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ORIGINAL ARTICLE

The impact of regulation and competition on the adoption of fiber-based broadband services: recent evidence from the European union member states

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Abstract Fiber deployment of next-generation high-speed broadband networks is considered to be a decisive development for any information-based society, yet investment activities and especially the adoption of fiber-based broadband services take place only very gradually in most countries. This work employs static and dynamic model specifications and identifies the most important determinants of the adoption of fiber-based broadband services with recent panel data from the European Union member states for the years from 2004 to 2012. The results show that the more effective previous broadband access regulation is, the more negative the impact on adoption, while competitive pressure from mobile networks affects adoption in a non-linear manner. Finally, we also find evidence for substantial network effects underlying the adoption process.

Keywords Next generation communications networks · Regulation · Competition · Fiber adoption

JEL H5 · L38 · L43 · L52

1 Introduction

The traditional ("first-generation" copper- or coax-based) broadband networks appear to be outdated and it has become necessary to speed up these networks in recent years to account for the growing demand for bandwidth/connection speed. According

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to “Nielsen’s law”, the broadband connection speed increases every year by 50 % (FTTH Council Europe 2012, p. 12). Next-generation fiber-based access (NGA) networks deployed on the ground provide much more bandwidth capacity. As these networks represent a general purpose technology, they are expected to induce significant productivity improvements and growth across major economic sectors such as health, electricity and transport (e.g. Czernich et al. 2011). However, substituting the traditional infrastructure with fiber-optic networks also involves high risks and massive investment volumes.[1]

The demand in terms of adoption (penetration) and supply-side activities in terms of investment in fiber-based network infrastructure (coverage) vary significantly in an international comparison. Most European countries lag far behind the leading Asian fiber nations (such as Japan, Korea, Taiwan and Hong Kong), but also behind the development in the US (Briglauer and Gugler 2013). As regards NGA adoption within Europe, Northern and Eastern European economies are leading by a large margin with NGA household adoption levels between ∼ 10% (Denmark and Latvia) and ∼26 % (Lithuania) at the end of 2011. Exceptional cases are Belgium and Luxembourg, where the focus on less expensive NGA deployment technologies has facilitated adoption levels of ∼ 45 and ∼85 %, respectively. However, most of the other European countries still show NGA adoption levels (far) below 5 %, including all the major Western and Southern European economies.[2]

Europe’s gap in NGA deployment was recognized by the European Commission (EC) and explicitly addressed in its “Digital Agenda”, which specifies goals in terms of high-speed broadband coverage and penetration.[3] In achieving these goals, one of the most controversial regulatory issues in Europe (and elsewhere) is whether the emerging NGA infrastructure should be subjected to sector-specific *ex ante* access regulation. Former—mostly state-owned—telecommunications monopolists (“incumbents”) argue that sector-specific *ex ante* regulation would be detrimental to dynamic efficiency in terms of investment incentives and infrastructure innovation. Instead, it would be sufficient to rely on market mechanisms and infrastructure-based competition in particular. Conversely, alternative operators that are dependent on access regulation (“service-based competitors” or “entrants”) as well as some national regulatory authorities (NRAs) fear the rise of NGA networks as another upcoming monopolistic infrastructure and that incumbent firms or other alternative NGA infrastructure operators would gain an essential and long-lasting competitive (“first-mover”) advantage. This implies the need to have appropriate ex ante regulation in place and regulatory-induced service-based competition would also have an immediate effect on static effi-

[1] The total investments in nationwide NGA deployment (coverage) depend inter alia on the network topology employed and the targeted coverage levels and amount to billions of euros (wik consult 2008).

[2] See Fig. 1 in the Appendix, which reports time-series plots for high- and low-cost NGA deployment scenarios for the European Union member states (EU27).

[3] The Digital Agenda “seeks to ensure that, by 2020, (i) all Europeans have access to much higher internet speeds of above 30 Mbps and (ii) 50 % or more of European households subscribe to internet connections above 100 Mbps” (European Commission 2010a, p. 19). Whereas the target in (i) refers to a coverage level of 100%, the target in (ii) is related to a minimum household adoption level subject to quality characteristics that can be realized only with NGA technologies.

ciency in terms of lower prices and hence on the adoption of (new) communications technologies on the demand side.

Based on an unbalanced panel of the EU27 member states for the years from 2004 to 2012, this paper addresses the following research questions: (i) What is the impact of broadband access regulations on NGA adoption? (ii) How does infrastructure-based competition stemming from wireless (mobile) networks influence the extent of NGA adoption? (iii) To what extent is NGA adoption driven by diffusion dynamics such as network effects or consumer inertia? This paper represents the first (European-based) attempt to quantify econometrically the determinants of NGA adoption with recent EU27 country-level data. A multiplicity of static and dynamic model specifications and a broad set of control variables serve as important robustness checks. Furthermore, we argue that there is no endogeneity problem in terms of reverse causality in the empirical specification, which relates first-generation broadband demand- and supply-side factors to second-generation NGA markets and services.

The remainder of the paper is organized as follows. First, we review the recent and most relevant contributions in the empirical literature in Sect. 2. Section 3 briefly provides the necessary background information on the technical context of NGA networks. Section 4 then describes basic hypotheses concerning the role of sector-specific regulation and competition as well as the other main cost and demand factors. Section 5 describes our data set. Section 6 presents the empirical specification and the underlying identification strategy. Section 7 discusses the main empirical results. To conclude, Sect. 8 summarizes and contains some final remarks.

2 Empirical evidence

The empirical literature related to the impact of broadband access regulations and competition can be divided into three broad categories: (i) quantitative analysis focusing on the impact on investment; (ii) quantitative analysis focusing on the impact on adoption (penetration); and (iii) qualitative analysis with a focus on penetration or investment. The latter appears to be most meritorious in the case of too few observations in which quantitative analysis cannot provide reliable guidance. However, we think that the availability of NGA-related data is sufficient now to allow robust statistical analysis. Accordingly, in this section we focus on quantitative studies only and do not review the literature related to qualitative studies.[4] When reviewing the quantitative literature, one has to be aware of the heavily interest-driven nature of the discussion and of the fact that a large number of contributions represent directly industry-sponsored work. Therefore, our literature review also excludes industry-sponsored work that has not been published in peer-reviewed academic journals.

Regarding the impact of regulation on investment (i), Jung et al. (2008), who use US data for the years from 1997 to 2002, find that infrastructure competition increases

[4] A comprehensive overview of qualitative studies can be found in Berkman Center (2010, pp. 121–136).

the investment incentives while mandatory access obligations at best have a weak effect on the investment of infrastructure operators. Recent work with data from EU countries exhibits similar results: Grajek and Röller (2012) investigate the relationship between regulation and total investment in the telecommunications industry over ten years. Their study is among the few that explicitly account for the endogeneity problem of regulation and investment. Investment is quantified therein rather broadly by the tangible fixed assets of telecommunications operators and, thus, does not explicitly refer to broadband or NGA deployment. Wallsten and Hausladen (2009) are the first to estimate the effects of broadband access regulation on NGA deployment. They find that countries where broadband access regulation is more effective experience lower fiber deployment. However, they use data for the years from 2002 to 2007, which only cover the NGA roll-out in its very early stage and the authors do not capture the investment dynamics. Briglauer et al. (2013) investigate the determinants and dynamics of NGA investment with yearly data from 2005 to 2011. They find that stricter previous broadband access regulation has a negative impact on NGA deployment, while competitive pressure from cable and mobile networks affects NGA deployment in a non-linear manner.

Regarding the literature on the impact of regulation on adoption (ii), there are several contributions related to broadband markets, but no NGA-related publications. Using US data from 2001 to 2004, Denni and Gruber (2007) find that infrastructure-based competition has a positive impact on broadband diffusion in the longer term, whereas regulatory-induced service-based competition has a positive impact only if the number of service-based entrants is not too large. Non-US-based work mainly refers to OECD country-level data. Bouckaert et al. (2010) examine the determinants of broadband penetration for the years from 2003 to 2008. They find that infrastructure-based competition has a positive impact on broadband penetration, whereas service-based competition is an impediment to penetration. Lee et al. (2011) analyze the determinants of broadband diffusion for the years from 2000 to 2008. With respect to unbundling obligations, the authors find a positive and significant effect on the speed of diffusion. They admit, however, that unbundling might have a negative impact on long-term investment and the broadband saturation level. Cava-Ferreruela and Albau-Munoz (2006) find that infrastructure-based competition has a significant and positive impact on broadband penetration, whereas unbundling has no significant effect for data from 2000 to 2002. Finally, some contributions refer to data from European countries. Distaso et al. (2006) analyze EU-related data from 2001 to 2004 and find that infrastructure-based competition is the main driver of broadband take-up and plays a more important role than service-based competition, especially in the longer term. Höffler (2007) examines data for sixteen Western European countries for the years from 2000 to 2004. He concludes that broadband deployment was predominantly triggered by infrastructure-based competition, with service-based competition playing a secondary role.

Summarizing, the majority of the empirical literature suggests that infrastructure-based competition has a positive impact on both investment and penetration. In turn, the evidence regarding service-based competition relying on broadband access regulations tends to be negatively related to investment activities, while the impact on broadband adoption seems to be less clear. To the best of the author's knowledge, there is no empirical work that examines the impact of regulation and competition on NGA adoption. This paper intends to fill this gap.

