Information Economics and Policy 25 (2013) 142–153

Contents lists available at SciVerse ScienceDirect

Information Economics and Policy

journal homepage: www.elsevier.com/locate/iep

The impact of infrastructure and service-based competition on the deployment of next generation access networks: Recent evidence from the European member states

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ARTICLE INFO

Article history:
Available online 7 December 2012

JEL classification:
L38
L43
L52

Keywords:
Next generation access networks
Service-based competition
Infrastructure-based competition
Investment
Adjustment process

ABSTRACT

This work identifies the most important determinants of next generation access (NGA) network deployment, using data from the EU27 member states for the years 2005–2011. Our results indicate that the more service-based competition is pronounced the more negative is the impact on NGA deployment, while competitive pressure from broadband cable and mobile affects NGA deployment in an inverted U-shaped manner. We further find that there are severe adjustment costs and stickiness towards the desired long-term level of NGA infrastructure. It appears that the approach of the European Commission to force service-based competition via cost-based access regulation will not elicit the huge new investment needed for a comprehensive NGA roll-out.

1. Introduction

In recent years, fibre-deployment of telecommunications access networks (“next generation access” – NGA) has become a major issue for sector-specific regulators as well as for investing firms. Operators of traditional (“first generation” copper- and coax-based) telecommunications networks have to speed up their networks to meet the growing demand for bandwidth arising from new/interactive multimedia services like streamed video on demand, high definition television, 3-D applications, cloud computing, etc. The renewal of existing networks and their (partial) replacement by fibre-optic infrastructure require high investment volumes of billions of Euros.[2] Although the future central importance of ultra-high-speed broadband infrastructure as a key socio-economic factor is well recognised, NGA network deployment activities vary significantly in international comparison (see Fig. 1 in Section 2).

Since the beginning of the liberalisation of electronic communications markets in the European Union (EU) in 1997/98, there has been an ongoing debate about the role of infrastructure-based (inter-platform) and service-based competition. Infrastructure-based competition relies solely upon the existence of independent and competing infrastructure platforms. It is deemed to be favourable in the long run as it enables sustainable competition and a gain in dynamic efficiency in terms of investment and innovation. Moreover, it involves a much lower regulatory

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[2] See, for instance, Jay et al. (2012) for recent cost estimates for a nationwide NGA deployment in Germany.

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http://dx.doi.org/10.1016/j.infoecopol.2012.11.003

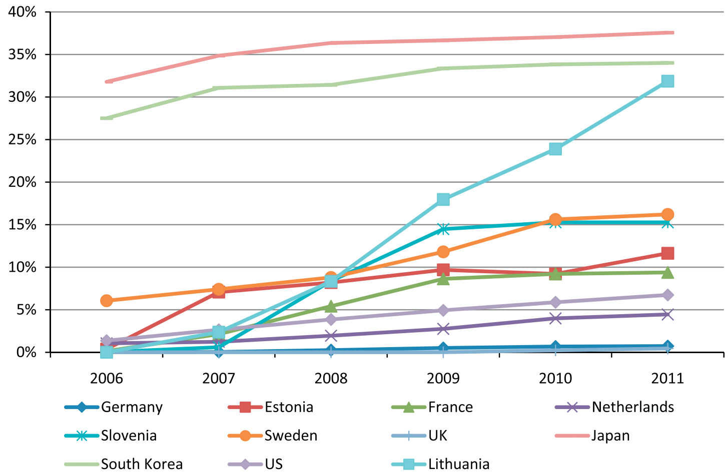

Fig. 1. FTTH/B coverage in international comparison (“homes passed per capita”).

micro-management of the industry and thus lower administrative costs. Service-based competition hinges on a set of ex ante regulations. Proponents of service-based competition argue that mandatory access is essential to induce market entry in network industries with a quasi-monopolistic market structure and that it has an immediate positive effect on static efficiency. Thus, a key policy question is which mode of competition is preferable in order to lower prices *and* to achieve high investment in terms of network coverage.

Based on an unbalanced panel of the EU27 member states during the period of 2005–2011, this paper addresses the following research questions: (i) What is the relation between regulation-induced service-based competition on broadband markets and the extent of NGA deployment? (ii) How does infrastructure-based competition in related markets influence the extent of NGA deployment? (iii) Finally, what do the dynamics and the adjustment process of NGA deployment look like? It should be emphasised here that our focus is on NGA deployment/investment only, not on welfare.[3]

Our paper represents the first European-based attempt to quantify the determinants of recent and actual NGA deployment. Our empirical specification incorporates country-level data where estimates are obtained through various dynamic panel methods. Applying GMM as well as LSDVC estimation techniques explicitly accounts for the endogeneity bias arising from the dynamic investment specification. Furthermore, we argue that there is no endogeneity problem with respect to investment activities and regulation-induced service-based competition in our case, as we relate access regulations imposed on the preceding broadband market years ago to investment activities in an emerging (NGA) market. We therefore acknowledge both potential sources of endogeneity, which are only partly (e.g. Grajek and Röller, 2011), if at all, addressed in the literature.

The remainder of the paper is organised as follows: Section 2 provides necessary background information on the technical and regulatory context of NGA networks. In Section 3 we review the telecommunications-related literature. Section 4 describes our basic hypotheses concerning investment incentives on the one hand and the role of infrastructure and service-based competition on the other hand. Section 5 outlines the dataset underlying our empirical examination. Section 6 presents the empirical specification and related econometric issues. Section 7 describes and interprets the main results. Section 8 summarises and compiles the most relevant aspects for future regulatory policy.

2. Institutional framework

Originally, first-generation networks were set up to provide narrow bandwidth voice telephony services (POTS/ISDN) only. Many decades later, they were made capable of supporting broadband services by means of DSL transmission technology.[4] In EU member states, where sector-specific regulation is in place, alternative operators can rent the local loop from the incumbent operator based on cost-oriented wholesale charges (“unbundling”). This allows alternative operators to use their own DSL equipment to provide (first of all) broadband services. Alternative operators may also offer retail broadband services by purchasing “bitstream” as a wholesale service from the incumbent operator. Just like unbundling, bitstream is usually associated with DSL services but at a more service-based level of

[3] However, more investment is likely to be better also from a welfare point of view. In telecommunications, the “Averch–Johnson” effect (too much capital employed) can be expected to be small due to ex ante regulation and because service-based as well as infrastructure competition have been established for more than ten years. Moreover, one can expect huge positive externalities of NGA investment towards other major sectors of the economy such as health care, energy and transportation (OECD, 2009).

