Essays on competition in the telecommunication industry

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General introduction

My experiences as a scientific associate at WIK GmbH motivated this dissertation and the topics it addresses. In this period, which extended over the first half of my Ph.D. studies, I supported public policy makers to design, adapt, and alter regulation regimes imposed on the telecommunication markets and supported ministries in the context of 5G and broadband state aid. The issues, debates, and concerns I encountered during this period sparked my interest in conducting research on three different policy-relevant issues in order to provide rigorous evidence for the policy debate while also advancing the existing literature.

The dynamic nature of the telecommunications industry is characterized by the constantly increasing demand for faster, more reliable, and flexible broadband connections. These performance improvements require significant investments by competing actors on the supply side. Over the past three decades, services evolved quickly from providing basic fixed telephony services via fixed copper lines to a nearly ubiquitous provision of broadband and telephony services not only over fiber, coaxial cable, and copper-based fixed networks, but also wirelessly via 2G to 5G technologies (Lemstra, 2018). Such short innovation cycles and massive investment requirements pose significant challenges for public policy makers because not only do they need to keep up with the pace of technological innovation to adjust regulatory remedies accordingly, they must also consider the competitive dynamics among the actors in the telecommunication markets while preserving incentives to invest (Vogelsang, 2017).

Previous literature has focused on exploring and analyzing the intersection of competition economics, public policy, and technology within the telecommunication industry. Indeed, these issues attract continuous attention among scholars and practitioners. My thesis contributes to the understanding of technological innovations and their implications on regulation, merger control decisions, and competition law. All three chapters of this dissertation build on an in-depth analysis of the technology and the competition dynamics on the telecommunication market. However, this common basis affects the chapters, and especially the methodology, in different ways. In the first chapter it primarily drives the models' assumptions, while in Chapter 2 it motivates the dataset choice as well as the estimation strategy. Chapter 3, in turn, presents the new technology, 5G, and derives potential effects on the competitive landscape which I discuss in regards to the respective policy implications.

This dissertation divides the telecommunications realm into two partly interrelated segments: the fixed and the mobile. The fixed broadband segment encompasses the supply and demand for (location-)fixed residential and business broadband access. Chapter 1 addresses the question of which measures public policy makers may adopt in order to facilitate voluntary vertical separations (i.e. the split between the infrastructure ownership and the service provider role). To address this question, I analyze the underlying technoeconomics of a greenfield fiber-to-the-premise rollout by utilizing a Net Present Value (NPV)-modeling approach. Chapter 2 employs an econometric model to investigate the competitive dynamics between cable and fiber infrastructure rollouts. This chapter provides an extensive historical and technological background of the cable network rollouts, which serves as a sound basis for understanding the data and explains why my chosen econometric approach diverges from those used in the existing literature. Chapter 3 addresses the mobile segment by exploring the disruptive effect

5G may have on the broader wireless segment. The research draws on the technological potential of 5G and identifies implications for competition in the mobile segment based on the 5G-visions, 5G-investment requirements, and 5G-deployments models.

The first chapter addresses the potential role of wholesale-only networks from a public policy perspective. One of the most pressing challenges public policy makers face currently is the need to preserve incentives for private firms to invest in fiber-to-the-premises (FTTP) infrastructure while simultaneously enabling effective competition. With regard to the latter objective, the ability of vertically integrated operators to discriminate against downstream rivals is regarded as a major regulatory problem, especially as policing nondiscrimination obligations is notoriously difficult for vertically integrated operators. Under the European regulatory framework, national regulation authorities may mandate functional separation to eliminate discrimination incentives (see e.g., Cadman, 2019; Kongaut & Bohlin, 2014; Nucciarelli, Sadowski & Achard, 2010; Ovington, Smith, Santamaría, & Stammati, 2017). However, this measure comes with significant drawbacks and caveats while also resembling a strong market and ownership intervention. Chapter 1 discusses how voluntary vertical separation can achieve the positive effect of a vertically separated industry structure without the need for strong market interventions. I use a discounted cash flow model to compare the financial attractiveness of wholesale-only and integrated business models for a greenfield FTTP rollout. I then discuss and test how public policy makers could positively affect the profitability of a wholesale-only business model. Based on my findings, I recommend that public policy makers and national regulation authorities: (1) Proactively and precisely define separation scenarios and respective ex ante regulation reductions; (2) make adjustments to broadband state aid programs that favor wholesale-only providers; and (3) critically reflect the hampering effect of incumbents' volume and time discount wholesale tariff structures on the emergence of wholesale-only networks.

In the second Chapter, I analyze the effect of cable networks on fiber to the x (FTTx) network expansions by drawing on data from a sample of 28 European countries spanning from 2011 to 2017. I deviate from the existing literature by drawing on technology coverage data instead of penetration data (see e.g. Fourie and de Bijl, 2018) in order to measure the full competitive pressure that cable networks exert. I also employ different estimators to distinguish between different phases of cable network rollouts accounting for the thesis that the rollout phases may have differently directed competitive effects. My main finding is a negative relationship between legacy cable network coverage and FTTx network expansion while there is a positive effect of cable network expansion areas. The restraining effect associated with legacy cable networks is not taken into account by the current regulatory regime, which is primarily designed to enable effective competition against the incumbent on copper- and fiber-based infrastructure. Therefore, my analysis is a crucial first step to designing a sound regulatory and competitive framework that achieves the ambitious broadband targets set by the European Commission and various national governments. Most importantly, I conclude that public policy makers should assess broadband markets distinctly for cable and non-cable regions to reflect the different competition dynamics between cable operators and operators investing in FTTx networks. The positive effect of cable expansion areas indicates that competitive dynamics vary greatly by geography since the positive effect shows functioning inter-platform competition in areas to which cable operators extend their legacy networks

The third Chapter, co-authored with William Lehr and Justus Haucap, addresses competition in the mobile segment in the 5G era. In recent years, significant attention has been directed toward the fifth generation of wireless broadband connectivity (5G) currently being deployed by mobile network operators (MNO). The step from 4G to 5G promises to be profound in two different ways: First, 5G is expected to improve LTE's performance in an evolutionary fashion (reduced latency, more bandwidth, higher resiliency). Secondly, it is expected to include a multitude of new functionalities and deployment options, expanding the usage of cellular technologies beyond providing mobile telephony and broadband connectivity to consumers and business users (ITU-R, 2015). In this paper, we present a framework for understanding how the transition to 5G and it's technical ability to expand beyond currently served markets may impact competition in the full extent of the wireless broadband ecosystem. Enabling effective competition has been a key objective for network regulation since the liberalization and continues to play a key role in the 5G era. In our framework, we present three key market opportunities within the 5G realm, each with different preconditions for competition. These include (1) enhanced Mobile Broadband (eMBB); (2) wide-area coverage for niche applications; and (3) local coverage and capacity markets. While MNOs in the markets are likely to compete in all of the market segments, they may be confronted with new competition from new facility-based entrants that provide 5G connectivity in the latter two market segments adopting a low-density wide area network supply model or the local private network supply model. We conclude our paper by describing an array of policy implications. We emphasize that access to available and suitable spectrum for new entrants is indispensable in both allowing for new market entries and in blocking MNOs from foreclosing potential competition. Furthermore, we underline that governments have a significant monopsony power as their demand for public safety connectivity represents a large demand source on its own. We argue that this power and respective effects on the competition in the broader wireless ecosystem ought to be considered when designing public safety mobile connectivity tenders.

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Chapter 1:

Towards a vertically separated broadband infrastructure: The potential role of voluntary separation

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1. Introduction

The social benefits of broadband infrastructure are hardly disputed within academia and politics. Broadband infrastructure is broadly seen as a key enabling technology in today's knowledge economy. Users can access information and entertainment services online and communicate with each other at lower costs than ever before, and businesses can enhance their efficiency and innovate faster and more easily. Numerous studies find empirical evidence that broadband infrastructure has a positive causal effect on economic growth, employment, and regional development, as well as on firms' productivity and performance (see Bertschek, Briglauer, Hüschelrath, & Niebel, 2016 for an overview). There is also evidence suggesting a stronger effect for broadband infrastructures providing higher bandwidths (Abrardi & Cambini, 2019; Hasbi, 2017; Lee & Brown, 2008).

Against this background it is unsurprising that there is a plethora of debates within politics, academia and the industry on how to expedite and expand the geographical scope of investments in broadband infrastructure. Among other already widely adopted measures, such as state aid, other less prevalent ideas are evaluated concurrently. These do not necessarily depict direct measures, but rather aim to facilitate roll-out models that are seen as beneficial for successful broadband rollouts[1]. This paper regards a vertical separation of wholesale and retail activities in the fixed broadband industry. Such structural separation, under which a firm either owns the network or retails broadband services to customers opposes the current prevalent industry structure in Europe, mainly comprising of vertically integrated firms. This paper presents the merits and caveats of a vertical disintegration alongside the existing literature and answers the question, how public policymakers could facilitate the emergence of voluntary separation while refraining from direct market interventions such as mandatory separation. Starting from the premise tat that market participants would increasingly adopt a wholesale-only model if it is In other words, if the wholesale only business model is financially at least as attractive as the integrated model or even superior, we test, one should expect the trend to strengthen. This paper aims to contribute test if if, and under which circumstances this could be the case. To do so, we first model the investment decisions of integrated and wholesale-only operators using a discounted cash flow (DCF) model. As a second step, we test sensitivities to

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[1] E.g. state aid or universal service obligations finance or stipulate a certain degree of additional broadband roll-outs and therefore can be considered direct measures. Contrarily, the facilitation of vertical separation or co-investment in itself does not lead to such certain roll-outs, but is expected to bring about positive effects on private firms investment decisions or regulatory issues.

identify and potential levers to increase the financial attractiveness of the wholesale-only model. Lastly, we discuss what measures can be taken by public policymakers to affect the levers identified. Our paper builds on broad research exploring the impact of vertical separation, but is unique to the extent that firm-level investment decisions are modeled[2] to draw conclusions for the regulatory and public policy domain. This approach allows to take the current market structure into account in order to yield actionable conclusions.

2. Industry background

In light of its aforementioned relevance, access to and adoption of high-speed broadband has become a top political priority in many countries. Nevertheless, incentivizing broadband investments is not the only objective public policymakers pursue. Most notably, national regulation authorities (NRAs) also strive to enable effective competition in order to optimize static efficiency. Achieving both aims, incentivizing investments while enabling competitive markets, is a challenging task. This is especially true for non-urban regions, where investment costs per household rise—in many instances, above the level at which more than one infrastructure is economically viable (Feijóo, Ramos, Armuña, Arenal, & Gómez-Barroso, 2018). In such regions, natural monopoly characteristics are exhibited by such broadband networks. To avoid consumer harm, the current regulatory regime in Europe mandates access to the infrastructure of so-called significant market power (SMP) operators.[3] Mandated access allows downstream competitors to be active on the retail market without their own (access) infrastructure, and therefore enables service competition. This separates the market vertically into wholesale (infrastructure) and retail (service) segments. Essentially, regulators seek to mandate access in order to allow for competitive retail markets, especially in regions in which multiple broadband access networks are not sustainable.

The regulatory approach applied today comes with a number of caveats. Firstly, SMP operators have incentives to discriminate against retail competitors in favor of their own retail arms (Cadman, 2010). This can take the form of price and non-price discrimination (de Bijl, 2005;

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[2] A similar approach has been taken by (Felten & Langer, 2016), though this paper focuses the effect of capital costs.

[3] SMP operators are defined as the dominant operator in a defined market (Article 12 Directive 2002/19/EC of the European Parliament and of the Council of 7 March 2002 on access to, and interconnection of, electronic communications networks and associated facilities). “Dominance” exists if a firm has the ability to behave, to an appreciable extent, independently of its customers and competitors (Cave, 2009).

Laffont & Tirole, 2001). Supplying its own retail arm with cheaper and higher-quality wholesale products allows an SMP to capture additional profits on the retail market. Regulators address these concerns by defining wholesale product prices and quality parameters, usually in the form of price caps, non-discrimination requirements or provisions for equivalence of input (Cadman, 2019).

Such extensive ex-ante regulation, however, comes with significant drawbacks, as regulatory decisions are oftentimes drawn out, and there is a danger of status quo inertia, unjustified intervention, and a reduction of freedom to compete and innovate (Vogelsang, 2017). Moreover, the SMP designation requires thorough market reviews that come with a need for extensive data and qualified personnel to cope with analyzing complex market environments. While this task is already challenging for NRAs on a national level, the markets in most European countries tend to have heterogenous operators and thus competitive landscapes throughout the country.[4] However, market reviews with regional market definitions or different remedies by region are the exception rather than the rule to date.[5] Conducting extensive market reviews on a more granular level, e.g. regional, or state-by-state in federal countries, would require even more NRA resources and more data, which is often not available. Moreover, such granular market reviews would need to be reviewed quickly and often, as market power can be subject to sudden changes due to market dynamics.[6] Against this background, it is not surprising that the SMP designation in European telecommunication markets is so far limited to former state monopolies (incumbents) and cable operators with near-national coverage (Netherlands and Belgium). Consequently, local or regional networks of alternative operators (altnets) that have built out their own access networks in sparsely populated areas operate a non-duplicable infrastructure in the absence of any access remedies. This is problematic, as it enables these altnets to foreclose the retail market, or set prices above those a competitive market would bear, potentially harming consumers.

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[4] Besides the stark differences in cable coverage (European Commission, 2018b) and competition, there is a multitude of different players active in European markets (e.g. utilities in Germany and Italy, municipal networks in the Netherlands, and new entrants, such as Cityfiber in the UK).

[5] Exceptions include Belgium, where each of the three cable operators have SMP in their respective footprints, and Spain, where ex-ante regulation is reduced in larger, competitive so-called ultra-fast-broadband (UFB) cities.

[6] Take the example of an alternative operator that builds out an FTTP network in a formerly underserved region and is then designated an SMP. If, for example, the incumbent subsequently builds out a second FTTP network in the same region, another market review would become necessary.

To summarize, the current SMP regime suffers from downstream discrimination incentives, high regulatory oversight costs due to extensive ex-ante regulations and potential unregulated local monopolies of non-SMP-designated altnets. These caveats could potentially harm consumers and detriment static efficiencies. To address this, the current regulatory toolbox encompasses a variety of countermeasures, including cost-oriented wholesale price caps, regulatory oversight, and open-access obligation in broadband state aid programs (see Bauer, 2010). The new European Electronic Communications Code (EECC)[7] further extends those by allowing for ex-post measures, symmetric regulation, and other measures. Public policymakers and NRAs now have the task of incorporating the new EECC recast into national law and need to choose instruments that preserve investment incentives while enabling effective competition. This paper deals with the potential contribution that a vertical separation (also referred to as a wholesale–retail split) could play in this pursuit.

A vertically separated industry structure, with a subset of operators exclusively active in the wholesale segment and another subset exclusively active in the retail segment, would eradicate downstream discrimination incentives, relax the need for extensive ex-ante regulation and supersede SMP designation for altnets owning non-replicable broadband networks. While the benefits are apparent and widely acknowledged (European Commission, 2010), the current market structure is highly vertically integrated, with just a few exceptions within Europe of a significant scale (with Openreach the most prominent example). Generally, this separation can be a product of either mandated vertical separation, voluntary separation, or new entrants opting for a wholesale-only business model. The first option has been widely discussed in the literature, including theoretical research and in-depth case studies (Cadman, 2019; Mancuso, 2012; Nucciarelli, Sadowski, & Achard, 2010; Ovington, Smith, Santamaría, & Stammati, 2017; Teppayayon & Bohlin, 2010). Mandated separation was already considered as a remedy during the liberalization phase around the 2000s in Europe. It has been incorporated in the European regulatory framework since 2007 when the European Commission allowed for functional separation to be mandated in cases "where all other regulatory tools have proved inadequate to address market and competition failures" (European Commission, 2007). Under functional separation, the regulated firm is required to separate its retail and wholesale functions, employees and information; while it may maintain common shareholding, it may not maintain ultimate ownership.

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[7] See European Parliament & Council, 2018

Mandatory separation has received increased attention in the political debate as related measures have been adopted in a handful of countries (see Crandall, Eisenach, & Litan, 2008 for a summary of cases in the UK, Italy, Sweden, New Zealand, and Australia), as well as in the context of the new EECC. The new EECC does not expand mandatory separation provisions to forms beyond functional separation (see Article 77, new EECC[8]). Instead, Article 78 addresses the case of voluntary separation of an SMP-designated operator and lays out a process for NRAs to analyze whether any obligations induced by regulation should be imposed, maintained, amended, or withdrawn after the separation took place. Moreover, NRAs are put in a position to commit to binding agreements related to voluntary separation of an SMP-designated operator (see new EECC[9]) in order to increase transparency and predictability. Article 80 further specifies under which circumstances wholesale-only providers designated SMPs could benefit from ex-ante reductions in regulation.

However, mandatory separation is perceived as a strong market and property rights intervention and is widely criticized as ineffective and potentially detrimental to the telecommunications sector performance (see Gonçalves & Nascimento, 2010). Thus, it should be seen as a measure of last resort that should only be considered when other measures fail to achieve regulatory goals. Voluntary separation constitutes another option to attain an increasingly vertically separated industry structure. While voluntary separation, also referred to as a wholesale-only business model, has been a rare exception in the decade following liberalization, it has seen rising practical relevance in the past few years. A rising number of new entrants, publicly funded entities and private operators voluntarily chose to adopt a wholesale-only business model without retail operations (see Table 1).

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[8] OJ C 25, 26.1.2013, p. 17

[9] OJ C 25, 26.1.2013, p. 75

Firm	Country	Characterization
Cetin	Czech Republic	Voluntary spin-off by incumbent O2 Czech (owned by financial investor)
Reggefiber	Netherlands	New entrant (financed by financial investor)
NöGig	Austria	New entrant (privately and publicly funded)
RuNe	Slovenia, Italy, Croatia	New entrant (privately and publicly funded)
Siro	Ireland	Joint venture between fixed operators
Stokab	Sweden	Utility
Open Fiber	Italy	New entrant (owned by energy provider Enel)
City Fibre	Uk	New entrant (financed by financial investor)

Table 1: Examples of voluntary vertically separated network operators in Europe

Such voluntary separation requires a deliberate decision by private companies, which is not directly influenced by governmental decisions. Nevertheless, these private business strategy decisions take place in a highly regulated market environment. Consequently, public policymakers do have the ability to indirectly influence private players' market decisions (Huigen & Cave, 2008; Peitz & Cave, 2008). This situation represents an opportunity to strengthen the aforementioned encouraging trend seen in a growing number of wholesale-only providers throughout Europe. Accordingly, it seems the right time to systematically assess (regulatory) measures that could further increase incentives for operators to adopt a wholesale-only business model while preserving incentives to invest.

3. Literature review

A broad strand of the literature has evolved that explores how various factors impact market players' willingness to invest in broadband infrastructure. In this regard, the impacts of regulation, competition, macroeconomic factors, and vertical integration have been subject to extensive research (see Abrardi & Cambini, 2019; Cambini & Jiang, 2009 for an overview). This paper contributes to the strand dealing with a vertical separation, also referred to as a wholesale–retail split. Research on such vertical separation can be divided into two parts.

Firstly, a large number of papers scrutinize the regulatory option to mandate separation on vertically integrated incumbents, which has been discussed intensively in academia and politics in the past and has been implemented in the UK and Sweden.[10] Secondly, a much smaller number of papers deal with voluntary vertical separation or a wholesale-only business model.