3 Industry background

Historically, first-generation networks of incumbent operators deployed twisted copper-wire pairs to overcome the last mile (“local loop”) to the subscriber in order to provide narrow bandwidth voice telephony services only. Many decades later, they were made capable of supporting broadband services by means of digital subscriber line (DSL) transmission technology. However, due to technical reasons, the bandwidth of DSL technologies is limited. In order to realize the NGA characteristic bandwidth, 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 that house distribution frames [fiber to the cabinet (FTTC)]. In the remaining copper-wire line of the last mile, the latest DSL transmission technology is used. This solution can provide bandwidths up to 100 Mbit/s. In addition to upgrading first-generation copper-wire (DSL) networks in the local loop, the roll-out of high-speed communications networks might also be realized by upgrading cable (coax) television networks, which is referred to as “fiber to the last amplifer”, which provides bandwidths up to 150 Mbit/s. Similar or even higher bandwidths (above 100/150 Mbit/s) can be achieved if optical fiber is extended to or into the building [fiber to the building (FTTB)]. In case of FTTB only the remaining wiring inside the building relies on conventional copper wires. If the optical line is directly connected to the individual home [fiber to the home (FTTH)], this would be the most future-proof technological solution, as it enables nearly unlimited bandwidth (RTR 2010, pp. 189–191; Briglauer et al. 2013, pp. 2–3).

FTTx stands for a family of technologies that includes all the NGA scenarios described above. As such, it differs from a more narrow definition that refers to cost-intensive FTTH/B technologies.[5]

During the relevant analysis period (2004–2012), mobile broadband access has already been facilitated by 3G+ technologies (GPRS, EDGE, UMTS and HSDPA). Moreover, the industry expects long-term evolution (LTE) to enable transmission rates similar to wireline NGA (FTTx) scenarios in the near future. However, LTE is still in the test phase and the aforementioned mobile broadband standards are far from achieving FTTx-specific bandwidth levels. Therefore, mobile broadband is not considered to be a relevant (second-generation) NGA technology in the empirical analysis.

4 Hypotheses

From the empirical literature, one can infer that there is a common understanding that both demand-side and supply-side factors have an influence on the adoption of

[5] Because the length of FTTH/B lines is longer compared with other FTTx technologies and thus services a much smaller customer base in the local loop, the average investment per FTTH/B connection is disproportionately higher (wik consult 2008).

fiber-based broadband services. Furthermore, most studies implicitly refer to a direct and positive relationship between investment (coverage) and adoption (penetration). Clearly, network coverage is a pre-condition for the successful adoption of NGA services and therefore the higher the available infrastructure stock, the higher the potential subscriber base (Wallsten and Hausladen 2009; Bouckaert et al. 2010).[6] This section identifies the determinants of NGA investment and adoption and sets out corresponding hypotheses, which are aligned with the underlying research questions. Sections 4.1 and 4.2 focus on regulation and competition as the main explanatory variables that directly impact on the supply side, i.e. NGA investment. Likewise, cost conditions will shift the supply curve but also exert an indirect impact on NGA adoption (Sect. 4.3). Finally, the adoption process will be directly influenced by diverse demand-side factors and network effects (Sect. 4.4). However, the demand will also be related to regulation and competition, which affect prices and quality and thus indirectly the adoption of NGA services.

4.1 Regulation

NGA regulations will be defined and imposed by NRAs only in future decisions or, if already implemented, the effectiveness of these decisions still remains to be seen (Cullen International 2011, Tables 4, 9 and 10). It can be argued, however, that past regulation in first-generation broadband markets has clearly shaped the expectations for NGA regulations. This has been confirmed in NGA-relevant recommendations of the EC as well as in previous court decisions.[7] In EU member states basically three kinds of *ex ante* (cost-based) access regulations are imposed on first-generation broadband markets since the beginning of market liberalization in 1997/1998: (i) alternative operators can rent the local loop from the incumbent operator (“unbundling”). (ii) service-based entrants may also offer retail broadband services by purchasing “bitstream” as a wholesale input from the incumbent operator but at a more service-based level of the value chain. Finally, (iii) “resale” means that access-seeking service providers resell a wholesale input of the incumbent operator with virtually no scope for technological product differentiation (RTR 2010, pp. 176, 179).

On the one hand, stricter wholesale access regulations increase service-based competition at the retail level in terms of lower broadband prices, exerting a positive impact on the demand side.[8] On the other hand, tight regulation of existing broadband access infrastructure most likely, as mentioned above, creates corresponding expectations

6 In our panel data set, Pearson’s bivariate correlation coefficients for FTTx coverage and FTTx adoption are 0.7014 and 0.6982 in terms of connections per household and per capita, respectively.

7 The NGA recommendation of the European Commission (2010b) as well as former draft versions clearly indicated that the EC was very much determined to extend its cost-based regulatory approach to the emerging NGA communications infrastructure. The reader is also referred to the earlier decision of the German Government to exempt the incumbent operator (Deutsche Telekom AG) from wholesale access obligations to its new infrastructure network (“regulatory holidays”). The EC, however, took Germany to court over this legal provision in 2007, which finally decided against it in 2009 (C-424/07).

8 Lower first-generation broadband prices do not necessarily imply higher levels of adoption of second-generation NGA services. Section 5.2.3 outlines the potential impact of broadband prices in more detail as well as the underlying hypotheses.

about the future regulation of NGA access infrastructure that decrease the investment incentives of (potential) infrastructure operators for the following: (i) imposing cost-oriented access prices for bottleneck inputs typically reduces profits or precludes excess profits of the regulated firm, which results in asymmetric distribution of the expected profits and, therefore, in a lower net present value of investment projects (Valletti 2003). Furthermore, access regulation typically ignores (ii) the opportunity costs of real options (Guthrie 2009) and the fact that (iii) risks were distributed asymmetrically among regulated incumbent and entrant operators. Therefore, (iv) regulation reduces not only the investment incentives of regulated infrastructure operators but also those of potential entrant infrastructure operators who benefit from a risk-free option due to mandatory access obligations (Pindyck 2007). Finally, pending decisions on NGA regulations have already led to substantial regulatory uncertainty, which constitutes another investment impediment. According to Nitsche and Wiethaus (2011), who model the effects of different regulatory regimes on NGA investment, a regime of less intense access regulations or regulatory holidays would have the most positive effects on investment, whereas the EU standard of strict cost-based access regulation turns out to be inferior.[9]

Summarizing, we expect that ex ante sector-specific regulation in the form of mandatory access regimes has a negative impact on NGA investment and hence indirectly also on the adoption of NGA services. Higher levels of regulatory-induced service-based competition, however, might also have an opposite effect via lowering prices, which would increase demand and NGA adoption.

4.2 Competition

Telecommunications, by all means, have become one of the most dynamic and competitive industries since the beginning of the EU liberalization process. Likewise, recent and future investment in NGA is driven by infrastructure-based competition, most notably from mobile networks ("intermodal"), which "threaten" first-generation (copper and cable) networks and services. The so-called phenomenon of fixed-to-mobile substitution has already been quite intense with respect to narrowband voice telephony services at the beginning of NGA deployment (around 2005) and has become increasingly important until now, not only regarding voice telephony but also more and more to broadband services.[10]

With respect to the potential impact of intermodal competition on NGA investment, one first has to distinguish the following opposing effects (Aghion et al. 2005):

[9] See also Briglauer and Gugler (2013), who evaluate NGA deployment and adoption in different geographical areas (Asia, the EU and the US) in view of the underlying regulatory approaches with a particular focus on the investment incentives embedded in the current EU regulatory framework.

[10] The average EU mobile broadband penetration of all users (PCs/laptops and handheld devices) is about 41 %, whereas the EU average fixed broadband penetration is 27.7 % (including basic and high-speed connections) as of January 2012. Regarding the number of subscribers, fixed-to-mobile substitution is even more pronounced: whereas the average EU number of mobile subscribers increased constantly up to 127 % by the end of 2011, the average number of fixed-line connections has decreased significantly in recent years. All the data are available from the EC's Digital Agenda Scoreboard website: http://ec.europa.eu/digital-agenda/en/scoreboard.

On the one hand, competitive markets bear incentives for innovative investment in view of temporary market power rents that can be captured (the "escape competition effect"), leading to a positive relation between intermodal competition and NGA investment. Indeed, the deployment of NGA networks can be seen as the "last chance" for traditional wireline infrastructure operators to escape successfully from broadband competition stemming from mobile networks with high-bandwidth-demanding NGA services that cannot be realized by means of mobile broadband technologies in the foreseeable future. On the other hand, intense intermodal competition in terms of pronounced fixed-to-mobile substitution will eventually reduce the potential rents and, thus, increasingly counteract NGA investment because operators will no longer be able to appropriate the necessary profits from NGA investment (the "Schumpeterian" effect).

Second, one has to consider the "replacement effect" (Arrow 1962), according to which new NGA investment would "cannibalize" quasi-monopolistic profits from old first-generation infrastructure services, increasing the opportunity costs and thus reducing the incentive to invest.[11] The replacement effect appears to be of practical relevance, as most EU27 member states have well-established first-generation infrastructure in view of both network coverage and recent and foreseeable advances in wireline DSL/cable technology standards. As a result, conventional broadband services enjoy broad consumer acceptance in most EU member states, which also establishes non-negligible switching costs on the consumers' side and hinders migration to the new technology unless its incremental benefits are large and transparent enough for consumers (Grajek and Kretschmer 2009, p. 241).

