_2 > \widehat{z}_2 \end{cases}, \tag{5}$$

where, as shown above, the threshold $\widehat{z}_2$ is defined as the lowest z_2 so that $\Pi_1(z_1^c, z_2) \geq \Pi_1(z_1^m, z_2)$, i.e. the lowest level of the cable's coverage that makes it unprofitable for the incumbent's to still continue to invest in competing NGA areas, with $\widehat{z}_2 \in [z_1^c, z_1^m]$.

The incumbent's and the cable operator's best-response functions (4) and (5) decrease (weakly) with the coverage of the rival, thus implying that the investment decisions are *strategic substitutes.*[15] From (4) and (5), it is also possible to see that the model yields

[13]Note that for if $z_i^c < z_j$ firm i, $i = 1, 2$, would incur losses to match firm j over the $[z_i^c, z_j]$ interval, while profits are increasing from $[z_j, z_i^m]$. The smaller z_j is, the smaller the interval over which firm i faces losses in the case of investments.

[14]Note that $\widehat{z}_1$ is a function of a, but its variation in general is indeterminate, and depends on the competitive setting used to model retail competition. In Bourreau et al. (2012), for example, the authors used a Katz and Shapiro (1985)'s competition model and showed that $\widehat{z}_1(a)$ is an increasing function of a.

[15]In the case of a sequential, rather than a simultaneous game, the investment decisions could be either *strategic complements* or *strategic substitutes*. Solving the model using the same approach as that of Bourreau et al. (2012), an additional equilibrium emerges with respect to our benchmark model; this

multiple equilibria that are defined by all the (z_1^m, z_2^c) and (z_1^c, z_2^m) couples. This means that either of the firms could be an investment leader and act as a monopolist NGA provider in some areas characterized by intermediate investment costs (monopoly areas). In areas where the investment costs are low enough, both the incumbent and the cable operators will invest in NGA networks. Finally, no fiber networks will be deployed in the highest cost areas; these areas will be served by the old legacy networks.

It is now possible to determine the impact of the access price a on the firms' investment decisions. When the cable operator is the leader, in terms of fiber network coverage (i.e. the equilibrium is (z_1^c, z_2^m)), the impact of the access price is given by $dz_1^c/da = \left(\frac{d\pi_1^{N,N,O}(a)}{da} - \frac{d\pi_1^{O,N,O}(a)}{da}\right)$ and $dz_2^m/da = \left(\frac{d\pi_2^{O,N,O}(a)}{da} - \frac{d\pi_2^{O,O,O}(a)}{da}\right)$. When the incumbent is the leader (i.e. the equilibrium is (z_1^m, z_2^c)), the impact of the access price is $dz_2^c/da = \left(\frac{d\pi_2^{N,N,O}(a)}{da} - \frac{d\pi_2^{N,O,O}(a)}{da}\right)$ and $dz_1^m/da = \left(\frac{d\pi_1^{N,O,O}(a)}{da} - \frac{d\pi_1^{O,O,O}(a)}{da}\right)$.

The investment decision made by the fixed incumbent is affected by two countervailing effects: the *retail-migration* effect and the *wholesale revenue* one. The former is given by $d\pi_1^{N,l,O}(a)/da \geq 0, l = N, O$ and means that a higher access price inflates the telecom entrant's costs and thus the retail prices of legacy-network-based services. This makes it easier for the incumbent operator to migrate consumers to new services based on the NGA infrastructure. The latter effect, given by $d\pi_1^{O,l,O}(a)/da \geq 0, l = N, O$, measures the effect of the access price on the incumbent operator's opportunity cost of moving consumers to the new infrastructure; the higher the access price is, the higher the wholesale revenues from renting the legacy infrastructure and thus the opportunity cost of moving to the new infrastructure. This result corroborates a similar result that was obtained in the absence of a cable operator in Bourreau et al. (2012).

The key novelty of our model arises from the cable investment decision: a higher access price, a, by inflating the telecom entrant's costs, not only increases the incumbent's profit, but also that of the cable operator from NGA-based services ($\frac{d\pi_2^{k,N,O}(a)}{da} \geq 0, k = N, O$), thus boosting the incentives to invest in fiber. However, investment in fiber comes at an opportunity cost, which is given by the retail profit lost from legacy-network-based services. When the telecom entrant faces a cost disadvantage, due to a higher access price,

equilibrium implies that the incumbent (cable) operator always mimics (i.e., "follows suit") the cable (incumbent) operator's investment decisions. Therefore, in the case where the cable operator invests first, it might emerge that the incumbent operator reacts positively to a cable investment (implying complementarity), but the cable operator (as first mover) does not react to the incumbent operator's investment. The extension that includes sequential moves is available from the authors upon request.

the retail prices for legacy-network-based services are higher, and so is the opportunity cost of investing in a fiber network for the cable operator. Hence, an increase in the access price raises the profitability of both legacy networks, because of a reduced competitive constraint from the entrant. This effect, measured by $\frac{d\pi_2^{k,O,O}(a)}{da} \geq 0, k = N, O$, which we label the *reduced competition effect*, counterbalances the previous one. Thus, in a similar way as for the incumbent, the overall effect of an increase in the access price a on the cable operator's incentive to invest is ambiguous and depends on the balance between these two countervailing effects.

We summarize these findings in the following Proposition:

Proposition 1. *In the broadband coverage equilibrium:*

(i) regardless of whether an incumbent dominates broadband investment or not, the incumbent's incentives to invest (z_1^m and z_1^c, respectively) depend on the relative strength of the retail-migration and the wholesale revenue effects. When the former (latter) dominates, the impact of a on investment is expected to be positive (negative);

(ii) regardless of whether a cable operator dominates broadband investment or not, the cable operator's incentives to invest (z_2^m and z_2^c, respectively) depend on the relative strength of the retail-migration and the reduced competition effects. When the former (latter) dominates, the impact of a on investment is expected to be positive (negative).

3.2 Extension 1: An investment leading cable firm with partial coverage and investment cost advantage

In the benchmark model, we assumed that the cable operator, when present on the market, has its own legacy network rolled-out over the entire country. However, it might be that, even in those countries where cable operators are present, cable coverage is not complete.[16] In this section, we extend our benchmark model to account for the possibility that a cable operator's legacy infrastructure only partially covers the country. We further assume that the cable operator does not seek access to the incumbent copper infrastructure.[17]

[16] In fact, a recent report of the Association of European National Regulators - states that "[...] while upgrades have been made to existing coax cables, there has only been a minimal increase in extending the footprint of cable coverage in recent years. Cable coverage in other Member States is generally limited to dense urban areas and, to a lesser extent, to some suburban or semi-urban areas. There is very little non-urban presence in most countries" (BEREC, 2016, pp. 12-13).

[17] We contacted Cable Europe, an association of European cable companies, and received confirmation about this assumption. Cable companies that seek to extend their coverage would rather do it by

As shown in the previous section, two cases can emerge: either the incumbent operator dominates NGA coverage or the cable operator does. In this extension, we focus on the latter case, i.e. the cable operator dominates the NGA market by investing more than the telecom incumbent operator, i.e. $z_2^m > z_1^c$, which is more common in our data and thus more representative of EU countries. In what follows, we report the main insights obtained from this extension, while all the technical details of the analysis can be found in Appendix B.

When the cable operator's legacy partial coverage is larger than the monopoly NGA coverage, that is $\widehat{z} > z_2^m$, the equilibrium of the game remains almost unchanged with respect to the benchmark model. The total NGA coverage by cable is affected by the access charge, depending on the two countervailing effects pointed out in Proposition 1. However, when the coverage of the legacy cable network is below the NGA monopoly coverage, new results emerge. As reported in Appendix B, in this case, the equilibrium becomes $z_1 = z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a)\right)$, as in the benchmark case, and $z_2 = z_2^m = \left(\pi_2^{O,N,O}(a)\right)$. The cable operator's investment, and hence the total coverage, is in this case positively influenced by a, due to the impact of the *retail level migration effect.*

However, the above case assumes that the investment cost is continuous and increasing in z. But this assumption may not reflect the real market conditions. As a result of substantially higher investment costs, cable operators do not generally roll out NGA infrastructure in areas that were previously uncovered by the cable TV network, as pointed out in section 4.2 on the stylized facts regarding NGA networks in Europe. If we take this into account, and assume that the investment cost function is discontinuous in $\widehat{z}$, i.e. $c(z) = +\infty$ for $z \in (\widehat{z}, \overline{z}]$, the equilibrium will change in an important way. Per equation (5), the incumbent operator's best response in this case is to choose investment level z_1^c whenever $z_2 > \widehat{z}_2$, and as a result the cable operator will remain the investment leader, but will not achieve z_2^m, because of the binding constraint at $z = \widehat{z}$. Instead, the cable operator's equilibrium investment will be to cover all *possible* areas with NGA given the constraint, i.e. it will choose $z_2 = \widehat{z}$. Because in this equilibrium, that is $z_2 = \widehat{z} \leq z_2^m$, any change in a, if it causes z_2^m to change, will leave equilibrium $z_2 = \widehat{z}$ unchanged. Thus, partial cable coverage may render cable NGA investment insensitive to access charge a when the investment costs dramatically increase in the areas previously uncovered by the

acquiring another firm or by building the fiber infrastructure anew, if at all.

legacy cable network.

We summarize these findings in the following Proposition:

Proposition 2. *When a cable legacy network partially covers a country and its coverage is below the monopoly NGA area (i.e.* $\widehat{z} < z_2^m$*):*

(i) the cable firm's fiber investment increases with a*, if the investment costs are continuous and increasing in* z*;*

(ii) instead, if the investment costs are discontinuous in z*, with* $c(z) = +\infty$ *for* $z \in (\widehat{z}, \overline{z}]$*, then the cable firm's NGA coverage is unaffected by* a*.*

Another important feature of cable firms, compared to incumbent telecom operators, is that the upgrading network costs of cable firms is much lower than the investment cost faced by incumbents (see Taga et al., 2009; European Commission, 2016b, p. 19). In Appendix C, we modify our benchmark model by allowing the marginal costs of fiber infrastructure deployment to be as follows: $c(z_1) = z_1$ and $c(z_2) = z_2 - \Delta$. This implies that for the same level of coverage, i.e. $z_1 = z_2$, one of the two firms faces a lower marginal cost to deploy the network, with the parameter $\Delta > 0$ representing the (marginal) cost advantage.

The equilibria remain the same as in the benchmark model, i.e., we have multiple equilibria given by all the couples $(\overline{z}_1^m, \overline{z}_2^c)$ and $(\overline{z}_1^c, \overline{z}_2^m)$. However, when Δ is positive, more areas are covered by the cable operator (i.e., $\overline{z}_2^m$ and $\overline{z}_2^c$ both increase). Hence, the cost advantage induces the cable operator to invest more than the incumbent operator. These equilibria are shown in figure 1.

