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Wolfgang Briglauer, Carlo Cambini,
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Zentrum für Europäische
Wirtschaftsforschung GmbH

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Wolfgang Briglauer†
ZEW

Carlo Cambini‡
Politecnico di Torino

Michał Grajek§
ESMT

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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 network infrastructure. To this end, we develop a theoretical model explaining investment incentives by incumbent telecom operators and heterogeneous entrants and test its main predictions using panel data from 27 EU member states over the last decade. Our theoretical model extends the existing literature by, among other things, allowing for heterogeneous entrants in internet access markets, as we consider both other telecom and cable TV operators as entrants. In the empirical part, we use a novel data set including information on physical fiber network investments, legacy network access regulation and recently imposed fiber access regulations. Our main finding is that more stringent access regulations for both the legacy and the fiber networks harm investments by incumbent telecom operators, but, in line with our theoretical model, do not affect cable TV operators.

Keywords: Internet access market, Access regulation, Investment, Infrastructure, Next Generation Networks, Broadband, Telecoms, Cable operators and Europe.

JEL Classification Numbers: L96; L51.

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†ZEW Mannheim & MaCCI. *E-mail*: briglauer@zew.de.

‡Politecnico di Torino, Deparment of Management and Economics & EUI. *E-mail*: carlo.cambini@polito.it.

§ESMT Berlin. *E-mail*: michal.grajek@esmt.org.

1. Introduction

Next Generation Access (NGA) networks are based, in part or entirely, on fibre-optic technologies that provide radically improved quality in terms of high-speed broadband Internet access for 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 telecommunications 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 European Commission aims to strengthen the competitiveness of Europe's economy with an explicit focus on digital communications 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 in 2010 (European Commission, 2010).

Whereas the economic importance of new internet access infrastructure is widely recognized, there are various approaches to promoting the deployment of NGA networks via competition, sector-specific regulation and public subsidies. Currently, the EU regulatory framework imposes rather comprehensive and strict access obligations on incumbent operators compared to jurisdictions in the US or leading East-Asian fiber nations. Further, the EU's access obligations cover not only legacy (copper-based), but also NGA (fiber-based) infrastructures.

In this paper, we shed light on how the existence of parallel regulations for copper and NGA infrastructures shapes the incentives to invest for the two main types of NGA network owners: incumbent telecom and cable TV operators. These operators, which own decades-old legacy networks and enjoy substantial cost advantages over telecom entrants in terms of NGA infrastructure deloyment, jointly account for 85.8% of the EU's NGA

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

lines in 2014, the last year of our data set.

Our theoretical model extends the existing literature on transition from old to new network infrastructures (Bourreau, Cambini and Dogan, 2012, 2014; Inderst and Peitz, 2012) by, most importantly, allowing for heterogenous entrants to internet access markets. In particular, our model accomodates both cable operators, which have different footprints across EU member states, and telecom entrants, which have followed different NGA investment patterns to cable operators. We further extend the literature on transition from copper to fiber by considering an asymmetric NGA regulation regime, in which only the incumbent firm's fiber infrastructure is ex ante regulated. These extensions allow us to derive testible predictions and policy implications, which fit the differential competition conditions across the EU's internet access markets, in particular with respect to cable operators, which lead the NGA deployment in many EU member states.

Our empirical tests of these predictions complement existing evidence on the effect of access regulation on infrastruture 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 less direct accounting measures used in other studies. 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 investment incentives has not yet been empirically studied.

The rest of the paper is organized as follows: Section 2 briefly describes the relevant regulations and the theoretical and empircal 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. The final section 5 concludes.

2. Transition from copper to fiber: EU's regulations and related literature

Within the EU markets for electronic communications networks and services have been regulated according to the 2002 eCommunications framework.[2] Among its main provisions is the mandated sharing of network infrastructure, which allows entrants to compete with incumbent operators, mostly successors of state-owned monopolies owners of copper-based (legacy) communications networks. The most relevant mandated sharing provisions are know as local loop unbundling (LLU) and specify, among other things, 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 the 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 experience of countries leading in NGA deployment shows that fibre-based infrastructures do not immediately replace the existing copper or cable legacy networks and that during a transition phase these different infrastructures co-exist. The incentives to invest in NGA infrastructures will therefore not only be influenced by the terms of mandated access to the NGA networks, but also to the legacy copper networks.[3]

The existing economic literature provides theoretical models and some empirical evidence on the effect of access regulation on the deployment of new infrastructure. 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 the copper network may have positive or negative impact on the incumbent operator's invstment in fiber networks. These models also predict that higher access fees unambiguously

[2]For an overview of the relevant directives, regulations and recommendations of the EU regulatory framework, the reader is referred 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 ante access obligations asymmetrically imposed on dominant operators.

[3]In the remaining part of the text, we use the terms NGA network and fiber network interchangeably.

incentivize the entrants to invest in NGA. Bourreau Cambini and Dogan (2014) extend these models to the presence of access regulation to fibre networks and find that it dilutes the incentive to invest. This strand of literature assumes, however, that entrants use the copper network managed by the incumbent operator to compete in the downstream market for internet services provision. We additionally consider cable operators, which can provide internet services via own legacy cable TV infrastructure and, indeed, have led the NGA infrastructure deployment in the EU.