In summary, we expect a non-linear relationship between NGA investment and the intensity of infrastructure-based (intermodal) competition from mobile networks. An increase in the intensity of intermodal competition might have—in the same manner as regulatory-induced service-based competition—a positive impact on the adoption of NGA services, i.e. on the demand side, as infrastructure-based competition enhances services[12] and reduces the average broadband price level. With respect to the replacement effect, we expect that a higher diffusion of first-generation broadband (intramodal) connections leads to a lower adoption rate of second-generation NGA services.

4.3 Cost factors

The civil engineering and construction costs related to digging represent by far the most relevant cost drivers for NGA deployment. As these cost factors are largely fixed and sunk costs, one can expect that the average deployment costs will decrease with the number of broadband/NGA subscribers ("economies of density"; wik consult 2008). Furthermore, these deployment costs will crucially depend on largely time-invariant

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

[12] Whereas the main merits of regulation and service-based competition refer to lower prices, including pricing innovations and customer care, infrastructure-based competition also has the technical potential to enhance services via quality innovation.

topographic and demographic characteristics, such as urbanization, population or household density and housing structure, in particular, the number of multi-dwelling units (FTTH Council Europe 2012, pp. 24–25).

Relevant legal and institutional factors, such as regulations on capital costs, rights of way and digging or other allowances and technical standards, local availability and reusability of ducts and dark fiber or NGA-specific state aid policies, also show hardly any variation with respect to the relevant time frame.

4.4 Demand factors

The demand depends on the average price for high-speed broadband services, the overall market size in terms of total communications expenditure and consumer wealth in general. Consumers with higher average communications expenditures can be regarded as having greater affinity with information and communications technologies (ICT), which might result in higher levels of NGA adoption (FTTH Council Europe 2012, p. 42). The demand for NGA services is also driven by a variety of consumer preferences, referring to the overall affinity with ICT, conventional Internet usage and usage intensity of high-speed broadband services. Consumers' needs are furthermore determined by their average education levels, since higher levels of education improve e-literacy skills, which considerably increases the utility derived from NGA technologies. Also, more highly educated people tend to be more prone to adopting and experimenting with new ICT (Kiiski and Pohjola 2002, p. 302).

Finally, one has to consider network effects as a special type of externality underlying the NGA adoption process, in case the number of subscribers (and/or producers) has an impact on the consumers' utility (firms' profit) (Shy 2010). In general, increases in the adoption rates also lead to increases in the usage intensity of the respective services (Grajek and Kretschmer 2009, p. 240). Consumers' utility can be related to the possibility of communicating with one another at the consumer level either directly, e.g. via different "Web 2.0" platforms, or indirectly, in the case of network effects occuring at different producer levels. For instance, the more users subscribe to (high-speed) Internet services, the more specific content and related applications will be programmed, which increases the consumers' utility and willingness to adopt such (NGA) services. The same is true for the development of related hardware and electronic equipment. Furthermore, it is likely that the NGA adoption process is subject to learning spillovers, inasmuch as the value added of NGA services appears to be a priori unknown to potential consumers, whose valuation inter alia depends on the information gathered by the already-existing subscriber base (Grajek 2010, p. 133). Operators simply benefit from the network size, since an increase in the total number of subscribers lowers the average costs significantly in view of the NGA network topology and thus increases the profits.

All the network effects described above give rise to a self-propelling endogenous growth process, which suggests that the contemporaneous and previous NGA adoption rates are positively related: the higher the existing subscriber base, the higher the potential network benefits.

5 Data and variables

The empirical specification is based on the following data sources. The "EU Progress Report" provides yearly data for all the relevant wholesale broadband access regulations. The second main source is the database of FTTH Council Europe, which includes the annual numbers of connected NGA lines for all the EU27 member states. EUROSTAT/COCOM provides data on the total population, education, Internet usage and ICT labor costs as well as the housing structure. We use the International Telecommunications Union (ITU) data to measure intermodal infrastructure competition and Quantum-Web tariff data as a representative measure of the average broadband price that is related to the first-generation infrastructure. Finally, data from the World Bank provide us with the GDP per capita, the European Intelligence Unit (EIU) with measures of labor and wage costs and the percentage of people living in urban areas and EUROMONITOR with telecommunications revenues and the number of households and Internet users.

As the data availability differs by variable, we use an unbalanced panel data set of EU27 countries for the time range from 2004 to 2011 for yearly data on our independent variables and from 2005 to 2012 for yearly data on our dependent variable. All the variable definitions, expected signs and sources as well as summary statistics are listed in detail in the Appendix in Tables 3 and 4, respectively.

5.1 Dependent variable

The dependent variable, *FTTx_hh*, measures adoption as the actual number of NGA connections divided by a country's total number of households.[13] In line with the description in Sect. 3, the relevant wireline NGA/FTTx technologies include FTTH/B/C and fiber to the last amplifier. The dependent variable represents the number of households exhibiting sufficient willingness to pay and actively using one of the FTTx-based (NGA) services under a commercial contract.

5.2 Independent variables

The independent variables can be divided into the following categories: (i) regulation, (ii) infrastructure-based competition, (iii) prices and (iv) cost and demand controls.

5.2.1 Regulation

The regulation variable, *reg_bb*, measures the lines actively used by service-based competitors as the share of the total regulated wholesale broadband lines (includ-

[13] The other metric commonly used refers to per capita terms. Both measures have their strengths and weaknesses. Adoption in per capita terms refers to both business and residential users, whereas household penetration omits business customers. However, household subscription data seem to be the more correct measure as fixed-wireline (NGA) connections are typically related to a single household but not to an individual subscriber (as is the case for wireless subscriptions). Hence, we prefer household data, but—as it will be shown—the estimates are robust to the alternative specification in per capita terms.

ing unbundling, bitstream and resale) related to the total retail broadband lines.[14] Therefore, this variable not only includes all the relevant wholesale broadband access regulations as outlined in Sect. 4.1, but also provides an immediate measure of their effectiveness.[15] We expect a negative sign of *reg_bb*, as we also control for the opposed price effect of service-based competition (Sect. 5.2.3)

Furthermore, we argue that access regulations, *reg_bb*, imposed on the "old" network infrastructure typically many years ago, are exogenous with respect to the deployment of the "new" NGA infrastructure and the adoption of NGA services. At the same time, previous regulation on broadband markets is a rather reasonable— and in fact the best—proxy for (expected) NGA regulation, inasmuch as *reg_bb* represents the most relevant remedial measures within the EU regulatory framework.

5.2.2 Competition

The main form of infrastructure-based competition related to first-generation infrastructure services stems from mobile networks. The variable *fms* states the share of fixed landlines in the total number of fixed landlines and mobile subscriptions and hence expresses the extent of fixed-to-mobile substitution, *fms*, in a country. This variable is expected to exhibit a non-linear relationship and its net impact depends on the relative importance of the escape competition and Schumpeterian effect.

bb_lines_hh measures a country's diffusion of first-generation (copper and coax) broadband connections and services and, therefore, it directly captures the replacement effect and is expected to exert a negative impact on NGA adoption on average. The variable *cable* measures the share of broadband coax lines run by cable entrants, which represent the main intramodal competitors of the incumbent's broadband DSL services. Because we can directly control for the relevant (intramodal) replacement effect, *fms* solely reflects the escape competition and Schumpeterian effect.

5.2.3 Prices

As outlined in Sects. 4.1 and 4.2, the net impact of regulation and competition on NGA adoption is apriori undetermined, since regulatory-induced service-based competition influences prices and thus adoption on the demand side but it also negatively affects NGA investment on the supply side, which decreases NGA adoption. Likewise, a high

[14] The denominator of the variable *reg_bb* excludes (unregulated) cable lines in order to avoid biases due to the extent of first generation cable infrastructure. However, the estimation results are robust towards an alternative specification of the variable *reg_bb* that includes (unregulated) cable lines (results are available from the author upon request).

[15] As a consequence, we do not have to rely on broadly defined indices, dummy-based scorecards or other proxies, which are commonly used in the related literature but hardly related to fixed broadband wholesale access regulations (such as the OECD regulatory index for the telecoms sector). The "Polynomics Regulation Index 2012" (Zenhäusern et al. 2012) is the most related to the EU regulatory framework, but it is available only up to 2010 and captures only the formal aspects of regulation and not its effectiveness. However, certain access regulations imposed by NRAs might exist on paper for years without any real effect on the relevant markets. In contrast, our measure incorporates the actual market effectiveness of ex ante regulations by linking these to the corresponding market outcomes [the same argument in favor of effectivity-based measures can be found in Bacache et al. (2012) or Briglauer et al. (2013)].

level of infrastructure-based competition brings down broadband prices but, beyond a certain level, also deteriorates NGA investment. In order to isolate the direct supply-side effects of the competition and regulation variables, one has to account for the market outcome that is related to first-generation competition by controlling for the average broadband price level, *price_bb*. The net impact of the variable *price_bb* on NGA adoption is determined by the following effects: (i) in the case that first- and second-generation broadband services are substitutes, an increase in *price_bb* shifts demand and increases NGA adoption; (ii) to the extent that *price_bb* stands as a proxy for NGA prices, an increase in *price_bb* will decrease NGA adoption alongside the demand curve (own-price effect); (iii) if *price_bb* stands as a proxy for a general broadband price level that reflects the supply determinants, such as the number of intramodal competitors and first-generation network topology or the extent of public broadband subsidies, a decrease in *price_bb* increases NGA adoption due to more favorable market conditions. Also, a lower broadband price level increases the customer base that might eventually be migrated to NGA services and hence increases NGA adoption. Since the definition and the quality characteristics of the broadband price variable, *price_bb*, are distinctively different from representative NGA services, we assume that the effects in (iii) dominate the other effects and thus expect a negative sign of *price_bb*.