3.1. Mandatory separation

Mandatory separation has been a vibrantly discussed topic since the liberalization of telecommunication markets and continues to be the subject of extensive research to date. Although our paper is primarily focused on voluntary disintegration, we also survey the literature on mandatory separation because those findings relate strongly to our research. The academic literature on vertical integration mainly concerns the efficiencies that come along with vertical integration and the effect of separation on investment incentives. The following section presents these arguments and discusses the extent to which the findings apply to the present market environment and the case of voluntary disintegration. Moreover, the research on voluntary wholesale-only networks is surveyed.

The regulatory option to mandate functional separation was integrated into the European regulatory framework as a last-resort remedy in 2002 by the European Parliament & Council (2002). Since then, many papers have been written on that chapter, dealing mainly with the effects of mandatory separation on i) efficiency and ii) investment incentives:

i) Efficiencies in vertical integration: The discussion on the efficiency of vertical integration regards the economic question of what defines company borders. In the absence of vertical integration, production is coordinated through market transactions between firms, with price and quality the main coordination mechanisms. Integration leads to a structure in which the firm has to coordinate the production instead. Coase (1937) addresses the question of why the latter exists at all, given the market takes over the allocation mechanism. He argues that the market approach adds costs associated with defining and enforcing contractual property and contractual rights. Those costs include, among others, search and information costs, bargaining costs, policing costs or legal costs and are summarized under transaction costs. He concludes that vertical integration takes place when the transaction costs exceed the organizational costs. Williamson (1985) extends this idea and argues that transactions with uncertain outcomes that

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[10] Both were technically voluntary separations; however, they occurred as a consequence of regulatory pressure (Teppayayon & Bohlin, 2010).

are conducted frequently and require investments in highly specific assets are most efficiently organized under vertical integration.

Another argument put forth against separation is the risk of double marginalization (Bolle & Breitmoser, 2006; Chen & Sappington, 2009; Höffler & Kranz, 2011). Double mark-ups occur when the wholesale buyer pays more for the input than the wholesaler's marginal costs and raises prices above marginal costs (Spengler, 1950). Thus, the welfare loss which results in pricing well above marginal cost is duplicated for the wholesaler and the wholesale buyer. Pricing above marginal cost, however, is not feasible if the market is perfectly competitive. Thus, the double marginalization problem only occurs if there is imperfect competition in downstream markets. The double mark-up problem also vanishes even in imperfectly competitive environments if the trading parties engage in efficient bargaining with non-linear pricing structures, such as two-part tariffs.

An additional efficiency loss that comes with vertical separation is seen in the loss of economies of scale. It is argued that economies of scale are higher without separation because a single provider on one infrastructure reduces overall investment costs and avoids duplication in consumer acquisition efforts, billing, and operational support systems (OECD, 2001). This argument originates from a time before the positive effects of service competition on price and innovation were widely acknowledged (Cambini & Jiang, 2009). With today's open access interfaces, mandated access regulation, and vividly competitive European retail markets, these arguments become less relevant.[11]

Some researchers point out that economies of scope between the retail and wholesale segments can be substantial, to the point that an integrated market structure is more effective (Cave & Martin, 1994; Kahn, 2004; OECD, 2001). It is apparent that certain facilities can be used jointly and some cost categories can be spread between both segments. However, these associated cost reductions are unlikely to have a substantial effect, as retail and wholesale operations have limited overlaps. Moreover, the economies of scope in operating infrastructure and delivering the services (broadband or telephony) to which these authors referred apply to the days of PSTN networks, in which the service layer was tightly coupled with the infrastructure layer. Today, networks have developed toward an all-IP infrastructure, which realizes fixed telephony services and TV services using a common IP platform (see (Gonçalves & Nascimento, 2010;

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[11] The transaction costs incurred to a connect service provider to a network are non-neglectable (Van Der Wee et al., 2015). However, they are a prerequisite for intra-platform competition and therefore not specific to vertical separation.

Kirsch & von Hirschhausen, 2008). The IP platform is fully decoupled from the infrastructure layer and can be offered irrespective of the communication infrastructure (mobile, fiber-to-the-curb (FTTC), FTTP, or cable). This constitutes the decoupling of the infrastructure and service layer. Consequently, the potential for economies of scope are substantially reduced for all-IP networks. This argument is in line with empirical results obtained by Bruno & Manello's (2015) analysis of recent financial data from 13 European incumbents. Their results suggest "that probably vertical economies of scope are not so relevant in the Telecommunications sector, or, at least, they are more than compensated by efficiency gains" (Bruno & Manello, 2015, p. 136).

Summing up, we still see potential efficiencies associated with vertical integration, but they are likely of limited magnitude. They are composed of transaction costs between wholesalers and retail operators that exceed organizational costs, as well as economies of scope through joint usage of facilities or personnel. Most transaction costs, however, are not specific to vertical disintegration, as they are also incurred as part of a transaction between the SMP operator and a service provider making use of mandated wholesale access provisions. Accordingly, these transaction costs represent a necessary cost to enable competitive retail markets.

ii) Reduced investment incentives

High upfront costs in network upgrades and rollouts require significant investment from private market players. Thus, incentives to foster investment are one key objective policymakers consider when designing regulatory measures. Mandatory separation has been widely criticized as detrimental to investment incentives. Numerous papers model several institutional setups to compare a vertically integrated institutional structure against a disintegrated structure in network industries.

In particular, two papers (Buehler, Gärtner, & Halbheer, 2006; Buehler, Schmutzler, & Benz, 2004) conclude that a disintegrated provider invests less as profits from the service provisioning are not considered in investment decisions. Furthermore,Sarmento (2015) finds that investment incentives are lower under disintegration, irrespective of whether access price regulation is in place. Moreover, the findings of Millious (2004) suggest that vertical disintegration furthermore leads to less investments in R&D. Similarly, Cremer & De Donder (2013) compare integration without regulation with ownership separation, and find that investment levels and welfare gains are higher under functional than under ownership separation.

However, a paper by Avenali, D'Annunzio & Reverberi (2013) challenges those findings. The authors model a situation in which an upstream monopolist provides network access to all downstream firms using a regulated linear access charge. They conclude that investment incentives may increase under ownership separation while also increasing social welfare. Along the same lines, Cadman (2019) finds that integration gives investments an additional strategic value, as it allows operators to benefit from a retail market foreclosure, and thus the Net Present Value (NPV), and in turn, the incentive to invest, is higher than under disintegration. However, he points out that effective regulation rules out the foreclosure option, eliminating the difference.

The literature leans towards the notion that vertical disintegration reduces investment incentives. Therefore, and due to other disadvantages of imposed structural separation, including irreversibility, implementation costs, and the potential for a lower quality of service (Brito, Pereira, & Vareda, 2011; Teppayayon & Bohlin, 2010), we follow the recommendation of Gonçalves & Nascimento (2010) to mandate separation only as a remedy of last resort.

3.2. Voluntary seperation

The research on voluntary vertical disintegration is far less abundant. Most papers explore different levels of opening the network and discuss the factors leading to success or failure based on experiences with wholesale-only providers (Brennenraedts & Maltha, 2008; Lehr, Sirbu, & Gillett, 2004; Magnago, 2004). Our paper, in contrast, relates to the strand of literature comparing the integrated business model with a wholesale-only model in regard to the ability to recover the investments necessary to rollout FTTP networks.

In an early paper, Banerjee & Sirbu (2005) develop a techno-economic model to compare the profitability of a wholesale-only operator with that of an integrated operator. They conclude that municipalities or communities building out FTTP wholesale-only networks can realize sustainable prices, are likely to create greater welfare and are just as likely as an integrated operator to recover costs. While Banerjee & Sirbu consider an urban setting with 10,000 households, Felten & Langer (2016) differentiate between regions with deviating cost structures. They use a business case model to compare the percentage of the population that can be covered by a wholesale-only and an integrated operator without subsidies. They argue that wholesale-only operators could achieve higher penetration rates and lower financing costs and therefore are significantly better positioned to recover FTTP investments than an integrated operator. Additionally, they point out the sensitivity of capital costs, and thus draw the conclusion that public policymakers should aim to derisk infrastructure and promote the emergence of wholesale-only networks.

In summary, the literature on voluntary open access leans towards an optimistic view on wholesale-only networks, while the literature on mandatory separation finds efficiencies of vertical integration and argues that incentives to invest are higher under vertical integration. However, the existing research discussed here, along with numerous case studies on vertically separated industry structures (Cadman, 2019; Mancuso, 2012; Nucciarelli et al., 2010; Teppayayon & Bohlin, 2010) do not address the question of how public policymakers can incentivize market participants to voluntarily adopt a wholesale-only business model, thereby fostering voluntary disintegration while preserving incentives to invest. We aim to close that gap by developing a DCF model that compares the profitability of an integrated operator and a wholesale-only operator and discussing potential (regulatory) measures that can serve the aim outlined above.

4. Comparing the business models using an NPV model

When the European Commission (EC) introduced mandatory separation provisions for the first time in 2007, the concern was raised that under strong forms of vertical separation,

> “the largest part of the potential reward for taking the risk of investing in [...] new networks would accrue to external service providers rather than an internal services division. According to the EC, only direct regulatory incentives for the network operator (in the form of guaranteed rates of return) might overcome the reluctance of a separated access provider to make such investments, which then puts the burden of determining the pace of innovation onto the regulator rather than the market” (European Commission, 2007, p. 102).

This argument presumes absent or impaired investment incentives for network operators without a retail arm compared to integrated operators. However, the demand and supply of broadband services have changed dramatically since 2007. Bandwidth-intensive services, such as high definition video-on-demand (HD-VoD) or over-the-top video conferencing, have reached mass adoption (Cisco, 2019), increasing the demand for new networks providing higher bandwidths (Stocker & Whalley, 2018). Given this change in demand, providing guaranteed rates of return through regulation may not be necessary to provide for necessary investment incentives. The wholesale-only business model may allow network providers to recoup investment costs just as they would in an integrated business model.

Following the analytical framework developed by Cadman (2019), we apply a discounted NPV model to compare the ability of wholesale-only and integrated providers to recoup investment costs. As Cadman described, a firm would choose to invest if the NPV is greater than zero, given a discount rate greater than its opportunity cost of capital. Using this analytical approach, we compare the discounted NPV of an integrated operator, NPV_{int}, for investing in FTTP with the NPV for a wholesale-only operator, NPV_{wo}. The integrated business model is more financially attractive than the wholesale-only model if $NPV_{int} > NPV_{WO}$, and vice versa.

In this chapter, we develop an NPV model for an integrated operator and a wholesale-only provider. In a second step, the model inputs for the wholesale-only provider are altered as a sensitivity analysis, which allows us to identify potential levers that could increase the financial attractiveness of an NPV model.

4.1. Base case model

Modeling the NPV basically requires simulation of the business case of an FTTP rollout. We do so by adopting a calculation methodology that is applied in several state aid programs throughout Germany, including the Bavarian subsidy scheme “Next generation network for commercial and accumulation areas in Bavaria.” That program is financed with an overall budget of €1.5 billion. It employs the gap-funding model, in which a municipality provides a grant for covering the so-called profitability gap of a network operator that builds, operates, and owns the new broadband infrastructure (see European Commission, 2008 for program description). The profitability gap is calculated as the sum of all anticipated discounted revenues subtracted by discounted investment and operating. Table 2 shows the relevant cost and revenue categories used within the Bavarian subsidy scheme.

Category	Position
Revenues	Direct service revenues from newly acquired customers Additional revenues deriving from existing customers' upgrades Indirect revenues, e.g. wholesale
Investment	Civil engineering Passive infrastructure Active infrastructure
Operating costs	Wholesale access (last mile access, etc.) Direct operating costs Capital costs

Table 2: Revenue and investment categories

Our model is based on three modules: The upfront cost module calculates investment costs for a nationwide greenfield FTTP network. The demand module forecasts penetration on the newly built FTTP infrastructure while considering competing operators and infrastructures. The last module is based on the demand model and calculates revenue and operating costs.

FTTP investment costs per household vary widely between regions. The main causes are differences in population density and different drop segment lengths. Our investment costs per household estimation is based on the cost modeling obtained by Jay, Neumann, and Plückebaum (2012), and a cost modeling survey by Feijóo, Ramos, Armuña, Arenal, and Gómez-Barroso (2018). In our model we apply the cost per households estimates shown in Figure 1 ranked by clusters, each of which represents 5% of all households. Cluster 1 includes all households located in the densest urban areas with lowest per household FTTP investment costs, while households in cluster 20 are located in the most rural areas and require the highest capital expense (CAPEX) to connect to an FTTP network. [12]

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[12] Although costs vary for other countries the general theme of varying costs among differently densely populated regions applies to each country (see Feijóo et al., 2018).

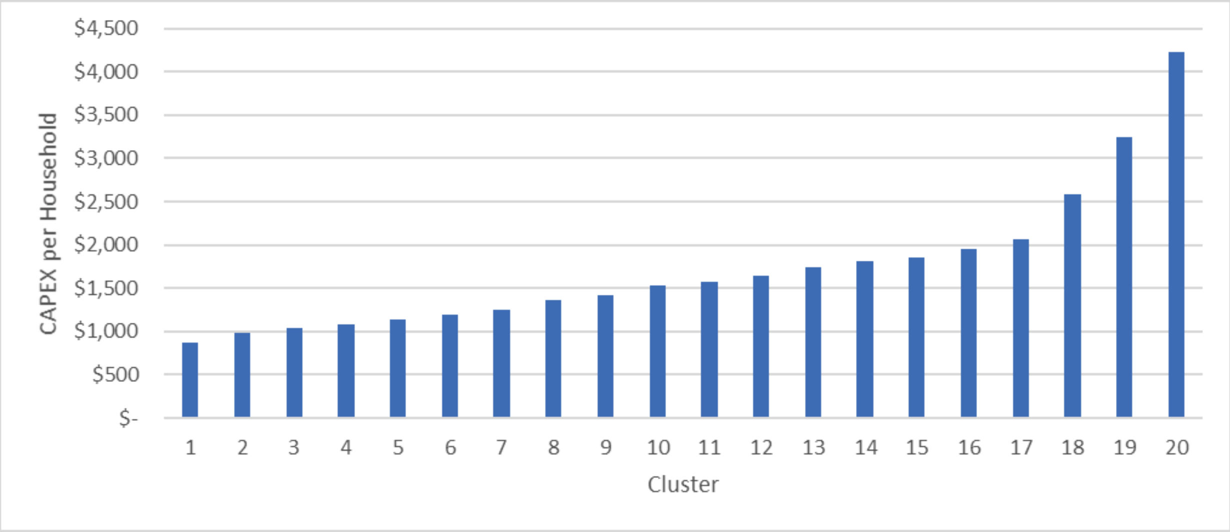

Figure 1: Investment costs per household model input

Using above household cost estimates, investment costs for each cluster, *c*, are calculated as follows:

$$Inv_c = \sum_{t=1}^{T} \frac{T_c*(H_c*S_t)}{(1+i)^t}, \text{ where}$$

Inv_c: Investment net present value for *c*

i: WACC

T_c: Investment costs per household in *c*

H_c: Households in cluster *c*

S_t: Share of households which are connected in period *t*

The variable S_t is used to reflect the constraint of civil engineering capacity making it infeasible to build out nationwide FTTP networks in only one year. Thus, we assume that costs are split equally between the first four years in each cluster. H_c equals the number of households in the respective clusters.

Demand model

The take-up (defined as households connected divided by households passed) on the infrastructure is driven by three major determinants. These are 1) migration of customers on legacy copper infrastructure to FTTP services, 2) the degree of inter-platform competition stemming from parallel FTTP or HFC infrastructure, and 3) the service providers' decision to migrate to FTTP networks from copper networks.

The diffusion trajectories of new technologies are often found to follow an S-curve pattern. Rogers (2003, pp. 136–167) highlighted that the S-curve consists of three sections: A slow growth incubation period that is characterized by a lack of demand for a newly introduced technology, followed by the fast growth stage, and concluded by a slow-growth maturity stage, in which adoption rises slowly as it reaches the market's capacity.

In our context, FTTP does not represent new technology. The ubiquity of mobile networks and IP-based services such as subscription video on demand (SVOD) has led to a surge of demand for fast broadband (see e.g. CERRE, 2017), while other quality parameters, such as delay, jitter, and packet loss also profoundly affect customers' quality of experience (Stocker & Whalley, 2018). Early empirical evidence also shows that bandwidth demand and the valuation of FTTH has grown significantly in recent years (Grzybowski, Hasbi, & Liang, 2018). Considering this, we do skip the incubation period, and therefore model the adoption curve over time as a limited exponential growth function, defined as follows:

$$Takeup_c(t) = F_c - F_c * e^{-kt}, \text{ where}$$

$Takeup_c(t)$: Adoption in cluster *c* in year *t*

F_c: Maximum take-up in cluster *c*

k: Growth factor

The value of F_c in year T reflects the circumstance that other competing infrastructures (cable, mobile and other FTTC or FTTH networks) are likely to account for substantial market share. These are likely to be found in urban and suburban areas, while rural areas throughout Europe have little or no HFC coverage and it will most likely be too costly for more than one FTTP network to become established (Feijóo et al., 2018). Thus, we assume the maximum take-up to be limited to 55% in urban cluster 1 (with the highest population density) and 80% for rural cluster 20 (lowest population density).[13] Adoption is modeled over an eight-year period.

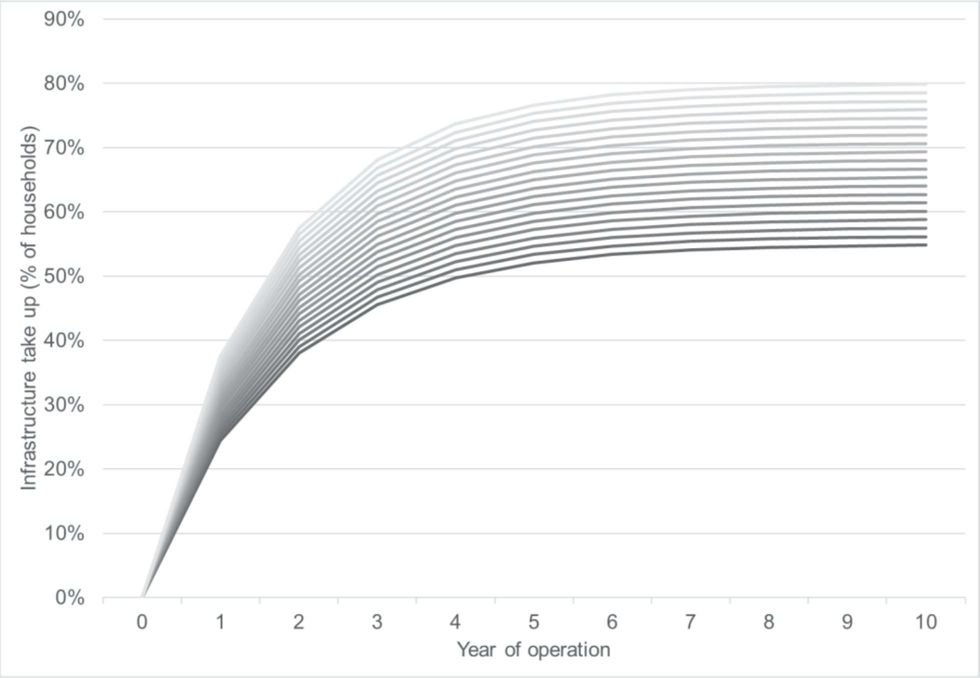

Figure 2: Take-up curve for all 20 clusters. The top line shows the modeled adoption curve for the most rural cluster, 1, while the lines below reflect clusters 2 to 20 in descending order.