3.3 Extension 2: Regulated access to fiber

As another extension of the benchmark model, we consider the case in which the incumbent is obliged to grant access to its new fiber infrastructure at the regulated access price $\widetilde{a}$. We instead assume that the cable operator is *not* subject to the same access obligation.[18] Because the telecom entrant, by assumption, does not invest in its own fiber network, it will have the option to either seek mandated access to the fiber network and provide higher quality internet services, or seek mandated access to the legacy network and provide lower quality internet services. We additionally assume that wherever the

[18] This is consistent with the current application of the EU regulatory framework in most member states.

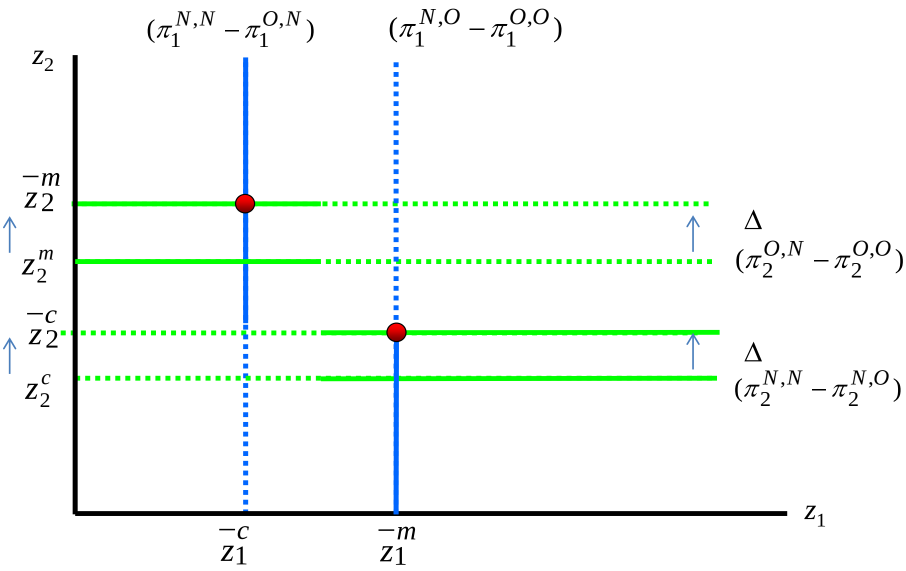

Figure 1: Best response functions of the model with cost asymmetry

incumbent's NGA network is available, the telecom entrant would seek access to fiber. We further extend Assumption 3(iii) by assuming that the cable operator never seeks access to the incumbent operator's legacy *or* to fiber networks.

As shown in Appendix D, the equilibria remain similar to those of the benchmark model, i.e., we have multiple equilibria given by all the couples $(\tilde{z}_1^m, \tilde{z}_2^c)$ and $(\tilde{z}_1^c, \tilde{z}_2^m)$. However, when access to fiber is regulated, the optimal coverage conditions for the cable and the incumbent operators change.

The optimal coverage conditions for the cable operator are given by the values $\tilde{z}_2^c(\tilde{a}) = \left(\pi_2^{N,N,N}(\tilde{a}) - \pi_2^{N,O,N}(\tilde{a})\right)$ and $\tilde{z}_2^m(a) = \left(\pi_2^{O,N,O}(a) - \pi_2^{O,O,O}(a)\right)$. From $\tilde{z}_2^c(\tilde{a})$, we observe that an increase in $\tilde{a}$ has two effects: a higher access charge $\tilde{a}$ increases the cable operator's profit in covered areas, i.e., $\pi_2^{N,N,N}(\tilde{a})$, because an increase in $\tilde{a}$ relaxes the retail price competition due to the *reduced competition* effect, by inflating the cost for the telecom entrant. At the same time, an increase in $\tilde{a}$ also increases the cable operator's profit in areas covered by the incumbent's fiber network, but only where the cable operator uses the legacy infrastructure ($\pi_2^{N,O,N}(\widetilde{a})$), as explained above. The overall impact of $\widetilde{a}$ on the cable operator is thus ambiguous in the case where the cable operator is the investment follower.

On the other hand, when the cable operator is the investment leader, its fiber investments do not depend on $\widetilde{a}$. This follows from the assumption that access to the cable operator's network is not regulated.[19]

For the incumbent operator, the optimal coverage conditions are given by the values $\widetilde{z}_1^c = \left(\pi_1^{N,N,N}(\widetilde{a}) - \pi_1^{O,N,O}(a)\right)$ and $\widetilde{z}_1^m(\widetilde{a}) = \left(\pi_1^{N,O,N}(\widetilde{a}) - \pi_1^{O,O,O}(a)\right)$. An increase in $\widetilde{a}$ positively affects the profit that the incumbent operator obtains in areas where it has invested ($\pi_1^{N,N,N}(\widetilde{a})$ and $\pi_1^{N,O,N}(\widetilde{a})$). This implies that an increase in the fiber access price unambiguously leads the incumbent operator to expand the areas covered by its NGA network. In other words, the presence of access regulation for fiber infrastructure lowers the incumbent operator's incentives to expand NGA coverage.[20]

To conclude our theoretical analysis, we summarize the above results in the following Proposition:[21]

Proposition 3. *The impact of access price $\widetilde{a}$ on the investment incentives is:*

(i) positive for the incumbent operator;

(ii) ambiguous for the cable operator being the investment follower, while it is neutral when the cable operator is the investment leader.

4 Empirical analysis

In order to test these theoretical predictions, we estimate an empirical model of the incumbent and cable operators' NGA investment using firm-level panel data for 27 EU member states from 2004 to 2014. Before presenting the regression analysis, we report

[19] In this case, the cable operator's investment only depends on a, the access price to the incumbent operator's legacy network, in the same way as in the benchmark model.

[20] This result complements a similar one given in Bourreau et al. (2014), who also pointed out the detrimental effect of fiber regulation on the incentives to invest.

[21] It is also possible, in our theoretical model, that a switch of roles occurs due to a change in access fee, so that the cable firm is no longer a leader, but a follower, or the other way around. Because the sign on the relationship between $\widetilde{z}_1$ and $\widetilde{a}$ is indeterminate, we do not know in which direction the roles will be switched, hence there is no clear prediction of the change in $\widetilde{a}$ on the investment incentives when such a switch occurs.

the trends in NGA network deployment across Europe and discuss how they interact with our theoretical model.

4.1 Data

The data on NGA infrastructure investment were collected from FTTH Council Europe, which provides the number of NGA lines (on an annual basis) separately for the incumbent operator and a group of alternative operators in each member state. While there is only one telecom incumbent operator in each member state, there are generally several alternative operators, such as cable operators and telecom entrants, as well as other organizations (e.g. public utilities and municipalities). By screening various FTTH Council Europe reports, we were able to single out a group of cable operators on each market. The number of local cable-TV operators varies from a very few to hundreds per country. However, we have verified with the EU Cable Operators Association that the cable operators are quite homogeneous in terms of business models and do not generally show a geographic overlap.[22] This means that i) a telecom incumbent faces a single cable operator in each local region, where cable is present, and ii) cable operators do not compete with one another. For these reasons, we aggregate investments across all cable operators in a given country in our empirical model. To the best of our knowledge, no other study has used such data, which are crucial to empirically test strategic interactions between the incumbent and cable operators, the main NGA infrastructure providers in the EU.

The EU Digital Agenda Scoreboard provides yearly data on regulatory measures pertaining to the legacy telecom network, above all on mandated access (LLU). The information on mandated access to fiber networks across EU member states comes from the notifications of EU member states under Article 7 and Article 7a of the Electronic Communications Framework Directive (European Commission, 2002a). In addition, we use data from WIK (2012), and some information provided on request by the Body of European Regulators for Electronic Communications (BEREC). The advantage of these country-and-firm level data is that they provide variations in the regulatory measures, across time and across EU member states, which is not the case of the more disaggregated

[22]Cable operators use the same internet access technology and are equally (non-)treated by access regulations in each member state. Furthermore, in most EU member states, a single cable operator serves more than 40% of the total number of cable customers and in many member states even more than 70% (see http://www.cable-europe.eu/ff-ye2014-cable-industry-consolidation/; accessed on January 12, 2017).

data used in other studies, which usually stem from a single country.

The data on intermodal competition from mobile technologies and intramodal broadband competition have been provided by Euromonitor, the International Telecommunications Union (ITU) and the EU Digital Agenda Scoreboard. Euromonitor also provides data on the number of households and the number of personal computers (PC) in use. Eurostat provides data on education and construction permits. Finally, the World Bank provides data on GDP.[23] A detailed description of all the variables and data sources is given in Table 1. Table 2 provides the summary statistics.

4.2 Dependent variables: NGA infrastructures in Europe

NGA investments by incumbent telecom operators (*inc_nga*) and cable operators (*cable_nga*) are measured by the total number of deployed access lines per household and thus represent the supply-side installed capacity, or "homes passed".[24]

Figure 2 presents the household-weighted deployment patterns of NGA investments broken down by country and firm (incumbent vs. cable) for the period of our analysis.[25] It reveals interesting differences across both firms and countries. First, it appears that the deployment of NGA lines follows a rather smooth curve for the telecom incumbents, whereas it often suddenly levels off after a period of rapid growth for the cable operators. This pattern, which we attribute to the relative ease with which the cable operators can upgrade their legacy cable TV networks to NGA networks, means that they are often the investment leaders, especially in the middle of our sample period. However, in a number of countries, the incumbent operators were able to catch up with and even surpass the cable NGA networks toward the end of our sample period. On average, the share of the total number of NGA lines owned by cable operators in our sample amounts to 32.3%, and goes up to 43.0% in 2014. The same numbers for the incumbent operators' NGA lines

[23] Although the dependent variables are available from 2004 to 2014, all the independent variables are available for the years from 2003 to 2013. Owing to the fact that some values are missing, there are fewer observations than 270, the maximum number in the period 2004 to 2013 (data on NGA investment are missing for the Czech Republic, Germany, Estonia, Poland, Slovenia and the United Kingdom in 2004, and for Latvia, Lithuania, Portugal, Romania and Slovakia in 2004 and 2005; values on broadband access regulations are missing for Bulgaria from 2003 to 2006, for Romania from 2003 to 2004, for Estonia for 2003, as well as for Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia and Slovakia for 2003; thus, most of the missing data are from Eastern European countries prior to their EU accession), and 0.8% of all the raw data was calculated using linear interpolation or had to be extrapolated.

[24] Here, we follow the FTTH Council Europe's definition of an NGA line (see details in table 1). These technologies can deliver access speed required by the Digital Agenda Europe targets.

[25] Data for Cyprus, where NGA deployment is essentially zero, and Luxembourg, where NGA coverage is equal to 2.31 in 2014, are not reported for expositional reasons.