5.2.4 Cost controls

We use the following measures for the demographic and topographic cost factors: Whereas *urban_pop* reflects different cost structures due to varying shares of rural and densely populated areas, *hh_dens* represents a country's average household size and therefore a measure of the housing structure. The yearly number of building permissions of multiple dwelling units, *mdw*, provides another measure of household structure.

We use the following measures for NGA construction costs: whereas *lab_cost* represents an annual labor cost index, *lab_cost_ICT* gives an annual labor cost index that is related to ICT industries and *wage* measures manufacturing costs per hour.

5.2.5 Demand controls

The total telecommunications revenues normalized to households, *telco_rev_hh*, act as a proxy for the ICT market size and, thus, for the overall willingness to pay for broadband/NGA services in a country. *GDP_pc_pp* measures income effects. Furthermore, we include the variable *iday*, which provides the share of the population that uses the Internet frequently, to cover NGA-relevant consumer tastes. The number of Internet users per capita, *int_user_pc*, represents another proxy for the overall ICT affinity within a country. The educational level, *edu*, is measured as the percentage of the adult population that has completed at least upper-secondary education.

Network effects are considered by adding the lagged dependent variable, $Fttx\_hh_{(t-1)}$, as a right-hand-side variable to the empirical specification. $Fttx\_hh_{(t-1)}$ measures the installed subscriber base and thus the aggregate demand in the previous period.

6 Empirical specification

We employ a two-fold empirical specification strategy: In Sect. 6.1 we first specify a simplified static reduced-form model which enables comparative static analysis. The latter appears to be of prime importance for policy makers and in view of the first two research questions. In Sect. 6.2 we more realistically consider a market which is not in equilibrium and explicitly account for an endogenous adoption process which primarily addresses the third research question.

6.1 The "static" adoption model

As can be inferred from the literature review in Sect. 2, some studies focus on broadband penetration, i.e. demand, while others focus on investment, i.e., the supply of broadband/NGA connections. Only a few empirical studies explicitly identify broadband/NGA supply and/or demand or outline the underlying reduced-form approach. The static baseline specification refers to a reduced-form model in which demand is expressed in terms of NGA household adoption (in logs), *ln(FTTx_hh)*.[16] Imposing the equilibrium condition (demand = supply) eliminates the endogenous NGA-related price variable and yields the following econometric reduced-form specification:[17]

$$\begin{aligned} \ln(Fttx\_hh_{it}) = \alpha_0 + \beta_1 reg\_bb_{i(t-1)} + \beta_2 fms_{i(t-1)} + \beta_3 fms^2_{i(t-1)} \\ + \beta_4 bb\_lines\_hh_{i(t-1)} + \gamma' Z_{i(t-1)} + \theta_i + [t] + \varepsilon_{it} \end{aligned} \quad (1)$$

Equation (1) depends on the main variables of interest, i.e., regulation and competition, in state i in year t, as well as on a vector of demand and cost controls ($\boldsymbol{Z}_{i(t-1)}$). Note that $\boldsymbol{Z}_{i(t-1)}$ also contains a measure of the average broadband price level, *price_bb*, which explicitly controls for the competitive outcome in first-generation broadband markets, allowing the estimation of the direct supply-side effect of regulation and competition. ε_{it} represents the additive error term and θ_i country-specific effects. Equation (1) includes lagged values of all the exogenous variables.[18]

6.2 The "dynamic" diffusion model

Any adoption process is inherently dynamic, most notably, due to network effects or consumer inertia. The vast majority of the related empirical literature finds that (ICT) adoption processes are best described through S-shaped (logistic or Gompertz)

[16] A log transformation helps to stabilize the series of our dependent variable. In order to formally test for stationarity, we perform "Im–Pesaran–Shin" and "Fisher-type" unit-roots tests which are designed for unbalanced panels. Including fixed effects (and time trends), these tests reject the null hypothesis that all panels contain unit roots for all the variables used in the static (and dynamic) model specifications.

[17] For similar static broadband adoption specifications see inter alia Bouckaert et al. (2010), Cava-Ferreruela and Albau-Munoz (2006), Distaso et al. (2006) or Wallsten and Hausladen (2009).

[18] With an insufficient number of observations one would run the risk of overfitting the data. The lagged specification in Eq. (1) allows the full employment of the available panel data set.

functional curves that represent different versions of an exponential growth model, which ultimately converges to a certain saturation level.[19] However, even in fiber-leading European countries, the NGA adoption processes are still in their early phase and far from being close to the inflection points. In particular, one can infer from Fig. 1 that almost all the EU27 states are far from the adoption target defined in the EC's Digital Agenda. Therefore, NGA adoption can be approximated by a simple exponential growth model which relates NGA adoption (in logs), $ln(FTTx\_hh_{it})$, to a linear time trend, $[t]$, which is added to Eq. (1).

Equation (2) below represents another dynamic extension of the baseline specification in Eq. (1) in which the lagged dependent variable, $ln(FTTx\_hh_{i(t-1)})$, is included as a right-hand side variable (instead of the linear time trend, t). The coefficient α_1 allows to measure the importance of network effects that give rise to an endogenous adoption process if $0 < \alpha_1 < 1$. $(1 - \alpha_1)$ measures the constant "speed of diffusion", λ, which comes from a Gompertz model of adoption (Kiiski and Pohjola 2002, pp. 299–300). λ is expressed as the percentage of the gap between the long-run (desired or target) stock of NGA subscribers and the subscribers in the previous period that is closed each period (Kiiski and Pohjola 2002; Andres et al. 2010) and hence represents a measure of consumer inertia.[20,21]

$$\ln(Fttx\_hh_{it}) = \alpha_0 + \beta_1 reg\_bb_{i(t-1)} + \beta_2 fms_{i(t-1)} + \beta_3 fms^2_{i(t-1)} + \beta_4 bb\_lines\_hh_{i(t-1)} + \gamma' Z_{i(t-1)} + \theta_i + \alpha_1 \ln(Fttx\_hh_{i(t-1)}) + \mu_{it} \quad (2)$$

6.3 Identification

The desire to measure causation and to avoid endogeneity in spite of the reliance on non-experimental data is the key concern in empirical economics (Wooldridge 2002, p. 421; Cameron and Trivedi 2005, p. 715). We argue, first of all, that endogeneity in the form of reverse causality is largely eliminated as we assess the impact of demand- and supply-side determinants related to first-generation broadband markets on emerging second-generation NGA markets; hence, we can hardly imagine that the current NGA adoption influences, for instance, the previous regulation on broadband markets that was implemented by NRAs typically many years ago. However, this line of reasoning might not be as compelling in view of all the other explanatory variables. Therefore, we also perform standard Granger causality tests (Granger 1969) to rein-

[19] For recent and ICT-related diffusion studies see e.g. Grajek and Kretschmer (2009), Czernich et al. (2011) or Lee et al. (2011).

[20] Let $Fttx\_hh^*_{it}$ denote the desired long-run stock of NGA subscribers; then, the Gompertz model of diffusion specifies the rate of change as $(\partial Fttx\_hh_{it}/\partial t)\,(1/Fttx\_hh_{it}) = \lambda(\ln(Fttx\_hh^*_{it} - Fttx\_hh_{i(t-1)}))$.

[21] For the sake of clarity, we drop the cross-sectional index in the remainder of the paper. Again, all exogenous right-hand side variables are lagged for the reason given in footnote 18. Moreover, assuming that adoption decisions at a particular point in time do not depend on contemporaneous but on the last period's conditions makes also sense in view of the dynamic specification in Eq. (2), as consumers' adoption process will typically be related to switching costs, which might become reinforced in the case when long-term broadband contracts exist at the retail level.

force the above argumentation on statistical grounds. The results, which are reported in Table 5 in the Appendix, indicate that there is no bidirectional causality. Second, we control for potential endogeneity due to unobserved and time-invariant heterogeneity by including fixed effects (θ_i) at the country level. Third, by lagging the explanatory variables, NGA adoption is related to pre-determined values of the independent variables. Whereas lagging explanatory variables only mitigates endogeneity problems due to time-variant heterogeneity in the static model [Eq. (1)], pre-determinedness, or sequential exogeneity, is reasonable for dynamic panel models such as the diffusion model in Eq. (2) (Wooldridge 2002, pp. 299–300).

7 Empirical results

Table 1[22] shows the main results using fixed-effects ("FE") regressions to estimate the static specification in Eq. (1).[23] Regression (1) reports the FE estimates for the model specification that contains all the demand and cost controls ("Full") as described in Sects. 5.2.4 and 5.2.5. The F-test (F_θ) following regression (1) shows that country-level FEs are significant, implying that pooled OLS would produce inconsistent estimates if the FEs are correlated with the independent variables. Regression (1) reports t-statistics assuming that the errors in Eq. (1) are i.i.d., which might induce misleading inference as well. Therefore, one has to control for both serial correlation and any arbitrary form of heteroskedasticity by calculating robust standard errors. For short panels ($T \leq 8$ in our case), this strategy is preferred to modelling a specific error correlation structure (Cameron and Trivedi 2005, p. 725). Regression (2) contains FE estimates for the full model based on robust standard errors ("rob"). Note, however, that robust standard errors still assume that there is no contemporaneous correlation across the panel units. Typically, spatial dependence is unlikely to exist at the country level with short time series. However, Pesaran's test of cross-sectional independence does not provide unambiguous evidence for all the "final" FE models in Tables 1 and 2. Regression (5) therefore reports the "Driscoll–Kraay" standard errors ("DK"), which are assumed to be heteroskedastic, autocorrelated up to some lag and possibly correlated between the panels (Driscoll and Kraay 1998; Hoechle 2007).