Revenue and operating costs model

The revenue and operating costs model is based on the revenue per household connected and the EBITDA margins. We assume the effective monthly revenues per household (ARPU) to be €45, corresponding to the average EU28 least expensive price for a 200+ Mbps tariff including voice telephony (European Commission, 2018a). The wholesale price is set €10 lower[14], reflecting the difference between retail prices and wholesale products. Wholesale-only providers lack the low margin and asset-light retail portion of the value chain and therefore generate higher operating margins. Our EBITDA margin assumptions are sourced from a European industry benchmark carried out by Barclays (2018), which reports 45% as a best-in-class EBITDA margin for integrated operators, while wholesale-only operators achieve an

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[13] Maximum take-up F_c for clusters 2 to 19 is assumed to increase linearly. The calculation is as follows:

$$F_c = F_1 + \frac{F_{20} - F_1}{20}$$

[14] Corresponds to the difference that can be observed between active bitstream prices and retail prices on European markets. See assumptions used in (Barclays, 2018b and; Felten & Langer, 2016)

average of 55%. Furthermore, we add an efficiency markup, eff_{int}, of €2 per month per connected household for the integrated operator in order to reflect the potential efficiencies of vertical separation described in Section 3. Using these model inputs, operating expenses (OPEX) are calculated as follows:

$$OPEX_t = (ARPU * Takeup_{ct}) * (1 - EBITDAmgn) + eff_{int}$$

Full model description and results:

The DCF is calculated for each cluster representing differently populated clusters. The full model is represented as (see Appendix for model input summary):

$$NPV_c = -inv_c + \sum_{t=1}^{T} \frac{(Takeup_{ct} * ARPU) - OPEX_t}{(1+i)^t}, \text{ where}$$

NPV_c: Net present value for cluster c

T: Business case horizon

Our model inputs consider the main arguments put forward by critics of separation. Vertical efficiencies decrease operating costs and the ability to capture profits on the retail market increases the economic value of a connected customer.[15] Figure 3 visualizes these results per cluster using the formula presented above.

The integrated operator reaches the breakeven point one to two years earlier than the wholesale-only operator. Moreover, the NPV for each cluster and each business case horizon is higher under vertical integration. These results explain the predominantly vertically integrated industry structure that can be found in European markets. Private players currently maximize their profits under a vertically integrated structure rather than by adopting a wholesale-only business model. The assumption chosen in this base model incorporates arguments against vertical integration while not considering factors that might have a beneficial effect on the financial performance of wholesale-only providers. Therefore, the following subsection will discuss such

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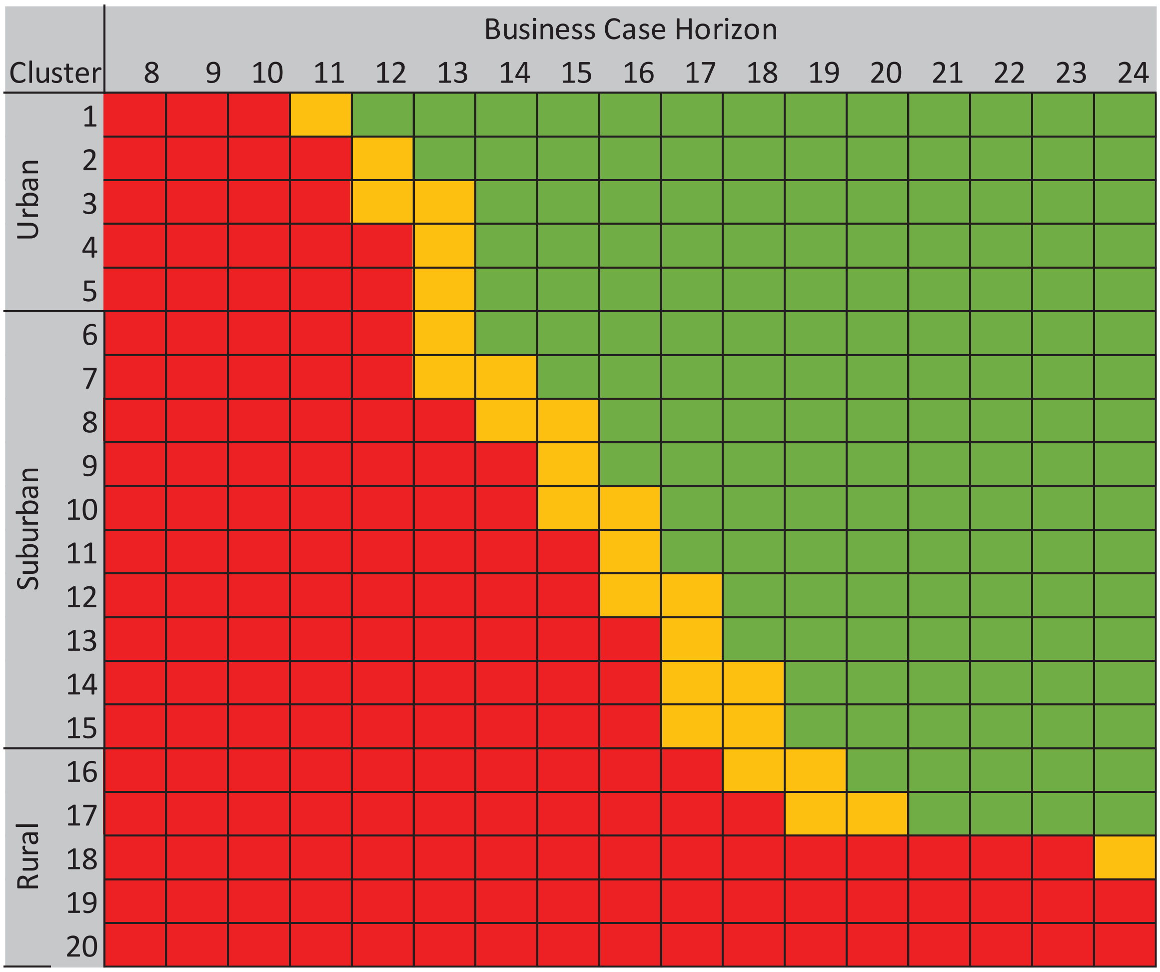
[15] The EBITDA contribution of a connected household is €20.25 for an integrated operator (€45 ARPU x 45% EBITDA margin) and €19.25 for a wholesale-only provider (€35 x 55%).

factors and their prerequisites and analyze their effects on the financial attractiveness of a wholesale-only business model by adjusting the DCF model inputs and testing sensitivities.



		Business Case Horizon																
	Cluster	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Urban	1	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	2	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	3	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	4	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	5	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Suburban	6	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	7	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	8	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	9	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	10	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	11	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	12	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	13	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	14	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩
	15	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩
Rural	16	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩
	17	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩
	18	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
	19	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	20	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Figure 3: DCF results for the base model. The rows reflect the clusters, c, while columns show the respective business case horizons, T. Red cells indicate that neither a wholesale-only provider nor an integrated operator could recover their investment. Yellow cells are profitable only for an integrated operator. Green cells indicate that wholesale-only and integrated operators can both recover their investment costs.

4.2. The up-side case for the wholesale-only model

As described in Section 2, there is a rising number of network providers voluntarily choosing to either spin-off their network business (e.g. O2 Czech/Cetin) or entering broadband markets with a wholesale-only business model (e.g. Austria's NöGig). The rationales these private firms communicate towards the financial markets hint of potential upsides of the wholesale-only model in regard to risk factors affecting costs of capital (often defined as weighted average costs of capital WACC) and anticipated take-up.

Firstly, the wholesale-only provider business model could benefit from lower WACC levels due to a lack of activities within the competitive retail segment. Infrastructure investors seek stable, predictable, and long-term cash flows and are willing to accept lower rates of returns on their invested capital. The lack of a retail arm benefits wholesale-only providers in that regard. Anecdotal evidence is already available in capital markets. O2 Czech, owned by private equity firm PPF, spun off its network division in 2015 to account for “different types of investments and horizons” between the network and retail business (CETIN, 2017). Furthermore, Windstream, an integrated operator in the US, pursued a similar strategy, spinning off its fiber and copper assets into a separate company that was later listed on the stock exchange. In their SEC filing, Windstream defended the spin-off by arguing it was expected to “create [the] opportunity to unlock shareholder value by creating two independent public companies with distinct investment characteristics” (Windstream, 2014).

The results obtained by Schaeffler & Weber (2013) point in the same direction—they find that integrated utilities do have higher risk levels when compared to pure utility network providers without their own retail operations. Lower costs of capital, however, require that regulation does not interfere. Regulatory costs affect the risk assessment profoundly and therefore affect capital costs (Gentzoglanis, 2007). Regulatory authorities directly influence capital costs, for example, through pledging to reduce ex-ante regulation for wholesale-only providers, as in the new EECC.

However, to the best of our knowledge, regulators throughout Europe have not proactively published guidelines on regulation reduction that would be granted in case of voluntary disintegration. Thus, the potential positive effect of reduced regulation is still subject to uncertainty, and therefore unlikely to play much of a role in private firms’ decision-making process. Thus, predefining reductions in ex-ante regulation in advance of any voluntary separation could be a measure to derisk a separation decision and reduce capital costs.

Another important factor concerns the anticipated take-up of infrastructure. A non-discriminatory wholesale-only provider will, at any given price, aim to attract as many service providers to sell products on the network as possible. If this aim succeeds, a wide variety of consumer offers will emerge, as service providers seek to differentiate themselves. In contrast, an integrated operator maximizes profits by acquiring as many profitable end-customers as possible while wholesale revenues are mostly seen as a regulatory requirement rather than a strategic priority.

The limited existing research on factors driving the adoption of ultrafast-broadband indicates that intra-platform competition has a positive effect (Fourie & de Bijl, 2018; Ovington et al., 2017). A similar argument can be made with respect to tariff diversity. An increase in service providers selling products on a network will likely lead to a broader diversity of customer acquisition strategies. This, in turn, increases the need to differentiate from fellow service providers, and thus ultimately leads to an increase in tariff diversity. Consequently, it is likely that customers will have a wider choice of tariffs on wholesale-only networks compared to a network operated by an integrated provider and therefore would choose to migrate to the FTTP network more quickly. This theoretical argument is aligned with empirical results obtained by (Haucap, Heimeshoff, & Lange, 2016) using cross-sectional data, and by Lange (2017) using time-series data. Both empirical analyses find that an increase in tariff diversity provides a significant impetus to broadband adoption.

Another important factor is the expected degree of inter-platform competition. Operators face two options: to enlarge the addressable market or to offer higher-quality products to their customers. Either they invest in their own networks or instead buy network access wholesale from other operators. The latter increases inter-platform competition but also duplicates costs and reduces take-up compared to the former option, where there are fewer networks competing for customers. Consequently, the anticipation of upcoming inter-platform competition is a key aspect affecting firms' investment decisions.

If operators expect not to be challenged by another infrastructure in a given region, they would anticipate take-up rates substantially higher than in another region in which they expect another operator to build out their own, separate infrastructure. Under vertical disintegration, there is no possibility for a wholesale-only provider to discriminate against its own retail arm. Accordingly, operators presented with the two options described above do not face the risk of being discriminated against. In contrast, this does not hold true for a case in which network access would be supplied by an integrated operator. Thus, there is reason to expect that there will be less inter-platform competition if a wholesale-only provider is present in the market. Nonetheless, wholesale-only providers might also have an incentive to discriminate in order to maximize profits (Krämer & Schnurr, 2014). Thus, a non-discriminatory market is key to achieve positive effects on anticipated take-up mentioned above.

While more intra-platform competition and less inter-platform competition represent potential upsides to wholesale-only take-up, there is a factor that prevents this upside from materializing. In many European markets, incumbents' wholesale tariff structures include significant quantity rebates.16 Service providers buying access products from incumbents do have an incentive to stick to the access products, even if other regional wholesale-only networks offer FTTP and the incumbent inferior xDSL-based access, as sourcing from both providers would effectively increase the access costs for all households. Another similar factor is the existence of long-term access pricing tariff structures, where wholesale buyers receive additional discounts for committing to longer periods.17

To summarize, a lower WACC and faster take-up evolution are two potential upsides for the wholesale-only business case. To analyze the impact on the comparison to an integrated operator model, we alter the input parameters for the wholesale-only provider by reducing the WACC by 1%, increasing the maximum take-up by 10% in cluster 1 (and Cluster 1 to 19 accordingly—see Section 4.1) and reduce the time until the final take-up is reached by one year.

These small changes in input produce quite a different picture (Figure 4). The wholesale-only provider reaches the break-even point for Clusters 1–18 one year earlier than an integrated operator. This result indicates that even a small reduction in capital costs and improved take-up could lift the financial attractiveness of a wholesale-only business model to a point at which rational market participants would choose such a model over an integrated structure. Our DCF model is limited by the fact that we assume a greenfield rollout scenario and do not include one-time break-up costs. Thus, it can only represent the rationale for incumbents to a limited extent. Nevertheless, the potential positive effect of reduced costs and higher take-up for a separated structure will be comparable, even in a brownfield scenario and if one-time break-up fees were included in the model.

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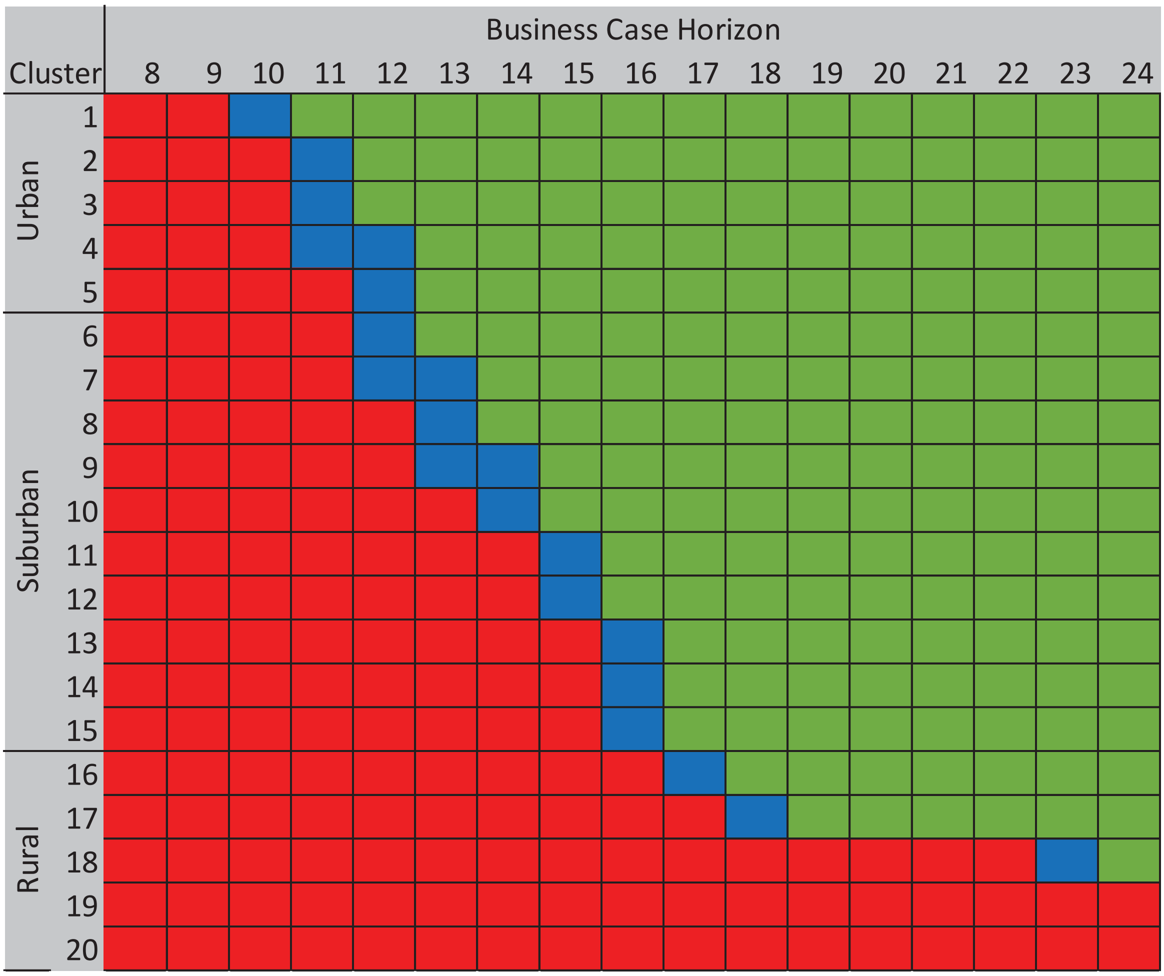
[16] The so-called "Kontingentmodell" of Deutsche Telekom serves as an example (see https://www.telekom.com/en/media/media-information/archive/contingent-model-telekom-gains-cooperation-partner-357974).

[17] As such tariff structures inhibit the risk of discrimination, Article 10 of the EU Access Directive only allows them if they reduce financing costs.



	Cluster	Business Case Horizon																
		8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Urban	1	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	2	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	3	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	4	🟥	🟥	🟥	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	5	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Suburban	6	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	7	🟥	🟥	🟥	🟥	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	8	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	9	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	10	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	11	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	12	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	13	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	14	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	15	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Rural	16	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	17	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩	🟩	🟩	🟩	🟩	🟩
	18	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟩
	19	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	20	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Figure 4: DCF results for the upside case. The rows reflect the clusters, c, while columns show the respective business case horizons, T. Red cells indicate that neither a wholesale-only provider nor an integrated operator could recover the investments. Blue cells are profitable only for a wholesale-only operator. Green cells indicate that wholesale-only and integrated operators can both recover their investment costs.

5. Discussion and policy implications

Ex-ante regulation in the telecommunications sector has succeeded in enabling retail competition by creating market structures that allow alternative operators to effectively compete with incumbent operators on the retail level as well as providing the stepping stone to build-out their own networks in urban and semi-urban environments. However, investment costs in semi-rural and rural regions do not allow more than one network to be economically viable.

This paper discussed a vertically separated industry structure as a potential answer to issues arising in such regions, most notably, potential downstream discrimination. We surveyed the existing literature and presented mandatory separation opponents and proponents' main arguments as well as reviewing the limited existing research on voluntary separation. Based on that review, we concluded that mandatory separation comes with significant drawbacks and issues, and therefore should remain a measure of last resort.

In regard to voluntary separation, we contribute to the literature by developing a DCF model to provide an analytical framework that allows a comparison of the financial incentives for firms to adopt either a wholesale-only or an integrated business model. In our base model, which aims to incorporate the existing literature findings and current market players' performance indicators, we found that an integrated business model prevails as beneficial throughout all clusters.

As a next step, we argued that NRAs and public policymakers do have levers and options to decrease the regulatory risk for wholesale-only providers and to positively affect prospective take-up for wholesale-only providers. Feeding these arguments into our model, we found that even slight improvements (1% WACC reduction and +~10% take-up up-side) are sufficient to tilt the financial attractiveness towards the wholesale-only business model.

Based on these analytical results, as well as the existing literature, we recommend public policymakers as well as NRAs adopt measures that incentivize market participants to adopt a wholesale-only business model. Doing so will allow society to reap beneficial effects of a separated industry structure while superseding the need for strong structural market intervention. In practical terms, we propose that to reduce uncertainty and regulatory risk, public policymakers and NRAs should adopt, refine, and make use of the new EECC provisions on voluntary separation.