[4] Digital Subscriber Line is a family of technologies (xDSL) that provides digital data transmission over the wires of a local telephone network. The data throughput typically ranges from 256 KB/s to 30 Mbit/s in the direction to the customer (downstream), depending on the DSL technology, the condition and length of the local loop, and service-level implementation.

the value chain. Finally, wholesale broadband access via simple resale services means that access-seeking operators receive and resell a wholesale input of the incumbent operator without any scope for technological product differentiation, i.e., value is added only at the retail level, such as branding (RTR, 2010, pp. 176, 179).

However, for technical reasons, the bandwidth of DSL technologies is rather limited. In order to overcome these limitations, it is necessary to shorten the length of the copper-based local loops by placing the DSL transmission equipment closer to the retail customers' premises, e.g. in the cabinets which house distribution frames. Deployment of DSL transmission systems in such a cabinet and connection to the fibre-based backbone network is referred to as "fibre to the cabinet" (FTTC). In the remaining copper-wire line of the last mile, VDSL and vectoring are used as the latest DSL transmission technologies. These solutions can provide bandwidths of approximately 20 Mbit/s to 100 Mbit/s. Even higher downlinks (above 100 Mbit/s) can be achieved if the final copper-wire line is shortened further. Fibre to the building (FTTB) extends the optical fibre to or into the building and only the remaining wiring inside the building relies on conventional copper wires. In cases where technical or economic considerations render it feasible to renew or replace in-house wiring, it is possible to eliminate copper lines entirely. In such a scenario, the optical line is directly connected to the individual apartment or home ("fibre to the home" – FTTH). From a technical point of view, this form of implementation would be the ideal solution, as it enables a large number of future services with nearly unlimited bandwidth (RTR, 2010, pp. 189–191).

In addition to the conventional copper-wire networks, the roll-out of high-speed NGA networks might also be realised by upgrading cable television networks (referred to as fibre-to-the-last-amplifier based on DOCSIS 3.0 technology) and mobile networks. The latest cable transmission technology already allowed for bandwidths of 150 Mbit/s and more. The mobile communications industry expects the future deployment of Long Term Evolution (LTE) advanced[5] technology to be able to offer data transmission rates in the same range. Although both of these last-mentioned technologies rely heavily on fibre in their backbone networks, only coaxial cable based on DOCSIS 3.0 is of current relevance for NGA deployment and is thus considered to be part of the FTTx technology family in our empirical analysis.

Fig. 1 gives an overview of the per capita FTTH/B deployment patterns in selected countries as of June 2011.[6] Some countries (such as Japan and Korea) have already reached fibre maturity and are still far beyond, especially compared to the average level of the EU27 (4.7%, not reported in Fig. 1) and the US (6.7%). The leading countries such as Japan (37.5%) and South Korea (~34%) are located in Asia, followed by Lithuania (31.9%) and a couple of other Eastern and Northern European countries with coverage levels between 16.2% (Sweden) and 11.6% (Estonia). Please note that for countries like Japan and South Korea these numbers imply almost full coverage in terms of households passed.[7] Except for some Northern and Eastern European followers, the vast majority of the EU27 still shows rather low coverage levels, including major economies such as Germany or the UK which had disastrous levels of around 0.5% by mid-2011.[8]

3. Literature review

A number of scientific studies examine the impact of regulation-induced service-based competition on broadband or telecommunications investment in general, but there are currently no empirical studies which focus on the impact on NGA deployment. Likewise, there are only a few theoretical contributions related to broadband/NGA deployment and the efficiency trade-offs involved, and we review these first.

Gayle and Weisman (2007) theoretically explore the relationship between wholesale broadband access pricing and static/dynamic efficiency. They find that even when charges for unbundling are priced to induce efficient make-or-buy decisions from a static perspective, service-based competition in terms of mandatory unbundling obligations reduces the incumbent's incentive to invest from a dynamic perspective. However, the authors find that within the range of prices that preserve the efficient make-or-buy decision, the incentive to invest in cost-reducing (process) innovation decreases with unbundling charges. Using a game-theoretical framework, Bourreau et al. (2012a) analyse the incentives for incumbents and entrants to migrate from old technologies to NGA networks. They find that NGA-related investment incentives are affected by access regulation charges on the old copper networks via three effects: (i) a replacement effect, according to which higher access prices force alternative operators to invest, because of the low opportunity cost of investment; (ii) a wholesale revenue effect, according to which a high access charge increases the incumbent's opportunity cost of investment to the extent that the incumbent's investment reduces the costs of the entrant's new investment; and (iii) a business migration effect, whereby a low access charge on the old infrastructure implies low retail prices and thus lower profit opportunities for new investment. Bender and Götz (2011) model broadband competition between an incumbent and an entrant firm which provide broadband access in regional markets with different population densities. They argue that the usual trade-off between static and dynamic efficiency does not apply, since higher access charges increase infrastructure-based competition and decrease retail prices. Brito et al. (2010) address the problem of investment in NGA in a duopoly model where a vertically integrated incumbent and a downstream entrant

[5] Mobile broadband access is already facilitated by the previous mobile technologies GPRS, EDGE, UMTS und HSDPA. Currently, LTE is in the test

[6] Since there is a lack of data on FTTC/Fibre-to-the-last-amplifier for Asian countries, the comparison in Fig. 1 is restricted to FTTH/B. Due to further data restrictions, NGA coverage in the US refers to FTTH deployment only, thus the corresponding values of FTTH/B coverage would be higher in the US.

[7] Average household size in, e.g., Japan was 2.46 in 2010 (source: ITU World Telecommunication/ICT Indicators Database) implying a 92% household coverage rate.

[8] See Briglauer and Gugler (2012), who evaluate the different underlying policy approaches.

compete. They show that introducing two-part access charges can solve the dynamic inconsistency problem in terms of regulatory opportunism and therefore enhance the incentives to invest in NGA infrastructure. Nitsche and Wiethaus (2011) analyse the effects of different regulatory regimes on investment incentives and welfare, and find that regimes of fully distributed costs or regulatory holidays are most positive for investment. Their simulations further show that a risk-sharing approach is best from a welfare point of view and that cost-based regulation is least conducive to investment. Finally, the reader is referred to Bourreau et al. (2012b), who survey recent economic literature on NGA investment, migration issues and wholesale regulation.