In regressions (3) to (5), we eliminate all except the significant demand controls ($int\_user\_pc_{(t-1)}$, $edu_{(t-1)}$) and the least insignificant cost controls ($wage_{(t-1)}$, $urban_{(t-1)}$). As it can be seen, the basic structure of the coefficients for the main variables remains effectively unchanged throughout regressions (1) to (5), which reassures us that those estimates are largely robust to alternative selections of control variables. The demand controls $int\_user\_pc_{(t-1)}$ and $edu_{(t-1)}$ are statistically significant with the expected signs and appear to capture ICT affinity and e-literacy best, respectively, as essential preconditions for the usage of high-speed

[22] STATA 12.1 is used to estimate the regressions.

[23] FE specifications are clearly preferable to random effects in view of our observational data set. Conceptually, our analysis focuses on the EU27 member states, which represent a particular set of rather homogenous countries and cannot be considered as a random sample drawn from the population of all countries. Empirically, a heteroskedastic- and cluster-robust Hausman test strongly rejects the random effects model (the Sargan–Hansen test statistic is 71.025) on the grounds that the random effects estimates will be inconsistent.

Table 1 Estimation results for the adoption model (dep. var.: $ln(Fttx\_hh_{it})$)

Regression (nr.)	(1) Full_FE	(2) Full_FE_rob	(3) Final_FE_rob	(4) Final_FE_rob_i	(5) Final_FE_DK
$reg\_bb_{(t-1)}$	−2.4439***	−2.4439***	−2.4050**	−2.4512**	−2.4050***
	(−3.42)	(−2.95)	(−2.48)	(−2.34)	(−3.65)
$price\_bb_{(t-1)}$	−0.0312**	−0.0312*	−0.0333*	-0.0309	−0.0333***
	(−2.60)	(−1.92)	(−2.00)	(−1.67)	(−8.93)
$fms_{(t-1)}$	46.3133***	46.3133*	37.1846*	45.9448**	37.1846***
	(3.56)	(2.05)	(1.99)	(2.13)	(3.88)
$fms^2_{(t-1)}$	−118.522***	−118.5224**	−107.9046**	−120.9295**	−107.904***
	(−4.78)	(−2.55)	(−2.61)	(−2.63)	(−5.37)
$bb\_lines\_hh_{(t-1)})$	−4.7610**	−4.7610**	-1.6642	−2.5625**	−1.6642*
	(−2.51)	(−2.26)	(−1.55)	(−2.06)	(−1.88)
$int\_user\_pc_{(t-1)}$	4.7430	4.7430	6.0861**	4.9290*	6.0861***
	(1.38)	(1.36)	(2.46)	(1.93)	(3.50)
$edu_{(t-1)}$	0.2390***	0.2390***	0.2133**	0.2683***	0.2133***
	(3.24)	(3.52)	(2.72)	(3.37)	(2.83)
$telco\_rev\_hh_{(t-1)}$	−153.2427	−153.2427			
	(−0.39)	(−0.23)			
$i\_iday_{(t-1)}$	4.8560	4.8560			
	(1.37)	(0.82)			
$gdp\_pc\_ppp_{(t-1)}$	0.0001	0.0001			
	(0.86)	(1.25)			
$hh\_dens_{(t-1)}$	2.7844	2.7844			
	(0.80)	(0.71)			
$labcost\_ict_{(t-1)}$	0.0111	0.0111			
	(0.59)	(0.58)			
$labcost_{(t-1)}$	0.0089	0.0089			
	(0.68)	(0.69)			
$wage_{(t-1)}$	−0.1896	−0.1896	0.8247		0.8247
	(−1.09)	(−1.19)	(1.02)		(1.46)
$urban_{(t-1)}$	−0.2842	−0.2842	0.1573		0.1573
	(−1.23)	(−0.98)	(0.38)		(0.58)
$mdw_{(t-1)}$	−0.0016	−0.0016			
	(−0.49)	(−0.38)			
$urban * wage_{(t-1)}$			−0.0123		−0.0123
			(−1.11)		(−1.70)
$bb\_lines * cable_{(t-1)}$				−1.3457	
				(−0.11)	
$cable_{(t-1)}$				0.9451	
				(0.08)	

Table 1 continued

Regression (nr.)	(1) Full_FE	(2) Full_FE_rob	(3) Final_FE_rob	(4) Final_FE_rob_i	(5) Final_FE_DK
$bb\_lines * Eastern_{(t-1)}$				3.1124*	
				(1.99)	
Constant	−13.2967	−13.2967	−32.4730	−27.6838***	−32.4730*
	(−0.65)	(−0.51)	(−1.16)	(−4.48)	(−2.06)
Adjusted R^2	0.658	0.713	0.715	0.714	
R^2_o	0.0520	0.0520	0.0900	0.1865	
R^2_w	0.7399	0.7399	0.7315	0.7310	0.7315
F	23.1167	48.0826	24.9222	29.6084	17728.08
F_θ	8.4553				
RMSE	0.9561	0.8756	0.8781	0.8695	
Observations	172	172	175	174	175

Regressions (1) to (5) include country-specific fixed effects (FE), which are not reported. The t-statistics in parentheses are based on panel robust standard errors in regressions (2) to (5). Indeed, a Wooldridge test for autocorrelation indicates that there is first-order autocorrelation in the data. Likewise, a Wald test for groupwise heteroskedasticity clearly rejects the null hypothesis of a constant variance. Regression (5) employs "Driscoll–Kraay" standard errors ("DK"), whereby the autocorrelation structure has a lag length of $m(T) = floor\left[4(T/100)\hat{}(2/9)\right]$, which turned out to be robust to alternative lag specifications.
$* p < 0.10$, $** p < 0.05$, $*** p < 0.01$

broadband services. The cost controls $wage_{(t-1)}$ and $urban_{(t-1)}$ are insignificant and the latter variable also has an unexpected sign in regressions (1) and (2). Whereas insignificant cost estimates appear to be primarily due to country FEs (low within variation), the unexpected sign of $urban_{(t-1)}$ might be attributed to two opposing effects. First, in densely populated areas, NGA deployment can serve more customers at the same time, thus reducing the costs for a single fiber connection (economies of density). Second, however, the total digging costs are much higher in urban areas, where construction activities become more labor-intensive. We therefore include the interaction term $urban * wage_{(t-1)}$ in regressions (3) and (5) to capture this relationship. Indeed, $urban_{(t-1)}$ then shows the expected sign and its impact on NGA adoption decreases with increases in the wage level, $wage_{(t-1)}$, in regressions (3) and (5).

Overall, we refer to regressions (3) to (5) as final regressions ("Final") as these are the most efficient specifications. When comparing regression (3) with regression (5), one finds that imposing "Driscoll–Kraay" standard errors substantially increases the significance levels. However, as the estimator is based on an asymptotic theory, we have to consider the results with caution in view of our short panel and thus treat the estimation results of model "Final_FE_rob" in regression (3) as the preferred ones.

Regarding the main variables of interest, one first finds a significant and non-linear relationship with respect to our infrastructure-based competition variable, $fms_{(t-1)}$ and $fms^2_{(t-1)}$, for all the FE regressions. The maximum of the non-linear relationship informs us about the optimal competitive market conditions for NGA adoption. For instance, one can infer from the corresponding coefficient estimate that a share

Table 2 Estimation results for the "Final" diffusion model (dep. var.: $ln(Fttx\_hh_{it})$)

Regression nr.	(6) Final_FE_rob_t	(7) Final_FE_rob_pop_t	(8) Final_LSDVC	(9) Final_LDV_rob	(10) Final_OLS_rob
$lnFttx\_hh_{(t-1)}$			0.7056***	0.5682***	0.7800***
			(8.82)	(6.60)	(10.58)
$reg\_bb_{(t-1)}$	−2.3515***	−2.3608***	−2.1195***	−2.1849**	-0.9706
	(−2.99)	(−2.99)	(−2.83)	(−2.47)	(−1.71)
$price\_bb_{(t-1)}$	−0.0270	−0.0274	−0.0243***	−0.0262**	−0.0167*
	(−1.58)	(−1.60)	(−2.70)	(−2.37)	(−1.84)
$fms_{(t-1)}$	45.0935**	44.9592**	18.0557*	19.8921*	2.5754
	(2.27)	(2.26)	(1.90)	(1.98)	(0.38)
$fms^2_{(t-1)}$	−115.5386**	−115.5528**	−39.9050**	−47.8787*	−3.9925
	(−2.75)	(−2.73)	(−2.08)	(−1.95)	(−0.32)
$bb\_lines\_hh_{(t-1)}$	−4.9070*	−4.9498*	−1.0464	−1.1389	0.3124
	(−1.99)	(−2.01)	(−0.72)	(−1.27)	(0.48)
$int\_user\_pc_{(t-1)}$	5.1423**	5.0215**	2.0246	3.3042**	0.1498
	(2.14)	(2.11)	(0.91)	(2.65)	(0.18)
$edu_{(t-1)}$	0.1577**	0.1581**	0.0338	0.0608	0.0044
	(2.22)	(2.22)	(0.50)	(0.95)	(0.34)
$urban_{(t-1)}$	0.1094	0.1164	−0.0107	−0.0334	−0.0194
	(0.31)	(0.33)	(−0.04)	(−0.12)	(−1.65)
$wage_{(t-1)}$	0.9914	1.0140	−0.0699	−0.1204	−0.0873
	(1.40)	(1.43)	(−0.11)	(−0.20)	(−1.49)
$urban * wage_{(t-1)}$	−0.0161	−0.0164	0.0002	0.0005	0.0011*
	(−1.57)	(−1.60)	(0.02)	(0.05)	(1.74)
t	0.4268*	0.4325*			
	(1.71)	(1.73)			
Constant	−25.0351	−26.3051		−4.0605	0.6330
	(−1.07)	(−1.12)		(−0.25)	(0.39)
Adjusted R^2	0.731	0.732		0.817	0.884
R^2_o	0.0226	0.0173		0.5627	
R^2_w	0.7482	0.7493		0.8296	
F	26.5819	26.7343		83.5753	134.2713
RMSE	0.8530	0.8532		0.6550	0.7938
Observations	175	175	162	162	162