Although EECC Articles 78 and 80 list precise procedural and organizational requirements (e.g. three months’ notice, no common control or ownership, no exclusive agreements), they do not define the extent to which ex-ante regulation is reduced for voluntarily separated operators. SMP-designated operators can generally be subject to the full scope of ex-ante regulation—obligations of transparency, non-discrimination, access or price-control, and cost accounting (see Article 78 new EECC[18])—but may be subject only to non-discrimination, access or fair and reasonable pricing obligations (Article 80 paragraph 2). These provisions represent guidelines rather than precise provisions for the extent to which regulation would be reduced in case of a voluntary separation, and thus do not reduce uncertainty and achieve the effect discussed in Section 4.2.

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[18] OJ C 25, 26.1.2013, p. 161f.

To address this gap, we propose that regulators proactively define the ex-ante reduction if a vertically integrated SMP operator voluntary separates its wholesale and retail business under the fulfillment of the requirements of Article 80 Paragraph 1 (sections a and b). This can take the form of binding commitments given by NRAs (already proposed in the new EECC[19]). NRAs could commit to binding agreements in order to proactively initiate consideration of such a move at the SMP operator, even if operator is not yet considering a voluntary separation.

Secondly, regulators need to consider the hampering effect of wholesale tariffs featuring volume or long-term discounts. These tariff structures incentivize retail providers to buy access products from the incumbent in regions even if a wholesale-only provider also provides access to FTTP networks. In such cases, buying from the incumbent would be rational for the retail provider, as it is contractually obliged (long-term discount), or doing so decreases the average cost per subscriber. To preclude associated negative effects on the anticipated take-up of a wholesale-only provider, NRAs should carefully weigh the benefits of volume and long-term wholesale tariffs.

These approaches are intended to nudge private firms toward a wholesale-only business model. Public policymakers also have also the option to more directly influence the business model with broadband subsidy schemes. In recent years, governments throughout Europe have increasingly funded broadband deployment with state aid (see Feasey, Bourreau, & Nicolle, 2018 for a European overview). These programs represent an opportunity to foster the emergence of additional wholesale-only networks, as public policymakers could tailor the programs accordingly. Italy can be examined as a rather extreme example in that sense; the government's state aid program strictly excluded integrated operators from public tenders (European Commission, 2016). This approach, however, risks decreasing the competitiveness of the tender process and therefore decreases the intervention's efficiency. As a result, public policymakers should extensively analyze the market structure and potential effects of such restrictions. Conveniently, the European guidelines for state subsidies in broadband deployment[20] allow favoring wholesale-only proposals by awarding them additional points. Granting additional points in the tender would not exclude vertically integrated operators but could further nudge operators towards voluntary vertical separation.

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[19] OJ C 25, 26.1.2013, p. 75

[20] See paragraph 80b of European broadband state aid guidelines: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2013:025:0001:0026:EN:PDF

Our findings show that mandatory separation is not the only route towards a separated industry structure. Public policymakers and NRAs do have many levers to strengthen the observed trend toward voluntary separation. We suggest they proactively use those opportunities both in state aid programs as well as precise, binding commitments defining the potential reduction in ex-ante regulation in cases of voluntary separation.

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Chapter 2:

Competitive effects of cable networks on FTTx deployment in Europe

Fabian Queder

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1. Introduction

The European Union and its member states have set themselves ambitious broadband targets. By 2025, the EU aims to provide 100 Mbps connectivity to all European citizens and gigabit connectivity for all major socio-economic institutions, such as schools and hospitals (European Commission, 2016). Many member states even aim at providing more widespread gigabit coverage (Die Bundesregierung, 2016; UK Department for Digital, Culture, Media & Sport, 2018).

In light of the massive investments in Next Generation Access (NGA) deployment that will be necessary to reach these targets, the economic and market conditions that may foster telecommunications operators' investments in fibre to the premises (FTTP)[21] infrastructure are a topic of intense interest and discussion. The related literature, however, hardly analyses the role cable operators play in this pursuit (Abrardi & Cambini, 2019). The limited empirical evidence to date indicates that cable network competition has positive effects on broadband penetration and on investment by incumbents and alternative operators. However, the models used in those studies mainly focus on the impact of regulatory measures and thus do not account for the specifics of (cable) inter-platform competition. Hence, they shed only limited light on the competitive dynamics between cable networks and fibre to the x (FTTx)[22] operators.

To fill this gap, this paper focuses on the past and current roles of cable network operators (CNOs) in broadband markets and examines the competitive dynamics between cable and FTTx networks. On this basis, we develop an econometric model, which analyses the effect of cable networks on FTTx expansion in recent years.

With the introduction of DOCSIS,[23] which has enabled cable networks to deliver broadband services, European policymakers have considered cable networks an important source for competition in fixed telecommunications markets. The so-called "cable ownership directive" of 1999 (European Parliament & Council, 1999) required EU member states to unbundle cable and copper network ownership. Subsequently, due to increasing regulatory pressure, European incumbents divested their cable business to CNOs. This structural separation and the introduction of DOCSIS has enabled a substantial proportion of European households, for the

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[21] Also referred to as Fibre to the building or home (FTTB/H).

[22] Where x stands for either cabinet (FTTC) or premises (FTTP)

[23] The Data over Cable Service Interface Specification (DOCSIS) is the technology standard used to transmit data over cable networks.

first time, to choose between different telephony and broadband providers with fully independent networks (inter-platform competition[24]). Thus, cable networks became the single source of inter-platform competition in the early 2000s. Subsequently, this has slowly changed with the emergence of new entrants building out FTTP networks. Nevertheless, to date, facility-based competition in Europe continues to be dominated by cable networks accounting for approximately two-thirds of non-incumbent-owned access lines (COCOM, 2018).

Given the current debate on how to design a policy mix that encourages market participants to invest in FTTP and considering the ambitious broadband targets within the EU, it seems appropriate to review the effects of cable networks on FTTx network expansions.

European broadband markets have evolved under a common regulatory framework since the liberalisation of the telecommunications—beginning in 1997 and 1998 (European Parliament & Council, 2002)—and therefore exhibit many similarities. However, this does not apply to the cable industry. A simple comparison of cable network coverage in 2011 and 2017 across European countries reveals profound differences (Figure 1). While there are virtually no cable networks in Italy and Greece, other countries, such as Montenegro, the Netherlands, and Belgium, exhibit near-national cable coverage. Moreover, Figure 1 shows that cable coverage expansion in recent years has been limited in quantity and limited to a subset of countries.

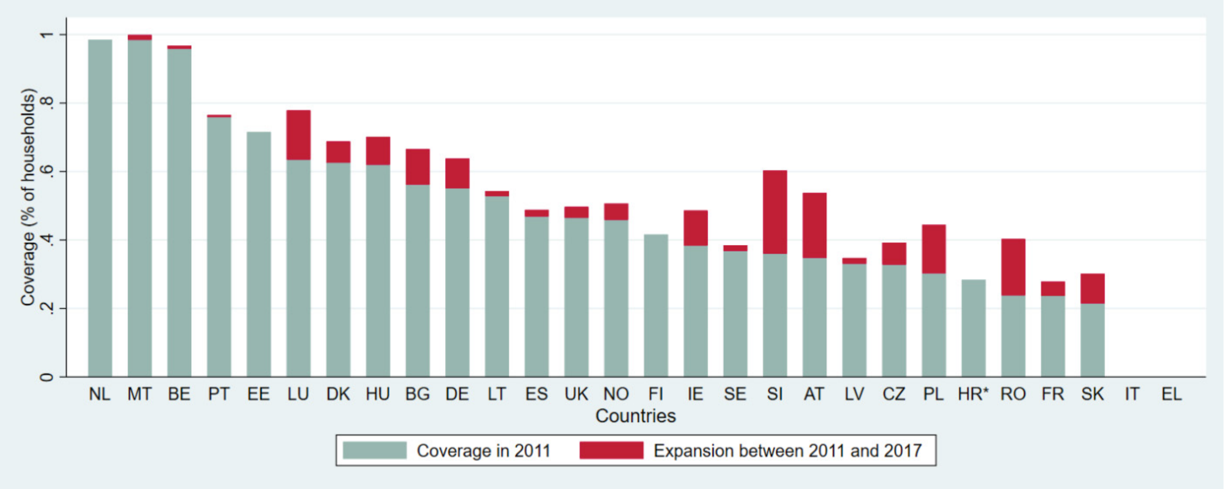

Figure 1: Cable network coverage in the EU by country Source: own calculations based on European Commission (2012, 2018)

** Data for Croatia (HR) is not available before 2013. Coverage for that country in 2011 is thus provided as of 2013.*

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[24] Inter-platform competition describes competition on the network and service layer, in contrast to intra-platform competition, where a multitude of operators use a common infrastructure and mainly compete on the retail level

This paper adds to the vibrant debate—currently predominantly based on assumptions rather than empirical findings—about the effect of cable networks on FTTx investment. On the one hand, it is argued that higher or more cable coverage increases investment in FTTx, as incumbents and alternative operators upgrade their networks in order to avoid losing market share to competing cable networks (Arthur D. Little, 2016). On the other hand, it is also conceivable that the existence of cable networks could hamper investment in FTTx networks, since operators investing in areas with existing coax-cable networks execute these investments against an existing high-speed- infrastructure and an existing customer base. This *penetration risk* due to a lower anticipated take-rate could effectively reduce revenues and the ability to recover investment costs and consequently to invest without government subsidies. This paper adds to the debate by drawing on the heterogeneity of cable markets within Europe to explore the effect cable networks have on the FTTx expansion decisions of both incumbents and alternative operators.

This study contributes to the literature in three ways: First, by advancing the understanding of the role that CNOs have historically played in European broadband markets. Second, by analysing a novel data set of (mainly) coverage data for European countries from 2011 to 2017. In contrast to the existing literature, this data set allows conclusions to be reached on the full extent of the competitive pressure exerted by cable networks, rather than limiting the analysis to penetration or technology market shares. Third, we analyse the effect on FTTx network expansion, relevant to the most pressing challenge the market and policymakers face today—bringing fast broadband networks to more households.

The remainder of the paper is structured as follows: Section 2 surveys the existing literature. Section 3 describes the history of cable networks to provide background on the industry. Section 4 develops hypotheses on the effect of cable networks on FTTx expansions. Section 5 provides the empirical analysis and discusses the results. Section 6 concludes the work by discussing policy implications.

2. Literature review

This paper is related to the broad body of empirical research seeking to identify the factors that drive broadband investments or penetration. Among this body, studies examining the impact of regulation-induced intra-platform competition account for the largest research strand. A large portion of these studies compare the impact of intra- and inter-platform competition, related to our research; here, we review relevant results on inter-platform competition. We refrain from presenting main research questions and findings—previously presented in detail by Cambini & Jiang (2009) and Abrardi & Cambini (2019)—and instead focus on the parts dealing with the impact of cable network and inter-platform competition in general. The existing research subdivides into two categories: studies that use i) penetration or ii) investment measurements as the dependent variable.

There are several contributions in the literature using penetration as the dependent variable to examine whether cable market share or a derived infrastructure competition index explains variation in broadband penetration. In an early paper, Höffler (2007) weighs the positive effect of cable networks on penetration against the costs of duplicating fixed networks. He finds an inverted U-shaped relationship between cable coverage and broadband penetration using a data set comprising 16 western European countries and spanning the time from 2000 to 2004. Höffler uses OLS and IV estimations without applying a fixed effect estimation; he argues that fixed effect estimations would be misleading as they neglect between-country effects and that other explanatory variables are relatively time-invariant.

Höffler's work has sparked considerable research into the effect of inter- and intra-platform competition on various outcomes. A recent paper by Ovington, Smith, Santamaría, & Stammati (2017) finds a positive broadband penetration effect of platform competition, measured as new entrants' non-DSL market share. In that work, OLS, IV, and GMM specifications are applied to a data set, including the EU27 countries and spanning the time from 2004 to 2011. Their fixed effect estimations yield slightly negative, albeit statistically insignificant coefficients, which the authors explain as due to insufficient within-country variance. By adding interaction terms of inter- and intra-platform competition, they find that the intra-platform competition is subject to diminishing returns and crowds out positive effects of inter-platform competition.

Another recent study by Fourie & de Bijl (2018) explores the factors driving FTTP penetration. The study draws on a data set comprising data for 27 European countries 2004–2015. The main finding is a positive non-linear effect of DSL market competitiveness on FTTP penetration. The authors include an inter-platform competition variable that measures the concentration of technologies using a Herfindahl–Hirschman Index (HHI) based on connections per technology—DSL, cable, fixed wireless access (FWA) and others, excluding fibre—while also including cable penetration as an additional independent variable. The fixed effect estimation yields a polynomial effect of inter-platform competition on fibre penetration. The authors describe the effect as overall positive while there is a strong negative effect in highly competitive markets. The cable penetration variable exhibits a strong negative effect on FTTP penetration. The dependent variable used by Fourie and de Bijl only captures FTTP penetration, neglecting fibre to the cabinet (FTTC) penetration. Consequently, the analysis does not allow for general conclusions on the effect of cable penetration and inter-platform competition but is instead limited to FTTP penetration.

Along similar lines, Kongaut & Bohlin (2014) employ data for 2002–2008 from 30 OECD countries. Much like the studies described above, the authors use technology penetration data to create an infrastructure competition variable. Using a random effects model, they find a significant positive effect of infrastructure competition on broadband penetration that is limited to countries with middle and high degrees of infrastructure competition. Using data from 2004 to 2014 for 27 European countries, Briglauer (2015) is one of the first to analyse the effect of various factors on FTTx penetration. Briglauer's regressions include country-level fixed effects and indicate that mobile network competition has a non-linear, but overall positive effect on FTTx penetration, while the cable market share variable has no significant effect.

In summary, and in line with comprehensive literature surveys (Abrardi & Cambini, 2019; Cambini & Jiang, 2009), we find that the existing evidence suggests that infrastructure competition encourages broadband penetration. The only previous study on FTTx penetration (Briglauer, 2015), however, does not find that inter-platform competition encourages FTTx penetration to a statistically significant degree.

The literature dealing with the effect of cable network competition or inter-platform competition on investments is far smaller, though more relevant to the present paper. A paper by Briglauer, Ecker & Gugler (2013) is most closely related to our research. They use a data set containing 27 EU countries with data between 2005 and 2011. Country- and time-fixed effects are included in their model, while cable penetration is used to measure inter-platform competition. Their results show an overall positive inverted U-shaped effect of cable competition on FTTx coverage expansion.

A paper by Yoo (2014) compares broadband developments between the US and European countries. Among other research questions, he addresses the impact of cable inter-platform competition on FTTx coverage. The data set he employs is sourced from the European Commission and contains observations on 28 European countries for the years 2011 and 2012. Yoo uses FTTx coverage as the dependent variable, while cable coverage serves as the main explanatory variable. His OLS regressions show a strong positive linear effect of cable coverage. The author concludes that cable broadband is not only a direct driver of NGA availability, but it also spurs investments in FTTx. Yet the limited sample size, as well as the methodology, limits the validity and relevance of Yoo's results. The observations on the dependent variable, FTTx coverage, are highly serially correlated, as the coverage in 2012 equals coverage in 2011 plus the additional deployments that occurred during 2012.

Garrone & Zaccagnino (2015) analyse a comprehensive firm-level data set (incumbents in 27 OECD countries) examining factors driving incumbents' investments. The market share of new entrants in the trunk telephony market and the market share of new entrants in access lines (excluding unbundled lines) are used to measure competition intensity. While the former includes both inter- and intra-platform competition, the latter consists primarily of cable- and fixed wireless access-based technologies. Examining both country- and time- fixed effects, they find no significant effect on incumbents' investments.

In a firm-level study, Briglauer, Gugler & Haxhimusa (2016) analyse factors that drive capital expenditure (CAPEX) of 23 European incumbents between 2003 and 2011. Using GMMSYS and LSDVC models, all of which include firm fixed effects, they find a positive effect of fixed broadband inter-platform competition, measured by new entrant lines related to the total number of retail broadband lines.

In summary, the studies surveyed above find inter-platform competition has mixed effects on investment variables. In these studies—with the exception of Yoo (2014)—inter-platform competition is measured using broadband penetration data of cable, FWA or other competing technologies.

Our major criticism of the literature surveyed above relates to the use of cable penetration data to measure the intensity of inter-platform competition, particularly where country- or firm-fixed effects are applied. Generally, cable networks can incentivise incumbents and alternative operators to invest in FTTx in three different ways: First, in order to acquire new broadband customers that are currently cable broadband customers. Second, to avoid migration of existing customers to a cable network that has been deployed in the past. Third, to avoid customer losses in areas where cable network operators expand their network. Accordingly, measuring the competitive pressure stemming from cable networks must include all of these building blocks. The data generating process causing cable penetration within variance, however, only captures the customer migration in cable regions between the cable network and competing technologies and the share of customers that are located within a cable expansion area that migrates to the CNO for broadband services in the same period (see Figure 2). Therefore, using cable network penetration to measure inter-platform competition intensity while applying country- or firm-level fixed effects neglects the competitive pressure from households within cable regions that could potentially migrate to the CNO in the future. In summary, using the time-series information of cable penetration variables measures cable network inter-platform competition only partially and imperfectly.

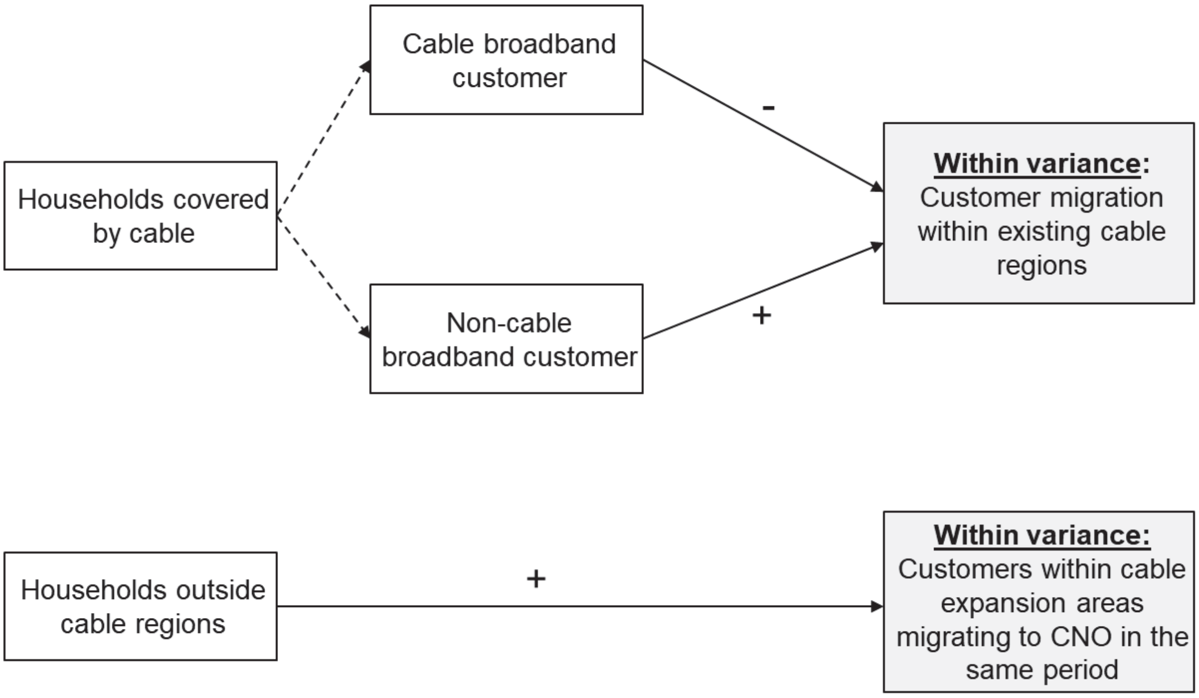

Figure 2: Data generation process for cable penetration within variance.