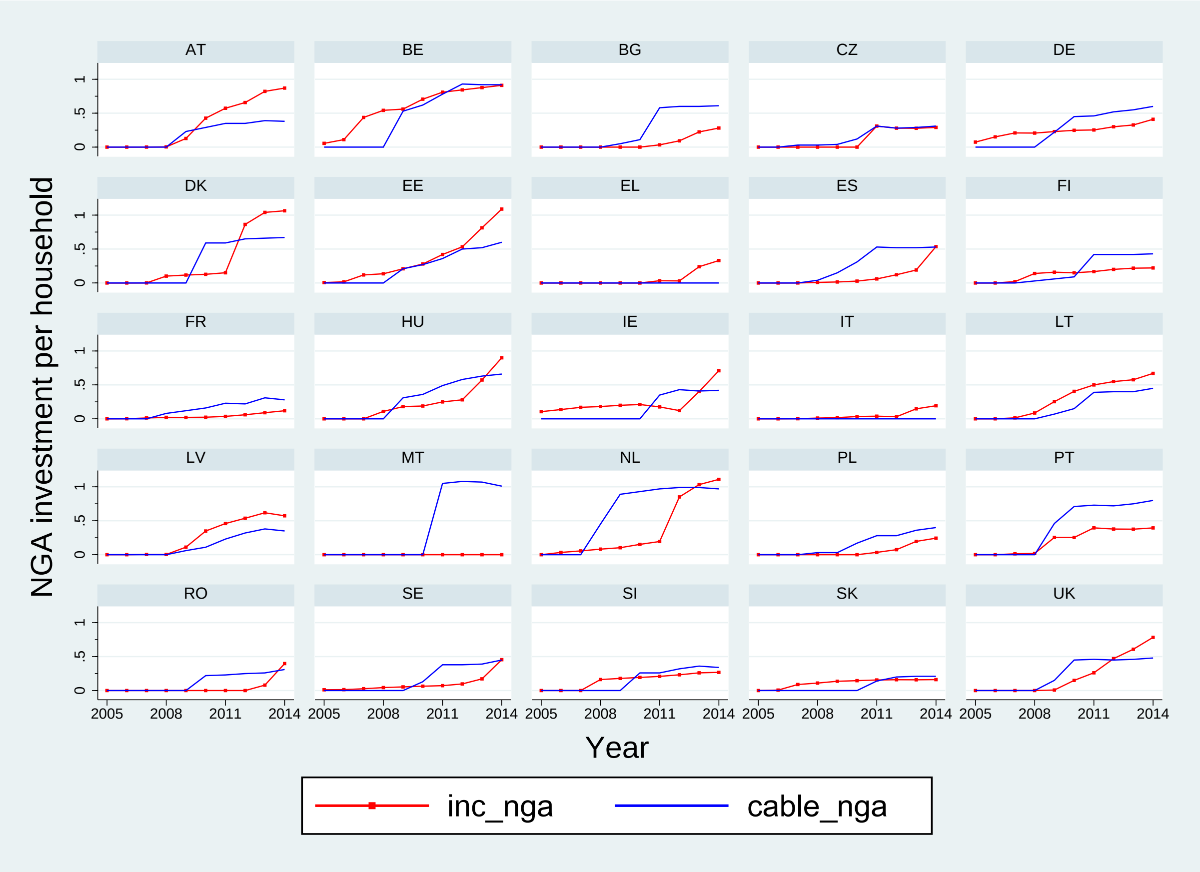

Figure 2: NGA lines per number of households in 25 EU member states for 2005 to 2014 (Source: FTTH Council Europe)

are 33.0% and 42.8%, respectively. Taken together, incumbent and the cable operators clearly dominate NGA investment in Europe.[26]

Second, there is substantial heterogeneity, in terms of NGA network coverage across countries. In particular, cable NGA deployment appears to stop at different levels in different countries, which corresponds to the differences in cable TV coverage across EU member states.[27] Moreover, the incumbent firms' NGA investment differs widely for a given level of cable NGA deployment. For instance, Germany's and the UK's cable NGA networks cover roughly 50% of households, but BT, the UK's incumbent operator, covers twice as many households with NGA infrastructure than Deutsche Telekom, its German counterpart.

[26]The remaining 14.2% of the NGA lines in 2014 was due to telecom entrants, public utilities, municipalities and other entrants, for which we do not have reliable data. While small on average, these NGA investments are substantial in some countries, such as Italy, Romania, Sweden and France.

[27]Cable NGA deployment has de facto been restricted to the cable TV footprint, because cable firms have focused on hybrid, i.e. coax-fiber, NGA deployment during our period of analysis. See also footnotes 9 and 10.

These trends in NGA deployment are important to understand the link between access regulation and NGA investment. As predicted by our theoretical model, if a cable firm's NGA investment area is limited by its cable TV footprint, it may be insensitive to the mandated access price to the copper lines a (see Proposition 2). We predict the same for $\widetilde{a}$, the mandated access price to NGA lines, when the cable operator is an investment leader (see Proposition 3), which appears to be the case for a substantial share of our sample.

4.3 Explanatory variables

Our main variables of interest are regulatory measures that grant entrants mandated access to an incumbent's infrastructure. We measure regulations imposed on both the incumbent's legacy networks and the NGA networks. The former is captured by the monthly access price, that is the LLU price, which is independently set for each country by a national regulator. The latter is captured by a binary indicator variable *nga_reg*, which is equal to one for those years in which NGA regulations are in force in a given EU member state, and zero otherwise.[28] The expected effects of these regulation variables are given by Propositions 1 - 3 of our theoretical model.

Second, we measure the quality of the existing legacy infrastructure of the incumbent operator by considering the number of active fixed landlines in a country, *legacy*. Presumably, the higher the number of active fixed lines is, the better the quality of the existing legacy infrastructure, and the higher the opportunity cost of investing in new NGA infrastructures. We thus expect *legacy* to have a negative impact on the incumbent operator's NGA investments. The impact of *legacy* on the cable operators' investment may be positive or negative, depending on whether the quality of the existing legacy infrastructure and of the cable infrastructure are strategic substitutes, or complements.

Another NGA-specific cost shifter we consider is *mdwell_perm*, the number of building permits for multi-dwelling houses issued in each country. Since most newly-built houses are equipped with fiber-optic cables that are ready to be connected by a telecom operator, the cost of connecting new NGA lines to such houses is low. If the incum-

[28] These regulations require the dominant operator to provide various forms of wholesale access to its NGA infrastructure, such as wholesale "bitstream access" or "fiber unbundling". Both legacy network unbundling and NGA regulations are only imposed on the dominant operators, which results in an asymmetric regulation regime in almost every EU member state, whereby the incumbent telecom operator is subject to these regulations, but the cable operators and other entrants are not.

bent operator is, for the most part, the firm of choice for such connections, we expect *mdwell_perm* to show a positive effect on its investments. However, the effect for cable firms is expected to be negative, because of the specific NGA technology they generally use.[29]

Third, we use a number of country-specific demand shifters in our empirical specification of the NGA investment equations: basic broadband access adoption, *bb_adop*, adjusted for purchasing power per-capita GDP, *gdp_pc_ppp*, and the percentage of population with secondary or higher education, *edu*. All these variables are expected to increase the future demand for fast internet access on NGA networks, thereby spurring investments by both incumbents and cable operators.

Finally, in order to account for competition between mobile networks and fixed-line networks, we use the variable fms, which stands for fixed-to-mobile substitution; it measures the number of mobile broadband subscriptions relative to the sum of fixed landline broadband subscriptions and mobile broadband subscriptions in each country. In line with the existing literature, we allow the relationship between the level of competition and investment to be nonlinear by additionally including a squared fms term in the empirical investment equations and make no additional assumptions about the shape of this relationship.[30]

4.4 Empirical specification and identification

The incumbents' investment equation, which we use to assess the impact of regulation on NGA deployment, is given by:

$$\begin{aligned} ln(inc\_nga_{i,t}) &= \alpha_i^I + \beta^I ln(inc\_nga_{i,t-1}) + \gamma^I ln(cable\_nga_{i,t}) \\ &+\delta_1^I llu\_price_{i,t} + \delta_2^I nga\_reg_{i,t} + X_{i,t}\Theta^I + \epsilon_{i,t}^I, \end{aligned} \tag{6}$$

where X is a set of cost, demand and competition control variables, and as described in the previous section, the superscript I denotes the coefficients pertaining to the incumbents' investment equation (6) and the subscripts i and t denote the member state and year, respectively. We assume that the error term $\epsilon_{i,t}^I$ is independently, but not necessarily

[29] DOCSIS technology used by cable companies cannot be used for the fiber lines deployed in new buildings. These buildings can only be connected to telecom fiber networks unless they are additionally equipped with coaxial cable lines, which is not economically viable.

[30] Aghion et al. (2005) argue in favor of an inverted-U relationship, whereas Sacco and Schmutzler (2011) show that this relationship can also be U-shaped.

identically distributed, thus our estimates are robust to any form of heteroscedasticity. Since we use the logarithm of NGA access lines as our measure of the infrastructure stock, the estimation results are interpreted as percentage changes, which facilitates cross-country comparisons.

Since large infrastructure projects, like NGA network investment, can take years to complete in practice, and the investment plans of companies are generally known before an investment actually happens, we include the lagged dependent variable, $inc\_nga_{i,t-1}$, as a right-hand side regressor in (6) in order to capture a dynamic investment adjustment process, even though our theoretical model does not explicitly account for such dynamics. Additionally, we capture the effects of any time-invariant variables, such as the population density, geographic conditions, etc., which can influence the investments, by including the country-specific coefficients α_i^I in (6).

The cable operators' investment equation is specified in a similar way:

$$\begin{aligned} ln(cable\_nga_{i,t}) = \alpha_i^C + \beta^C ln(cable\_nga_{i,t-1}) + \gamma^C ln(inc\_nga_{i,t}) \\ + \delta_1^C llu\_price_{i,t} + \delta_2^C nga\_reg_{i,t} + X_{i,t}\Theta^E + \epsilon_{i,t}^C, \end{aligned} \tag{7}$$

where the superscript C denotes the coefficients pertaining to the cable operators' investment equation (7) and the error term $\epsilon_{i,t}^C$ is independently, but not necessarily identically distributed.

Equations (6) and (7) can be interpreted as linearized best-response functions (4) and (5), respectively, in our theoretical model. To this end, the coefficients on the regulation variables can be used to test the Propositions we obtain in our theoretical model. The dynamic specification of equations (6) and (7) can also be empirically tested. If the βs are equal to 0, then there are no dynamics or inertia in the NGA infrastructure investment. An estimate of the βs between 0 and 1 is consistent with an adjustment process that leads to a steady state, which we interpret as one of the multiple equilibria in our theoretical model.[31]

The identification of coefficients on the endogenous variables in (6) and (7) is possible due to specific exclusion restrictions: the lagged level of the incumbent's (cable operators')

[31] In the empirical analysis, we ignore the "active" telecom entrants but we believe that this does not affect our results for two reasons. First, as shown in the extension of our theoretical model (Appendix A), our theoretical results in Propositions 1-3 are not affected by the presence of the "active" entrants, and therefore we do not expect the presence of active entrants to moderate the estimated effects of regulation on the incumbent or cable operators' investment. Second, the magnitude of the "active" entrants' investments, compared to that of the cable and incumbent operators, is small; it amounts to 14.2% of the total number of NGA lines in 2014.

infrastructure is assumed to have an impact on the current level of the incumbent's (cable operators') infrastructure, but not on the current level of the cable operators' (incumbent's) infrastructure. These exclusion restrictions assume away the possibility to strategically react to the past levels of rival operator's infrastructure, but not to the present levels.