The t-statistics in parentheses are based on panel robust standard errors in regressions (6) to (7) and (9) to (10). The LSDVC standard errors in regression (8) are bootstrapped based on 100 iterations with bias correction initialized by the Arellano and Bond estimator for estimates up to order O(1/T).
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

of ∼17.2 and 19.5 % of fixed landlines is optimal in regression (3) in Table 1 and regression (6) in Table 2 (including the time trend), respectively. The grand mean of $fms_{(t-1)}$ is ∼ 26.88 % and thus above this optimal value, which means that the escape competition effect still dominates the Schumpeterian effect and fixed-to-mobile substitution has exerted a positive impact on NGA adoption in the past. However, increasing competition from mobile networks brought the average value of this variable close to its optimum during the analysis period with $\overline{fms}_{(2004)} = 0.3317$ and $\overline{fms}_{(2011)} = 0.2314$.[24]

The coefficient of the variable $bb\_lines\_hh_{(t-1)}$ is negative and significant in regressions (1), (2) and (5) but not in regression (3) which provides unclear evidence as regards the replacement effect. In regression (4) we therefore examine the replacement effect in greater detail by testing potentially relevant interaction effects. As the replacement effect refers to both DSL and cable connections, we first test whether there is a differential effect with respect to these forms of intramodal competition by including an additional interaction term, $bb\_lines * cable_{(t-1)}$, in regression (4) in Table 1. As the corresponding coefficient is insignificant (as well as the coefficient of the main effect, $cable_{(t-1)}$), we conclude that there is no differential impact and the replacement effect comes equally from both types of fixed broadband infrastructure. This result appears to be reasonable in view of the rather similar quality and price characteristics of intramodal coax and copper/DSL broadband retail services. Second, the replacement effect might be subject to a differential effect with respect to the extent of broadband infrastructure in the individual member states. Most notably, one can safely assume that the lack of well established first generation broadband infrastructure in Eastern European transition economies pushed migration towards NGA services in those countries and simultaneously opened up an opportunity for operators to directly deploy NGA infrastructure at much lower opportunity cost (Briglauer and Gugler 2013). And, in fact, regression (4) shows that the coefficient of $bb\_lines\_hh_{(t-1)}$ is now significant as well as the interaction term $bb\_lines\_hh * Eastern_{(t-1)}$. Moreover, the negative marginal effect of the first generation broadband for the average European member state is more than offset, if we control for the group of Eastern European member states. This implies that the replacement effect is of relevance only in the non-Eastern European Union member states which typically exhibit well-established first generation broadband infrastructure.

Finally, we find a coefficient of the regulatory variable, $reg\_bb_{(t-1)}$, which is estimated in the quite narrow range of −2.4050 to −2.4512 for all the FE regressions in Table 1 and significantly negative throughout all the estimations (including those in Table 2). This strongly supports our hypothesis outlined in Sect. 4.1 that the more effective broadband access regulation is, the more negative is the impact on the adoption of NGA services. The average estimate of the coefficient of $reg\_bb_{(t-1)} (\sim -2.42)$ in regressions (1) to (5) implies that an increase in regulatory intensity of 10 % points leads to a decrease in NGA adoption of 21.49 % ([=$exp(-2.42 \times 0.1) - 1] \times 100$). Evaluated at the grand mean, which represents the average EU27 member state, this implies an average decrease from 0.05147 to $\sim$ 0.04041 NGA lines per household.

[24] It is interesting to contrast this result with the finding of Briglauer et al. (2013), who measure mobile competition in a different way (based on survey data for the years from 2005 to 2010) but also find that competition stemming from mobile networks has increased but is well below its optimum value on average.

The average broadband price variable, $price\_bb_{(t-1)}$, is negative and significant in most FE regressions from which we infer that the price variable mainly stands proxy for a general broadband price level as presumed in Sect. 5.2.3. If we drop $price\_bb_{(t-1)}$ from the regressions, the coefficient of $reg\_bb_{(t-1)}$ increases throughout in absolute terms [e.g., from ~ -2.405 to ~ -2.535 in regression (3)], which shows that the price effect is opposed to the negative effect of regulation on NGA investment. However, since this increase is not substantial, we infer that the negative direct impact of regulation on supply-side investment activities dominates the price effect on the demand side.

Table 2 contains the estimation results of the dynamic specification for the "final" diffusion models. Regression (6) first reports the results for the exponential growth model that includes a linear time trend, t. As expected the coefficient is positive, indicating diffusion effects, and significant at the 10 % level. Overall, the other coefficient estimates are not changed substantially when compared with the "final" specifications of the static adoption model in Table 1. We also estimate regression (6) as two-way FEs by including year dummies instead of the linear time trend. However, the year dummies are jointly insignificant (the F-statistic is 0.92; not reported in Table 2) and hence their inclusion would result in less efficient estimates. Regression (7) shows that the coefficient estimates remain virtually unchanged if we normalize our dependent variable with respect to the total population ("pop") instead of the total number of households.[25]

Regression (8) includes the lagged dependent variable, $ln(Fttx\_hh_{(t-1)})$, as an additional regressor in order to control for endogenous growth in terms of network effects. Estimating regression (8) by means of an ordinary FE estimator would yield inconsistent and biased results, since the lagged dependent variable and the error terms would be correlated (Nickell 1981). The usual way to work around this source of endogeneity is applying GMM estimators. However, a weakness of GMM estimators is that their properties only hold for a large number of cross-sectional units ($n \leq 27$ in our case). Monte Carlo evidence supports a bias-corrected LSDV estimator, which proves to be (much) more efficient than various instrumental variable-type estimators when n is small (Kiviet 1995). Bruno (2005a,b) developed a bias corrected estimator for unbalanced panel data ("LSDVC").

Although the basic structure of the LSDVC estimation results in regression (8) is still similar to that of the previous regressions, the focus here is on the coefficient of the lagged dependent variable, $ln(Fttx\_hh_{(t-1)})$, which is highly significant and substantial ($\alpha_1 = 0.7056$). This gives us an initial indication of the relevance of the network effects underlying. However, a high value of α_1 is not necessarily due to true state dependency as it might be also the result of correlation with unobserved heterogeneity (θ_i) or error dynamics in a static model. Fortunately, it can be shown that OLS and FE estimators are likely to be biased in opposite directions in autoregressive models (Bond 2002). Whereas OLS leads to upward biased estimates of α_1, since the values of the lagged dependent variable are positively correlated with the omitted country fixed effects, FE estimates are downward biased for small T. Hence, if the

[25] The same result holds for the static adoption models in Table 1 (results are available upon request).

dynamic model in Eq. (2) is correctly specified, the true estimate of α_1 capturing state dependency is between OLS and FE estimates. Comparing the respective coefficient estimates in regressions (8) to (10), one can infer that the LSDVC estimate for α_1 lies nicely within the interval [0.5682; 0.7800]. Even if we refer to the lower bound, we can thus safely conclude that a causal mechanism via the last period and hence substantial network effects exist which autonomously push the adoption of new ICT services, as outlined in Sect. 4.4. The speed of diffusion ($\lambda = 1 - 0.7056$) suggests that it will take around 6.5 years to close 90 % of the gap between the average number of NGA connections per household (0.05147) and the Digital Agenda's target value (0.5). Also, note that speed of diffusion is significantly greater than zero for all values of $\alpha_1 \in [0.5682; 0.7800]$, which confirms that migration to NGA services is indeed subject to some non-negligible switching costs on the side of the consumers.[26]

8 Summary and final remarks

This work identifies the effects of sector-specific ex ante regulation and infrastructure competition on the adoption of NGA services in Europe using static and dynamic model specifications with recent panel data from the EU27 member states. As opposed to the related literature, the econometric specification explicitly addresses the endogeneity problem mainly by relating NGA adoption to regulation and competition in preceding broadband markets.