Exploiting both within and between cable penetration variance, as done in some of the studies mentioned above, only partially solves this problem. In principle, this approach suffers from the same drawbacks described above, as it neglects the competitive pressure from cable households that could potentially migrate to the CNO for broadband services. However, cable penetration correlates strongly with cable coverage (Pearson correlation coefficient of 0.81 in our dataset). Thus, it is, though only to a limited extent, a proxy for coverage when cross-sectional information is exploited. Nevertheless, we argue that using coverage data is a superior approach because it measures precisely the full extent of cable networks' competitive pressure, including both customers that already migrated to the CNO and those that are reached by a cable network and could potentially migrate in the future.

3. Broadband competition between cable and FTTx networks

As argued in Section 2, it is necessary to employ cable network coverage data in order to evaluate the effects of inter-platform competition fully. This section describes the historical evolution of cable coverage in Europe, and how the technology, as well as the institutional and political environment, has changed in the past decades. This overview serves as a basis to derivate hypotheses on the competition effects of cable networks on FTTx expansions.

In this paper, cable network deployments will be divided into three periods, each exhibiting a different political and demand and supply context.[25] The periods are presented below and include the pre-liberalisation era, the exponential fixed broadband penetration phase, and the recent bandwidth demand growth phase. The first is the (broadband) pre-liberalisation era, during which cable was complementary to copper networks. The exponential fixed broadband penetration growth phase spans the time from 2001 to 2011 and is characterised by rapidly growing fixed broadband markets, as well as moderate bandwidth demand in the mass market, with bandwidth demands typically within the range DSL technology provides. The last, the bandwidth demand growth phase, corresponds to the data sample employed in the present paper (2001–2011). During this period, bandwidth-intensive services such as high definition video on demand (HD-VoD) achieved mass adoption, which increased bandwidth demand beyond the technical limitations of DSL.

3.1. Pre-liberalization (before the 2000s)

Most European cable access networks were built at a time when cable technology was designed to deliver TV and radio broadcasting services, and when roll-out decisions or license awards were driven by media-politic reasoning rather than private investment decisions. In general, during this first or initial wave, the political environments and overall market conditions were quite heterogeneous across Europe in terms of media market liberalisation, TV penetration, satellite market success, subsidies or governmental cable investment plans (Bauer, 2010). This phase ended when incumbents divested their cable networks and most cable network operators began to offer broadband services over cable, around 2001 (Ismail, 2003).[26] Until then, 50 million households were covered by a cable network in the then 15 EU states (European Commission, 2001), and approximately 24 million households[27] in the 13 countries that joined the EU in subsequent years. Overall, cable networks built before 2001 provide 72% of all European households with access to a cable network today. By 2001, incumbents accounted

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[25] These periods do not apply exactly to each country; rather, they resemble rough approximations and serve to illustrate differences in the context in which cable deployments occurred historically.

[26] Liberalization did not occur in a specific year for all European households; rather, 2001 marks the year around which most liberalization processes came to fruition.

[27] According to IDC (2002), 62% of all households in EU candidate countries in 2002 had access to a cable network. Thus, approximately 24 out of the 38.6 million households have acquired cable networks coverage in these years.

only for 2%[28] of all cable broadband lines, indicating that joint ownership of cable and copper networks was the exception, not the rule. Accordingly, the regulatory pressure on incumbents to divest their cable business gave rise to a separated industry structure with CNOs on one side and incumbents on the other.

3.2. Fixed broadband penetration growth phase (the 2000s to 2010)

The second wave, beginning in 2001 and ending in 2011, marks the beginning of the data set employed in this study. This period in Europe is characterised by sharply rising broadband penetration from below 5% at the beginning of the period to 27% in 2011 (COCOM, 2012). Before 2011,[29] bandwidth-intensive services such as HD over-the-top video services, 3-D applications and high-quality video conferencing had not yet achieved widespread adoption (Ezell, Atkinson, Castro & Ou, 2009). Against this background, the period from 2001 to 2011 is characterised by moderate bandwidth demand, which is also reflected in typical speeds for broadband tariffs in that period: In 2011, the share of broadband households with a contractual speed limit below 30 Mbps ranged between 57% in Romania and 100% in Italy and Greece, averaging 89.9% in the 27 EU countries. By 2017, the latter number dropped to only 50%, indicating the rising demand for faster broadband connection subsequent to 2011.[30]

Cable network coverage continued to expand between 2001 and 2011. Unfortunately, due to the lack of country-level data, it is only possible to describe the magnitude on an aggregated European level. Before 2011, cable networks had expanded to 14.2 million additional households,[31] which corresponds to an average increase of 1.8% each year. The spread of internet services in this period led to a continuous rise in broadband subscribers, reaching 136 million active broadband lines in the EU27 countries alone in 2011. CNOs grew their broadband customer base significantly at that time. Still, the broadband market relevance of cable networks

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[28] Our own calculations based on (COCOM, 2003).

[29] The years chosen may seem somewhat arbitrary, owing to the heterogeneous demand and supply of broadband services among European countries.

[30] Clearly, the lower share in 2011 can be explained by the lack of supply of higher bandwidth connections. However, technologies supporting bandwidths above 30 Mbps had already reached a significant number of European households in 2011 (European average of 22% for VDSL, 12% for FTTP and 38% for DOCSIS 3.0—see (European Commission, 2012))

[31] Own calculation based on European Commission data: In 2011, the European commission collected coverage data for broadband technologies for the first time. According to the first study of its kind (European Commission, 2012), 87.78 million households within the (then) 27 EU countries were covered by cable networks in 2011. In addition, Croatia had 0.4 million households covered by cable networks, for a total of 88.2 million households in today’s 28 EU countries.

evolved heterogeneously among European states (see Figure 3). In some countries (AT, CZ, DK, LT, NL, UK), CNOs enjoyed early success and achieved relatively high market shares early on, followed by a later decrease in market share. In the remaining countries, cable market share remained either stable (BE, ES, MT, SK, FI, LV, FR, BG, PT[32]) or increased only marginally (DE, CY, LU, HU).

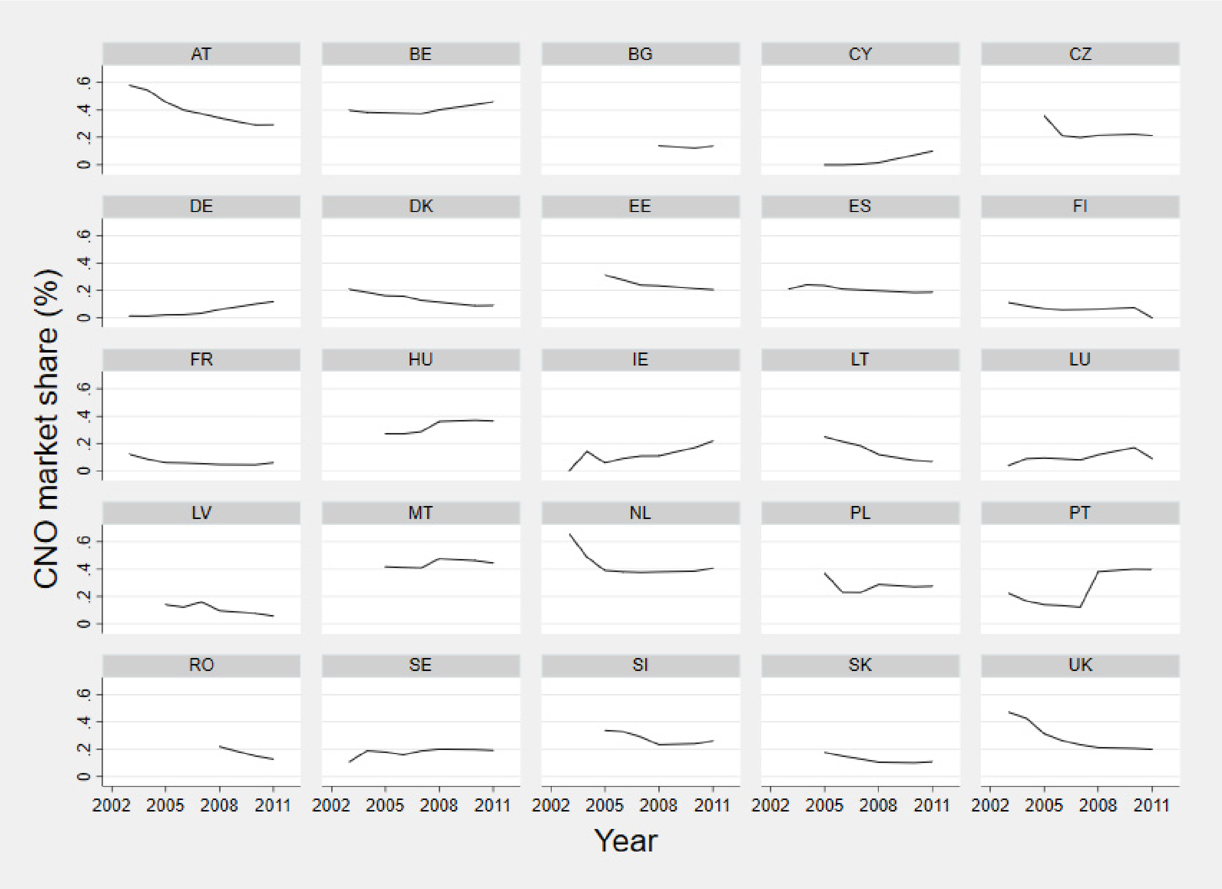

Figure 3: CNO market share in European countries between 2003 and 2011[33]

Factoring in the cable network expansions and the enlarging addressable market leads to the impression that CNOs resembled a strong competitor in a rapidly growing market, but, with few exceptions, grew the customer base either proportionally, or less than proportionally to the growth of the broadband market. Moreover, during the period from 2001 to 2011, alternative operators and incumbents began to invest in FTTx. As shown in Figure 4, these investments

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[32] The spike in Portugal in 2008 was caused by incumbent cable divestitures; see http://pharol.pt/pt-pt/press-releases/noticias/Paginas/2007/COM071107.aspx

[33] See e.g. (COCOM, 2018) for 2017 report

were primarily limited[34] to urban areas, defined as areas with more than 100 persons per square kilometre.

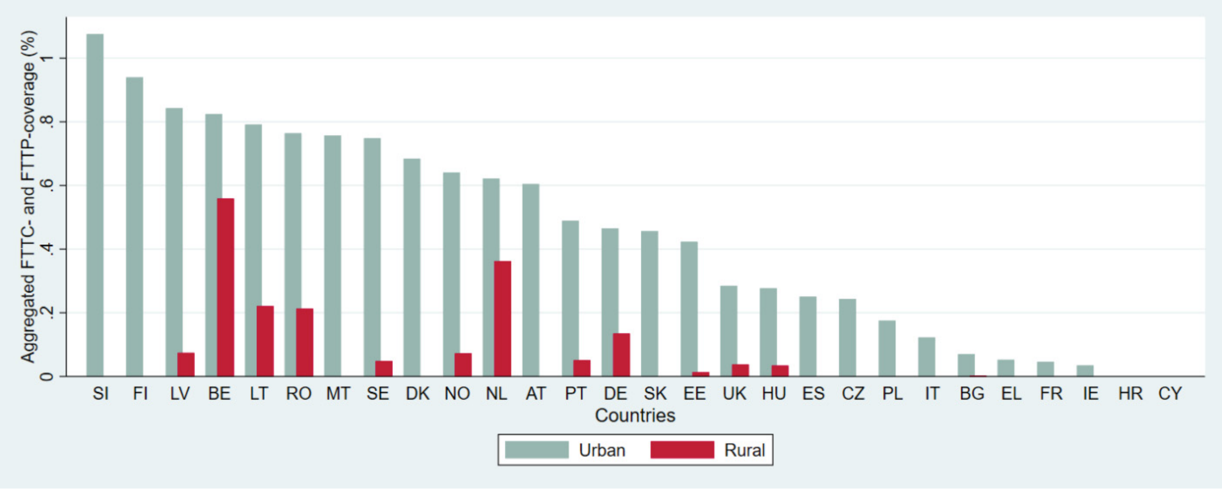

Figure 4: Aggregated FTTC and FTTP coverage by country for urban and rural areas in 2011

3.3. Bandwidth demand growth phase (2011–2017)

Technological progress is widely acknowledged as a potential cause for structural shifts in market dynamics and market share distributions (Asimakopoulos & Whalley, 2017; Giachetti & Dagnino, 2014; Gomez, Lanzolla & Maicas, 2016; Hill & Rothaermel, 2003; Klingebiel & Joseph, 2016). As telecommunications is a rapidly changing industry, demand evolution is a strong potential source for such structural shifts. The mass market adoption of bandwidth-intensive services between 2011 and 2017 resembles such a demand evolution. For example, subscriptions to video-on-demand services grew exponentially from only 0.6 million subscribers in 2011 to 52.9 in 2017 (European Audiovisual Observatory, 2017, 2018). While video services were the main driver of broadband IP traffic growth (Cisco, 2019) in the period, other services, such as online gaming and cloud storage, added to the growing demand.

Alternative operators and incumbents anticipated this evolution before 2011 and upgraded parts of their DSL networks by replacing copper lines with fibre between the main distribution frame (MDF) and cabinet (FTTC) or by rolling out FTTP (source and see Figure 4). However, between 2011 and 2017, the demand for a significant share of households exceeded ADSL's technical limits of a maximum of 16 Mbps downstream (Pereira, 2013; Rokkas, Katsianis & Varoutas, 2010; Winzer & Massarczyk, 2015). As demand outgrew DSL supply limits, the

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[34] The large differences among the European countries in both rural and urban regions result from many sources, including differences in demand, competitive or political pressure, or the lack of legacy copper networks.

competitive position of cable improved significantly. DOCSIS 3.0 enabled CNOs to offer downstream speeds exceeding 50 Mbps with relatively small incremental costs. DSL operators, in contrast, were required to invest in costly FTTx upgrades requiring substantial civil work (Feijóo, Ramos, Armuña, Arenal & Gómez-Barroso, 2018). Consequently, between 2011 and 2017, CNOs gained market share in most European countries, which stands in stark contrast to the prior period (see Figure 3 for the 2003 to 2011 period and Figure 5 for the third). Cable market share increased in 16 countries (AT, BE, BG, CY, DE, DK, FI, FR, HR, HU, IE, LU, MT, NL, PL, SI) while stagnating or decreasing slightly in only eight countries (UK, SK, SE, PT, ES, EE, CZ, LT, RO). This market share growth cannot be explained by coverage growth and a resulting larger addressable market, as cable network expansions during the period were limited to just a few percent in a small number of countries (see Figure 1). In fact, only 9 million (~10%) additional households were connected to cable networks between 2011 and 2017. Consequently, it can be inferred that the rising demand for bandwidth exceeding the technical limitations of DSL contributed to cable's growth in market share in most European countries in this period.

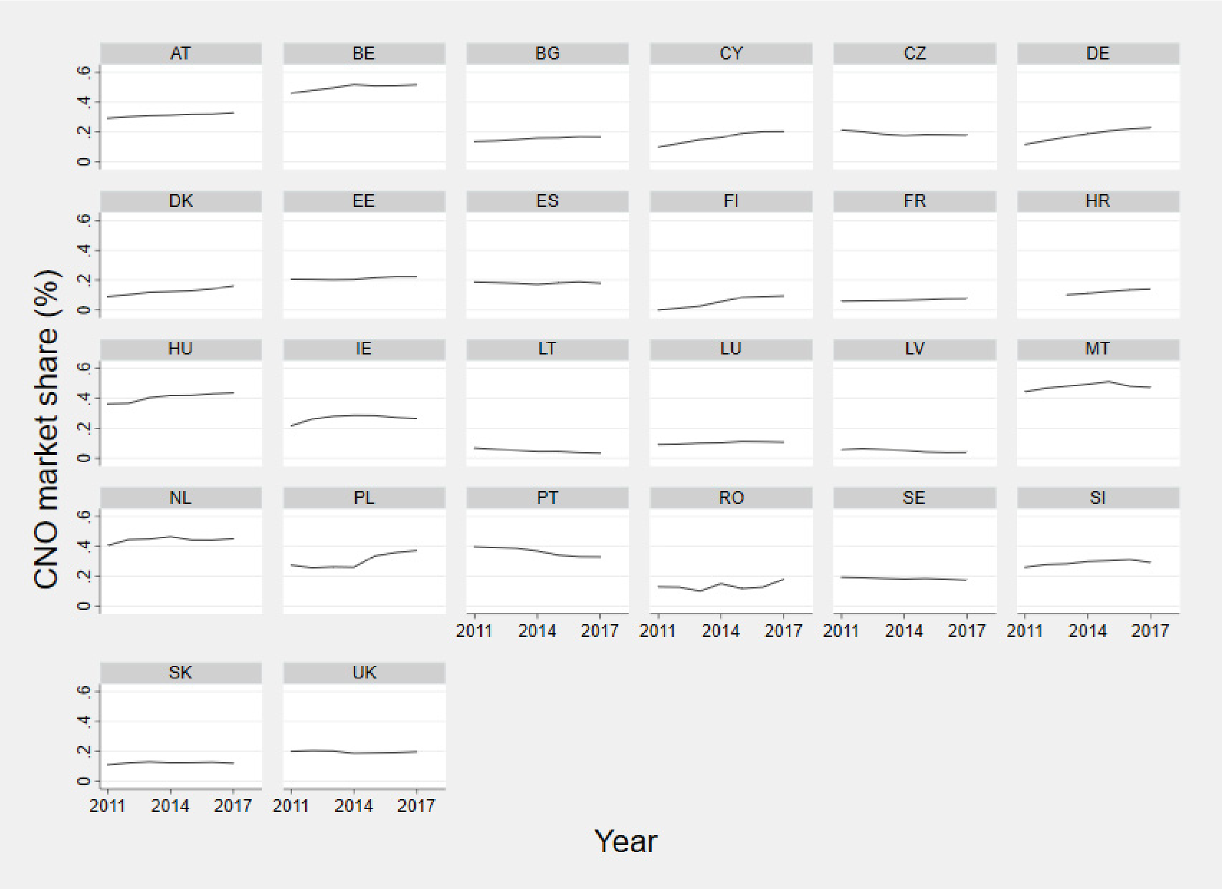

Figure 5: CNO market share in European countries between 2011 and 2017. Source: own calculations based on yearly COCOM reports[35]

4. Hypothesis on the effect of cable network competition on FTTx expansions

Essentially, firms expand their FTTx networks as long as their expected net present value (NPV) is positive. As these investment opportunities are shared with competitors, strategic aspects are considered. The expanded NPV (ENPV) formula, which is rooted in real options theory (see Dixit & Pindyck, 1994), incorporates this dimension by adapting the classic NPV calculus as follows (Li & Johnson, 2002; Trigeorgis, 1996):

$$ENPV = NPV + (Deferability\ value - Competitive\ Loss) \qquad (1)$$

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[35] See e.g. (COCOM, 2018) for 2017 report

The deferability value refers to the value of flexibility to defer undertaking the investment. Postponing an FTTx investment reduces demand uncertainty and reduces capital costs. Competitive loss describes the loss of value that occurs if the firm does not decide to invest and the value is instead captured by competitors. We can express the EPNV for an FTTx investment in a region j as follows:

$$ENPV_j = \sum_{t=0}^{T} \frac{CF_j * TakeRate_{tj}}{(1+i)^t} - CAPEX_j + \sum_{t=0}^{T} \frac{DV_{jt} + CL_{jt}}{(1+i)^t} \qquad (2)$$

where CF_j is the cash flow generated by a subscription; $TakeRate_{tj}$ the anticipated take-up rate defined as the anticipated number of households in region j that will subscribe in period t; i the interest rate, $CAPEX_j$ the initial capital expenses to build the network; CL_{jt} the competitive loss, and DV_{jt} the deferability.