Jung et al. (2008) use US data for the years 1997–2002 and show that strengthening competition is a key to restoring telecoms investment. However, it is questionable whether service-based competition in terms of mandatory access obligations stimulates the incumbent's incentives to invest in new infrastructure. Using data on European countries for the years 2002–2006, Waverman et al. (2007) show that the intensity of service-based competition in broadband markets negatively affects broadband infrastructure investment. However, the authors do not use any NGA-specific data and their estimate of total broadband investment is derived from a simulation exercise. Grajek and Röller (2011) also use data from EU countries and investigate the relationship between regulation and total investment in the telecommunications industry. This study is among the few which explicitly accounts for the endogeneity problem of regulation and investment. The authors find that access regulation negatively affects both total industry and individual firm investment. Investment, however, is quantified rather broadly by tangible fixed assets of telecommunications operators and, thus, does not explicitly refer to broadband, let alone NGA deployment. Wallsten and Hausladen (2009) are the first to estimate the effects of service-based competition in terms of unbundling and bitstreaming regulations on NGA deployment, with data from EU27 countries. However, the role of infrastructure-based competition is considered only rudimentary and the authors use highly fragmentary data from the EU's Communications Committee for the years from 2002 to 2007, which only covers the NGA roll-out at the very early stage. Bacache et al. (2012) examine the interrelationship between service-based and infrastructure-based competition with reference to the so-called "ladder of investment hypothesis". They find that there is no support with respect to the last rung of the ladder which relies on self-deployed infrastructure, and only weak support for the transition from lower rungs of the ladder, e.g. from bitstream to unbundling. Finally, Cambini and Jiang (2009) survey the empirical literature and find that the majority of the studies conclude that service-based competition in terms of cost-based access regulation discourages both incumbents and alternative operators from investing in fixed networks.

Summarising, the general efficiency trade-offs are well recognised in the theoretical as well as empirical literature. However, all previous empirical studies suffer from too broad or unsuitable measures of NGA investment to truly inform the debate on the optimal role of both modes of competition and hence on the future regulatory policy towards emerging NGA infrastructure. Our work intends to fill this gap and is the first that explicitly employs a direct measure of real and most recent NGA investment.

4. Hypotheses

This section identifies determinants for previous NGA investments in Europe (EU27) and sets out corresponding hypotheses, which are aligned to the research questions outlined in the introduction.

4.1. Infrastructure-based competition

The different NGA scenarios of fibre infrastructure deployment involve substantial degrees of sunk costs (60–80% of total costs) and very long amortisation periods (ERG, 2007, pp. 16–17) against the background of rather uncertain future market conditions. Overall, NGA deployment risks and the expected profitability of NGA investments are crucially influenced by the competitive intensity in relevant communications markets.

With respect to the potential impact of infrastructure competition on investment activities, one has to consider the so-called "replacement effect", the "escape competition effect", and the "Schumpeterian effect", as outlined in Aghion et al. (2005): First, at low levels of competition the replacement effect (Arrow, 1962) occurs, because NGA investment "cannibalises" quasi-monopolistic profits from preceding broadband services based on copper- and coax infrastructure and thus reduces profitability and the incentive to invest. With higher levels of competition, this replacement effect becomes less important as the economic rents to be replaced are smaller.[9] Second, more competitive markets increase incentives for innovation by giving the innovator the chance to jump ahead of rivals and earn temporary market power rents. This so-called "escape competition effect" will lead to a positive relation between competition and investment, if there is a reasonable threat of another firm investing in capturing these rents. However, a state close to perfect competition will eventually reduce potential rents and, thus, increasingly counteract investment because operators are not able to generate necessary profits for innovation and investment. This appropriability effect can, thirdly, be referred to as "Schumpeterian". Indeed, as Aghion et al. (2005) showed in view of these multiple effects, an inverted U-shaped relationship is expected with respect to investment and competitive intensity.

In the context of NGA deployment, one might expect a non-linear relation for a similar line of reasoning. Recent and future investment in NGA is driven by competitive pressure, most notably from cable and mobile networks, which "threaten" first-generation networks as regards new broadband services and substantially reduce the replacement effect in many EU countries. The NGA network upgrade can also be seen as the "last chance" for traditional fixed-line operators to successfully escape

[9] See Bourreau et al. (2010) for a more general description of the replacement effects in the communications industry.

broadband competition stemming from these alternative infrastructure platforms with innovative and high-bandwidth demanding services. At the same time, well-established infrastructure-based competition can counteract investment in NGA by making NGA projects riskier – with lower expected profits or even losses. As Bauer (2010, p. 69) concludes, "[t]he empirical shape of this relation for the next generation network [...] is not known and will only be revealed over time".

Summarising, due to the existence of these opposing effects, we expect a non-linear inverted U-shaped relationship between NGA investment and the intensity of infrastructure-based competition from cable and mobile broadband services.

4.2. Service-based competition

Service-based competition via mandatory access has been considered to be essential to induce market entry in network industries with a quasi-monopolistic market structure and to have an immediate effect on static efficiency in terms of lower prices. Whereas infrastructure operators are confronted with significant capital outlays as well as high risks, service-based operators benefit from a risk-free option to rent the infrastructure as required, due to mandatory access obligations imposed on the dominant operator (Pindyck, 2007). As a consequence, service-based operators do not face sunk costs and the same uncertainty related to the appropriability of NGA investments. Also, as service-based competitors do not own first-generation infrastructure, they are not confronted with a corresponding replacement effect. Finally, infrastructure innovation such as NGA deployment is de facto limited to infrastructure operators, which might have an incentive to escape competition at a certain level of inter-platform competition.

The main criticism against mandatory access regulation refers to the trade-off between static and dynamic efficiency, according to which gains in short-term competition in terms of lower prices are accompanied by lower investment incentives for incumbent and alternative infrastructure operators (Gayle and Weisman, 2007). The EU regulatory framework tries to resolve the involved trade-offs of dynamic and static efficiency with reference to the so-called "ladder of investment" (Cave and Vogelsang, 2003; Cave, 2006), which is also deemed to be a guiding principle for NGA networks (European Commission, 2010a, recital 3). According to this hypothesis, national regulatory authorities (NRAs) should initially encourage alternative operators to engage progressively in backward integration after having entered the market as simple resellers on the basis of cost-oriented charges. Wholesale broadband access, resale and bitstream should facilitate quick and easy market entry during the first stage of liberalisation, followed by an increasing migration towards unbundling and ultimately self-deployed infrastructure investment. The latter would constitute the highest rung of the ladder, where alternative operators were fully integrated and no longer depended on ex ante access obligations. Thus, at the bottom of this principle, there is the vision of a continuous transition path from monopoly towards self-sustaining competition, with regulation-induced service-based competition being only a necessary intermediate phase. However, there has been hardly any convincing empirical support for the ladder of investment concept so far (Bacache et al., 2012; Bourreau et al., 2010, pp. 690–691; Waverman et al., 2007, p. 7). In particular, due to the natural monopoly characteristics of the last mile, achieving the goal of infrastructure-based competition (the last rung of the ladder) has been largely forestalled. The dynamic concept of a transition from service-based towards infrastructure-based competition becomes even more unlikely, since the economic replicability of NGA deployment is even lower.[10]

Summarising, we do not expect a non-linear inverted U-shaped relationship between (NGA) investment and the extent of service-based competition, since it reduces investment incentives and we do not expect a positive impact of service-based competition on NGA investment as idealised by the ladder of investment hypothesis. Therefore, our second hypothesis is that the higher the extent of service-based competition is, the lower the NGA infrastructure investment will be.