Furthermore, since equations (6) and (7) form a dynamic panel data model with unobserved country-specific effects, we estimate them by applying first-differencing and the standard Arellano-Bond-type instruments for lagged dependent variables. Additionally, we apply Anderson-Hsiao-type instruments for other endogenous variables in X. We also use the Anderson-Hsiao-type instruments for the lagged dependent variables in some estimations, in order to reduce the total number of instruments and thus avoid a potential overfitting problem (Roodman, 2009).

Finally, we use two external instrumental variables: (i) the average value of the NGA regulation indicator in EU countries (excluding the focal country) and (ii) the per-capita number of personal computers (PCs) in use. The rationale behind the first variable is the harmonization process within the EU, which makes it difficult for a single member state to radically deviate from the regulatory measures undertaken in the rest of the EU. In short, the eCommunications framework contains some explicit and implicit rules to incentivize harmonization and "punish" deviating national regulators by requiring a greater burden of proof in the course of consultation and notification procedures with the European Commission. The second instrument is meant to capture computer literacy and it is correlated with independent variables such as basic broadband adoption. We argue that as this is a "low-tech" variable, the number of PCs is not linked directly to our dependent variables, which represent "high-tech", state-of-the-art internet access.

4.5 Results

The estimation results of the incumbent equation (6) and the cable operator equation (7) are shown in Tables 3 and 4, respectively. The columns in the two tables differ in terms of the instrumental variables employed; the first two columns only use the Anderson-Hsiao instruments, and are thus labeled 2SLS, whereas the last two columns use Arellano-Bond instruments and are labeled GMM. Moreover, columns 1 and 3 use the endogenous explanatory variables lagged by two and three periods as instruments; columns 2 and 4 use the endogenous variables lagged by only two periods.

All the exogenous variables (i.e., *gdp_pc_ppp*, *mdwell_perm* and *edu*) serve as instruments in Tables 3 and 4. Additionally, we included two external instruments: the geographic instrument for fiber access regulation (*nga_inst*) and the per-capita number of PCs in use (*comp_pen*), as explained in the previous section. The first-stage results for the incumbent's and the cable investment equations are given in the Appendix, in Tables A1 and A2, respectively. Partial R^2 and F-tests of the excluded instruments reported in Tables A1 and A2 demonstrate the strength of our instruments in all the first-stage regressions.

All the regressions in Tables 3 and 4 pass the standard post-estimation tests. In particular, the AR(2) test statistics do not reject the assumption of no second-order serial correlation in the residuals, which justifies the use of lagged variables as instruments.[32] Furthermore, the Sargan and the Hansen tests do not reject the assumption of the exogeneity of employed instruments in our regressions. The difference-in-Hansen tests do not reject the exogeneity of the external instruments either.

The estimated coefficients are consistent across columns, but the estimates obtained using the Arellano-Bond instruments generally show more statistical significance. In all the specifications, the coefficient on the lagged dependent variable is positive, but smaller than one, and highly significant, which means that the NGA infrastructure stock is subject to significant inertia, as expected. Interestingly, the coefficient on the lagged dependent variable is consistently lower in all the specifications in Table 4, compared to Table 3. Accordingly, the speed of adjustment, $1 - \beta$, is higher for the cable operators, which indicates their faster convergence toward the long-run, desired infrastructure stock. This aligns well with the observation that the costs of NGA deployment are substantially lower for the technologies used by the cable operators, as explained in section 4.2.

Among the control variables, basic broadband adoption (*bb_adop*) is consistently positive and significant across all the specifications in Table 3, as is per-capita GDP (*gdp_pc_ppp*), as expected. The competition from mobile networks, as captured by the variables *fms* and fms^2, also shows a mostly significant impact on the incumbent's NGA investments, in line with the existing literature.[33] The coefficient on the quality of the

[32]The AR(1) test statistics show that there is a first-order serial correlation in the residuals, which is to be expected when the error terms in the original equations (6) and (7) are not serially correlated.

[33]The magnitude of the estimated coefficients may seem excessively large, but at the beginning of our sample, all the countries had virtually zero fiber lines (and towards the end of our sample, NGA

incumbent's legacy network is negative, as expected, albeit only significant in the GMM estimations in Table 3. In Table 4, *legacy* shows a more significant, but positive impact. Thus, cable operators react to a higher quality legacy network by increasing investments in NGA, presumably to overcome competition from the basic internet access provided by the incumbent telecom operator. Other significant effects in the cable operators' investment equation are due to *mdwell_perm* and *edu*, and the direction of these effects is in line with our expectations.

The incumbent operator's investments are positive, but not statistically significant in Table 4. The cable operators' NGA investments are positive and statistically significant, albeit only in the last two columns of Table 3. The (weak) evidence of the strategic complementarity of investments by incumbent and cable operators is thus only found for the incumbent operator in the GMM, but not in 2SLS estimations.[34] This strategic complementarity is in line with the results of other studies (e.g., Bouckaert et al., 2010; Nardotto et al., 2015; Bourreau et al., 2017).

Finally, the regulatory variables result to be highly significant in Table 3. The LLU price is positive and significant, which suggests that a higher access price, i.e., less stringent regulation of the legacy network, incentivizes the incumbent firm to invest in NGA networks. Considered from the theoretical perspective, this result means that the *retail migration* effect dominates the *wholesale revenue* effect in Proposition 1(i). The magnitude of this effect is also economically significant. An increase in the LLU price of 11.87 cents (i.e. 1% of the average LLU price in our sample) leads to roughly 10% more fiber lines being deployed by the incumbents (the coefficient on *llu_price* varies between 0.836 and 1.064 across the specifications in Table 3).[35] However, this apparently strong effect is achieved at a relatively low base, because the telecom incumbents had virtually no fiber lines in the initial years of our sample, as shown in figure 2.[36]

Moreover, the NGA regulation is negative and mostly significant across the specifications in Table 3, which is consistent with the prediction in Proposition 3(i): more stringent regulation of fiber access disincentivizes the incumbent operator from investing.

---

coverage exceeded 50% of households in many countries). This implies that the increases we observed in (log) percentage terms tend to be very large.

[34]Such (asymmetric) strategic complementarity is not featured in our benchmark model, but can be obtained under certain specific assumptions, which we discuss in Section 3.1 (footnote 12).

[35]With the dependent variable in logarithm, the effect is approximately in percentages for small changes in the LLU price.

[36]The long-run effect is further magnified as a result of the impact of a lagged dependent variable.

The coefficients in *nga_reg* range from -4.302 to -6.886 in Table 3, which means that the adoption of fiber access regulation leads to a roughly 99% reduction in the incumbents' investments.[37] In other words, the fiber access regulation, as implemented in the EU, almost entirely eliminates the telecom incumbents' incentives to invest in fiber lines. Thus, implementing such a regulatory regime is clearly at odds with the intention of fostering investment in very-high capacity networks, as explicitly targeted by the European Commission (European Commission, 2016a).

Unlike the incumbents, the cable operators do not seem to react to access regulation: neither the LLU price nor the existence of NGA regulation is significant in Table 4. The LLU neutrality result could be due to the two countervailing effects found in Proposition 1(ii): the *retail migration* effect and the *reduced competition* effect. Another theoretical explanation for the LLU neutrality result, which is shown in Proposition 2(ii) (section 3.2), relies on cable operators being investment leaders with a limited geographical footprint of cable TV networks and an extremely high cost for NGA deployment in areas not covered by cable TV. This is in line with the stylized facts about the EU telecom market, which we present in section 4.2. Thus, there is some empirical support for this explanation, but, ultimately, we cannot empirically distinguish between our theoretical explanations for the LLU neutrality result. The NGA neutrality result follows directly from Proposition 3(ii) (section 3.3) coupled with the observation that cable operators lead the NGA investments in many EU telecom markets.

5 Conclusion

The existing theoretical literature on transitioning from old to new broadband networks points out that the incentives to invest in infrastructures differ for incumbent operators and entrants. Incumbent operators may invest more in a new infrastructure when the mandated access price to the old network is raised, but the effect could also be the opposite, depending on the specific demand and costs characteristics. Telecom entrants are generally expected to speed up the deployment of new infrastructures, when the mandated access charge to the old infrastructure is high. The empirical evidence from NGA-related empirical literature indicates a negative impact of sector-specific access reg-

[37] Note that a change in *nga_reg* from 0 to 1 is not a small change, so the coefficients do not approximate percentages. The large magnitude of this effect is also, to some extent, driven by the low base of fiber investment in the first years of our sample.

ulations imposed on incumbents' legacy networks (and related service-based competition) on aggregate NGA investment. It thus appears that the results of the earlier literature on broadband markets, which generally indicate a negative impact of access regulation on infrastructure investment, carry over to NGA investments.

In this paper, we extend the literature on access regulation and investment on telecommunication markets in two important ways. First, we develop an analytical model, in which we allow some operators to own a legacy network infrastructure, which makes them more similar to the incumbents rather than other entrants that do not own a legacy infrastructure. This extension accommodates cable operators, who has been shown to be important providers of NGA infrastructure in the EU, and allows us to formulate theoretically motivated testable hypotheses. These hypotheses depend, in a non-trivial way, on the pre-existing market conditions, such as the extent of the legacy infrastructure's coverage, as well as on the access regulations imposed on the incumbent's legacy and fiber infrastructures. Second, we collect novel data on NGA investments and access regulations, which allow us to complement and improve the existing empirical evidence. More importantly, we are able to empirically study the investment game between incumbent operators and the cable operators using precise NGA investment and access regulation measures pertaining to both old, legacy infrastructures and new, NGA infrastructures.

Our main empirical results indicate that a 1% increase in the regulated access price to a legacy network increases the number of telecom incumbents' fiber lines by 10% on average, while the adoption of fiber regulation almost completely eliminates incumbents' incentives to invest. On the other hand, access regulations do not affect the investments of cable operators. These results are consistent with the existing literature, which finds similar effects using NGA investment data aggregated at the country level (Briglauer, 2015), or a regulation measure aggregated across legacy and NGA networks (Bacache et al., 2014). Moreover, we also find that the NGA infrastructure investment is subject to significant inertia, and that the speed of adjustment of such an investment is higher for cable operators, thus indicating faster convergence toward the long-run, desired infrastructure stock. This result is again in line with the observation that the cost of NGA deployment is substantially lower for technologies used by cable operators, as theoretically shown in our model.