The effect of competition from cable networks on the FTTx investment calculus can be threefold[36] (see Figure 6): Firstly, competition from cable networks reduces the anticipated FTTx take-rate. Secondly, the presence of a cable operator increases the risk that existing customers will migrate to the cable network if the DSL operator does not invest in FTTx, and therefore increases the potential competitive loss, CL_{jt}. Thirdly, the existing competition from CNOs decreases the replacement effect (Arrow, 1962)—the cannibalisation of legacy DSL revenues by DSL services. As CNOs already possess a substantial market share in cable regions, the technology market share of DSL services is typically lower when compared to non-cable regions. Consequently, the replacement effect is lower in cable regions, which positively affects the anticipated cash-flows, CF_j.

In summary, cable networks have opposing effects on the investment decisions of alternative operators and incumbents. Moreover, it is important to stress that $CAPEX_j$ depends on population density, as lower population density increases the civil engineering efforts required to cover each household, and these costs account for the most substantial proportion of deployment costs (Feijóo et al., 2018; Jay, Neumann & Plückebaum, 2012). Accordingly, the ENPV will vary strongly with the region's population density.

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[36] We excluded effects on CF as there is no empirical support that inter-platform competition reduces price—see Calzada & Martínez-Santos (2014)

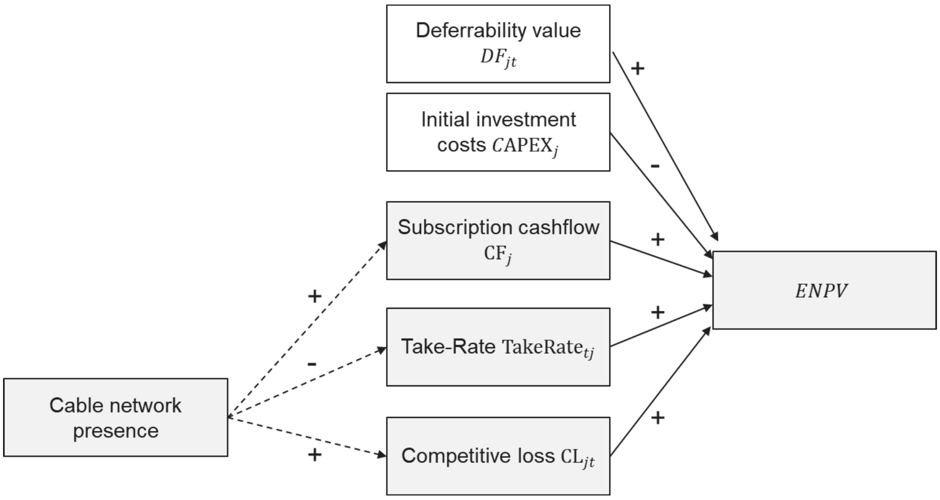

Figure 6: Effects of cable networks on the FTTx investment calculus of firms (after Bauer 2010)

This paper aims at empirically identify which of the opposing effects mentioned above prevails for the period from 2011 to 2017. In our data set, it is important to distinguish between the 89 million cable households that were covered before 2011, hereafter referred to as legacy cable areas, and those nine million that were built within the period captured by our sample hereafter referred to as cable expansion areas (see Figure 1). We make a distinction between legacy and expansion cable areas since there are structural differences in the competitive loss, CL_{jt}, as well as the subscription cashflow, CF_i, between these regions. CNOs have been a contender since the introduction of DOCSIS, leading up to a 39% broadband market share within their cable footprint in 2011.[37] Thus, 39% of households that are already served by CNOs will not be considered as a potential competitive loss. In cable expansion areas, however, the situation is different. Cable network expansions pose an immediate risk ('competitive shock') for both incumbents and alternative operators in those new cable regions. Within a short period, former DSL-only customers are given a choice to switch to cable operators providing a service that satisfies their demand for faster bandwidth. The potential competitive loss, and consequently, the ENPV, increases immediately. Accordingly, we expect that there is a difference in the effect that cable network expansion areas have in comparison to legacy cable areas, as incumbents and alternative operators are incentivised to counter-invest in FTTx in these regions in order to avoid or to mitigate customer migration to the CNO. To account for that hypothesis, the research question will be addressed separately for legacy cable and cable expansion areas.

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[37] Own calculations: EU-wide cable technology market share of 16% (COCOM, 2012) at a coverage of 41% (European Commission, 2012).

5. Empirical implementation

This paper aims to analyse the effect of cable networks on FTTx coverage expansions during the period from 2011 to 2017. To do so, we employ coverage data, which allows us to capture the full extent of cable network inter-platform competition. To test our hypothesis that cable network expansion areas may experience a different effect than legacy cable areas, we utilise the panel structure of our data. Each increase in cable coverage can be ascribed to a CNO expanding their footprint to new households. In general, cable coverage almost exclusively[38] increases within countries (see Figure 8). Accordingly, the within variance of the cable coverage variable corresponds to cable expansion areas. Hence, we can identify the sum of the cable expansion areas in a given year using the within variance of the national country coverage variable. In contrast, between variance, i.e. the coverage differences between countries, is a product of roll-outs that occurred before 2011 (predominantly before 2001—see Section 3.1) and thus equals the sum of legacy cable areas. Accordingly, the between and within variance in the cable coverage variable correspond to mutually exclusive regions illustrated in Figure 7. In other words, although our dataset contains only country-level data, we can analyse the different areas by examining the different types of variance separately.

Figure 8 shows the cable network coverage evolution for the countries included in our data set. While there is significant heterogeneity between countries (between standard deviation of 0.2653), there is only a relatively small increase in coverage within the countries throughout the six years included in our panel (within standard deviation of 0.0383). Our empirical implementation is designed to exploit the regional attribution of between- and within-country variance, and therefore distinctly address the effect of legacy cable areas and cable expansion areas, even though the European Commission does not collect data at that level.

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[38] The few exceptions in which coverage decreases in our data set (12 observations) can be explained either by measurement errors or by CNOs decommissioning uneconomic local cable networks. The latter may occur in small remote villages where fixed costs scale over too few households.

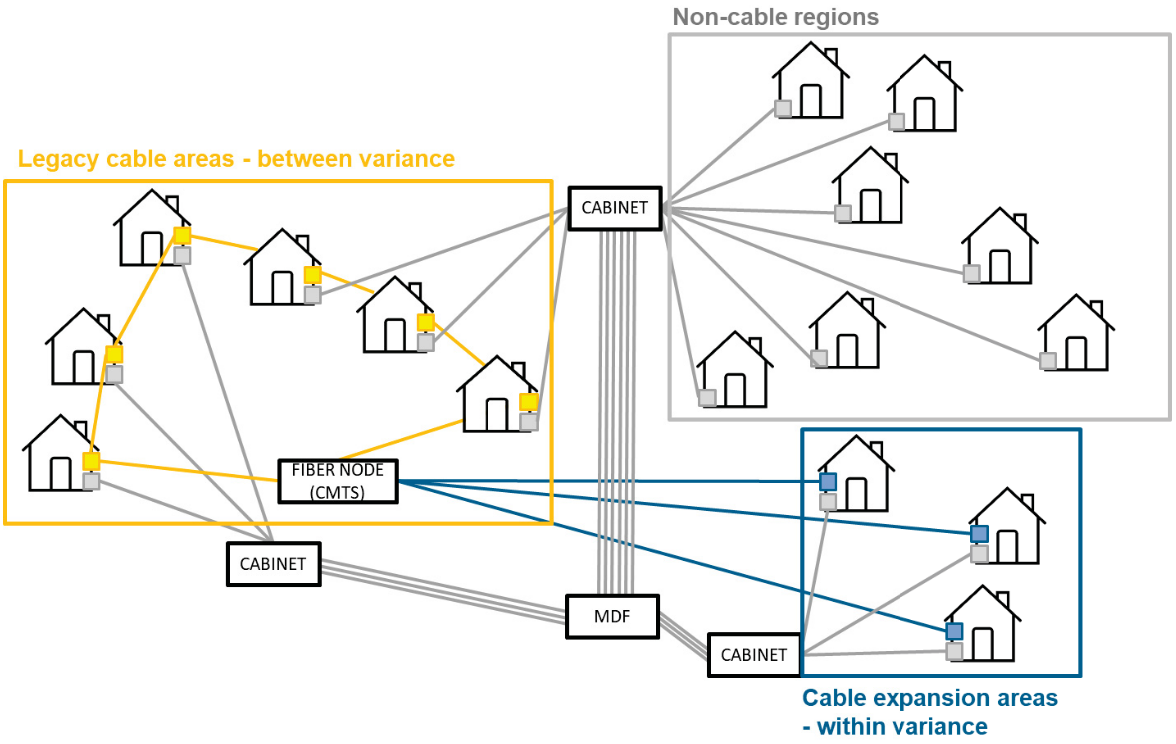

Figure 7: Illustration of legacy cable areas, cable expansion areas and non-cable areas and access network typologies. The fibre node or cable modem termination system (CMTS) connects households within legacy cable areas as well as cable expansion areas. The DSL network spans from the main distribution frame (MDF) over cabinets to households using copper cables.

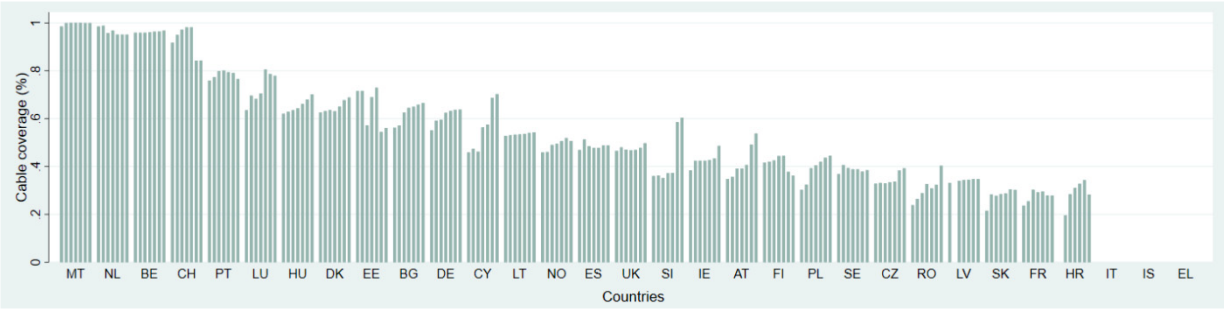

Figure 8: Cable coverage from 2011 to 2017 for sample countries. Each of the seven bars resembles one year. Source: European Commission (2012, 2018)

Our analysis relies on a panel data set, including 28 European countries[39] and covering the period from 2011 to 2017. Most of the data are drawn from the European Commission's study "Broadband Access in Europe",[40] which regularly provides information on the coverage of

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[39] The countries included are Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Greece, Spain, Finland, France, Croatia, Hungary, Ireland, Iceland, Italy, Lithuania, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia and United Kingdom.

[40] See https://ec.europa.eu/digital-single-market/en/news/study-broadband-coverage-europe-2017

different broadband access technologies by country and year.[41] The technologies included in the study are DSL, FTTC, FTTP, WiMAX, Cable, DOCSIS 3.0, HSPA, LTE, and Satellite. Due to different legacy infrastructures and business models, operators in some countries primarily choose to invest in FTTP, while in others, FTTC is the preferred technology (Feijóo et al., 2018). To account for these national differences throughout Europe, we aggregate the coverage data of both technologies in order to capture all investment strategies of incumbents and alternative operators jointly. The sum of FTTP and FTTC coverage exceeds 100% in countries where an alternative operator invests in FTTP overbuilding incumbents' FTTC networks. The geographical overlap thus is included in the aggregated FTTC and FTTP data. However, both network roll-outs represent an investment and thus need to be included in the variable, even if coverage above 100% may seem counterintuitive. Furthermore, we use the annual coverage percentage changes to avoid serial correlation (total coverage in year t1 correlates with that of t0) and to capture only the investments between 2011 and 2017 (total coverage in 2011 is a product of deployments before 2011 plus those of the year 2011).

Additionally, control variables are sourced from the World Bank database. A table in the Appendix presents the included variables and respective descriptive statistics in levels.

Our supply model is specified as follows:

$$\begin{aligned} & delta\_fttx\_cov_{it} \\ & = \beta_0 + \beta_1\, cb\_cov_{it} + \beta_2\, \text{pop\_dens}_{it} + \beta_3\, urban\ share_{it} \\ & + \beta_4\, gdp\_per\_cap_{it} + \beta_5 fbb\_pen_{it} + \beta_6 edu_{it} + \beta_7\, \lambda_t + \alpha_i + \varepsilon_{it}, \end{aligned} \tag{1}$$

,where

$\boldsymbol{delta\_fttx\_cov_{it}}$ states the annual percentage change of households that are additionally covered by either an FTTC or FTTP network

$\boldsymbol{cb\_cov_{it}}$ denotes household cable coverage in % country i and time t

$\boldsymbol{pop\_dens_{it}}$ population density measured as inhabitants per square kilometre

$\boldsymbol{urban\ share_{it}}$ is the population of country i living in an urban environment at time t

$\boldsymbol{gdp\_per\_cap_{it}}$ gross domestic product (GDP) per capita in $, adjusted for purchasing power parity (PPP), in country i and time t

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[41] We exclude observations for Estonia due to unreasonably high variation over time that is most likely due to measurement errors. Luxembourg is excluded as, in this duopolistic market, the incumbent is still state-owned and therefore has different investment considerations than all other privately-owned operators in our sample. Lastly, observations with a negative change in the aggregated FTTC and FTTP infrastructure were deleted due to implausibility (*delta_fttx_cov* < 0).

$\boldsymbol{fbb\_pen_{it}}$ is the fixed broadband penetration of households in country i and time t

$\boldsymbol{edu_{it}}$ is the education level measured as % of the population enrolled in tertiary education in country i at time t

$\boldsymbol{\lambda_t}$ are country-specific effects

$\boldsymbol{\alpha_i}$ is the unobserved heterogeneity across countries

$\boldsymbol{\varepsilon_{it}}$ is an unobservable error term

In our supply model, we account for different relevant demand and supply variables (all log) commonly used in the related literature presented in section 2. Although we use a coverage instead of a penetration dependent variable, we argue that both are influenced by various similar demand and supply-side factors. Accordingly, our supply model is oriented on the one used in (Fourie & de Bijl, 2018). Nevertheless, we refrain from including competition measuring variables such as the HHI since these are already included through our cable coverage variables.

On the supply side, the costs of deploying and operating telecommunications networks primarily depend on geographic factors (Jay et al., 2012; Van Der Wee et al., 2015). Lower population density and a higher share of population living in urban areas allow for cheaper network roll-outs on a per household basis, as higher geographical concentration allows operators to exploit economies of scale. Hence, network roll-out in densely populated areas is considerably less costly and broadband supply, in general, should be promoted. Increases in GDP, as an indication for purchasing power on the demand side, are expected to influence FTTx deployments positively. Similarly, a higher fixed broadband penetration indicates more demand, and should, therefore, increase FTTx expansions. Countries with higher education are also likely to have higher FTTx expansions as the population derives more value from a supply of fast broadband.

We furthermore address the potential issue that may arise from a correlation between cable coverage and FTTx coverage. Countries with higher cable coverage may have fewer households that have not been covered with FTTx before the beginning of our sample. This could potentially distort the coefficients for our cable and DOCSIS coverage variables. Accordingly, we control for an additional variable which captures the deployment potential by adding together the percentage of households not covered by FTTC and those not covered by FTTP[42]. Hence our second estimation is specified as follows:

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[42] The deployment potential variable $depl\_pot_{it}$ is calculated as $1 - fttc\_cov_{it} + 1 - fttp\_cov_{it}$

$$
\begin{aligned}
&delta\_fttx\_cov_{it} \\
&= \beta_0 + \beta_1\, cb\_cov_{it} + \beta_2\, depl\_pot_{it} + \beta_3\, \mathrm{pop\_dens}_{it} + \beta_4\, urban\ share_{it} \\
&+ \beta_5\, gdp\_per\_cap_{it} + \beta_6 fbb\_pen_{it} + \beta_7 edu_{it} + \beta_8\, \lambda_t + \alpha_i + \varepsilon_{it},
\end{aligned}
\tag{2}
$$

5.1. Econometric strategy

As explained in Section 4.4, we suspect that the effect of cable coverage between 2011 and 2017 on FTTx deployments may be twofold: On one hand, the presence of legacy cable networks built before 2011—which account for nearly 90% of the cable coverage today—may hamper FTTx network build-outs, as it increases the penetration risk for new infrastructures. On the other hand, cable roll-out in the third wave may have a countervailing effect, as incumbents and alternative operators may invest in protecting their market position.

In order to distinctly account for these two effects, we make use of different panel estimators. First, a 'between' estimator, which only draws on variation between countries, is used to compare the effect of the average degree of cable and DOCSIS roll-out in different countries (legacy cable areas) and its effect on FTTx investments. The between effect model regresses the time-average value of the dependent variable over the time-average values of the independent variables (Wooldridge 2012 p. 485). Thus, country-within variation is averaged out and only variation between countries is used. Unobserved heterogeneity is not considered, and the between estimator is consistent if the regressors are not linked to the error term (Wooldridge, 2012, p. 485). That concern and the fact that information about how the variables change over time are ignored explains why between-estimators are not commonly applied in the literature. However, prior research has acknowledged the benefits arising from the distinct use of cross-sectional information (Abeliansky & Martínez-Zarzoso, 2019; Biermann, Bitzer, & Gören, 2019; Fusco, 2015; Stern, 2010). In our case, this weakness is desirable merit for our research, as the different variance types refer to mutually exclusive regions (see Figure 7). The potential bias arising from a correlation between unobserved country specific effects and the explanatory variable cable coverage is mitigated by the fact that approximately 72% of the between variation stems from before 2001 (see Section 3), a time in which cable networks have been a supplement rather than a competitor on the broadband market we are examining. Despite the issues mentioned above that arise with the use of a between estimator, this approach allows drawing conclusions regarding the effect of legacy cable coverage distinctly if the coefficients are interpreted as the mean effect in the sample.

Second, we use a fixed effects estimator, which only uses within (time) variation for each country (and averages out the between variation), to isolate the effect of cable expansion regions. We also lag our main independent variable to account for the fact that firms need some time to react to competitors' investments and other changes in the market. Thus, with this approach, we test if cable expansion is accompanied (no lag) by FTTx expansions, which would indicate that firms either co-invest, or would hint at the simultaneous deployment of cable and FTTx networks to newly built homes, and we test if there is a competitive reaction in the subsequent year (lagged cable variable). Additionally, we drop observations in which cable coverage decreases, as this affects within-variance but does not correspond to cable network expansions.

Third, we estimate our model using an instrument variable (IV), Pooled ordinary least squares (POLS) and a random effects[43] estimator. The latter uses cross-sectional as well as time-series information and is a matrix-weighted average of both the fixed and the between-country effects (Gould, 2018). The POLS estimator pools all observations into a multivariant regression, whereas in an IV-estimation an exogenous variable is instrumented to estimate the causal effect of the main variable of interest. Given little within- but high between-country variation for cable and DOCSIS coverage (between variation is seven times higher than within variation), we expect the IV, POLS and random effects estimation to be determined by the between effect.