4.3. Dynamics, demand and supply side factors

Both the level and the speed of NGA deployment will also be influenced by variables related to consumer demand and (adjustment) costs of the infrastructure roll-out.

Costs will crucially depend on population or household density and topographic characteristics. Civil engineering and construction costs (including in-house wiring) represent by far the most relevant cost drivers for NGA deployment. Furthermore, costs are determined by a variety of institutional factors, such as rights of way or other allowances and technical standards and specifications which are partly still an open issue (FTTH Council Europe, 2012, pp. 36–46). Finally, the roll-out of new infrastructure is rather time-consuming as it involves complex technical network planning, and legal issues have to be resolved beforehand. Therefore, it is likely that adjustment to optimal infrastructure stocks will take place only gradually over time.

Demand and the willingness to pay depend on the overall market size in terms of relevant information and communications technology (ICT) expenditures and consumer wealth in general. Whereas traditional voice telephony exhibits fairly stable demand, demand for high-speed broadband services is much more uncertain and seems to have more luxury characteristics (Muselaers and Stil, 2010, p. 6). Finally, demand for access to NGA services is also driven by the degree of innovation and the intensity of consumers' use of broadband services.

5. Data and variables

We use the following data sources: The "Progress Report on the Single European Electronic Communications Market" (hereafter referred to as the "EU Progress Report") provides yearly data on all relevant wholesale broadband

[10] Also, it is highly unlikely that service-based entrants will initiate a "race" to update infrastructure as suggested in the context of pre-emption strategies (e.g. Gans, 2001).

access regulations as well as cable and DSL-related data for our competition variables.[11] Our second main source is the database of FTTH Council Europe,[12] which includes annual numbers of deployed NGA lines for most of the EU27 member states.[13] EUROSTAT[14] provides data on ICT expenditure, labour costs, the percentage of the population using mobile internet services via 3G and the percentage of heavy internet users. Finally, the World Bank's "World Development Indicators"[15] and the "World Economic Outlook" of the International Monetary Fund (IMF)[16] provide us with the percentage of people living in urban areas and GDP per capita, respectively. As data availability varies by variable, we use an unbalanced panel data set of EU27 countries for the time range from 2005 to 2010 for yearly data on our independent variables, and from 2006 to 2011 for yearly data on our dependent variable.

5.1. Dependent variable

In line with the technical description in Section 2, our dependent variable, $FTTx_{it}$, represents the total number of NGA connections deployed ("homes passed"), which are based on relevant *FTTx* technologies in per capita terms. This includes FTTH/B/C and fibre to the last amplifier. Our dependent variable thus represents real investment in physical units where the term homes passed refers to the number of consumers that have access via *FTTx*, but which do not necessarily have a corresponding retail contract. The number of homes passed therefore significantly differs from the number of homes connected, which represents the number of consumers exhibiting a sufficient willingness to pay and actively using one of the *FTTx* technologies. Thus, our dependent variable directly reflects the existing NGA infrastructure stock, which we consider the most suitable proxy for investment, for both empirical and conceptual reasons.[17]

5.2. Independent variables

In line with our hypotheses in Section 4, we can divide the explanatory variables into the following three categories: service-based competition, infrastructure-based competition and control variables, with the latter focusing on demand and cost shifters.

Service-based competition is measured by the percentage of regulated and actually used wholesale broadband lines (including unbundling, bitstream and resale) related to total retail broadband lines (*ms_comp*). Therefore, this variable includes all relevant remedial measures of wholesale broadband access regulation as outlined in Section 2, and provides a direct measure of the extent of service-based competition at the same time by counting the percentage of lines actively used by service-based competitors.[18] Furthermore, as outlined in Section 4.2, it can be argued that the extent of regulation-induced competition which is related to the "old" (broadband) network infrastructure, *ms_comp,* is exogenous with respect to the "new" (NGA) infrastructure deployment, $FTTx_{it}$. We expect a negative sign on *ms_comp*, since it reduces investment incentives, and the impact of the ladder of investment hypothesis is highly unlikely to become effective in terms of inducing service-based operators to engage in NGA infrastructure investment.

Infrastructure-based competition is measured in two ways which account for the two main forms of infrastructure-based competition: *ms_cable* is the ratio of cable connections provided by entrant cable operators to the total number of cable connections plus fixed DSL lines provided by both incumbents and entrants. The second competition variable, *iu*3*g,* states the percentage of people using 3G(+) technologies (UMTS or higher bandwidth such as HSDPA) to access the internet. These variables measure the competitive pressure stemming from fixed and mobile broadband services. The overall effect of these variables is ambiguous due to the opposing competition effects outlined in Section 4.1. Thus, we expect a non-linear inverted U-shaped relationship of investment with respect to *ms_cable* and *iu*3*g*.

Demand and cost shifters are included as control variables. GDP per capita, *GDP_pc,* captures income effects throughout our country set. Information technologies expenditure, *ict_exp*, acts as a proxy for the market size of the ICT industry and, thus, for the overall willingness to pay for broadband services in a country. Furthermore, we include the variable *iday,* which provides the share of the population that uses the internet frequently. The share of a country's urban population, *urban_pop,* reflects different cost structures due to varying shares of rural and densely populated areas. The variable *lab_cost* gives an annual labour cost index normalised to 100 in 2005 and serves as another cost proxy for infrastructure roll-out.

Finally, we include *country fixed effects* controlling for time-invariant and unobserved heterogeneity. Most notably, NGA-relevant and country-specific differences might

[11] Source: http://ec.europa.eu/information_society/policy/ecomm/library/communications_reports/index_en.htm and http://ec.europa.eu/information_society/digital-agenda/scoreboard/library/index_en.htm.