Our result concerning the fact that access regulation to legacy networks negatively affects incumbent operator's investments resolves the theoretical indeterminacy of this effect and corroborates the results of Grajek and Röller (2012), who arrive at a similar conclusion, albeit using a different measure of regulation and a less precise measure of investments. In this study, we further complement existing empirical evidence by showing that cable operators are not significantly affected by mandated access. We explicate this neutrality effect within the framework of our analytical model. The key assumptions responsible for this are: i) the existence of the legacy infrastructure, which raises the opportunity cost of investing in a new fiber network; this cost is due to the lost profitability of the legacy network, in the case of migration to a new network; ii) the cost advantage of cable operators, over incumbent telecom operators in terms of NGA deployment, which justifies why firms may coordinate on equilibrium where cable operators dominate the NGA market, and iii) limited coverage of the legacy cable network, which may make cable NGA investment outside of the legacy cable TV network's footprint prohibitively expensive. All these features are in line with the stylized facts about NGA deployment in the EU. Alternatively, the neutrality effect of mandated access on cable operators can be explained by the *retail-migration* effect which exactly offsets the *reduced competition* effects set out in our theoretical model.

Overall, our results imply a negative impact of access regulations on aggregate NGA investments in Europe.[38] This introduces important policy implications. Above all, if the European Commission would like to induce more investments in fiber-based networks, as it expressed in its recent telecom review, it should opt for more deregulatory approaches, i.e. access regulations should be less stringent on both old and new infrastructures. Apart from having a positive impact on total investment, this would also introduce a level-playing field between the incumbent telecom and cable operators. In fact, the latter currently enjoy a substantial advantage, not only in terms of lower fiber investment costs, but also concerning the absence of mandated access to their networks. Our results also suggest that a one-size-fits-all approach may not yield the best outcomes, in terms of NGA deployment. The EU member states differ extensively in their spatial reach of

[38] By assuming that regulation is decided ex ante, our theoretical model rules out the hold-up problem, which may be important in practice. This assumption of our model is shared with all the theoretical literature that we discussed in section 2. If firms correctly expected (and responded to) future regulation, then the effects of current regulatory changes, which we estimate, would underestimate the true total effect of regulation on investment. This is because the current change in regulation would merely resolve some uncertainties about the future regulations, which would ultimately matter. Thus, we can interpret our estimates as conservative.

cable TV legacy infrastructures, which, according to our results, is an important determinant of the role that the cable operators play in NGA deployment. Some countries, such as Belgium and the Netherlands, which have relatively wide-spread cable networks, are less negatively affected by the presence of access regulations and arguably need them less, given the presence of facility-based competition between the cable and the telecom operators. Access regulations in those countries could be eliminated, except for in limited geographical areas, where cable operators do not exert competitive pressure. Other countries, such as Italy and France, where cable competition is limited or even absent, face a more difficult trade-off between preserving competition and incentivizing infrastructure investment. One possible approach for these countries, as suggested by our and others results (e.g. Vogelsang, 2017), could be merely to relax the stringency of access regulations on the legacy and/or NGA infrastructures, rather than to eliminate them altogether, in order to provide greater incentives for the incumbent operators (and telecom entrants) to invest.

Our theoretical model, which we apply to data aggregated at the country level, could also, without much modification, be applied to more disaggregated, regional-level or municipal-level data spanning multiple countries. Covering multiple countries is necessary to have variations in the access regulations, the key variables of interest in our model. Testing strategic interactions between heterogeneous entrants and incumbents using disaggregated investment data is one important extension that we leave for future research.

Finally, our analysis has focused on the NGA coverage by telecom and cable operators. Operators decide first whether to upgrade their networks or not; this decision, which enables a new range of bandwidth levels, is influenced directly by access regulations. Then, operators compete at retail level over different combinations of speeds and prices; retail-level competition may further affect the investment decision to upgrade a network, though not necessarily to expand the number of NGA lines. Additional information on speeds, which are not available to us, would allow for further research and refinements of our results on the role of regulation for investments in NGA networks.

Appendix

A. Telecom entrant can invest in fiber

In this Appendix we futher expand the model by assuming that all three players including the telecom entrant can invest in fiber. Let z_i be the firm $i = 1, 2, 3$ level of coverage, and therefore of investment. In each area z, we use the superscripts "O" and "N" for the old (copper or cable) and new (fiber) networks, respectively. The profit of firm $i = 1, 2, 3$ in a given area, gross of investment cost, is denoted by $\pi_i^{k,l,j}(.)$, where $k, l, j = O, N$ refer to the network technology of the fixed incumbent (k), the cable operator (l) and the telecom entrant (j), respectively. Since the aim of this theoretical investigation is to provide sound, testable hypotheses, instead of solving all different subgames, we limit the analysis to the following two cases:

- the incumbent dominates the investment stage; the cable operator is the second relevant player; the service based entrant is the one that invests less, i.e., $z_1 > z_2 > z_{3;}$
- the cable operator dominates the investment game, with the incumbent operator as the second player and the telecom entrant as third, i.e., $z_2 > z_2 > z_{3.}$

The two above cases are the more realistic ones with respect to the EU scenario: indeed, EU data shows that, in the period 2004-2014, in 68% of cases the cable operators are the leader in NGA investment, while incumbent operators dominate the NGA lines in 32% of cases. Telecom entrants never hold a leadership position in NGA deployment. They are active mostly in a few countries (e.g., Greece and Italy) and they typically are the smaller operators in terms of NGA coverage.

A.1 The incumbent dominates NGA coverage

Assume that $z_1 > z_2 > z_3$. Recall that in all areas in which firm 3 does not invest, it requests access to the incumbent's legacy network and pays the access fee a. This is not the case for the cable operator who has its own cable network and thus does not need to rely on access to the incumbent network for the provision of retail services. However, it may indirectly benefit from higher access price paid by the telecom-based rival. Finally, we assume that the cable operator is not obliged to provide access to its own network;

hence, the telecom entrant can only access the incumbent's legacy infrastructure. In this scenario the profit functions of the three firms are the following:

$$\begin{aligned}
\Pi_1 &= -\frac{z_1^2}{2} + z_3\pi_1^{N,N,N} + (z_2 - z_3)\,\pi_1^{N,N,O}(a) + (z_1 - z_2)\,\pi_1^{N,O,O}(a) + \\
&\quad + (\overline{z} - z_1)\,\pi_1^{O,O,O}(a) \\
\Pi_2 &= -\frac{z_2^2}{2} + z_3\pi_2^{N,N,N} + (z_2 - z_3)\,\pi_2^{N,N,O}(a) + (z_1 - z_2)\,\pi_2^{N,O,O}(a) + \\
&\quad + (\overline{z} - z_1)\,\pi_2^{O,O,O}(a) \\
\Pi_3 &= -\frac{z_3^2}{2} + z_3\pi_3^{N,N,N} + (z_2 - z_3)\,\pi_3^{N,N,O}(a) + (z_1 - z_2)\,\pi_3^{N,O,O}(a) + \\
&\quad + (\overline{z} - z_1)\,\pi_3^{O,O,O}(a)
\end{aligned}$$

In equilibrium, we have a part of the country in which all three players will invest in fiber (denoted with $z_3 = z_3^t$), another part in which only two players (the incumbent and the cable operator) will invest (denoted with $z_2 = z_2^d$) and finally a monopoly NGA area in which only the incumbent invests ($z_1 = z_1^m$). In all areas $\overline{z} - z_1^m$ no firm will invest in fiber. The threshold levels are defined as follows:

$$\begin{aligned}
z_1^m &\rightarrow \frac{\partial \Pi_1}{\partial z_1} = -z_1 + \pi_1^{N,O,O}(a) - \pi_1^{O,O,O}(a) = 0 \\
z_2^d &\rightarrow \frac{\partial \Pi_2}{\partial z_2} = -z_2 + \pi_2^{N,N,O}(a) - \pi_2^{N,O,O}(a) = 0 \\
z_3^t &\rightarrow \frac{\partial \Pi_3}{\partial z_3} = -z_3 + \pi_3^{N,N,N} - \pi_3^{N,N,O}(a) = 0
\end{aligned}$$

We can now focus on the role of access regulation to incumbent operator's legacy network for investment in fiber infrastructure. We have the following:

$$\begin{aligned}
\frac{dz_1^m}{da} &= \left(\frac{d\pi_1^{N,O,O}(a)}{da} - \frac{d\pi_1^{O,O,O}(a)}{da}\right) \\
\frac{dz_2^d}{da} &= \left(\frac{d\pi_2^{N,N,O}(a)}{da} - \frac{d\pi_2^{N,O,O}(a)}{da}\right) \\
\frac{dz_3^t}{da} &= -\frac{d\pi_3^{N,N,O}(a)}{da} > 0
\end{aligned}$$

As in Bourreau et al. (2012), investment by the incumbent operator again depends on two countervailing effects: the *retail migration effect*, $\frac{d\pi_1^{N,O,O}(a)}{da}$, and the *wholesale revenues effect*, $\frac{d\pi_1^{O,O,O}(a)}{da}$; that is, the same effect as before but in a more intensively competitive situation (i.e., larger number of investing firms). As long as the first effect prevails over the second, an increase in the access charge, a, positively affects the incumbent's decision to invest. The telecom entrant's investment decision is positively affected by the access charge due to the *replacement effect*: a higher access charge increases its opportunity cost of remaining on the old network instead of migrating to the new one. Regarding the cable investment decision, as before, a higher access price a inflates the telecom entrant's costs, thus increasing the retail profit of cable operator ($\frac{d\pi_2^{N,N,O}(a)}{da} > 0$) and boosting its incentives to invest in fiber. However, this effect is counterbalanced by the *reduced competition effect*, the increased opportunity cost of moving to fiber when the profit from legacy-network-based internet access services increases due to the telecom entrant's cost disadvantage. Thus, the final effect of an increase in the access price a on the incentive to invest of both the incumbent and the cable entrant is not clear a priori and depends on the interplay between two countervailing effects.