5.2. Results and discussion

5.2.1. Empirical results

Table 1 summarises the results separately for cable expansions regions (using only time-series information), legacy cable areas (only cross-sectional variation), and all cable regions, using POLS, random effects and IV estimations. The results do not differ significantly if DOCSIS 3.0 coverage is used instead of cable coverage (see Appendix Table A2).

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[43] Generally, the random effects estimator is more efficient than the between estimator; consequently, most empirical studies only consider the random and fixed effects estimators. To decide between the two, the so-called Hausman test is usually applied. While this is a valid assumption for most research questions, it is not in our case. As outlined in Section 4, there are reasonable arguments to expect that both effects may differ. Consequently, we use the between estimator to quantify the average impact of an additional percentage of cable coverage between countries (legacy cable areas), and separately apply the fixed effects estimator to address the question of the impact of an additional percentage of cable coverage (cable expansion areas) on FTTx expansions.

The coefficients for cable network expansion areas are positive but only exhibit significance when the explanatory variables are lagged by one year. The expansion of cable networks seems to exert a positive effect on FTTx coverage expansion in the following year. This confirms our hypothesis that operators counter CNO investment in order to pre-empt customer migration. Moreover, the insignificance of the unlagged specification indicates that this effect is not caused by newly built households or simultaneous joint investments but instead by subsequent competitive investment. Unsurprisingly, population density has a strong positive significant coefficient. Interestingly, that positive effect is counterbalanced by a strong negative significant sign of *urban_share*, which also measures population concentration. The reason could be operators already rolled-out FTTx networks to large parts of the urban population before 2011 (see Figure 4). Per-capita GDP exhibits a significant negative coefficient, which is rather surprising. Fixed broadband penetration and education are not significant in either of our models.

Confirming our hypothesis, the coefficient of cable coverage is negative only if the between variation is exploited. The result implies that a 10% increase in cable coverage reduced the annual FTTx coverage expansion by a factor of 0.81. The results, which do not change if a lag is introduced for the explanatory variables, show that incumbents and alternative operators faced more challenges in expanding the FTTx network coverage in countries with pervasive cable networks. The control variables of population density and GDP per capita do not have significant coefficients. While we argued that it is reasonable to use the between estimator for the effect of cable coverage, the above-mentioned drawbacks of the between estimator causes us to refrain from interpreting signs and significance for control variables.

The estimations of POLS, random effects and IV serve as further robustness checks. Unsurprisingly, the random effect coefficient is slightly smaller than the between coefficient, as the random effects estimator also exploits within variation, and therefore blends cable expansion and legacy regions. Given that variation in the data predominantly stems from the difference between instead of within variation, these results are unsurprising but can be interpreted as a sign of robustness. The IV estimator using an external instrument, sourced from the TV market, shows a significant negative sign, which is even stronger than those obtained by the between estimator, and is another indication of the robustness of our results.

	Cable expansion areas (country fixed effects)		Legacy cable areas (between estimator)		Cable expansion and legacy cable areas with lagged ind. variables		
	Without lagging	**With lag**	**Without lag**	**With lag**	**POLS**	**RE**	**IV**
cb_cov	0.2229	0.414***	-0.082**	-0.081**	-0.068**	-0.065**	-0.184***
	(0.164)	(0.131)	(0.032)	(0.301)	(0.028)	(0.029)	(0.052)
pop_dens	0.641***	0.746***	0.016	0.015	0.017**	0.017**	0.038***
	(0.219)	(0.218)	(0.009)	(0.009)	(0.008)	(0.008)	(0.008)
urban_share	-0.566***	-0.527***	-0.159*	-0.174**	-0.187**	-0.189***	-0.207**
	(0.181)	(0.135)	(0.084)	(0.082)	(0.083)	(0.051)	(0.081)
gdp_per_cap	-0.234**	-0.273**	0.048	0.041	0.051*	0.051**	0.057*
	(0.093)	(0.121)	(0.029)	(0.029)	(0.027)	(0.021)	(0.031)
fbb_pen	0.098	-0.005	0.039	0.043	-0.003	-0.007	0.011
	(0.136)	(0.114)	(0.05)	(0.051)	(0.046)	(0.046)	(0.053)
edu	0.102	0.021	-0.019	-0.022	-0.007	-0.005	(0.037)
	(0.127)	(0.075)	(0.037)	(0.038)	(0.029)	(0.035)	-0.651*
N	143	143	163	163	163	163	126
p-value	<0.0001	<0.0001	0.0427	0.0399	0.0127	<0.0001	<0.0001
R^2	0.102	0.148	0.285	0.291	0.090	0.1287	0.063

Heteroscedasticity and autocorrelation robust standard errors in parentheses. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions include a constant which is omitted here for brevity.

Table 1: Estimation results for cable coverage as the explanatory variable

The results from estimation (2) deviate only marginally from those presented above (see Table 5 and 7 for estimation results using DOCSIS). The lagged cable coverage variable still has a significant positive effect in the fixed effects estimation. Moreover, the cable coverage coefficient remains significant and negative for the remaining estimators indicating that the negative effect prevails even if the model controls for the deployment potential (see Tables 4 and 5).

These results allow us to draw conclusions about how cable networks have affected FTTx investments in Europe from 2011 to 2017: The ability of incumbents and alternative operators to invest in FTTx was significantly reduced in countries with expansive cable networks. This effect can be explained by the penetration risk that operators face when investing in regions with existing cable service. The larger the present cable footprint, the larger the probability that cable networks, able to deliver speeds of up to 1 Gbps, account for a significant market share—even if an alternative operator invests in FTTx. The market share that operators anticipate gaining in a cable region is apparently insufficient to recoup the immense investment costs. Our results thus imply that legacy cable network coverage effectively limits incumbents and alternative operators in their ability to choose an FTTP rather than an FTTC typology, because the high costs associated with FTTP seem to be too high to be recovered within legacy cable regions. Additionally, we find support for the hypothesis that incumbents and alternative operators react to CNO’s network expansion through FTTx investments in order to pre-empt customer migration.

5.2.2. Findings in the temporal context of FTTx roll-outs

As mentioned in Section 4, the upfront investments needed to cover households with an FTTx network vary with the population density. Thus, the penetration risk arising from legacy cable networks has different implications for varying population densities. In urban areas, a relatively low roll-out cost per household mitigates penetration risk, and therefore still allows for investment despite the existing cable network. This, however, does not apply to suburban and rural legacy cable regions; in these regions, the penetration risk per connected cable household is unchanged, while investment costs rise substantially. This differentiation also allows us to set our empirical results in the context of the competition timespans presented in Section 3. It seems that before 2011, the FTTx investments of incumbents and operators were not reduced by the existence of cable networks, as urban areas still allowed for profitable investment despite the penetration risk. This changed between 2011 and 2017 when incumbents and alternative operators already have covered urban areas and thus had to shift to suburban areas for their FTTx expansions. There, the pre-existing cable network impeded the anticipated increase in profitability to the point that precluded investment.

Consequently, our results indicate that legacy cable areas reduce the ENPV, and therefore, reduce the number of regions in which operators can profitably invest in FTTx—that is, regions where the ENPV exceeds the investment costs. Figure 9 summarises our empirical results and relates them to the industry background given in Section 3; it shows that the ENPV exceeds the investment costs in densely populated areas for legacy and non-legacy cable areas. Thus, the penetration risk effect will decrease the profitability of FTTx investment for both incumbents and alternative operators but still allow for profitable investment.

In contrast, the higher ENPV for non-cable regions expands the range of profitable regions to incremental households with higher investment costs. In other words, the penetration risk imposed by cable networks reduces the regions in which alternative operators and incumbents can invest without state subsidies. Timewise, until 2011, FTTx investments primarily occurred in the first interval, before θ_1 in Figure 9. During that timeframe, operators deployed their capital in urban areas, which have been profitable regardless of cable network competition.

At the beginning of our data sample (2011–2017), large portions of urban regions were already covered by FTTx networks in many countries. Therefore, the FTTx investment focus shifted from urban to suburban areas. In these areas, however, the profitability risk effect changed the ENPV from positive to negative, leading firms to decide not to invest. This only applies to legacy cable regions, as the higher ENPV in non-cable regions effectively shifts the profitability intersect to θ_2 in Figure 9, which extends the profitable investment areas. On a country level, that shift indicates that countries with less cable network competition have had more regions in which operators could expand their FTTx networks profitably.

Lastly, and independent from legacy cable coverage, coverage expansion areas exhibited positive ENPVs because both incumbents and operators aimed to pre-empt or mitigate customer migration to the CNO.

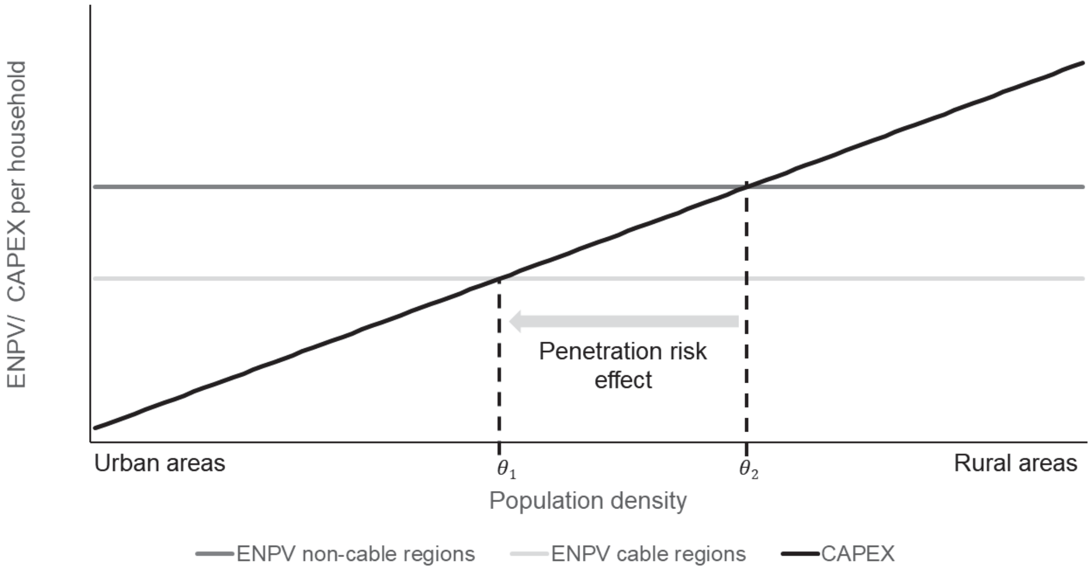

Figure 9: Penetration risk visualization. The x axis shows the population density, while the y axis shows the investment costs per household and corresponding ENPV. The rising line resembles a cost curve, which is assumed to be linear for simplicity. The ENPV for legacy and non-legacy cable regions are assumed to be static, while in the non-cable regions ENPV is higher because there is less competition from CNOs. The figure is only for illustration purposes as it is not based on cost data or model outputs and therefore simplifies CAPEX (not linear) and ENPV graphs.

6. Conclusion

This paper is the first to analyse the impact of cable and DOCSIS coverage on FTTx coverage expansions. In it, we apply panel data techniques to a sample of 28 European countries for the period 2011–2017, carefully accounting for possible endogeneity problems. The main result of this study is that we have established a robust negative correlation between legacy areas cable coverage and FTTx-network expansion, and our instrumental variable approach suggests that this link is causal. Thus, we document a considerable restraining effect of legacy cable coverage on annual FTTx roll-out. Hence, broader coverage of a competing legacy cable infrastructure, or, put differently, more inter-platform competition, has hampered the deployment of fibre-based networks in the period from 2011 to 2017. Notably, our results imply that higher costs associated with FTTP investments would, in many instances be too high to be recovered in regions with existing cable networks; we show that this is the case for the period starting in 2011.

Our results and the available data indicate that this hampering effect did not materialise before 2011, as low roll-out costs in urban areas allowed for profitable investment despite cable network competition. However, as most urban areas obtain FTTx coverage, the restraining effect of legacy cable network coverage effectively limits the ability of incumbents and alternative operators to invest profitably in cable-covered suburban and rural areas. While our empirical approach does not differentiate between FTTC and FTTP, it is reasonable to assume that the ability of alternative operators and incumbents to choose to invest in FTTP instead of FTTC is considerably reduced if cable networks are expansive.[44] DOCSIS 3.1 will further expand the bandwidths that can be delivered over cable while incurring comparably small incremental investments to upgrade the network. In contrast, the upgrade from FTTC to FTTP requires significant investment. Based on the hampering effect by cable networks on FTTx network expansions we found, it can be assumed that the magnitude of this effect will be even larger for future FTTP roll-outs. Thus, our results indicate that public policy makers should refrain from expecting that cable areas will be overbuilt by FTTP in the short-term. Instead, public policymakers should consider a scenario that includes suburban and rural cable regions in which there will not be a second infrastructure providing gigabit-class speeds or even 100 Mbps bandwidth. In these regions, CNOs would be the only provider for a subset of customers demanding higher bandwidths.

From a regulatory perspective, this is problematic, as the current regulatory regime in most European countries does have defined national geographic markets. Considering the limited cable coverage in most European countries (see Figure 8), it is unlikely that a CNO will be designated with significant market power in any product market. A potential solution would be a departure from national market definitions to a differentiation between cable and non-

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[44] Because FTTP rollouts incur investment costs significantly higher than FTTC (Jay et al., 2012; Van Der Wee et al., 2015).

cable regions, with a further distinction between competitive and non-competitive cable regions. Such nuanced geographical distinction would allow regulators to react to the market dynamics we have discovered exist between CNOs and their competitors in sparsely populated regions.

Furthermore, our finding that cable expansion is oftentimes answered by an FTTx counterinvestment shows the required meticulosity in regard to the nuanced and differentiated assessment of competitiveness in different regions throughout a country. Here, our findings suggest that the expansion of cable areas does not necessarily produce additional future potential cable gigabit monopolies. Instead, new platform competition through FTTx investment by incumbents and alternative operators will benefit customer welfare in the long term.

We are aware that our research may have two limitations. The first is potential unobserved heterogeneity in our regressions using the between operator. Although our control variables mitigate this potential bias, there is no statistical test that could further investigate whether the result suffers from significant unobserved heterogeneity (due to the expected varying effects of between and within variation). The second is the granularity of the data sample employed, geographically and timewise. Running the same estimations with a dataset with semi-annual and NUTS-3 level data would help to test the robustness of our results. The latter limitation is evidence of the difficulty of collecting comparable broadband coverage data on a more granular data level. Hence, we argue that institutions shall publish such data to enable empirical studies that could help to inform the policy debate in the broadband realm. We see an urgent need for further research in two directions: First, techno-economic models assessing the investment of incumbents and alternative operators in cable areas would allow assessing further the level of population density at which an FTTP or FTTC infrastructure could be operated profitably alongside existing cable networks. This, however, requires data on a much more granular level than the national level used in this paper. Second, we argue that analysing the effect of inter-platform competition on outcome variables by using cable penetration or market share data has severe drawbacks. Accordingly, we see a research gap that can be filled by studies that instead use coverage data and other relevant competition measures to examine the effect of inter-platform competition, for example on FTTx penetration, investments, or customer speeds.

7. Appendix

Variable	Description (units)	Mean	Min	Max	Std. Var.	N	Source
fttc_cov	VDSL coverage (%)	0.37	0	0.94	0.28	194	European Commission
fttp_cov	FTTP coverage (%)	0.30	0	0.95	0.26	193	European Commission
fttx_cov	Aggregate of fttc_cov and fttp_cov (%)	0.68	0.02	1.58	0.30	193	European Commission
delta_fttx_cov	Additional FTTC and FTTP coverage per year (%)	0.09	0	0.4892	0.08	155	European Commission
cb_cov	Cable coverage (%)	0.47	0	1	0.26	194	European Commission
dcs_cov	DOCSIS 3.0 coverage (%)	0.45	0	1	0.26	193	European Commission
pop_dens	*Population density (inhabitants per km²)*	*162.01*	*3.1*	*1375*	*248*	*196*	*World Bank*
labour_costs_ constr_ppp	*Labour costs index for the construction industry (PPP; 0100)*	*16.44*	*1.06*	*58.94*	*13.94*	*162*	*Eurostat*
gdp_per_cap	*GDP per capita (US dollars PPP)*	*36464*	*15676*	*75648*	*11780*	*196*	*World Bank*
tv_ms_dtt_sat	*TV market share of DTT and Satellite (%)*	*0.56*	*0.057*	*0.99*	*0.24*	*160*	*EC´s Financial indicators studies*[45]
depl_pot	*FTTx-deployment potential defined as 1-fttc_cov + 1-fttp_cov*	*1.31*	*0.412*	*1.97*	*0.313*	*193*	*own calculation*
d2_2014	*Dummy variable for year 2014 (0;1)*[46]						

Table 2: Variable description and summary

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[45] See most recent study: https://ec.europa.eu/digital-single-market/en/news/broadband-data-files-digital-scoreboard-2017

[46] We include a dummy variable in the regression analysis to account for changes in survey methodology.