[12] FTTH Council Europe is a non-profit industry organisation, whose aim is to enforce deployment of fibre optic technology in Europe. Data are collected by IDATE through desk research, direct contacts with *FTTx* players, information exchange with FTTH Council Europe members and from IDATE partners.

[13] Source: http://dx.doi.org/ftthcouncil.eu/resources?category_id=6. Data for Bulgaria and Malta are only available for 2010 and will therefore be dropped due to our dynamic approach as outlined in Section 6. Moreover, there are some missing values in the early years for Greece, Latvia, Cyprus, Luxembourg and Hungary.

[14] Source: http://epp.eurostat.ec.europa.eu/portal/page/portal/information_society/data/database.

[15] Source: http://data.worldbank.org.

[16] Source: http://www.imf.org/external/ns/cs.aspx?id = 28.

[17] For instance, using the firm-level investment to capital stock ratio on the left hand side, as seen in the literature, would not provide us with the NGA-specific investment activities which we are interested in, but typically with investment in a broad mixture of telecommunications segments such as backbone, traditional wireline, broadband or even wireless networks. Conceptually, we argue that any normative objectives concerning the socially optimal infrastructure stock are much more likely to be formulated in real terms (percentage of population/households to be reached) as opposed to a certain monetary investment amount; see, for instance, the guidelines of the European Commission (2010b, section 2.4) on the "Digital Agenda".

[18] As a consequence, we do not have to rely on broadly defined indices, dummy-based scorecards or other proxies, which are commonly used in related literature but are only weakly related to fixed broadband wholesale access regulations (such as the OECD regulatory index for the telecom sector).

Table 1
Variable definitions.

Variable	Description	Source
FTTx Homes passed/ population, *Fttx*	Number of deployed *FTTx* lines normalised to population	FTTH Council Europe
Service-based competition, *ms_comp*	Percentage of total retail broadband lines that are provided by service-based competitors on the basis of wholesale access regulations (local loop unbundling, bitstream, resale)	EU Progress Report
Cable broadband competition, *ms_cable*	Percentage of cable and DSL lines that are run by entrants	EU Progress Report
Mobile broadband competition, *iu3g*	Percentage of population using mobile internet services via 3G networks (UMTS or higher bandwidth)	EUROSTAT
Heavy internet users, *iday*	Percentage of population using internet services every or almost every day	EUROSTAT
GDP per capita, *gdp_pc*	Gross domestic product per capita in US$	IMF
ICT expenditure, *ict_exp*	Percentage of expenditure on information technologies to GDP	EUROSTAT
Urban population, *urban_pop*	Percentage of urban to total population	World bank development index
Labour costs, *lab_cost*	Annual labour cost index (for each country normalised to 100 in 2005)	EUROSTAT

be related to certain cost conditions, such as rights of way, regulations on digging, local availability of ducts and dark fibre, different levels of (regulated) capital costs, or topographic and demographic characteristics. Demand and supply will also be influenced by state aid policies, which show hardly any variation with regard to the time frame of our data set. All sources and variable definitions are listed in Table 1, while descriptive statistics are provided in Table 2.

6. Empirical specification

6.1. A partial adjustment model

We use a dynamic approach to incorporate investment and deployment patterns appropriately. As the literature (e.g. Cambini and Rondi, 2010; Grajek and Röller, 2011; Greenstein and McMaster, 1995) suggests, static models are not appropriate, as these would only account for effects that have an immediate impact on the infrastructure stock. We use a partial adjustment model, since firms are most probably unable to adjust their infrastructure stock to prevalent market conditions within one period. Thus, shocks today not only affect the current infrastructure stock, but also the stock in future periods, where the adjustment to a long-run optimal infrastructure stock is only gradual over time. This target or desired per capita infrastructure stock is given by:

$$Fttx^{*}_{it} = X_{it}\beta' + \theta_i + \epsilon_{it} \tag{1}$$

where $Fttx^{*}_{it}$ reflects the long-term optimal infrastructure stock for country i at time t, X_{it} is a matrix of explanatory variables, the θ_i are the country-specific fixed effects and ϵ_{it} is an error term assumed to be i.i.d. We assume that the change in infrastructure stock follows the partial adjustment process:

$$Fttx_{it} - Fttx_{it-1} = \alpha'(Fttx^{*}_{it} - Fttx_{i,t-1}) + \mu_{it}, \tag{2}$$

where $Fttx_{it}$ is the actual number of homes passed per capita in country i at time t. Every period, α' percent of the gap between the desired and actual infrastructure stock level is closed, with α' being the speed of adjustment, and $0 < \alpha' < 1$. Substituting (1) in (2) yields the empirically testable equation:

$$Fttx_{it} = \alpha Fttx_{i,t-1} + X_{it}\beta + \alpha'\theta_i + u_{it}. \tag{3}$$

where $u_{it} = \alpha'\epsilon_{it} + \mu_{it}$ and $\alpha = 1 - \alpha'$, $\beta = \alpha'\beta$. Short-term effects are given by β, and estimates of $\beta'(=\frac{\beta}{\alpha'})$ reflect the long-term effects of the X_{it} on the desired infrastructure stock.

In our empirical baseline specification, Eq. (4), we use the number of *FTTx* connections normalised to population as the dependent variable and lag the explanatory variables, because firms usually need some time to react to changing market conditions:[19]

$$\begin{aligned} Fttx_{i,t} &= \beta_0 + \alpha Fttx_{i,t-1} + \beta_1 ms\_comp_{i,t-1} + \beta_2 ms\_cable_{i,t-1} \\ &+ \beta_3 ms\_cable^2_{i,t-1} + \beta_4 iu3g_{i,t-1} + \beta_5 iu3g^2_{i,t-1} + \beta_6 iday_{i,t-1} \\ &+ \beta_7 gdp\_pc_{i,t-1} + \beta_8 ict\_exp_{i,t-1} + \beta_9 urban\_pop_{i,t-1} \\ &+ \beta_{10} lab\_cost_{i,t-1} + \theta_i + \vartheta_t + u_{it} \end{aligned} \tag{4}$$

The θ_i and ϑ_t are country-specific and time-specific fixed effects, respectively, and u_{it} are the error terms assumed to be i.i.d.