The early empirical literature on telecom infrastructure investment and access regulation is comprehensively surveyed in Cambini and Jiang (2009). They conclude that the literature by and large finds that the LLU, as implemented by many national regulators, discourages both incumbent and alternative telecom operators from investing in communications networks.[4]

More recently, a number of studies investigated the role of access regulation, and LLU price in particular, for the investments in NGA networks (e.g., Bacache et al., 2014; Briglauer, 2015). These papers generally find a negative impact of regulation on investment, but by using more aggregated data than ours, are not able investigate the impact of LLU and fiber regulations separately on incumbent telecom operators and cable operators. Nardotto, Valletti and Verboven (2015) use a very detailed data set from the UK and find that LLU entry has a positive impact on the quality of the internet service provided by telecom entrants. Also, Bourreau et al. (2017) find that local market presence of entrants using LLU positively influence fiber networks deployment in French metropolitan municipalities. Since these studies use data from a single country, however, they cannot assess the effects of the stringency of LLU regulation, as measured by LLU price for instance, on the quality of service or fiber networks deployment.

Most closely related to our empirical analysis is 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 total investment in the telecommunications industry. They find that access regulation negatively affects both total industry and individual operators' investments, but focus on the telecom entrants and incumbents, thus missing the cable operators, which have proven to be very important for NGA deployment in the EU. Moreover, in this paper, we utilize a better measure of infrastructure investment

[4]Briglauer et al. (2015) provide a recent comprehensive overview of the regulatory approaches and the economic literature related to NGA deployment.

than Grajek and Röller (2012): physical NGA lines, and derive testable hypotheses from an analytical model. Finally, neither of the above cited studies use two separate measures of regulation, one applied to legacy infrastructure and one to NGA infrastructure.

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; BCD hereafter) model in multiple 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 derive testable hypotheses about the role of access regulations for NGA investments. We empirically evaluate these hypotheses in section 4.

Most importantly, we account for heterogeneous internet access market entrants, which are present in many European markets. To this end, we consider the presence of three (rather than two, as in the original BCD model) different competitors: an incumbent telecom operator that owns a legacy copper-based telephone network, a cable operator that owns a legacy cable TV network, and a telecom entrant that does not own any legacy network. The first two firms provide internet services using their respective legacy networks; the third one relies on mandated access to the incumbent operator's legacy network. The competition between these three players reveals new effects that have not been previously identified and points to even more complex impacts of regulated access to legacy networks on the incentives to invest in new network infrastructures.

Moreover, we further extend our model by: i) allowing cable operator's legacy network to only partially cover the market, ii) allowing the incumbent operator's fiber infrastructure to be ex ante regulated (asymmetric NGA regulation), and iii) allowing for differences in investment costs faced by incumbent and cable operators. These extensions address arguably the most important stylized facts about NGA infrastructure investment in Europe, as discussed in section 4.3.

3.1 Main model structure

We consider a country as composed of a continuum of areas with a total size of $\overline{z}$. The fixed cost of deploying the 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 in the market: a fixed telecom incumbent operator (firm 1) manages a legacy copper network and leases it at a regulated access price ($a \geq 0$); a cable entrant (firm 2) owns a legacy cable TV network; a telecom entrant (firm 3) does not own any legacy network and seeks access to the incumbent firm's legacy network at the regulated price a.

A new fiber-based network, the NGA network, allows the firms to provide higher quality internet access, but it requires investment. In our main model (i.e. the benchmark model in section 3.2 and the extensions thereof in sections 3.3, 3.4 and 3.5), we impose the condition that the telecom entrant is passive, that is it does not invest in fiber infrastructure. In other words, all three firms compete at the retail level, but only the incumbent and the cable operators invest in the fiber infrastructure.[5] 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 $c'(x) > 0$, implying that the total cost of covering the area $[0, z_i]$ for firm i is then $C(z_i) = \int_0^{z_i} c(x)\, dx$, 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 firms have the same marginal (wholesale and retail) costs in all areas, which we normalize to zero.

In each area z, we use the superscripts "O" and "N" for the old/legacy (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 infrastructure of the incumbent operator (k), the cable entrant (l) and the telecom entrant (j), respectively. The telecom entrant is assumed to be passive, i.e. it does not invest in fiber (i.e. $z_3 = 0$) and relies on the access to the incumbent operator's legacy network instead (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 $\pi_2^{O,k,O}(.) \geq \pi_2^{N,k,O}(.)$.

[5] 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 the Appendix and show that it does not alter the testable hypotheses derived from the main model.

This assumption implies that, given its network infrastructure, firm i, $i = 1, 2$, makes more profit when the rival uses the old rather than the new network.

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

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

Assumption 3 For $k, l = O, N$, we have: (i) $d\pi_1^{k,l,O}(a)/da \geq 0$, for all $a \leq \widehat{a}^k$; (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. This is because, when a is low, an increase in a both increases the incumbent operator's wholesale revenues (a direct effect) and softens 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 the old network managed by the incumbent, its profit decreases with the access price, a.

Assumption 3(iii) is related to the behaviour of the cable entrant, which never seeks access to the incumbent operator's legacy network, because it either invests in own fiber network or uses its own legacy network. An increase in the access price a creates, however, a cost disadvantage at the retail level for the telecom entrant and, indirectly, a cost advantage for the cable entrant, which then competes less vigorously and increases its profit. This implies that the profit function of the cable entrant is positively influenced by the access price a.

The timing. The timing of the game is as follows: The regulator sets the access price on the copper network, a (and on the fiber network, $\tilde{a}$ if the fiber network is also regulated). 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 also decides on z_3). Finally, all three firms compete in the provision of internet services at the retail level.

3.2 The benchmark case

We start by studying a benchmark case, in which access to the fiber network is not mandated. Moreover, we consider the case in which the telecom entrant is passive, i.e. does not invest in the fiber network; however, the telecom entrant competes at the retail level thanks to the mandated access to the incumbent operator's legacy infrastructure. Thus, 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 network).*[6] 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 entrant deploys a fiber network; the firms obtain the gross profits $\pi_i^{O,N,O}(a), i = 1, 2, 3$; and (ii) the incumbent operator deploys a fiber network, while the cable entrant relies on the old cable TV network; the firms obtain the gross profits $\pi_i^{N,O,O}(a), i = 1, 2, 3$.