The results indicate firstly that NGA adoption is negatively influenced by the extent and effectiveness of the wholesale broadband access regulation that is imposed on the incumbent's first-generation DSL infrastructure. Also, it should be pointed out that the impact of regulation is quite substantial. Accordingly, the goals of the EC's Digital Agenda seem to be at odds with the sector-specific EU regulatory framework, which intends to expand access regulation to the emerging NGA infrastructure and corresponding NGA wholesale access services. Realizing the targets of the EC to reach 50 % adoption with 100 Mbit/s high-speed Internet connections by 2020 becomes much more unlikely if the prime importance is attached to high-cost FTTH/B deployment scenarios (Briglauer and Gugler 2013). Secondly, competition stemming from mobile networks affects NGA adoption in a non-linear way, as expected. With respect to the time frame of our analysis, the positive impact of the escape competition effect dominates the Schumpeterian effect. Thirdly, we also found evidence of a replacement effect underlying the first-generation broadband infrastructure, which appears to be of particular relevance in the "old" EU member states with well established infrastructure and might become even reinforced in the future in view of the potential of new DSL and coax technologies. Finally, our dynamic specification suggests that substantial network effects give rise to an endogenous NGA adoption process. As this process exhibits high growth potential, the adoption target of the EC appears to be still feasible time wise, if one refers to a broad NGA definition and if NGA adoption is not endangered by shocks on the demand or supply side or by wrong policy incen-

[26] This is also confirmed by a recent survey of the EC (2012, p. 60) which shows that a majority of EU citizens are not willing to switch to high-speed broadband services due to (i) lack of awareness of potential benefits, (ii) lack of experience with new services and (iii) expected price level of NGA services.

tives. Regarding the latter, it is interesting to note that the EC recently published a recommendation "on consistent non-discrimination obligations and costing methodologies to promote competition and enhance the broadband investment environment" (European Commission 2013) that holds out the prospect of departing from a strict cost-based access regulatory approach in the case in which NRAs impose sufficient non-discrimination obligations in conjunction with competitive safeguards. It appears that the massive criticism to the NGA recommendation (European Commission 2010) triggered a partial reversal within the sector-specific EU framework in the direction of more deregulatory policies.

It should be noted once again that the intention of this paper is neither to identify the demand *or* supply related to NGA adoption and deployment, respectively, which is a task of future research. In view of the dynamic interaction of supply and demand, a proverbial chicken-and-egg situation gives rise to a coordination problem: it is not clear a priori whether there has to be demand for new, attractive and bandwidth-hungry services in advance in order to enforce the deployment of new communications infrastructure or whether those services and applications will automatically evolve after the necessary infrastructure has been put in place. Internet history indicates that the development of content and applications usually follows infrastructure deployment, e.g. there would be none of the Web 2.0 services and social platforms available in a world with narrowband dial-up Internet infrastructure. This view suggests that the goals of the EC's Digital Agenda can be reached best if NGA deployment is primarily driven by the supply side, either by means of US-like deregulatory approaches or via favorable competitive market conditions, as indicated by our results and the vast majority of the previous and broadband-related literature.

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9 Appendix

See Figure 1 and Tables 3, 4, 5.

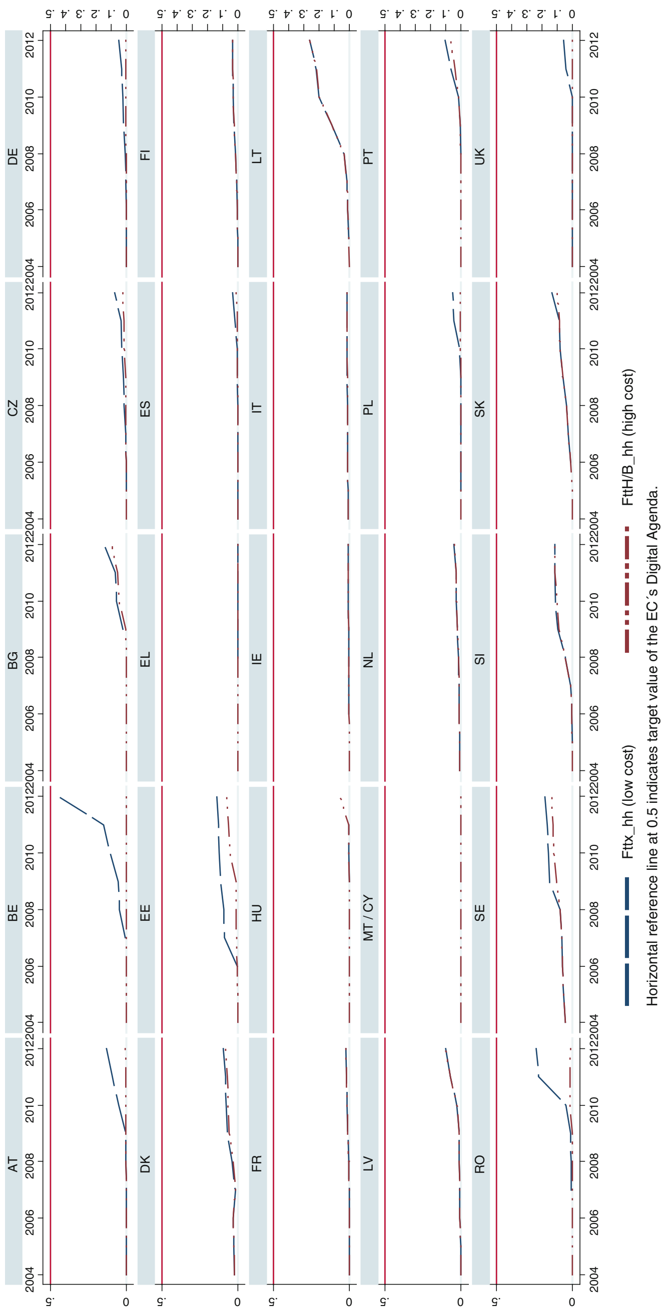

Fig. 1 NGA household adoption levels for FTTx and FTTH/B technologies in the EU27

Table 3 Variable description and sources

Variable (expected sign)	Description	Source[a]
Dependent variable(s)		
FTTx connections per household, *Fttx_hh (Fttx_pop)*	Number of households connected by FTTx technologies normalized to a country's total number of households (normalized to total population)	©FTTH Council Europe[b]
Main explanatory variables		
Extent of broadband access regulation, *reg_bb (-)*	Share of regulated lines (local loop unbundling, bitstream, resale) to total retail broadband lines (minus cable entrant lines)	EU Progress Report[c]
Broadband price, *price_bb (?/-)*	Average monthly cost of capped/uncapped residential fixed broadband for 1 Mbps–10 Mbps in euros excluding VAT. Tariffs are a weighted average of representative stand-alone products of incumbent and entrant operators whose accumulative subscribers are over 90% of each country's total broadband market	©Quantum-Web Limited[d]
Broadband lines, *bb_lines_hh (-)*	Number of total retail broadband lines (DSL and coax) as a share of the total number of subscribed households	EU Progress Report ©EUROMONITOR (households)
Fixed-to-mobile substitution, *fms (+(levels) - (squared term))*	Share of the total number of fixed landlines to the total number of fixed lines and mobile subscribers. *Mobile-cellular telephone subscriptions* include the number of postpaid subscriptions and the number of active prepaid accounts (which have been used during the last three months). They exclude subscriptions via data cards or USB modems. *Fixed-landlines* refer to the number of active lines connecting subscribers' terminal equipment to the PSTN	ITU[e]
Cable lines, *cable (?)*	Number of total retail broadband cable lines run by entrants as a share of the total retail broadband lines	EU Progress Report
Control variables		
Education, *edu (+)*	Percentage of the adult population (25–64 years old) that has completed at least upper-secondary education	EUROSTAT[f]
GDP per capita, *gdp_pc_ppp (+)*	GDP per capita and PPP adjusted in current US$	World Bank[g]
Average revenue, *telco_rev_hh (+)*	Total telecommunications revenues in mn US$ per household with constant 2011 prices and fixed 2011 exchange rates	©EUROMONITOR[h]
Heavy Internet users, *i_iday (+)*	Share of the population using Internet services every or almost every day	EUROSTAT/COCOM[i]
Household density, *hh_dens (+)*	Average number of household members, expressed as a share of a country's population in its total number of households	©EUROMONITOR (households) EUROSTAT (population)
Internet users, *int_user_pc (+)*	Internet users per capita	©EUROMONITOR

Table 3 continued

Variable (expected sign)	Description	Source[a]
ICT labor cost index, *labcost_ICT (-)*	Annual ICT labor cost index normalized to 100 in 2008	EUROSTAT
Labor cost index, *labcost (-)*	Annual labor cost index normalized to 100 in 2005	© EIU[j]
Multiple dwellings, *mdw (+)*	Annual building permits—number of two and more dwellings normalized to 100 in 2005	EUROSTAT
Wage per hour, *wage (-)*	Wage per hour manufacturing in US$ with constant 2011 prices, fixed 2011 exchange rates	© EIU
Urban population, *urban (+)*	Urban population as a percentage of the total population	©EIU
Eastern European, *Eastern*	Dummy variable equal to 1 if country is BG, CZ, EE, HU, LT, LV, PL, RO, SL or SK	

[a] Note that some sources are commercially available only (©), while others are publicly available

[b] FTTH Council Europe is a non-profit industry organization, the aim of which is to enforce the deployment of fiber-optic technology in Europe. Data are collected by IDATE (www.idate.org) through desk research, direct contact with FTTx players, information exchange with FTTH Council Europe members and from IDATE partners. Data from June 2005 to June 2011 and December 2011 (= 2012) are available at: http://www.ftthcouncil.eu/resources?category_id=6. Data for Bulgaria and Luxembourg are available only for 2009 onwards. There are no data for Malta and the number of subscribers for Cyprus is de facto time-constant and essentially null (with one rise from 100 to 120 FTTx lines)

[c] The EU "Progress Report on the Single European Electronic Communications Market" for data from 2004 to 2011 is available at: http://ec.europa.eu/information_society/policy/ecomm/library/communications_reports/index_en.htm. There are missing values for Bulgaria and Romania for the years from 2004 to 2006

[d] Data are based on a quarterly monitoring service that harvests over 2,000 fixed broadband tariffs across 100 countries. A few missing values for the variable *price_bb* had to be linearly interpolated

[e] The ITU World Telecommunication/ICT Indicators Database is available at: http://www.itu.int/ITU-D/ict/statistics/

[f] Data are available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/information_society/data/database. There are a few missing values for the variable *iday*, which had to be linearly interpolated

[g] The World Bank's "World Development Indicators" are available at: http://data.worldbank.org

[h] The Euromonitor International database is available at: http://www.euromonitor.com/. The number of households in 2012 was set equal to the number in 2011

[i] Data collected by EC services, through NRAs, for the Communications Committee (COCOM).