6.2. Econometric issues

Using panel data allows us to take into account both unobserved (country) heterogeneity and the dynamics of investment behaviour. However, estimating Eq. (4) by means of a fixed-effect (within or LSDV) estimator would yield inconsistent and biased results, since the lagged dependent variable and the error terms including the fixed effects would be correlated (Nickell, 1981). Bruno (2005) developed a bias-corrected LSDV estimator (LSDVC) for unbalanced panel data, which can be used if there is no endogeneity problem. Other methods are the general method of moments difference estimator (GMM-DIFF) developed by Arellano and Bond (1991) and the general method of moments system estimator (GMM-SYS). Arellano and Bover (1995) and Blundell and Bond (1998)

[19] Therefore, we can assume that investment made at particular points in time is dependent on last year's conditions and it makes good sense to use a data set where the right hand side variables are lagged once compared to the dependent variable.

Table 2
Descriptive statistics.

Variable	Number of observations	Mean	Standard deviation	Min	Max
log(*FTTX*)	111	−4.199	2.552	−10.539	−0.648
FTTX/pop	127	0.062	0.091	0	0.523
ms_comp	156	19.486	18.592	0	97.1
ms_cab	154	24.661	16.051	0	82.792
iu3g	132	3.592	3.867	0	20.4
iday	161	40.504	16.918	6.2	76.4
gdp_pc	162	30980.09	20829.53	3743.413	3743.413
ict_exp	101	2.047	0.766	0	4.2
urban_pop	131	69.475	15.564	15.99	97.759
lab_cost	129	107.558	11.886	80.04	150.27

show by Monte Carlo analysis that their GMM-SYS estimator, using a system of first-differenced and levels equations, has a smaller bias than GMM-DIFF for finite samples. In order to account for potential non-stationarity, we logarithmised the dependent variable.

Related literature (e.g. Grajek and Röller, 2011) suggests that reverse causality between regulation and investment has to be expected in general, as NRAs are likely to react to firms' previous investment decisions. However, in this paper, we look at the impact of regulation-induced service-based competition on NGA investment, where we assess the impact of *previous* service-based competition (based on mandatory DSL wholesale obligations and respective retail broadband services) on emerging NGA investment. The usual objection that investment in one market influences access regulation of the same market is thus not valid in our case. Indeed, one can hardly imagine that the current NGA deployment influenced the regulation of broadband markets, which was implemented by NRAs many years ago. In order to underline this argument, we also perform Granger causality tests (see e.g. Cambini and Rondi, 2012).

7. Discussion of main results

The regressions in Table 3 shows the results using GMM-SYS for our full model containing all control variables (regression (1)), with regressions (2)–(4) in the table serving as robustness checks consecutively eliminating control variables. While, apart from ict_exp_{t-1}, the coefficients of the control variables are insignificant throughout our estimations, we keep ict_exp_{t-1} and $urban\_pop_{t-1}$ as the most important demand and cost side controls in the final results, which are presented in Table 4. In addition to GMM SYS, we employ estimations using GMM DIFF, LSDVC and fixed effects (FE) of our final model as additional robustness checks.

Endogenous variables lagged two or more periods are valid instruments provided that there is no second-order autocorrelation in the first-differenced idiosyncratic error terms. The AR(1) and the AR(2) test statistics reveal the absence of respective first and second order serial correlation in the first differenced errors in all GMM estimations. The Sargan and Difference-in-Sargan or Difference-in-Hansen tests do not suggest rejection of the over-identifying restrictions at conventional levels in all equations and for the main variables, respectively. The GMM estimations (5) and (6) employ $t-2$ to $t-6$ lags of the dependent variable as internal instruments; in estimation (7), we reduce the lags to only $t-2$, which increases the efficiency of the estimates. Our explanatory variables, which are already lagged ($t-1$) in our specifications, are instrumented by $t-2$ variables.

Comparing the regressions of Tables 3 and 4 reveals that the major results as regards service-based and infrastructure-based competition are quite similar, across both specifications and estimation methods. Both GMM estimations and LSDVC deal with the dynamic panel bias, which exists due to the lagged dependent variable on the right hand side of Eq. (4). Direct comparison with FE results shows that this kind of dynamic bias seems to matter substantially throughout our baseline model specification.[20]

Before we discuss the main variables of interest, we look at our control variables. In line with our hypotheses in Section 4.3, we find a significant positive impact of our demand variable (ict_exp_{t-1}) in most regressions in Tables 3 and 4, which captures willingness to pay for broadband services. However, the cost variable (i.e. $urban\_pop_{t-1}$) is insignificant throughout all estimation methods and models. In addition to country fixed effects, this might be attributed to two opposing effects: First, in densely populated areas, *FTTx* deployment can serve more customers at the same time, so reducing the costs for a single fibre line. Second, however, digging costs are usually lower in areas with low population density due to the higher proportion of Greenfield constructions. Other NGA-specific cost factors such as labour costs (*lab_cost*) seem to be highly dependent on national circumstances and vary little across time (Neumann 2010, p. 6).[21] Introducing *lab_cost* as a further cost proxy basically leaves the structure and significance of the main variables of interest unchanged. Our presumption that fixed effects are largely driven by diverse cost factors is reasserted as fixed effects estimates turn out to be highly negative for all countries.

[20] In contrast, Grajek and Röller (2011) "found little difference" between LSDV and LSDVC estimates and thus concluded that the dynamic bias can be ignored. Indeed, it seems to be quite obvious that using a broadly defined measure of investment (fixed tangible assets) implies much less stickiness and adjustment costs compared with a direct measure of real NGA investment.

[21] Likewise, interest rates are fixed across most sample units (EU27 member states) and these show insufficient variation for estimation purposes.

Table 3
Determinants of NGA investment (full model).