3. *Infrastructure-based competition between the fiber networks.* Both the incumbent and the cable operators deploy their own fiber networks, while the telecom entrant still continues to use mandated access to the old netwrok; 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 entrant's profit is:

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

[6]In case the basic broadband connections using the copper and the cable networks lead to different service quality, the profit of the incumbent operator, the cable entrant and the telecom entrant may differ. In what follows, we assume that the quality of connections in both legacy networks is the same. In section 3.5, however, we allow for the asymmetry across firms in terms of the infrastructure deployment costs.

In order to determine the optimal investment of the cable entrant, first consider the case in which it 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 entrant 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 entrant 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 entrant 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 have $z_2^c = \left(\pi_2^{N,N,O}(a) - \pi_2^{N,O,O}(a)\right)$ 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 entrant invests.

Assume that firm 2 (i.e. the cable entrant) has covered the areas $[0, z_2]$. Firm 1's (i.e. telecom incumbent operator's) profit is 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 where 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 where firm 2 has not rolled out the 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 satisfy these two inequalities, respectively. We thus have $z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_1^{O,N,O}(a)\right)$ and $z_1^m = \left(\pi_1^{N,O,O}(a) - \pi_1^{O,O,O}(a)\right)$.

Given the above profit functions we can now write the respective reaction functions of the firms:

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

where the threshold $\widehat{z}_1$ is defined as the lowest z_1 such that $\Pi_2(z_1, z_2^c) \geq \Pi_2(z_1, z_2^m)$, i.e. the lowest level of the incumbent operator's coverage that makes the cable entrant's profit in the areas with competing NGA infrastructures equal to or above the cable entrant's profit in monopoly NGA areas.

Considering that $z_1^m > z_1^c$, firm 1's best response function is obtained in a similar way:

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

where $\widehat{z}_2 \in [z_2^c, z_2^m]$.

The incumbent and the cable operator's best-response functions (4) and (5) decrease (weakly) with the coverage of the rival, implying that the investment decisions are *strategic substitutes*. From (4) and (5), one can also see that the model yields multiple equilibria defined by all couples (z_1^m, z_2^c) and (z_1^c, z_2^m). This means that either of the firms will 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. Investment in these duopoly areas will be driven by the follower's incentive to duplicate the NGA network of the leader. Finally, in the highest cost areas no fiber networks will be deployed; 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 entrant 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 $dz_1^m/da = \left(\frac{d\pi_1^{N,O,O}(a)}{da} - \frac{d\pi_1^{O,O,O}(a)}{da}\right)$.

Thus, the investment decision by the fixed incumbent is affected by two countervailing effects: the *retail-migration* and the *wholesale revenue effect.* 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 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 obtained in the absence of the cable entrant in BCD (2012).

The key novelty of our model comes from the cable investment decision: a higher access price a by inflating the telecom entrant's costs not only helps the incumbent, but also the cable operator's profit from NGA-based services ($\frac{d\pi_2^{k,N,O}(a)}{da} \geq 0, k = N, O$), thus boosting its incentives to invest in fiber. This effect is indeed similar to the *retail migration effect* found for the incumbent. However, investment in fiber comes at an opportunity cost 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, the retail prices for legacy-network-based services are higher and so is the opportunity cost of investing in fiber network for the cable entrant. This effect, measured by $\frac{d\pi_2^{k,O,O}(a)}{da} \geq 0, k = N, O$, which we label the *business stealing effect*, counterbalances the previous one. Thus, similarly as for the incumbent, the overall effect of an increase in the access price a on the cable entrant's incentive to invest is ambiguous and depends on the balance between these two countervailing effects.

3.3 Extension 1: An investment leading cable firm with partial coverage

In the benchmark model, we assumed that the cable entrant, when present in the market, has its own legacy network rolled-out over the entire country. However, it might be that, even in those countries where cable entrants are present, cable coverage is not full.[7] In this section we extend our benchmark model to account for the possibility that a cable entrant's legacy infrastructure only partially covers the country. We further assume that the cable operator does not seek access to the incumbent copper infrastructure.[8]

As shown in the previous section, two cases can emerge: either the incumbent operator

[7] Indeed, 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 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).

[8] We have contacted Cable Europe, an association of European cable companies, and received a confirmation of this assumption. Cable companies that seek to extend their coverage would rather do it by acquiring another firm or building the fiber infrastructure anew, if at all.

dominates in the NGA coverage or the cable entrant does. In this extension, we focus on the latter case, which is more common in our data and thus more representative for the EU countries. In this case, the cable entrant dominates the NGA market by investing more than the telecom incumbent operator, i.e. $z_2^m > z_1^c$.

Assume first that the cable entrant's partial coverage is larger than the monopoly NGA coverage, that is $\widehat{z} > z_2^m$. The cable entrant'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 monopolisitc fiber areas, $(z_2 - z_1)\, \pi_2^{O,N,O}(a)$, and the profit in areas where the cable entrant 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 entrant, 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 $z_1 = z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_2^{O,N,O}(a)\right)$ 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 almost unchanged. The cable entrant's optimal NGA investment is not affected, even though it does not derive any profit from its legacy-network-based cable service in the uncovered areas.

A more interesting case of partial coverage is when $\widehat{z}_2 < \widehat{z} \leq z_2^m$. 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 entrant will invest more and its fiber network coverage will be larger than its legacy network coverage. As a result the cable entrant'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 $z_1 = z_1^c = \left(\pi_1^{N,N,O}(a) - \pi_2^{O,N,O}(a)\right)$, as in the benchmark case, and $z_2 = z_2^m = \left(\pi_2^{O,N,O}(a)\right)$. The cable entrant's investment, hence the total coverage, is in this case positively influenced by a due to the *retail level migration effect*.