[j] The Economist Intelligence Unit country database is available at: https://eiu.bvdep.com/frame.html

Table 4 Summary statistics

Variable	Variation	Mean	Std. Dev.	Min	Max	Obs
Fttx_hh	Overall	0.0514702	0.1047494	3.77E−06	0.8574688	$N = 191$
Fttx_pop	Overall	0.0212465	0.0406438	1.52E−06	0.3171702	$N = 191$
reg_bb	Overall	0.2435517	0.2218102	0	0.9947678	$N = 210$
price_bb	Overall	29.76357	15.75987	5.26	99.89	$N = 226$
fms	Overall	0.2688139	0.0746535	0.1076148	0.437505	$N = 216$
edu	Overall	68.26574	13.96395	26	86.1	$N = 216$
gdp_pc_ppp	Overall	29405.69	13476.8	8730.804	89055.8	$N = 216$
telco_rev_hh	Overall	0.0023742	0.0010328	0.0004868	0.0046744	N = 216

Table 4 continued

Variable	Variation	Mean	Std. Dev.	Min	Max	Obs
i_iday	Overall	0.4021399	0.1808903	0.036	0.8039	$N = 216$
bb_lines_hh	Overall	0.4201162	0.2130044	0.0069897	0.8752053	$N = 210$
cable	Overall	0.2415984	0.1615649	0	0.8279159	$N = 209$
cable_lines_hh	Overall	0.0898561	0.0843489	0	0.377342	$N = 209$
dsl_lines_hh	Overall	0.2796187	0.1734783	0.0061826	0.7938271	$N = 209$
hh_dens	Overall	2.507075	0.2827785	1.999367	3.204768	$N = 243$
int_user_pc	Overall	0.6064277	0.1844711	0.1500006	0.9325179	$N = 216$
labcost_ICT	Overall	96.27037	13.70907	47.7	165.1	$N = 216$
labcost	Overall	112.0291	21.62619	81.4439	226.7329	$N = 213$
mdw	Overall	89.98745	46.11853	9.96	344.11	$N = 216$
wage	Overall	16.00741	11.13623	1.6	51.4	$N = 216$
urban	Overall	72.08326	11.79625	48.6801	97.4358	$N = 216$
t	Overall	5	2.587318	1	9	$N = 243$

Table 5 Direct Granger causality tests with LSDVC

Regression nr.: Dependent var.: Independent var.:	(A.1) ***logFttx_hh***	(A.2) ***reg_bb***	(A.3) ***price_bb***	(A.4) ***fms***	(A.5) ***bb_lines_hh***
Lag 1: lnFttx_hh	0.7599***	**0.0172**	**−0.2171**	**0.0005**	**0.0063**
	(7.02)	(1.34)	(−0.21)	(0.37)	(1.34)
Lag 2: lnFttx_hh	−0.2251**	**−0.0103**	**1.2378**	**0.0004**	**0.0008**
	(−2.20)	(−0.77)	(1.25)	(0.26)	(0.18)
Lag 1: reg_bb	**−1.4602***	0.2077*	−4.6318	−0.0231*	−0.0136
	(−1.66)	(1.75)	(−0.48)	(−1.88)	(−0.33)
Lag 2: reg_bb	**−0.7297**	0.1999**	−4.6678	−0.0046	0.0324
	(−0.69)	(2.24)	(−0.49)	(−0.32)	(0.66)
Lag 1: price_bb	**−0.0213***	−0.0002	0.5096***	0.0000	−0.0008
	(−1.75)	(−0.14)	(3.97)	(0.03)	(−1.30)
Lag 2: price_bb	**−0.0115**	−0.0004	0.0173	0.0001	0.0007
	(−1.11)	(−0.23)	(0.15)	(0.60)	(1.23)
Lag 1: fms	**−3.7719**	2.9152	174.1643	1.2292***	0.1384
	(−0.14)	(0.77)	(0.54)	(13.39)	(0.10)
Lag 2: fms	**4.6910**	−3.9993	22.2926	−0.6351***	0.8075
	(0.17)	(−1.06)	(0.07)	(−3.14)	(0.62)
$Lag1 : fms^2$	**19.7170**	−10.3231	−380.4769	−0.9275***	1.0401
	(0.33)	(−1.28)	(−0.58)	(−3.44)	(0.37)
$Lag2 : fms^2$	**−16.0605**	12.9332*	−12.0118	1.0089**	−1.9191
	(−0.29)	(1.69)	(−0.02)	(2.39)	(−0.75)
Lag 1: bb_lines_hh	**−1.8601**	−0.3531	−73.4958**	0.0739	0.7056***
	(−0.61)	(−0.82)	(−2.40)	(1.47)	(8.71)

Table 5 continued

Regression nr.: Dependent var.: Independent var.:	(A.1) ***logFttx_hh***	(A.2) ***reg_bb***	(A.3) ***price_bb***	(A.4) ***fms***	(A.5) ***bb_lines_hh***
Lag 2: bb_lines_hh	**0.6942**	0.3409	34.6634	−0.0503	−0.0292
	(0.28)	(1.02)	(1.41)	(−1.44)	(−0.33)
Lag 1: int_user_pc	**4.0283**	0.2643	6.8033	0.0575	0.1564
	(1.28)	(0.61)	(0.22)	(1.14)	(1.04)
Lag 2: int_user_pc	**0.4455**	0.3211	17.2223	−0.0460	0.1075
	(0.15)	(0.77)	(0.59)	(−0.98)	(0.77)
Lag 1: edu	**0.0157**	0.0040	−1.9402*	−0.0029*	0.0004
	(0.15)	(0.26)	(−1.73)	(−1.80)	(0.07)
Lag 2: edu	**0.0168**	−0.0290***	1.0222	−0.0012	0.0025
	(0.20)	(−2.63)	(1.08)	(−0.84)	(0.57)
Lag 1: urban	−**0.0962**	−0.2081	12.1685	−0.0299	0.0124
	(−0.05)	(−0.86)	(0.62)	(−0.96)	(0.16)
Lag 2: urban	−**0.1714**	0.1179	−7.9139	0.0358	−0.0115
	(−0.09)	(0.47)	(−0.40)	(1.09)	(−0.14)
Lag 1: wage	−**0.0932**	0.0391	−4.4858**	−0.0000	−0.0168**
	(−0.46)	(1.45)	(−2.30)	(−0.01)	(−1.97)
Lag 2: wage	−**0.5508**	−0.3073**	7.5938	0.0001	0.0360
	(−0.66)	(−2.44)	(0.96)	(0.00)	(1.00)
*Lag 1: urban*wage*	**0.0087**	0.0045***	−0.0465	−0.0000	−0.0003
	(0.77)	(2.61)	(−0.43)	(−0.03)	(−0.57)
*Lag 2: urban*wage*	**0.0004**	−0.0009**	−0.0262	−0.0001**	0.0001
	(0.15)	(−2.40)	(−0.94)	(−2.00)	(0.56)
Granger causality tests with p-values of χ^2-tests of joint significance of coefficients displayed in bold in regressions (A.1) to (A.5):					
Prob > $\chi 2$ (Lag 2)	0.0373**	0.3927	0.4437	0.8613	0.2300
Observations	126	126	125	127	126
Prob > $\chi 2$ (Lag 3)	0.0154**	0.8718	0.9641	0.7171	0.2836
Observations	111	112	111	112	112

Since Granger causality tests require inclusion of lagged dependent variables, we had to use the LSDVC specification (regression (8) in Table 2). In order to test for reverse causality we used all variables of the "final" specification in regression (8). Predetermined explanatory variables are dated $t-2$ or earlier. The lower part of Table 5 shows the p-values for the Granger χ^2-test once for inclusion of two lags and once for inclusion of three lags (corresponding coefficient estimates and t-statistics for the latter case are not reported in Table 5). In regression (A.1) causation is established, since the coefficients of the independent variables (in bold) are jointly significant (Prob > χ^2(Lag 2) = 0.0373) in line with the baseline specifications in Eqs. (1) and (2). For regressions (A.2) to (A.5) the Granger causality χ^2-statistics are insignificant for both Lag 2 and Lag 3, suggesting that there are, as expected, no reverse causality patterns. Since a referee raised a concern that the variable *price_bb* might be endogenous, we also ran bivariate Granger causality tests. Again, there was no indication of reverse causality which reaffirms that there is also no bidirectional causality in the multivariate model (results are available from the author upon request). t-statistics in parentheses, LSDVC standard errors in regression (A.1) to (A.5) are bootstrapped based on 100 iterations. $* p < 0.10$, $** p < 0.05$, $*** p < 0.01$

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