GMM SYS	(1) $\log(fttx)_t$	(2) $\log(fttx)_t$	(3) $\log(fttx)_t$	(4) $\log(fttx)_t$
$\log(fttx)_{(t-1)}$	0.730***	0.718***	0.732***	0.600***
	(0.000)	(0.000)	(0.000)	(0.000)
ms_comp$_{(t-1)}$	−0.054***	−0.039*	−0.041*	−0.033*
	(0.003)	(0.057)	(0.073)	(0.075)
ms_cable$_{(t-1)}$	0.658***	0.568***	0.596***	0.415**
	(0.004)	(0.002)	(0.004)	(0.016)
$ms\_cable^2_{(t-1)}$	−0.014***	−0.013***	−0.014***	−0.009***
	(0.000)	(0.000)	(0.000)	(0.009)
iu3g$_{(t-1)}$	0.409*	0.366*	0.353*	0.228
	(0.066)	(0.083)	(0.054)	(0.143)
$iu3g^2_{(t-1)}$	−0.025**	−0.021*	−0.019*	−0.006
	(0.049)	(0.074)	(0.055)	(0.427)
urban_pop$_{(t-1)}$	0.078	0.076	0.071	0.034
	(0.209)	(0.207)	(0.194)	(0.483)
ict_exp$_{(t-1)}$	0.876	1.753*	1.938**	
	(0.466)	(0.078)	(0.026)	
iday$_{(t-1)}$	−3.342	−4.141	−5.022	
	(0.305)	(0.169)	(0.135)	
gdp_pc$_{(t-1)}$	−0.000	−0.000		
	(0.428)	(0.642)		
lab_cost$_{(t-1)}$	−0.016			
	(0.176)			
Constant	−7.531	−10.35*	−10.90*	−6.015
	(0.178)	(0.083)	(0.081)	(0.213)
AR(1) test *p*-value	0.428	0.486	0.527	0.630
AR(2) test *p*-value	0.679	0.588	0.598	0.991
Sargan-test *p*-value	0.746	0.858	0.870	0.267
N	71	76	76	79

Regressions (1)–(4) include country-specific fixed effects which are not reported for brevity. We did not include year dummies, because they were not significant, either jointly or individually. For the Arellano-Bond (AR(1) and AR(2)) tests and the Hansen–Sargan test of overidentifying restrictions, corresponding *p*-values are reported. *P*-values for estimated coefficients are reported in parentheses and are robust to heteroscedasticity and to within group serial correlation in GMM estimates.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Turning to our main results we find a significantly negative coefficient of around −0.04 on our measure of regulation-induced service-based competition (ms_comp_{t-1}) throughout all estimations. This strongly supports our hypothesis outlined in Section 4.1 that more intense service-based competition has a negative impact on NGA infrastructure investment. Hence, this is inconsistent with the ladder of investment hypothesis. Our estimations imply that, for a country like the UK, with a market share of regulated lines of 61%, a decrease by 10% points would increase the long-term *FTTx* infrastructure stock in this country by 40%. When including the squared term of *ms_comp*, both *ms_comp* and ms_comp^2 are insignificant.[22] This demonstrates that service-based competition does not follow the inverted U-shaped relationship hypothesized in Section 4.2.

In order to examine our assumption on the exogeneity of our competition variables, we carry out Granger causality tests using GMM-SYS and LSDVC, which are reported in Table A1 and in Table A2 in the Appendix. The results obtained here do not give any indication of a reversed causality pattern between NGA deployment and previous broadband regulation in terms of service-based competition as we expected.

Using a partial adjustment model allows us to disentangle short and long-term effects according to the model framework in Section 6. With α' in the range of 0.35 (GMM DIFF, regression (5)) and 0.42 (LSDVC, regression (8)), the respective long-term coefficient ($\beta'(=\frac{\beta}{\alpha'})$ of each explanatory variable rises significantly, which indicates substantial long-term economic effects. Our results suggest that around 40% of the gap to the desired infrastructure stock is closed in every period and it would take around 4.6 years for the average European country to close 90% of the gap to the desired long-term infrastructure stock. The magnitude of the coefficient on the lagged dependent variable indicates inherent inertia due to adjustment costs. This seems to be quite plausible with respect to the diverse technological and economic impediments underlying the deployment of new NGA infrastructure.

Our estimated EU average desired infrastructure stock from the baseline Eq. (4) implies an *FTTx* coverage of 50.9% of European households.[23] Accordingly, the explicit

[22] Results are available from the authors upon request.

[23] We actually estimated the number of lines per population in our main equation. To be able to compare the implied optimal long-term coverage with the aims of the European Commission (2010b), we have to take into account the average European household size, which was approximately 2.4 persons per household in 2009 (Source: EUROSTAT).

Table 4
Determinants of NGA investment (Final model).

Dependent variable: $\log(fttx)_t$	(5)	(6)	(7)	(8)	(9)
	GMM DIFF	GMM SYS	GMM SYS	LSDVC	FE
$\log(fttx)_{(t-1)}$	0.646***	0.606***	0.641***	0.576***	0.420***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
$ms\_comp_{(t-1)}$	−0.038**	−0.040*	−0.038**	−0.038*	−0.038**
	(0.042)	(0.083)	(0.038)	(0.074)	(0.040)
$ms\_cable_{(t-1)}$	0.467***	0.557***	0.464***	0.280*	0.196
	(0.003)	(0.008)	(0.002)	(0.055)	(0.140)
$ms\_cable^2_{(t-1)}$	−0.012***	−0.012***	−0.012***	−0.008***	−0.006**
	(0.000)	(0.001)	(0.000)	(0.003)	(0.032)
$iu3g_{(t-1)}$	0.286**	0.288*	0.261*	0.066	0.218
	(0.024)	(0.052)	(0.092)	(0.735)	(0.142)
$iu3g^2_{(t-1)}$	−0.016**	−0.016*	−0.015*	−0.005	−0.012
	(0.024)	(0.063)	(0.096)	(0.700)	(0.188)
$ict\_exp_{(t-1)}$	1.359*	1.808**	1.337	1.484	1.825
	(0.091)	(0.018)	(0.117)	(0.129)	(0.105)
$urban\_pop_{(t-1)}$	−0.180	0.056	−0.023	0.586	0.491
	(0.731)	(0.319)	(0.746)	(0.261)	(0.118)
Constant	6.772	−12.310**	−3.729		−38.550*
	(0.854)	(0.032)	(0.573)		(0.070)
AR(1) test *p*-value	0.651	0.597	0.584		
AR(2) test *p*-value	0.849	0.876	0.763		
Sargan-test *p*-value	0.949	0.827	0.945		
Diff-in-Sargan/(ms_comp) *p*-value	0.626	0.475	0.725		
Diff-in-Sargan/ (ms_cable) *p*-value	0.353	0.991	0.727		
Diff-in-Sargan/(iu3g) *p*-value	0.462	0.422	0.971		
Wald(X^2)-test	93.08***	159.98***	565.15***		
R-squared within					0.712
Number of instruments	11	17	12		
N	52	76	76	76	76

Regressions (5)-(9) include country-specific fixed effects which are not reported for reasons of brevity. We did not include year dummies, because they were not significant either jointly or individually. For the Arellano-Bond (AR(1) and AR(2)) tests, the Hansen–Sargan test of overidentifying restrictions and the Difference-in-Sargan and Difference-in-Hansen statistics, corresponding *p*-values are reported. *P*-values for estimated coefficients are reported in parentheses and are robust to heteroscedasticity and to within-group serial correlation in GMM estimates. In regression (6) the lagged dependent variable is instrumented by $t-2$ to $t-6$ lags, in regression (7) it is instrumented by $t-2$ lags only. LSDVC standard errors are bootstrapped based on 300 iterations with bias correction for estimates up to order $o(1/NT^2)$.