A.2 The cable operator dominates the NGA coverage

Assume that $z_2 > z_1 > z_3$. In this scenario the profit functions of the three firms are the following:

$$
\begin{aligned}
\Pi_1 &= -\frac{z_1^2}{2} + z_3\pi_1^{N,N,N} + (z_1 - z_3)\,\pi_1^{N,N,O}(a) + (z_2 - z_1)\,\pi_1^{O,N,O}(a) + \\
&\quad + (\overline{z} - z_2)\,\pi_1^{O,O,O}(a) \\
\Pi_2 &= -\frac{z_2^2}{2} + z_3\pi_2^{N,N,N} + (z_1 - z_3)\,\pi_2^{N,N,O}(a) + (z_2 - z_1)\,\pi_2^{O,N,O} + \\
&\quad + (\overline{z} - z_2)\,\pi_2^{O,O,O}(a) \\
\Pi_3 &= -\frac{z_3^2}{2} + z_3\pi_3^{N,N,N} + (z_1 - z_3)\,\pi_3^{N,N,O}(a) + (z_2 - z_1)\,\pi_3^{O,N,O}(a) + \\
&\quad + (\overline{z} - z_2)\,\pi_3^{O,O,O}(a)
\end{aligned}
$$

In equilibrium, the optimal investment levels are the following:

$$
\begin{aligned}
z_1^d &\rightarrow \frac{\partial \Pi_1}{\partial z_1} = -z_1 + \pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a) = 0 \\
z_2^m &\rightarrow \frac{\partial \Pi_2}{\partial z_2} = -z_2 + \pi_2^{O,N,O}(a) - \pi_2^{N,O,O}(a) = 0 \\
z_3^t &\rightarrow \frac{\partial \Pi_3}{\partial z_3} = -z_3 + \pi_3^{N,N,N} - \pi_3^{N,N,O}(a) = 0
\end{aligned}
$$

The impact of access regulation for incumbent's legacy network is the following:

$$
\begin{aligned}
\frac{dz_1^d}{da} &= \left(\frac{d\pi_1^{N,N,O}(a)}{da} - \frac{d\pi_1^{O,N,O}(a)}{da} \right) \\
\frac{dz_2^m}{da} &= \left(\frac{d\pi_2^{O,N,O}(a)}{da} - \frac{d\pi_2^{O,O,O}(a)}{da} \right) \\
\frac{dz_3^t}{da} &= -\frac{d\pi_3^{N,N,O}(a)}{da} > 0
\end{aligned}
$$

The investment decision of the cable operator, depends as before on two effects: the *retail migration effect,* $\frac{d\pi_2^{O,N,O}(a)}{da}$, and the *reduced competition effect,* $\frac{d\pi_2^{O,O,O}(a)}{da}$. Similarly, the incumbent's investment depends on two countervailing effects: the *retail migration effect,* $\frac{d\pi_1^{N,N,O}(a)}{da}$, and the *wholesale revenues effect,* $\frac{d\pi_1^{O,N,O}(a)}{da}$,. When the first effect prevails over the second, then an increase in the access charge, a, will positively affect the incumbent's decision to invest. Finally, the telecom entrant's investment decision is positively affected by the access charge due to the *replacement effect.*

B. Cable firm with partial coverage

Assume first that the cable operator's partial coverage is larger than the monopoly NGA coverage, that is $\widehat{z} > z_2^m$. The cable operator's profit is then:

$$
\Pi_2(z_1, z_2) = -\frac{z_2^2}{2} + z_1 \pi_2^{N,N,O}(a) + (z_2 - z_1)\, \pi_2^{O,N,O}(a) + (\widehat{z} - z_2)\, \widehat{\pi}_2^{O,O,O}(a).
$$

It is composed of the profit in the duopolistic fiber areas, $z_1 \pi_2^{N,N,O}(a)$, the profit in the monopolistic fiber areas, $(z_2 - z_1)\, \pi_2^{O,N,O}(a)$, and the profit in areas where the cable operator uses its legacy network up to the maximum coverage, $(\widehat{z} - z_2)\, \widehat{\pi}_2^{O,O,O}(a)$.

The incumbent operator's profit instead is given by:

$$\Pi_1(z_1,z_2) = -\frac{z_1^2}{2}+z_1\pi_1^{N,N,O}(a)+(z_2-z_1)\,\pi_1^{O,N,O}(a)+(\widehat{z}-z_2)\,\widehat{\pi}_1^{O,O,O}(a)+(\overline{z}-\widehat{z})\,\pi_1^{O,.,O}(a),$$

where $\pi_1^{O,.,O}(a)$ is the per area profit in all uncovered areas by the cable operator, i.e., where only the incumbent operator and the telecom entrant compete at the retail level.

As before, firm 1's optimal investment level is given by $z_1 = z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a)\right)$ and the total coverage is given by $z_2 = z_2^m = \left(\pi_2^{O,N,O}(a) - \widehat{\pi}_2^{O,O,O}(a)\right)$. Thus, the equilibrium found in the benchmark model remains similar to the benchmark case.

Assume now that $\widehat{z}_2 < \widehat{z} \leq z_2^m$. Per Assumption 1, using the new technology generates more profit than using the old one (i.e. $\pi_2^{O,N,O}(.) \geq \widehat{\pi}_2^{O,O,O}(.)$), so the cable operator will invest more and its fiber network coverage will be larger than its legacy network coverage. As a result the cable operator's profit becomes:

$$\Pi_2(z_1,z_2) = -\frac{z_2^2}{2}+z_1\pi_2^{N,N,O}(a)+(z_2-z_1)\,\pi_2^{O,N,O}(a).$$

Firm 1's profit is:

$$\Pi_1(z_1,z_2) = -\frac{z_1^2}{2}+z_1\pi_1^{N,N,O}(a)+(z_2-z_1)\,\pi_1^{O,N,O}(a)+(\overline{z}-z_2)\,\pi_1^{O,.,O}(a)$$

In this case, the equilibrium is $z_1 = z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a)\right)$, as in the benchmark case, and $z_2 = z_2^m = \left(\pi_2^{O,N,O}(a)\right)$. The cable operator's investment, hence the total coverage, is in this case positively influenced by a due to the *retail level migration effect*.

C. The impact of asymmetry in investment costs

In this section we extend the benchmark model by allowing the fiber deployment costs to differ across firms. For simplicity, we disregard the telecom entrant in this extension. Further, the cable operator never seeks access to the incumbent operator's copper network, because it has full coverage of the country with its own legacy network. The access price a is thus not relevant and dropped.

The marginal costs of fiber infrastructure deployment are the following: $c(z_1) = z_1$ and $c(z_2) = z_2 - \Delta$, where the parameter Δ represents the (marginal) cost advantage.[39]

[39] Given current NGA technologies, cable operators can upgrade their legacy networks at a lower cost than telecom incumbent operators (see, e.g., Taga et al., 2009), which implies that $\Delta > 0$.

Given this cost asymmetry, the profit functions of the incumbent and cable operator become:

$$\begin{aligned}\Pi_1 &= -\frac{z_1^2}{2} + \begin{cases} z_1\pi_1^{N,N} + (z_2 - z_1)\,\pi_1^{O,N} + (\overline{z} - z_2)\,\pi_1^{O,O} & \text{if } z_1 \leq z_2 \\ z_2\pi_1^{N,N} + (z_1 - z_2)\,\pi_1^{N,O} + (\overline{z} - z_1)\,\pi_1^{O,O} & \text{if } z_1 > z_2 \end{cases} \\ \Pi_2 &= -\frac{(z_2 - \Delta)^2}{2} + \begin{cases} z_2\pi_2^{N,N} + (z_1 - z_2)\,\pi_2^{N,O} + (\overline{z} - z_1)\,\pi_2^{O,O} & \text{if } z_2 \leq z_1 \\ z_1\pi_2^{N,N} + (z_2 - z_1)\,\pi_2^{O,N} + (\overline{z} - z_2)\,\pi_2^{O,O} & \text{if } z_2 > z_1 \end{cases}.\end{aligned}$$

and give the following interior maxima:

Incumbent firm	**Cable firm**
$\overline{z}_1^c = \left(\pi_1^{N,N} - \pi_1^{O,N}\right)$ for $z_2 > \widehat{z}_2$	$\overline{z}_2^c = \left(\pi_2^{N,N} - \pi_2^{N,O}\right) + \Delta$ for $z_1 > \widehat{z}_1$
$\overline{z}_1^m = \left(\pi_1^{N,O} - \pi_1^{O,O}\right)$ for $z_2 \leq \widehat{z}_2$	$\overline{z}_2^m = \left(\pi_2^{O,N} - \pi_2^{O,O}\right) + \Delta$ for $z_1 \leq \widehat{z}_1$

The equilibria remain the same as in the benchmark model, i.e., we have multiple equilibria given by all couples $(\overline{z}_1^m, \overline{z}_2^c)$ and $(\overline{z}_1^c, \overline{z}_2^m)$. When Δ is positive, however, more areas are covered by the cable operator (i.e., $\overline{z}_2^m$ and $\overline{z}_2^c$ increase). Hence, the cost advantage induces the cable operator to invest more than the incumbent operator.

D. Regulated access to fiber

Denote with $\widetilde{a} < \arg\max \pi^{N,N,N}(\widetilde{a}))$ the access price to fiber. The cable operator's profit becomes:

$$\Pi_2(z_1, z_2) = -\frac{z_2^2}{2} + \begin{cases} z_2\pi_2^{N,N,N}(\widetilde{a}) + (z_1 - z_2)\,\pi_2^{N,O,N}(\widetilde{a}) + (\overline{z} - z_1)\,\pi_2^{O,O,O}(a) \\ \text{if } z_2 \leq z_1 \\ z_1\pi_2^{N,N,N}(\widetilde{a}) + (z_2 - z_1)\,\pi_2^{O,N,O}(a) + (\overline{z} - z_2)\,\pi_2^{O,O,O}(a) \\ \text{if } z_2 > z_1 \end{cases},$$

where $\pi_2^{N,N,N}(\widetilde{a})$ is the per area profit of the cable operator where it invests in its own fiber network and the telecom entrant rents the incumbent operator's fiber infrastructure, while $\pi_2^{N,O,N}(\widetilde{a})$ is the per area profit where, unlike the incumbent, the cable operator does not invest and uses its legacy infrastructure instead. Note that an increase of the access charge $\widetilde{a}$ will—by increasing the telecom entrant's cost—lead to higher retail prices in the higher quality internet access market; in turn, this will increase profit for the cable operator, which provides lower quality internet access using its legacy network. We thus have $\frac{d\pi_2^{N,O,N}(\widetilde{a})}{d\widetilde{a}} \geq 0$.

The optimal coverage conditions for the cable operator are given by the values $\widetilde{z}_2^c(\widetilde{a}) = \left(\pi_2^{N,N,N}(\widetilde{a}) - \pi_2^{N,O,N}(\widetilde{a})\right)$ and $\widetilde{z}_2^m(a) = \left(\pi_2^{O,N,O}(a) - \pi_2^{O,O,O}(a)\right)$.

For the incumbent operator, the profit function is given by:

$$\Pi_1(z_1, z_2) = -\frac{z_1^2}{2} + \begin{cases} z_1\pi_1^{N,N,N}(\widetilde{a}) + (z_2 - z_1)\,\pi_1^{O,N,O}(a) + (\overline{z} - z_2)\,\pi_1^{O,O,O}(a) \\ \text{if} \quad z_1 \leq z_2 \\ z_2\pi_1^{N,N,N}(\widetilde{a}) + (z_1 - z_2)\,\pi_1^{N,O,N}(\widetilde{a}) + (\overline{z} - z_1)\,\pi_1^{O,O,O}(a) \\ \text{if} \quad z_1 > z_2 \end{cases}.$$

The optimal coverage conditions for the incumbent operator are given by the values $\widetilde{z}_1^c = \left(\pi_1^{N,N,N}(\widetilde{a}) - \pi_1^{O,N,O}(a)\right)$ and $\widetilde{z}_1^m(\widetilde{a}) = \left(\pi_1^{N,O,N}(\widetilde{a}) - \pi_1^{O,O,O}(a)\right)$.