The above case assumes that the investment cost is continuous and increasing in z. This assumption may not reflect the real market conditions, though. Because of substantially higher investment costs, cable operators typically do not roll out NGA infrastructure in the areas previously uncovered by the cable TV network, as dicussed 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 eq. (5), the incumbent operator's best response in this case is to choose investment level z_1^c whenever $z_2 > \widehat{z}_2$, so the cable entrant will stay the investment leader, but will not achieve NGA coverage equal to z_2^m because of the binding constraint $\widehat{z}$. Instead, the cable entrant'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 $z_2 = \widehat{z} \leq z_2^m = \left(\pi_2^{O,N,O}(a) - \pi_2^{O,O,O}(a)\right)$, any change to a, if it causes z_2^m to decrease by an amount small enough, or to increase, will leave equilibrium cable investment $z_2 = \widehat{z}$ unchanged. Thus, partial cable coverage may render cable NGA investment insensitive to the access charge a when the investment costs dramatically increase in the areas previously uncovered by the legacy cable network.

3.4 Extension 2: Regulated access to fiber

As another extension to the benchmark model, we allow that the incumbent is obliged to grant access to its new fiber infrastructure at the regulated access price $\widetilde{a}$. We assume that the cable entrant is *not* subject to the same access obligation.[9] Because the telecom entrant is passive by assumption, i.e., it 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 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 entrant never seeks access to the incumbent

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

operator's legacy *and* fiber networks.

The access price to fiber satisfies $\widetilde{a} < \arg\max \pi^{N,N,N}(\widetilde{a}))$, which means that it is below the level of the access price that would maximize the incumbent operator's profits in the areas covered by its NGA network (and by the cable entrant's NGA network). Given this extension of the benchmark model, the cable entrant'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 entrant 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 entrant, 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 entrant are $z_2^c(\widetilde{a}) = \left(\pi_2^{N,N,N}(\widetilde{a}) - \pi_2^{N,O,N}(\widetilde{a})\right)$ and $z_2^m(a) = \left(\pi_2^{O,N,O}(a) - \pi_2^{O,O,O}(a)\right)$. From $z_2^c(\widetilde{a})$ we observe that an increase in $\widetilde{a}$ has two effects: a higher access charge $\widetilde{a}$ increases the cable entrant's profit in covered areas, i.e., $\pi_2^{N,N,N}(\widetilde{a})$, because an increase in $\widetilde{a}$ relaxes the retail price competition by inflating the cost for the telecom entrant. At the same time, an increase in $\widetilde{a}$ also increases the cable entrant's profit in areas covered by the incumbent's fiber network only where the cable entrant uses the legacy infrastructure ($\pi_2^{N,O,N}(\widetilde{a})$), as explained above. The overall impact of $\widetilde{a}$ on the cable entrant is thus ambiguous in case the cable entrant is the investment follower.

In contrast, when the cable entrant is the investment leader, its fiber investments do not depend on $\widetilde{a}$. This follows from the assumption that access to the cable entrant's network is not regulated.[10]

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

[10] The cable entrant's investment in this case still depends on a, the access price to the incumbent operator's legacy network, in exactly the same way as in the benchmark model.

$$\Pi_1(z_1, z_2) = -\frac{z_1^2}{2} + \begin{cases} z_1 \pi_1^{N,N,N}(\widetilde{a}) + (z_2 - z_1)\, \pi_1^{O,N,O}(a) + (\overline{z} - z_2)\, \pi_1^{O,O,O}(a) \\ \text{if } \; z_1 \le z_2 \\ z_2 \pi_1^{N,N,N}(\widetilde{a}) + (z_1 - z_2)\, \pi_1^{N,O,N}(\widetilde{a}) + (\overline{z} - z_1)\, \pi_1^{O,O,O}(a) \\ \text{if } \; z_1 > z_2 \end{cases} . \tag{6}$$

The optimal coverage conditions for the incumbent operator are $z_1^c = \left(\pi_1^{N,N,N}(\widetilde{a}) - \pi_1^{O,N,O}(a)\right)$ and $z_1^m(\widetilde{a}) = \left(\pi_1^{N,O,N}(\widetilde{a}) - \pi_1^{O,O,O}(a)\right)$. Note here that an increase of $\widetilde{a}$ 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. Moreover, the regulated access price is expected to be lower than the access price that the incumbent operator would set in the absence of regulation; such optimal (for the incumbent operator) access price $\widetilde{a}$ would further increase $\pi_1^{N,N,N}(\widetilde{a})$ as well as $\pi_1^{N,O,N}(\widetilde{a})$. In other words, the presence of access regulation for fiber infrastructure lowers the incumbent operator's incentives to expand NGA coverage.[11]

3.5 Extension 3: 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 passive telecom entrant in this extension. Further, the cable entrant 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 in this section.

To analyze how the difference in costs affects investment equilibria, we modify the marginal costs of fiber infrastructure deployment 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; the parameter Δ represents the (marginal) cost advantage.[12]

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

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

[12] 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 $\Delta > 0$. We thus maintain this assumption.

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

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

And the best responses of the two are:

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 entrant (i.e., z_2^m and z_2^c increase). Hence, the cost advantage induces the cable entrant to invest more than the incumbent operator. These equilibria are shown in figure 1.