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

policy goal of the European Commission's Digital Agenda that all Europeans should have access to internet speeds of above 30 Mbps (European Commission, 2010b, p. 19), which actually implies a 100% *FTTx* coverage, seems to be rather unrealistic under current investment conditions.

As regards our infrastructure-based competition variables (ms_cable_{t-1}; $ms\_cable^2_{t-1}$; $iu3g_{t-1}$; $iu3g^2_{t-1}$), all estimation models show a non-linear relationship between investment and cable as well as mobile competition variables. The variables are significant in GMM and partially significant in LSDVC estimations. Generally, the coefficients on the linear terms of cable tend to be more significant and larger, and thus evoke a stronger competitive pressure on investment to escape it. This is perfectly in line with market experience: Broadband services of cable operators already exceed quality characteristics (such as bandwidth) of incumbents' DSL services at similar price levels. In contrast, mobile broadband offers typically much lower bandwidth (shared medium) than high-speed wireline connections (coax and xDSL), and thus probably represents a better complement for some users (out-of-home usage), whereas only a certain segment of narrow-bandwidth customers is willing to fully replace wireline (cable) broadband with 3G(+) services. Hence, mobile broadband has on average exerted much less competitive pressure than cable in the past.

The maximum of the inverted U-shaped curve, showing the relationship between investment and competition, informs us about the optimal competitive market conditions for investment. For instance, one can infer from the corresponding coefficient estimates of our GMM-SYS model (regression (6)) that a respective market share of cable entrants and a mobile internet usage rate of around 22% and 9%[24] are optimal for NGA investment. The average market share of cable entrants is 24.7% in our data set and is thus broadly in line with this optimum value for NGA investment. In contrast, the average penetration rate of mobile internet is 3.6% and thus well below the 9% threshold.[25]

[24] Respective values for regressions (1) and (3) are quite similar: GMM-DIFF: 19.3% (cable) and 9.1% (mobile); LSDVC: 16.5% (cable) and 6.4% (mobile).

[25] Of course, more intense competition could lead to more static efficiency, and the optimum values with respect to total welfare are unclear.

Our results indicate that, for example, in France, the country with the lowest cable penetration in 2010, an initially higher level of cable penetration (the optimal 22% instead of 5.6%) would have resulted in an average increase of *FTTx* population coverage of 21.6%. With 22% of cable penetration in 2010, the UK is already close to the optimal level for NGA investment. But, with a share of the population using high-speed mobile services of as low as 0.4% in 2010, a rise to the European mean of 3.6% would result in an average increase of *FTTx* population coverage by 22% in the UK.

8. Conclusions and final remarks

In this paper, we determine the effects of infrastructure- and service-based competition on the deployment of NGA networks in Europe. In doing this, we used a panel data set of EU27 member states on NGA investment, as well as the main competition and control variables. As opposed to previous related literature, our econometric specification suffers neither from the dynamic panel bias nor from an endogeneity problem with respect to investment and service-based competition where the latter directly hinges on sector-specific ex ante regulations.

Our results indicate that NGA deployment is determined by service-based competition which relies on the incumbent's first-generation infrastructure platform and its regulated wholesale DSL services, and by the extent of inter-platform competition stemming from cable operators and mobile networks. Whereas the effect of infrastructure-based competition corresponds to the inverted U-shaped hypothesis, stricter previous service-based competition negatively affects total NGA investment of both incumbent and entrant infrastructure operators.

Our conclusions are not only of significant relevance for understanding the roles of both modes of competition but also of immediate relevance for future regulatory decisions, as the setting of the regulatory agenda for NGA investment and innovation is currently to be implemented and specified by NRAs across most EU member states. Considering the role of service-based competition and the underlying set of sector-specific access regulations, our results reaffirm the US policy of adopting a deregulatory approach of broadband markets in 2005 and, since then, experiencing significantly higher NGA deployment levels and annual growth rates compared with the EU average (Briglauer and Gugler, 2012). In turn, reinforcing the role of service-based competition by adopting a strictly cost-based access regime towards regulating emerging NGA infrastructure, as the EU suggests in its sector-specific regulatory framework (European Commission, 2010a), and neglecting inherent trade-offs between static and dynamic efficiency, would, according to our results, not allow the ambitious goals outlined in the Digital Agenda to be achieved.

Acknowledgements

The authors would like to thank the editors and referees for highly valuable comments. Furthermore, the authors are grateful for helpful comments and suggestions of the participants at the research seminar in economics at WU and the scientific seminar at the EUI in Florence as well as at the 22nd ITS conference in Budapest and the 39th Annual EARIE Conference in Rome on a former version of this paper.

Appendix A

(See Tables A1 and A2).

Table A1
Granger causality tests (direction: reverse causality) – GMM-SYS.

GMM SYS Dependent variable	(1) ms_comp	(2) ms_cab	(3) iu3g
$\log fttx_{(t-1)}$	−0.00975 (0.460)	−0.00162 (0.380)	0.00130 (0.300)
$ms\_comp_{(t-1)}$	0.944*** (0.000)		
$ms\_cab_{(t-1)}$		0.635*** (0.000)	
$iu3g_{(t-1)}$			1.273*** (0.000)
_cons	0.000 (1.000)	0.068** (0.012)	0.015** (0.036)
Time dummies	Yes	Yes	Yes
N	60	60	59

P-values in brackets, one lag was used instead of two because otherwise there would not be a sufficient number of observations left. Results for GMM-DIFF were not computed for the same reason.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Table A2
Granger causality tests (direction: reverse causality) – LSDVC.

LSDVC Dependent variable	(1) ms_comp	(2) ms_cab	(3) iu3g
$\log fttx_{(t-1)}$	0.013 (0.250)	0.000 (0.720)	0.001 (0.490)
$ms\_comp_{(t-1)}$	0.489*** (0.009)		
$ms\_cab_{(t-1)}$		0.569*** (0.000)	
$iu3g_{(t-1)}$			0.958*** (0.000)
Times dummies	Yes	Yes	Yes
N	60	60	59

P-values in brackets.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

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