Firm i's reaction function, with $i, j = 1, 2$ and $i \neq j$ is:

$$z_i^{\mathrm{BR}}(z_j) = \begin{cases} z_i^m & \text{if} \quad z_j \leq \widehat{z}_j \\ z_i^c & \text{if} \quad z_j > \widehat{z}_j \end{cases},$$

where $\widehat{z}_j$ is the lowest z_j such that $\widetilde{\Pi}_i(z_j, \widetilde{z}_i^c) \geq \widetilde{\Pi}_i(z_j, \widetilde{z}_i^m)$ holds. Note that, as in Bourreau et al. (2014), the threshold $\widehat{z}_j$ depends on both a and $\widetilde{a}$ in a indeterminate way.

Assuming $\widehat{z}_j \in [z_i^c, z_i^m]$, multiple equilibria emerge for all couples $\left(\widetilde{z}_i^m, \widetilde{z}_j^c\right)$ and $\left(\widetilde{z}_i^c, \widetilde{z}_j^m\right)$, with $i, j = 1, 2$ and $i \neq j$.

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Table 1: Variable definitions and sources

Variable	Description	Source
Dependent variables		
Log of incumbent firm's NGA lines *ln_inc_nga*	(Logarithm of) Total number of homes passed by incumbent operators with one of the available FTTx technologies (FTTx = Fiber-to-the home (FTTH) / Fiber-to-the building (FTTB) / Fiber-to-the Cabinet (FTTC) / Fiber-to-the node (FTTN); "Homes passed" is the total number of premises, i.e. a home or place of business; note that incumbent operators mainly deploy NGA lines based on FTTC and VDSL technology	FTTH Council Europe[(a)]
Log of cable firm's NGA lines *ln_cable_nga*	(Logarithm of) Total number of homes passed by coaxial cable operators with NGA lines based on FTTN and DOCSIS 3.0 technology	FTTH Council Europe[(a)]
Main explanatory variables		
NGA regulation *nga_reg*	NGA regulation including all remedies imposed on dominant operator: i) cost-oriented unbundling incl. sub-loop unbundling (access to FTTN/DOCSIS/ FTTC/VDSL networks incl. virtual undbundled local access (VULA)) and FTTH/FTTB unbundling at the Metropolitan Point of Presence incl. VULA, ii) cost-oriented products based on fiber in the access network (local and regional wholesale broadband access to FTTN/FTTC and FTTH networks); NGA regulation is measured as a binary indicator, which is equal to one in years in which at least one of the remedies are in force in a given EU member state and otherwise zero	EC, WIK, BEREC[(b)]
Price for LLU *llu_price*	Average total cost (=access price) for full local loop unbundling (LLU) in €, which is calculated as the regulated monthly fee plus the regulated fixed connection fee distributed over three years	EU Digital Agenda Scoreboard[(c)]

Table 1 (continued): Variable definitions and sources

Competition and other control variables		
Fixed legacy networks *legacy*	Total number of active fixed landlines per 100 inhabitants; an active line connects the subscriber's terminal equipment to the public switched telephone network PSTN lines	ITU[(d)]
Basic broadband adoption *bb_adop*	Number of total broadband internet subscribers based on access equal to 256 kbit/s, or greater, as the sum of the capacity in both directions (normalized by country's total number of households)	EU DAE Scoreboard[(c)]
Fixed-to-mobile substitution *fms*	Percentage share of the total number of mobile broadband subscriptions (with internet access equal to 256 kbit/s) to the total number of mobile and fixed broadband subscriptions (with internet access equal to 256 kbit/s)	ITU[(d)]
GDP in PPP *gdp_pc_ppp*	GDP per capita in current international dollars by PPP adjustment; the purchasing power of an international dollar is the same as that of the U.S. dollar in the United States	World Bank[(e)]
Education *edu*	Percentage of population with educational attainment of secondary education or higher, population aged 25 to 64 years	Eurostat[(f)]
Building permits *mdwell_perm*	Building permits for two and more dwellings as annual index normalized to 100 in 2010	Eurostat[(f)]
(External) Instrumental variables		
PCs number *comp_pen*	Total number of personal computers (PCs) in use in 000 persons in a country	Euromonitor[(g)]
EU NGA regulation *nga_inst*	Share of EU countries (other than the focal country) that already introduced regulations of NGA networks	EC, WIK, BEREC[(b)]

[(a)] The data are available to FTTH Council Europe members at: http://www.ftthcouncil.eu/resources?category_id=6.

[(b)] WIK (2012), BEREC (2016); Public notifications of EU member states under Article 7 and Article 7a are available at https://circabc.europa.eu/faces/jsp/extension/wai/navigation/container.jsp.

[(c)] Data are publicly available at the following EC websites: https://ec.europa.eu/digital-single-market/en/digital-scoreboard.

[(d)] Data are publically available at: http://www.itu.int/ITU-D/ict/statistics/.

[(e)] Data are publically available at: http://data.worldbank.org.

[(f)] Data are publically available at: http://ec.europa.eu/eurostat/de/data/database.

[(g)] Data are commercially available at: http://www.euromonitor.com/.

Table 2: Summary statistics

	obs	mean	sd	min	max
ln_inc_nga	297	8.530	6.353	0	16.87
inc_nga	297	1153655.1	2767211.4	0	21170000
ln_cable_nga	324	6.141	7.033	0	17.03
cable_nga	324	1389751.8	3436341.9	0	24963580
llu_price	281	11.87	4.805	5.280	42
nga_reg	324	0.346	0.476	0	1
fms	297	74.86	10.35	55	100
fms2	297	5710.6	1631.6	3025	10000
legacy	297	1.004	0.336	0.288	1.696
bb_adop	296	0.449	0.235	0	0.925
gdp_pc_ppp	297	29584.6	13552.8	7723.4	90789.6
edu	297	70.37	14.81	21.90	93.40
mdwell_perm	297	153.8	130.1	12.54	913.4
comp_pen	297	10342.5	16901.5	108.1	75284.8
nga_inst	324	0.346	0.366	0	0.962

Table 3: Estimation results for incumbent's investment equation (dependent var.: *ln_inc_nga*)

Regression:	(1)	(2)	(3)	(4)
Estimator_(# of lags):	2SLS_(3)	2SLS_(2)	GMM_(3)	GMM_(2)
Lagged ln_inc_nga	0.648***	0.797***	0.752***	0.782***
	(3.62)	(3.13)	(3.62)	(3.39)
ln_cable_nga	0.173	0.328	0.310**	0.390**
	(0.87)	(1.29)	(2.18)	(2.19)
llu_price	0.914*	1.064*	0.836**	0.900**
	(1.69)	(1.79)	(1.99)	(1.97)
nga_reg	-4.302*	-5.082	-6.152**	-6.886**
	(-1.83)	(-1.62)	(-2.48)	(-2.42)
fms	-4.494	-9.872**	-7.315**	-8.442**
	(-1.33)	(-1.99)	(-2.55)	(-2.54)
fms2	0.027	0.054**	0.041***	0.046***
	(1.28)	(1.97)	(2.64)	(2.61)
legacy	-3.969	-20.581	-19.898**	-22.892**
	(-0.32)	(-1.36)	(-2.31)	(-2.20)
bb_adop	30.061***	37.075**	29.748**	33.149**
	(2.71)	(2.31)	(2.48)	(2.50)
gdp_pc_ppp	0.000*	0.001**	0.001**	0.001**
	(1.88)	(2.24)	(2.16)	(2.30)
mdwell_perm	0.005	0.006	0.004	0.005
	(0.83)	(0.80)	(0.79)	(0.86)
edu	-0.130	-0.244	-0.202	-0.270
	(-0.81)	(-1.04)	(-1.31)	(-1.56)
F-test (2SLS) / $\chi 2$ (GMM) (p-value)	0.000	0.000	0.000	0.000
AR1 test (p-value)	0.021	0.028	0.005	0.007
AR2 test (p-value)	0.746	0.328	0.145	0.115
Sargan test (p-value)	0.787	0.621	0.475	0.309
Hansen test (p-value)	0.816	0.256	0.475	0.309
Diff-in Hansen test (p-value) (excl. instr.)	0.507	0.143	0.525	0.412
# instruments	18	14	25	19
# clusters	27	27	27	27
# observations	185	212	212	212

Notes: Columns (1) and (2) are based on the 2SLS estimator (Anderson-Hsiao, 1981). Columns (3) and (4) are based on the one-step GMM-Diff estimator (Arellano-Bond, 1991) and include GMM-style instruments for the lagged dependent variable with a maximum number of three lags (column 3) or two lags (column 4). Lagged levels of other endogenous variables are used to construct IV-style instruments. Country-specific (fixed) effects are included in all regressions. Jointly insignificant year-specific effects are excluded. Standard errors are clustered at the country level and robust to arbitrary forms of heteroscedasticity. *t* statistics in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Estimation results for cable investment equation (dependent var.: *ln_cable_nga*)

Regression:	(1)	(2)	(3)	(4)
Estimator_(# of lags):	2SLS_(3)	2SLS_(2)	GMM_(3)	GMM_(2)
Lagged ln_cable_nga	0.617***	0.582***	0.614***	0.630***
	(3.77)	(3.74)	(3.93)	(3.98)
ln_inc_nga	0.155	0.064	0.066	0.047
	(0.83)	(0.31)	(0.33)	(0.23)
llu_price	-0.607	-0.643	-0.455	-0.460
	(-0.84)	(-1.52)	(-1.22)	(-1.22)
nga_reg	0.033	2.575	1.512	1.499
	(0.02)	(1.20)	(0.73)	(0.74)
fms	2.583	5.613*	3.504	3.558
	(0.64)	(1.75)	(1.32)	(1.27)
fms^2	-0.018	-0.032*	-0.021	-0.021
	(-0.72)	(-1.84)	(-1.43)	(-1.38)
legacy	14.690	29.120***	22.523***	24.317***
	(1.24)	(3.13)	(2.93)	(3.03)
bb_adop	2.908	-15.224	-6.394	-6.323
	(0.17)	(-0.98)	(-0.46)	(-0.44)
gdp_pc_ppp	-0.000	-0.000	-0.000	-0.000
	(-0.33)	(-0.66)	(-0.38)	(-0.33)
mdwell_perm	-0.008*	-0.011***	-0.010***	-0.010***
	(-1.84)	(-3.03)	(-2.87)	(-2.91)
edu	0.413**	0.504**	0.462**	0.472**
	(2.00)	(2.47)	(2.38)	(2.39)
F-test (2SLS) / χ2 (GMM) (p-value)	0.000	0.000	0.000	0.000
AR1 test (p-value)	0.003	0.002	0.001	0.001
AR2 test (p-value)	0.347	0.317	0.349	0.343
Sargan test (p-value)	0.940	0.944	0.995	0.944
Hansen test (p-value)	0.606	0.861	0.666	0.444
Diff-in Hansen test (p-value) (excl. instr.)	0.750	0.861	0.633	0.652
# of instruments	18	13	21	17
# of clusters	27	27	27	27
# of observations	200	212	212	212