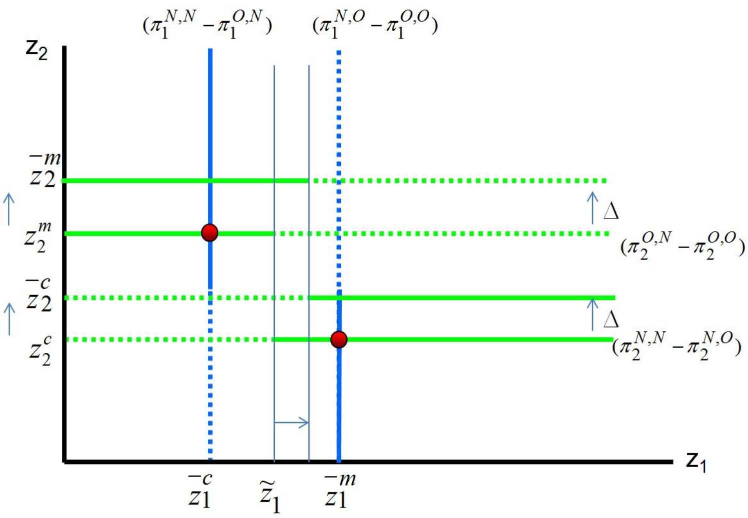

Figure 1: Best response functions of the model with cost asymmetry

Moreover, the cable entrant's cost advantage has an additional effect on the threshold level $\widehat{z}_1$. Recall that $\widehat{z}_1$ is defined as the lowest z_1 such that $\Pi_2(z_1, \overline{z}_2^c) \geq \Pi_2(z_1, \overline{z}_2^m)$. Since $\overline{z}_2^c > z_2^c$ and $\overline{z}_2^m > z_2^m$ and the profit of firm 2 increases with both, while it decreases with z_1, the new threshold $\widehat{z}_1$ also shifts outward, as shown in figure 1. This implies that, when the cost advantage Δ is high enough, then $\widehat{z}_1$ increases so that $\widehat{z}_1 > \overline{z}_1^m$. When this happens, the incumbnet operator cannot be the investment leader any longer, instead the cable entrant will be the only leader in equilibrium. Hence, once we allow the cable entrant to have a cost advantage, the more likely equilibrium of the investment game becomes $(\overline{z}_1^c, \overline{z}_2^m)$.

3.6 Testable hypotheses

Results obtained from the above model and its extensions provide us with a set of testable hypotheses on the strategic interaction of firms in the NGA market and the impact of access regulation on infrastructure investments.

3.6.1 Strategic reaction to rival's investment.

Because of the multiplicity of equilibria in our model, the impact of cable (incumbent) operator's investment on incumbent (cable) operator's investment is not straightforward. If the firms coordinate on a particular equilibrium, for instance, due to a significant deployment cost asymmetry, then we expect no impact; the investments of cable and incumbent operators will be neither strategic substitutes nor strategic complements. If the firms do not coordinate, then the investments will be (weak) strategic substitutes.

3.6.2 The impact of mandated access to the legacy network on incumbent telecom operator's investment.

The impact of access price a on the investment incentives of the incumbent operator is ambiguous and depends 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).

3.6.3 The impact of mandated access to the legacy network on cable entrant's investment.

The impact of access price a on the investment incentives of the cable entrant is similar to that of the incumbent operator in the case when the cable entrant fully covers the country with its own legacy network. In this case the impact of a depends on the relative strength of the *retail-migration* and the *business stealing* effects. When the former (latter) dominates, the impact of a on investment is expected to be positive (negative).

When the cable entrant does not fully cover the country with its legacy network (and the cost of deploying the NGA network in these uncovered areas is prohibitively high), the cable entrant's investment incentives may be insensitive to a. Thus, the lack of an effect of a on the cable entrant's investment can be explained by the *retail-migration* and *business stealing* effects cancelling each other out, or by the limited cable coverage.

3.6.4 The impact of mandated access to the NGA network on incumbent telecom operator's investment.

The impact of access price $\widetilde{a}$ on the investment incentives of the incumbent operator is unambiguously positive. Hence, a less stringent fiber access regulation (i.e. a higher access price or lack of regulation) incentivizes the incumbent operator to invest more in its NGA network.

3.6.5 The impact of mandated access to the NGA network on cable entrant's investment.

The impact of access price $\widetilde{a}$ on the investment incentives of the cable entrant is positive only in case the cable entrant is the investment follower. In case the cable entrant is the investment leader, it is insensitive to $\widetilde{a}$. Thus, a less stringent fiber access regulation (i.e. a higher access price or lack of regulation) incentivizes the cable entrant to invest more only when it is a follower in NGA deployment, otherwise it has no effect.

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

4.1 Data

The data on NGA infrastructure investment have been collected from FTTH Council Europe, which provides the number of NGA lines (on an annual basis) separately for incumbent operator and a group of entrants in each member state. While there is only one telecom incumbent operator in each member state, there are typically several entrants, such as the cable and alternative telecom operators, as well as other organizations (e.g. public utilities and municipalities). By screening various FTTH Council Europe reports we were able to single out the group of cable entrants in each market. 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.[13]

The EU Digital Agenda Scoreboard provides yearly data on regulatory measures pertaining to the legacy telecom network, most importantly on mandated access (LLU). The information on mandated access to fiber networks across EU member states come 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 variation in the regulatory measures, across both time and EU member states, which is not the case for the more disaggre-

[13]We treat cable NGA infrastructure in each member state as provided by a single cable operator in our empirical analysis. This is justified for the folloing reasons: First, in most EU member states a single cable operator serves more than 40% of total 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); Second, cable networks' geographical overlap is almost nonexistent, so cable operators do not compete with one another, but they always compete with incumbent telecom operator in internet access provision; Third, cable operators use the same internet access technology and are equally treated by access regulations in each member state.

gated data used in other studies, which typically 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.[14] A detailed description of all variables and data sources is given in table 1. Table 2 provides the summary statistics.

4.2 Dependent variables: NGA infrastructures in Europe

NGA investment by incumbent telecom operators (*inc_nga*) and cable entrants (*cable_nga*) is measured by the total number of deployed access lines per household and thus represents the supply-side installed capacity, or "homes passed".[15]

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.[16] It reveals interesting differences both across firms and countries. First, it appears that the deployment of NGA lines follows a rather smooth curve for the telecom incumbents, whereas for the cable operators it often suddenly levels off after a period of rapid growth. 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. In a number of countries, however, the incumbent operators were able to catch up with and even surpass the cable NGA neworks toward the end of our sample. On average, the share of total number of NGA lines owned by cable operators in our sample amounts to 32.3% going up

[14]Whereas the dependent variables are available from 2004 to 2014, all 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, 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 due to Eastern European countries prior to their EU accession), and some 0.8% of all the raw data were calculated using linear interpolation or had to be extrapolated.

[15]Here, we follow the FTTH Council Europe's definition of an NGA line as based on one of the relevant fiber technologies (more details are in table 1). These technologies can deliver access speed required by the Digital Agenda Europe targets.

[16]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 purposes.

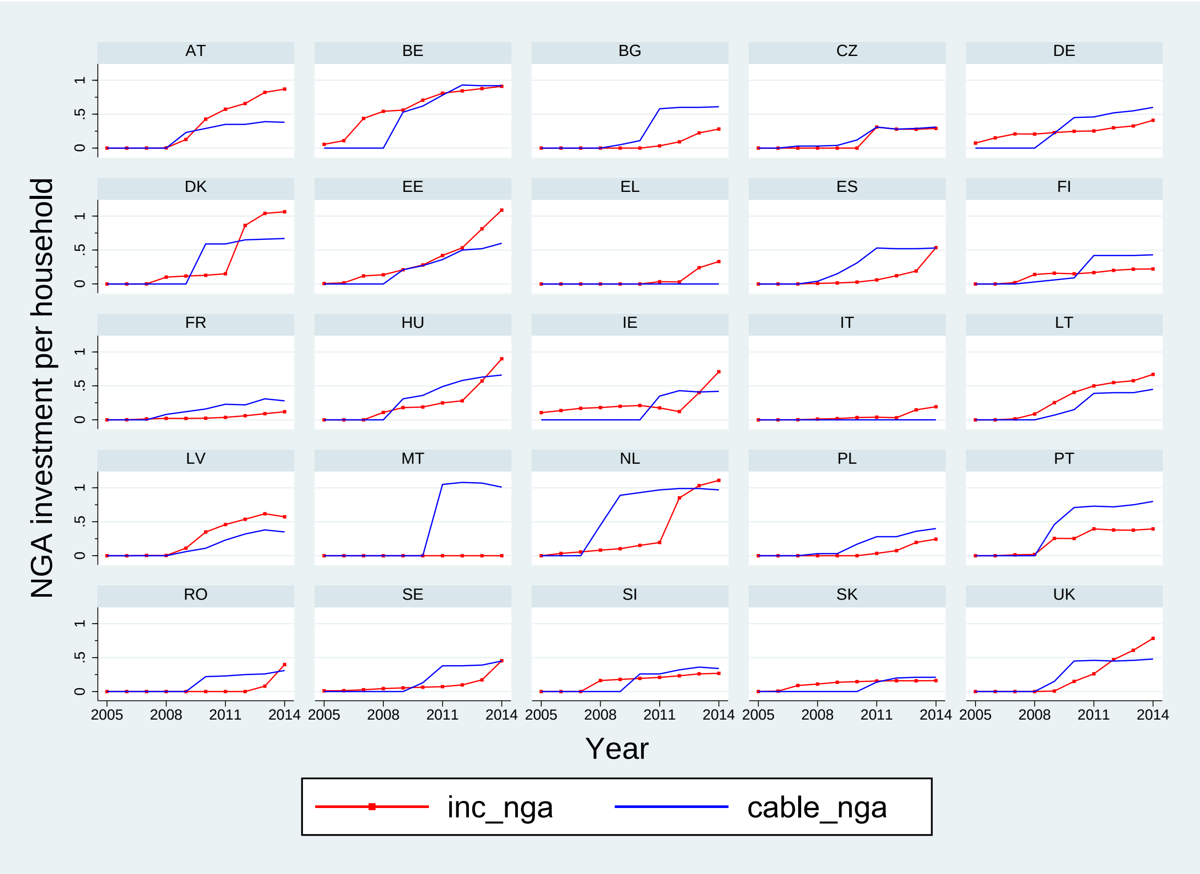

Figure 2: NGA lines per number of households in 25 EU member states for the years from 2005 to 2014 (Source: FTTH Council Europe)

to 43.0% in 2014. The same numbers for incumbent operators' NGA lines are 33.0% and 42.8%, respectively. Taken together, incumbent and the cable operators clearly dominate NGA investment in Europe.[17]

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 mirroring the differences in cable TV coverage across EU member states.[18] Also, for a given level of cable NGA deployment, incumbent firms' NGA investment differs widely. For instance, Germany's and the UK's cable NGA networks cover roughly 50% of households, but BT, the UK' incumbent operator, covers twice as many hoseholds with NGA infrastructure than Deutsche Telekom, its German counterpart.

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

[18]Cable NGA deployment has been de facto 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 7 and 8.

These trends in NGA deployment are important for understanding 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 the section 3.3). We predict the same for $\tilde{a}$, the mandated access price to NGA lines, when the cable operator is an investment leader (see the section 3.4), 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 the 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, 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 in years in which NGA regulations are in force in a given EU member state, and zero otherwise.[19] The expected effects of these regulation variables are given in section 3.6, which summarizes the testable hypotheses from our theoretical model.