Notes: Columns (1) and (2) are based on the 2SLS estimator (Anderson-Hsiao, 1981). Columns (3) and (4) are based on the one-step GMM-Diff estimator (Arellano-Bond, 1991) and include GMM-style instruments for the lagged dependent variable with a maximum number of three lags (column 3) or two lags (column 4). Lagged levels of other endogenous variables are used to construct IV-style instruments. Country-specific (fixed) effects are included in all regressions. Jointly insignificant year-specific effects are excluded. Standard errors are clustered at the country level and robust to arbitrary forms of heteroscedasticity. *t* statistics in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A1: First-stage results for incumbent's investment equation

Regression:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dep. Variable:	LD.*ln_ inc_nga*	D.*ln_cab le_nga*	D. *llu_price*	D. *nga_reg*	D. *fms*	D. *fms*^{2}	D. *legacy*	D. *bb_adop*
D.*gdp_pc_ppp*	-0.000	-0.000	-0.000	0.000	0.000	0.004	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.014)	(0.000)	(0.000)
D.*mdwell_perm*	-0.005	-0.008	0.001	-0.000	0.002	0.362	-0.000	0.000
	(0.004)	(0.006)	(0.002)	(0.000)	(0.002)	(0.301)	(0.000)	(0.000)
D.*edu*	0.029	0.340*	0.012	-0.010	-0.074**	-10.470*	0.002	-0.001
	(0.098)	(0.185)	(0.040)	(0.010)	(0.035)	(5.134)	(0.002)	(0.002)
L2.*ln_cable_nga*	-0.013	-0.214***	-0.003	-0.004	-0.008	-0.900	-0.000	-0.000
	(0.029)	(0.045)	(0.015)	(0.005)	(0.019)	(2.847)	(0.001)	(0.001)
L2.*llu_price*	0.243*	-0.082	-0.163**	-0.004	-0.018	-2.268	0.002	-0.001
	(0.133)	(0.143)	(0.063)	(0.010)	(0.066)	(10.763)	(0.002)	(0.002)
L3.*llu_price*	-0.185**	0.088	0.025	-0.006	0.037	5.918	-0.003**	0.001
	(0.073)	(0.157)	(0.043)	(0.006)	(0.038)	(6.048)	(0.001)	(0.001)
L2.*nga_reg*	-0.119	-0.829	0.434	-0.292***	0.385	46.492	-0.030*	-0.009
	(0.720)	(0.744)	(0.310)	(0.048)	(0.323)	(49.008)	(0.017)	(0.009)
L3.*nga_reg*	-0.622	0.017	-0.471*	-0.038	-0.035	-2.612	-0.000	0.005
	(0.533)	(0.763)	(0.238)	(0.023)	(0.311)	(45.231)	(0.019)	(0.010)
L2.*bb_adop*	3.800***	5.193***	0.757	0.373***	-0.451	-50.833	-0.001	-0.108***
	(1.333)	(1.364)	(0.746)	(0.110)	(1.180)	(179.66)	(0.033)	(0.022)
L2.*fms*	0.014	0.037	0.034*	-0.004	0.096***	14.999***	-0.002	0.002
	(0.054)	(0.067)	(0.018)	(0.004)	(0.024)	(3.719)	(0.001)	(0.001)
L3.*fms*	0.023	-0.018	-0.036**	0.004	-0.022*	-3.370*	0.001*	-0.000
	(0.028)	(0.040)	(0.013)	(0.002)	(0.012)	(1.937)	(0.000)	(0.000)
L2.*fms*^{2}	-0.000	-0.000	0.000	0.000	-0.001***	-0.108***	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.025)	(0.000)	(0.000)
L2.*legacy*	-3.399	1.718	1.268	-0.707*	-1.665	-371.472	0.022	0.185**
	(3.327)	(5.887)	(1.516)	(0.349)	(2.985)	(447.17)	(0.119)	(0.076)
L3.*legacy*	2.267	-3.597	-0.566	0.744**	1.100	250.122	-0.023	-0.135
	(3.627)	(5.947)	(1.400)	(0.360)	(2.757)	(412.15)	(0.117)	(0.082)
L2.*ln_inc_nga*	-0.204***	0.094	-0.014	-0.004	-0.004	-0.834	0.001	-0.000
	(0.067)	(0.118)	(0.025)	(0.006)	(0.033)	(5.095)	(0.001)	(0.001)
L3.*ln_inc_nga*	-0.029	-0.059	-0.001	0.014*	-0.021	-2.417	-0.001	-0.000
	(0.034)	(0.122)	(0.027)	(0.007)	(0.033)	(4.859)	(0.001)	(0.000)
D.*nga_inst*	-5.127**	4.909	-0.221	0.120	0.087	7.179	0.010	-0.013
	(2.402)	(3.367)	(0.827)	(0.290)	(1.244)	(177.00)	(0.040)	(0.021)
D.*comp_pen*	0.001***	0.000	0.000	0.000	-0.000	-0.007	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.014)	(0.000)	(0.000)
Partial R^2 of excl. instruments	0.2803	0.1621	0.2156	0.2300	0.2075	0.2161	0.2235	0.5912
F-test (15, 26) of excl. instruments	19.95***	16.01***	9.65***	31.04***	6.57***	6.65***	9.42***	24.80***
# observations	185	185	185	185	185	185	185	185

Notes: The estimates correspond to regression (1) in table 3. Standard errors are in parentheses.
L, L2 and L3 stand for values lagged by one, two and three periods, respectively
D stands for first difference
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A2: First-stage results for cable investment equation

Regression:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dep. Variable:	LD.*ln_cable_nga*	D.*ln_inc_nga*	D.*llu_price*	D.*nga_reg*	D.*fms*	D.fms^2	D.*legacy*	D.*bb_adop*
D.*gdp_pc_ppp*	-0.000	0.000*	-0.000	0.000	0.000**	0.031**	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.014)	(0.000)	(0.000)
D.*mdwell_perm*	0.004	-0.000	0.001	-0.000	0.003	0.486	-0.000	0.000
	(0.003)	(0.003)	(0.002)	(0.000)	(0.002)	(0.353)	(0.000)	(0.000)
D.*edu*	-0.217*	0.027	0.004	-0.011	-0.068**	-9.595*	0.002	0.000
	(0.117)	(0.081)	(0.028)	(0.009)	(0.031)	(4.824)	(0.002)	(0.002)
L2.*ln_inc_nga*	0.085	-0.222***	-0.013	0.006**	-0.051	-7.660	0.000	-0.000
	(0.053)	(0.043)	(0.010)	(0.003)	(0.052)	(8.583)	(0.001)	(0.001)
L2.*llu_price*	-0.006	-0.251**	-0.084	-0.001	0.104	16.487	0.002	-0.001
	(0.065)	(0.105)	(0.054)	(0.006)	(0.108)	(17.182)	(0.001)	(0.001)
L3.*llu_price*	-0.050	0.115	0.006	-0.007	-0.031	-4.894	-0.002***	0.000
	(0.061)	(0.106)	(0.039)	(0.005)	(0.072)	(11.629)	(0.001)	(0.001)
L2.*nga_reg*	-0.101	0.239	0.513	-0.236***	0.184	15.306	-0.028	-0.012
	(1.180)	(0.473)	(0.378)	(0.042)	(0.401)	(60.917)	(0.019)	(0.009)
L3.*nga_reg*	0.252	-0.008	-0.542*	-0.039	-0.093	-9.591	0.001	0.004
	(0.996)	(0.560)	(0.275)	(0.028)	(0.362)	(55.152)	(0.018)	(0.010)
L2.*bb_adop*	4.995**	1.880	0.388	0.373***	0.058	30.944	-0.006	-0.097***
	(1.962)	(1.492)	(0.631)	(0.101)	(1.256)	(192.00)	(0.030)	(0.019)
L2.*fms*	-0.057	0.102*	0.012	-0.002	-0.138	-23.552	-0.002*	0.001
	(0.080)	(0.057)	(0.016)	(0.004)	(0.104)	(17.437)	(0.001)	(0.001)
L3.*fms*	0.048	-0.007	-0.031***	0.002	0.062*	10.346*	0.001*	-0.000
	(0.038)	(0.034)	(0.011)	(0.002)	(0.033)	(5.772)	(0.000)	(0.000)
L2.fms^2	0.000	-0.001	0.000*	0.000	0.001	0.168	0.000	-0.000
	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.141)	(0.000)	(0.000)
L2.*legacy*	-11.923**	7.560	1.103	-0.509	-3.752	-702.228	0.032	0.175**
	(5.057)	(5.453)	(1.612)	(0.375)	(4.135)	(643.23)	(0.122)	(0.077)
L3.*legacy*	10.610**	-8.371	-0.255	0.527	4.941	872.925	-0.036	-0.126
	(4.970)	(5.641)	(1.497)	(0.389)	(4.437)	(700.57)	(0.119)	(0.082)
L2.*ln_inc_nga*	-0.344***	-0.017	0.010	0.003	-0.050	-7.818	0.000	-0.001
	(0.055)	(0.037)	(0.014)	(0.008)	(0.031)	(4.643)	(0.001)	(0.001)
L3.*ln_inc_nga*	0.047	0.024	-0.008	-0.010	0.013	1.988	-0.001	0.001
	(0.061)	(0.051)	(0.022)	(0.008)	(0.026)	(3.935)	(0.001)	(0.001)
D.*nga_inst*	9.313*	0.414	-0.414	0.079	-2.577	-425.530	0.009	-0.018
	(5.028)	(1.621)	(0.849)	(0.268)	(2.463)	(394.97)	(0.043)	(0.024)
D.*comp_pen*	0.000	0.000**	0.000	0.000	0.000	0.005	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.018)	(0.000)	(0.000)
Partial R^2 of excl. instruments	0.3382	0.2419	0.1702	0.2260	0.1377	0.1360	0.2270	0.5745
F-test (15, 26) of excl. instruments	16.97***	12.89***	13.77***	31.08***	9.71***	7.73***	12.58***	25.97***
# observations	200	200	200	200	200	200	200	200

Notes: The estimates correspond to regression (1) in table 4. Standard errors are in parentheses.
L, L2 and L3 stand for values lagged by one, two and three periods, respectively
D stands for first difference
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$