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

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

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

is, for the most part, the firm of choice for such connections, we expect *mdwell_perm* to show a positive effect on its investments. The effect for cable firms is expect to be negative though, because of specific NGA technology they typically use.[20]

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*, per-capita, adjusted for purchasing power GDP, *gdp_pc_ppp* and the percentage of population with secondary or higher education, *edu*. All these variables are expected to increase future demand for fast internet access on the NGA networks, thereby spurring investments by both incumbent and the 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 and 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 in the empirical investment equations, without taking any priors as to the shape of this relationship.[21]

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:

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

where X is a set of cost, demand and competition control variables, as described in the previous section, the superscript I denotes the coefficients specific to the incumbents' investment equation (7) 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 identically distributed, thus our estimates are robust to any form of heterescedasticity. 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.

[20]Hybrid coax-fiber technologies are not used on the fiber lines deployed in new houses.

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

Because big infrastructure projects like NGA network investment can take years to complete in practice, we include the lagged dependent variable, $inc\_nga_{i,t-1}$, as a right-hand side regressor in (7) to capture a dynamic investment adjustment process, even though our theoretical model does not explicitely 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 (7).

The cable entrants' investment equation is specified in an analogous way:

$$\begin{aligned} ln(cable\_nga_{i,t}) = \alpha_i^E + \beta^E ln(cable\_nga_{i,t-1}) + \gamma^E ln(inc\_nga_{i,t}) \\ +\delta_1^E llu\_price_{i,t} + \delta_2^E nga\_reg_{i,t} + X_{i,t}\Theta^E + \epsilon_{i,t}^E, \end{aligned} \tag{8}$$

where the superscript E denotes the coefficients specific to the entrants' investment equation (8) and the error term $\epsilon_{i,t}^E$ is independently, but not necessarily identically distributed.

The equations (7) and (8) can be interpreted as linearized best-response functions in our theoretical model.[22] To this end, the coefficients on the regulation and the rival investment variables can be used to test the hypotheses from our theoretical model, as summarized in section 3.6. The dynamic specification of equations (7) and (8) 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 leading to a steady state, which we interpret as one of the multiple equlibria in our theoretical model.

The identification of coefficients on the endogenous variables in (7) and (8) is possible due to specific exclusion restrictions: the lagged level of incumbent's (entrants') infrastructure is assumed to have an impact on the current level of incumbent's (entrants') infrastructure, but not on the current level of entrants' (incumbent's) infrastructure.

Further, since equations (7) and (8) 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. In some estimations, we also use the Anderson-Hsiao-type instruments for the lagged dependent variables in order to reduce the total number of instruments and thus avoid the potential overfitting problem (Roodman, 2009).

[22] The best-response functions are given by (4) and (5) in the benchmark model.

Finally, we use two external instrumental variables: (i) the average value of the NGA regulation indicator in the 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 essence, the eCommunications framework contains some explicit and implicit rules to incentivize harmonization and "punish" deviating national regulators by requiring a stronger burden of proof in the course of consultation and notifications procedures with the European Commission. The second instrument is meant to capture computer literarcy and correlate with independent variables such as basic broadband adoption. We argue that being a "low-tech" variable, the number of PCs is not directly linked to our dependent variables, which represent the "high-tech", state-of-the-art internet access.

4.5 Results

The estimation results of the incumbent equation (7) and the cable entrant equation (8) are in tables 3 and 4, respectively. Columns in both tables differ in terms of the instrumental variables employed; the first two columns use only the Anderson-Hsiao instruments and are thus labelled 2SLS, whereas the last two columns use Arellano-Bond instruments and are labelled GMM. Also, 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 two periods only.

All 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 entrants' investment equations are in the Appendix, in tables A1 and A2, respectively. Partial R^2 and F-tests of excluded instruments reported in tables A1 and A2 demonstarte the strength of our instruments in all first-stage regrssions.

All 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.[23] Further, the

[23]The AR(1) test statistics show that there is first-order serial correlation in the residuals, which is to be expected if the error terms in the original equations (7) and (8) are not serially correlated.

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 Arellano-Bond instruments generally show more statistical significance. In all 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 specifications of table 4, as compared with table 3. Accordingly, the speed of adjustment, $1-\beta$, is higher for the cable entrants indicating faster convergence towards the long-run, desired infrastructure stock. This aligns well with the observation that the costs of NGA deployment is substantially lower for technologies used by the cable entrants, as explained in section 4.2.

Among the control variables, basic broadband adoption (*bb_adop*) is consistently positive and significant across all 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 litarature.[24] The coefficient on the quality of the incumbent's legacy network is negative, as expected, albeit significant only in the GMM estimations in table 3. In table 4, *legacy* shows more significant, but positive impact. Thus, cable operators react to a higher quality legacy network by increasing investment in NGA, presumably to escape the competition from basic internet access offered by the incumbent telecom operator. Other significant effects in the cable entrants' investment equation are due to *mdwel_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. Cable operators' NGA investments are positive and statistically significant, albeit only in the last two columns of table 3. Evidence of the strategic interaction of investments by incumbent and cable operatorss are thus only found in the GMM estimations for the incumbent firm's equation. Still, this appears to contradict our theoretical model's prediction, in which the incumbent's and cable operator's investments are (weak) strategic

[24]The magnitude of estimated coefficients may seem excessively large, but in the beginning of our sample all countries had virtually zero fiber lines (and toward the end of our sample NGA penetration exceeds 50% of households in many countries). This implies that the increases we observe in (log) percentage terms tend to be very large.

substitutes rather than strategic complements. One possible explanation of this apparent contradiction is an investment race, which may happen if both firms try to tilt the market toward their preferred equilibrium.[25] In fact, our model predicts that there is going to be one investment leader, which will dominate the NGA market. However, unless the cost asymmetries are large, the model does not predict which firm will become the leader (see section 3.5). According to the stylized facts discussed in section 4.2, the cable operators were often leading in NGA deployment, but the incumbent operators successfuly caught up with and even surpassed them in many markets toward the end of our sample. Thus, the stylized facts give some additional plausibility to the investment race interpretation. This result is also in line wiht the literature on access regulation in telecommunications using more dissagregated data (Nardotto et al., 2015; Bourreau et al. 2017).

Finally, the regulatory variables turn out to be highly significant in table 3. The LLU price is positive and significant, which suggests that higher access price, i.e., less stringent regulation of the legacy network, incentivizes the incumbent firm to invest in NGA networks. Viewed from the theoretical perspective, this result means that the *retail migration* effect dominates the *wholesale revenue* effect. Also, the NGA regulation is negative and mostly significant, which is consistent with the prediction of our theoretical model: more stringent regulation of fiber access disincetivizes the incumbent operator from investing.

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. This is consistent with our theoretical model and the stylized facts presented in section 4.2. Cable operatos in our sample are for the most part the leaders in NGA infrastructure deployment, but their geographical footprint is significantly limited in most EU member states by coverage of legacy TV networks. Both, investment leadership and limited coverage can make the cable firms insensitive to access regulation, as shown in our theoretical model. Overall, our results imply a negative impact of access regulations on aggregate NGA investments in Europe.

[25]This point is similar to Vareda and Hoernig's (2010) race for preemption, which they find to be one of the possible equilibria in their model of investment timing.

5. Conclusion

The theoretical literature on transitioning from old to new telecommunications network stresses that the incentives to invest in infrastructures differ between the incumbent operators and entrants. The 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 opposite, depending on the specific demand and costs characteristics. The 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 regulations 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 telecom markets, which generally indicate a negative impact of access regulation on infrastructure investment, carry over to NGA investment.

In this paper, we extend the literature on access regulation and investment in telecommunications markets in two important ways. First, we develop an analytical model, in which we allow some entrants to own a legacy network infrastructure, which makes them more similar to the incumbents rather than other entrants that do not own legacy infrastructure. This extension accomodates cable operators, which proved to be important providers of NGA infrastructure in the EU, and allow 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. Second, we collect novel data on NGA investment and access regulation, which allow us to complement and improve the existing empirical evidence. Most importantly, we are able to empirically study the investment game between incumbent operators and the cable entrants using precise NGA investment and regulation measures pertaining to both old, legacy infrastructure and new, NGA infrastructure.

Our main empirical results show that more stringent access regulation to both legacy and NGA networks discourages deployment of new NGA lines by the incumbent operators, but leaves the cable entrants unaffected. These results are consistent with the existing literature, which finds similar effects using investment data agreggated at the country level (Briglauer, 2015), or a regulation measure aggregated across legacy and NGA networks (Bacache et al., 2014). Our result that access regulation to legacy networks negatively affects incumbent operator's investments resolves the theoretical indeterminacy of this effect and corroborates Grajek and Röller (2012), who arrive at a similar conclusion, albeit using a different measure of regulation and a less precise measure of investments. Grajek and Röller (2012) also find that more stringent access regulation discourages individual telecom entrants' investment, a result, which is seemingly inconsistent with Nardotto's et al. (2015) finding that the telecom entrants using LLU access provide higher speed internet access than incumbents.[26] In this study, we further complement existing empirical evidence by showing that cable entrants are not significantly affected by mandated access. We explicate this non-effect within the framework of our analytical model. The key assumptions responsible for this are: i) the cost advantage of cable entrants over incumbent telecom operators in terms of NGA deployment, which justifies why the firms may coordinate on the equilibrium where cable entrants dominate the NGA market, and ii) limited coverage of the legacy cable network, which may make cable NGA investment outside of the legacy cable TV network's footprint prohibitively expensive. Both assumptions are in line with the stylized facts about NGA deployment in the EU.

This study carries important policy implications. Our results suggest that a one-size-fits-all approach may not yield the best outcomes in terms of NGA deployment. The EU member states widely differ in the spatial reach of cable TV legacy infrastructure, which, according to our results, is an important determinant of the role the cable operators play in NGA deployment. Some countries, such as Belgium and the Netherlands, which used to have relatively wide cable TV networks, are less affected by the regulation-investment trade off than other countries, such as Italy and France. The regulators in the former, are able to harness the benefits of access regulation aided competition, without compromising all too strong on NGA investment led by cable operators. The regulators in the latter seem to face a more difficult trade-off. One possible approach for these countries, also suggested by our results, could be to relax the stringency of access regulation on the legacy and/or NGA infrastructures, in order to provide stronger incentives for the incumbent operators and telecom entrants to invest.

Our theoretical model, which we take to data aggregated at the country level, could,

[26] However, these results are not directly comparable, because, Grajek and Röller (2012) use an accounting measure of investments, while Nardotto's et al. (2015) infer investments from the service quality. The studies use also different measures of regulation.

without much modification, also be applied to more disaggregated, regional-level or municipal-level data spanning multiple countries. Testing strategic interactions between heterogenous entrants and incumbents using such data is one important extension that we leave for future research.

Appendix

A. Extension 4: Active telecom entrant

In this section we futher expand the model by assuming that all three players 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 domintates 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 entrant 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 only 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 player (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 BDC (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*: 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 increasesing 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 counterbalenaced by the *business stealing 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 now 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, as before, the optimal investment levels are given as follows:

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

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 *business stealing 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*.

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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 is issued 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 entrants´ 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 entrants' 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
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$