	Cable expansion areas (country fixed effects)		Legacy cable areas (between estimator)		Cable expansion and legacy cable areas with lagged ind. variables		
	Without lagging	With lag	Without lag	With lag	POLS	RE	IV
dcs_cov	0.308	0.427***	-0.081**	-0.087**	-0.067**	-0.063**	-0.194***
	(0.198)	(0.127)	(0.032)	(0.033)	(0.028)	(0.03)	(0.055)
pop_dens	0.901***	0.699***	0.015	0.017*	0.016**	0.016**	0.039***
	(0.228)	(0.214)	(0.009)	(0.009)	(0.008)	(0.008)	(0.008)
urban_share	-0.824***	-0.489***	-0.160*	-0.177*	-0.0181**	-0.184***	-0.187**
	(0.308)	(0.174)	(0.083)	(0.086)	(0.084)	(0.052)	(0.083)
gdp_per_cap	-0.150	-0.205	0.046	0.043	0.05*	0.049**	0.057*
	(0.106)	(0.146)	(0.028)	(0.031)	(0.027)	(0.022)	(0.031)
fbb_pen	0.047	-0.084	0.044	0.048	-0.011	-0.011	0.011
	(0.110)	(0.130)	(0.049)	(0.054)	(0.046)	(0.048)	(0.054)
edu	0.124	0.077	-0.013	-0.01	-0.007	-0.003	-0.023
	(0.126)	(0.082)	(0.037)	(0.04)	(0.029)	(0.035)	(0.037)
N	148	147	164	163	163	163	126
p-value	<0.0022	<0.0001	0.0476	0.0785	0.0127	<0.0001	<0.0001
R^2	0.156	0.135	0.275	0.228	0.090	0.143	0.056

Table 3: Estimation results for DOCSIS coverage as explanatory variable

	Cable expansion areas (country fixed effects)		Legacy cable areas (between estimator)		Cable expansion and legacy cable areas with lagged ind. variables		
	Without lagging	With lag	Without lag	With lag	POLS	RE	IV
cb_cov	0.229	0.413***	-0.085**	-0.078**	-0.045	-0.037	-0.140**
	(0.187)	(0.133)	(0.034)	(0.034)	(0.032)	(0.039)	(0.059)
depl_pot	-0.167**	-0.140*	-0.011	0.008	0.073***	0.084**	0.069**
	(0.073)	(0.075)	(0.038)	(0.037)	(0.027)	(0.035)	(0.033)
pop_dens	0.364	0.867***	0.016	0.015	0.009	0.008	0.029***
	(0.328)	(0.240)	(0.010)	(0.010)	(0.008)	(0.010)	(0.009)
urban_share	-0.657***	-0.449***	-0.157*	-0.175**	-0.184**	-0.187***	-0.206***
	(0.220)	(0.146)	(0.086)	(0.084)	(0.079)	(0.056)	(0.070)
gdp_per_cap	-0.356**	-0.105	0.046	0.042	0.050*	0.049**	0.062**
	(0.131)	(0.130)	(0.030)	(0.030)	(0.026)	(0.024)	(0.029)
fbb_pen	-0.101	-0.116	0.034	0.047	0.050	-0.054	0.049
	(0.153)	(0.123)	(0.054)	(0.055)	(0.052)	(0.074)	(0.056)
edu	0.168	0.006	-0.020	-0.021	-0.006	-0.002	-0.023
	(0.136)	(0.086)	(0.038)	(0.039)	(0.029)	(0.038)	(0.036)
N	148	147	164	163	163	163	126
p-value	<0.0001	<0.0001	0.0753	0.0716	0.0046	<0.0001	<0.0001
R^2	0.169	0.197	0.252	0.257	0.133	0.124	0.140

Table 4: Estimation results for cable coverage as explanatory variable controlling for depl_pot

	Cable expansion areas (country fixed effects)		**Legacy cable areas (between estimator)**		**Cable expansion and legacy cable areas with lagged ind. variables**		
	Without lagging	**With lag**	**Without lag**	**With lag**	**POLS**	**RE**	**IV**
dcs_cov	0.265	0.494***	-0.085**	-0.078**	-0.042	-0.030	-0.148**
	(0.220)	(0.147)	(0.034)	(0.036)	(0.032)	(0.042)	(0.062)
depl_pot	-0.191***	-0.172**	-0.013	0.023	0.074***	0.090**	0.068**
	(0.067)	(0.081)	(0.036)	(0.036)	(0.027)	(0.036)	(0.034)
pop_dens	0.623**	0.828***	0.017	0.015	0.008	0.007	0.029***
	(0.274)	(0.244)	(0.010)	(0.010)	(0.008)	(0.011)	(0.009)
urban_share	-0.850**	-0.446***	-0.157*	-0.178*	-0.180**	-0.186***	-0.191***
	(0.366)	(0.161)	(0.085)	(0.088)	(0.080)	(0.059)	(0.073)
gdp_per_cap	-0.297**	-0.019	0.044	0.044	0.047*	0.044*	0.060**
	(0.134)	(0.149)	(0.029)	(0.031)	(0.026)	(0.026)	(0.029)
fbb_pen	-0.164	-0.057	0.037	0.059	0.052	0.057	0.050
	(0.126)	(0.121)	(0.053)	(0.057)	(0.052)	(0.075)	(0.057)
edu	0.186	0.055	-0.014	-0.009	-0.007	-0.003	-0.023
	(0.138)	(0.090)	(0.037)	(0.040)	(0.028)	(0.039)	(0.036)
N	148	147	164	163	163	163	126
p-value	0.055	<0.0001	0.0753	0.1149	0.0047	<0.0001	<0.0001
R^2	0.229	0.199	0.252	0.206	0.131	0.172	0.135

Table 5: Estimation results for DOCSIS coverage as explanatory variable controlling for depl_pot

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Chapter 3:

5G and Mobile Broadband Disruption

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1. Introduction

The transition to 5G wireless has the potential to significantly disrupt the competitive landscape for wireless. For Mobile Network Operators (MNOs), 5G represents the fifth generation of cellular-based networking technology.[47] As the first large-scale deployments of 5G commercial services began to roll out in late 2019, two expectations are commonly stressed. First, 5G has the potential to deliver substantial innovations and capabilities that will significantly expand demand for MNOs existing services and unlock demand for new services in legacy and new markets (5GPP, 2016). Second, realizing the 5G vision is expected to increase requirements for MNO network investment to expand capacity to support the continued exponential growth in traffic, to exploit higher band spectrum (above 24GHz), and to enable the order-of-magnitude performance improvements promised by 5G (ITU, 2015; Oughton & Frias, 2018; Oughton, Frias, van der Gaast, & van der Berg, 2019; Schneir et al., 2019). Together, these trends are pushing wireless toward increased reliance on smaller cell architectures. Responding to these forces of supply and demand will confront MNOs with significant challenges while at the same time opening the door to new vectors for competition and wireless business models that have the potential to significantly disrupt the wireless and broadband networking ecosystem.

The goal of this paper is to present a framework for understanding how the transition to 5G and beyond may impact the wireless broadband ecosystem of MNOs and other network providers. We begin the analyses by considering the economic forces that have given rise to the current industry/market structure dominated by a handful of national scale MNOs. Over time, the fundamental economics of operating as an MNO have driven the industry toward increased concentration. Today, most markets are capable of sustaining three to four MNOs that compete on the basis of national coverage networks offering legacy consumer and business mobile telephony and broadband services.[48]

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[47] The first generation (1G) emerged in the 1980s, based on analog mobile technology that transitioned to 2G digital in the 1990s. The first generation of mobile broadband services became available with 3G in the mid 2000s. With 4G based on the converged LTE standard, true broadband mobile data became available after 2010. The first 5G standards were completed in 2017 and the first commercial deployments began in early 2019. However, the 5G versions available today do not support the full-spectrum of order-of-magnitude performance improvements called for in the ITU specifications (ITU, 2015).

[48] Most operators have also expanded into providing additional services, including Machine-to-Machine (M2M) connectivity. Although these services account for a small share of total connections and an even smaller share of total revenues (since the ARPU for m2m connections is substantially lower than for mobile broadband connections), the M2M share of connections is projected to grow significantly. In 2014, the GSMA estimated that "M2M connections will reach 974 million by 2020, growing at 26% per year (CAGR)" and representing "just over 10% of the global mobile connections market, up from just

The economic forces that helped drive toward increased concentration included (1) network costs with a significant share of fixed, sunk and/or shared costs, resulting in large scale and scope economies; (2) strong network effects coupled to switching costs which contributed to first-mover advantages; (3) the need to access bottleneck resources such as scarce spectrum and back-haul facilities; and (4) regulations that constrained competition. These same forces historically justified regulating fixed telephony as a natural monopoly, and following the introduction of competition, have continued to ensure that local markets for wired network services remain highly concentrated. As we will explain further below, 5G has the potential to alter these economic forces, and thereby, significantly impact broadband competition.

The balance of the paper is organized as follows. Section 2 discusses how today's MNO industry structure emerged. Section 3 highlights the key economic forces that characterized the evolution of the MNOs through the first four generations of cellular technologies. Section 4 explains how 5G differs technically from earlier generations of cellular technologies and Sections 5 and 6 identify key implications for how the MNO networking environment is changed by the transition to 5G both in terms of how the networks need to be designed and operate and the new revenue opportunities that 5G enables. Section 7 explains what those developments mean for the economics of the MNO business model. Section 8 speculates about how future competitive dynamics may evolve in three key markets in which MNOs will compete, and the potential competitors MNOs may face in each of those markets. Section 9 summarizes some of the important roles for policymakers to ensure that the future of 5G is as competitive as it can be.

2. The evolution of MNOs and the current wireless industry structure

Whereas the history of mobile telecommunication services has been dominated by the cellular MNOs and those firms are likely to play leading, if not dominant, roles in the future of 5G, several of the trends that are associated with the transition to 5G challenge that prognosis. The first four generations of cellular technologies (1G through 4G) were developed by industry consortia focused on MNOs and their network equipment vendors. The core business model was of cellular networks that (eventually) built out national coverage networks to (initially) support narrowband mobile telephony service, offering their customers national coverage for a

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over 3%" in 2014. (See GSMA (2014), "Cellular M2M Forecasts and Assumptions: 2010-2020," September 2014, available at https://www.gsma.com/iot/wp-content/uploads/2016/09/GSMA-Intelligence-Cellular-M2M-forecasts-2010-2020.pdf).

monthly subscription service. To provide service, MNOs must first built out their networks in their coverage areas. Then, MNOs added revenues by expanding their subscribership (number of connections) in their serving areas and by expanding the average revenue per unit (ARPU) associated with those connections. At the same time, technical innovations and scale and scope economies were lowering the costs per MB, which contributed to the virtuous cycle of falling prices and expanding demand as per-user traffic increased.

As the market for mobile communication services grew the MNOs added capacity and transitioned toward ever-more capable cellular network technologies, adding broadband internet access and other services to their original core telephony service. Whereas historically, the demand for and need to provision a network capable of supporting any-to-any, real-time voice telephony was the principal focus of MNOs, in today's 4G LTE networks, voice telephony is just another application on what has become a general purpose mobile broadband platform capable of supporting diverse applications and services. The investment in getting to 4G LTE focused on significantly expanding the capacity, reliability, and efficiency of delivering wide-area mobile connectivity services to millions of individuals with personalized handheld devices over a shared wireless network.

Because of the design of the networks, limitations in the available technology, and the need to share the significant capital investment efficiently,[49] MNOs have relied on exclusively licensed spectrum in specific bands. With earlier legacy technologies (even including 4G in many contexts), the cellular network equipment is RF-band specific, meaning that the investments in the network equipment and physical structures (e.g., location of antennas, etc.) is co-specialized with the investments in spectrum assets. A key goal of the converged 4G LTE technology was to expand the spectrum flexibility of cellular networks on the radio access network (RAN) side, while facilitating the replacement of specialized networking hardware with more generic IP hardware on the network side.[50]

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[49] A fundamental feature of telecommunications networks is that they are provisioned to provide capacity to meet peak demand and since users demands are not perfectly correlated and may be shifted in time (sometimes with the assistance of economic incentives such as peak load pricing), average provisioning costs are lowered if the capacity and network resources are shared. Multiplexing, switching, and traffic management are fundamental networking technologies that facilitate the requisite sharing.

[50] Earlier 2G and 3G cellular technologies were based on multiple, incompatible standards (e.g., GSM and CDMA for 2G and subsequent variants for 3G). 4G represented the convergence of the cellular industry on a common standard which contributed to realizing industry-wide cost economies.

Concurrent to the development of the MNO cellular technologies, different consortia and companies developed alternative wireless technologies designed to cater to end-user deployed localized networking situations. That included the IEEE P802 family of Wi-Fi standards that are used in most Wireless LANs (WLANs), as well as technologies catering to niche demands (also referred to as verticals) such as those for Public Safety (which may be referred to as "PPDR," which is short for Public Protection Disaster Relief) communications, for media broadcasting, for industrial connectivity and factory automation, for network utilities (e.g., water, electric power, and natural gas distribution networks), and for special event programming (often referred to as "PMSE," which is short for Program Making and Special Events). For a subset of these specialized demands, distinct wireless technologies such as ACTS or DVB-T for broadcasting; TETRA, Tetrapol or P25 for PPDR; and numerous WiFi or Bluetooth adaptations were developed and have been deployed by niche providers on dedicated networks.

The most important of these MNO-competing technologies are associated with WLANs and the family of Wi-Fi related technologies which expanded from business deployments into wider mass market deployments alongside the growth of fixed broadband services. WLANs enhanced the usability and demand for fixed broadband connectivity by supporting device portability and user mobility in limited local areas (within a hundred meters of a Wi-Fi access point). Indeed, as mobile broadband and fixed broadband adoption have swelled, MNOs have taken advantage of the widespread availability of Wi-Fi connectivity in user handsets and in many locations where users find themselves to offload cellular traffic to fixed broadband services. Off-loading cellular traffic to fixed broadband freed up more expensive cellular network capacity (and expensive licensed spectrum) and, in many cases, provided the end-user with faster data rates than could be supported using 3G or even 4G services.[51]

In the vast majority of cases, the alternative non-cellular wireless networks are deployed in private, local area networks that are not connected to and do not offer national/wide-area coverage; or when such coverage is offered, the service and network are architected to meet specialized demand requirements. Moreover, most of these alternative wireless networks operate in unlicensed spectrum and most of the significant investment in equipment and wireless networking infrastructure is undertaken by the end-users. This began to change with

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[51] It is worth noting that the first iPhone released in June 2007 was a 2G handset that allowed users to access the Internet via its included Wi-Fi radio. Subsequent, iPhones and smartphones from other producers of handsets included both 3G and later 4G radios along with Wi-Fi, Bluetooth, GPS, and sometimes other radio connectivity options.

the emergence of national aggregators of Wi-Fi hotspot services like Boingo that offered service in airports, coffee shops, and other retail locations nationwide or even internationally. Today, fixed broadband providers like Comcast and Charter with national coverage footprints of residential and small business fixed broadband customers with extensive deployments of Wi-Fi access points are offering mobile broadband services that compete with MNOs.[52] Although Wi-Fi connectivity does not support the high-speed mobility of cellular MNOs, it does offer a viable alternative for nomadic mobile broadband access to using an MNO's service. With nomadic mobility, a user travels to within range of a WLAN hot spot for broadband data access, but does not try to move (rapidly) among access points. The extent to which such mobility represents a viable substitute for the sort of mobility offered by MNOs depends on what the user is doing and how fast they are moving.

Whereas the development of the first four generations of cellular technologies were MNO-centric, the development of 5G involved a larger group of stakeholders from the beginning that included a wider selection of firms from the telecommunications and networking equipment and services industry, as well as participants from vertical application markets (5GPP, 2016). Consequently, 5G was designed to be a multi-purpose wireless technology with potential applications extending beyond legacy MNO-markets and thereby breaking the legacy standards development pattern for cellular that had focused primarily on improving the services delivered to existing customers. The more inclusive design strategy for 5G effectively dissolves the technical boundaries between the different wireless connectivity product markets, opening up the potential for broader competition across both legacy and new wireless markets. Concurrent with expanding the range of customer demands that may be addressed by 5G, it also expands the range of providers that might compete with MNOs to service that demand. Furthermore, many of the wireless usage contexts foreseen for 5G do not inherently require wide-area coverage or support for high-speed mobility (as was the case with the mobile telephony services that motivated the emergence of national MNOs in the first place). For example, satisfying end-user demand for localized wireless usage is not limited to public network providers but can also be satisfied directly by end-user deployed, local private networks in spatially contiguous but

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[52] A number of these, including Google and Comcast, lease capacity at wholesale from MNOs and operate as Mobile Virtual Network Operators (MVNOs) to provide mobile broadband service to support high-speed mobility and coverage where they lack network facilities, allowing them to offer services that are indistinguishable to consumers from the service provided by the MNOs. For example, Comcast's Xfinity Mobile service operates as an MVNO using Verizon's national network (see https://www.fiercewireless.com/wireless/editor-s-corner-here-s-exactly-who-xfinity-mobile-stealing-customers-from-and-why).

limited areas. Additionally, some of the 5G vertical niche markets that may also be addressed by general-purpose MNOs may also be addressed by dedicated wide-area networks with low base station density (e.g. similar to broadcasting networks).

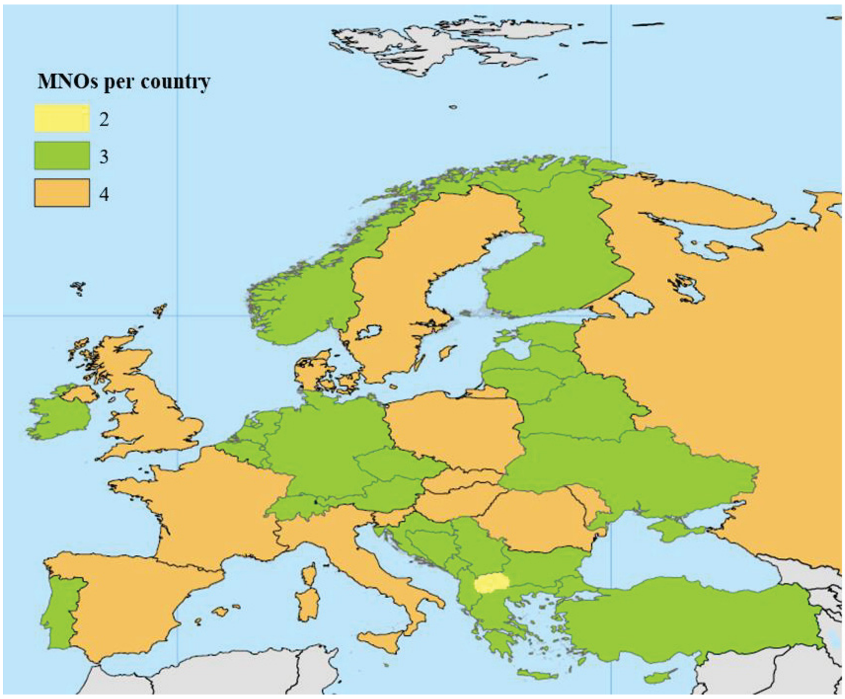
For many years, the quality adjusted price for fixed and mobile broadband (measured as the $ per GB transferred) has been falling. While the speed and traffic delivered via broadband services has increased exponentially (Cisco, 2019), MNO monthly per subscription revenue has remained relatively flat or grown slightly (Tefficient, 2018). Moreover, in many developed markets, MNO subscriber adoption rates exceed 100 percent (GSMA, 2019), meaning that future growth in wireless revenue for MNOs will depend on selling additional services and/or additional connections to existing subscribers. Expanding the addressable market of subscribers means expanding subscriptions to the Internet of Things (IoT). MNOs are looking toward the new opportunities promised by 5G for their future revenue growth, while at the same time confronting new classes of competitors in both their legacy and new markets. MNOs are betting on the traditional economic forces of scale and scope economies, network effects, and potentially, their control of scarce resources (e.g., exclusively-licensed spectrum and access to network backhaul and local distribution facilities such as antenna sites) to enable their success in the 5G future.

The success (or failure) of the MNOs will depend on the confluence of multiple factors, including the evolution of end-user demand for different 5G applications that will assuredly progress in uneven growth across application domains, verticals and geographic markets; the continued evolution of 5G technologies and standards; spectrum and competition (antitrust) policies; and a number of other factors.

3. MNO economics from 1G to 4G

The classic business model for MNOs was based on providing wide-area coverage to (a) sustain uninterrupted connectivity at high-way speeds; and (b) supporting anywhere connectivity for mobile users. From the first generation (1G) of analog services in the 1980s to the second generation (2G) digital services of the 1990s, that meant supporting narrowband, real-time voice telephony services. The third generation (3G) cellular networks introduced mobile data services in the 2000s, but is was not until the introduction of the fourth generation (4G) LTE services after 2010 that cellular providers were able to provide true, converged mobile broadband services. Throughout these earlier generations the core economic forces giving rise to the oligopoly industry structure among MNOs remained the same and collectively have helped propel the industry toward increased consolidation.

The current mobile wireless industry with 3 to 4 MNOs competing in most markets is fairly concentrated with HHIs that exceed 2500 in most developed nations (see Figure 1).[53] The economic factors that have driven this industry consolidation have been several, incuding (1) economies of scale and scope; (2) network effects; (3) first mover advantages; and (4) regulations that have distorted competition, including control over access to bottleneck resources (e.g., spectrum). Taken together, these supply and demand side economic forces combine to confront potential entrants with significant entry barriers that helps sustain the consolidated industry structure, nevertheless, competition among the MNOs has remained fierce and customer-churn rates are relatively high.



Selected other countries

3 MNOs:
- China
- Singapore
- Australia
- New Zealand
- South Korea

4 MNOs:
- USA
- Canada

5 MNOs:
- Israel

Figure 1: Mobile network operator per country. Source: own research based on (European Commission, 2018)

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[53] Even conservatively assuming a four-operator market with equally distributed market shares, the HHI would still equal 2500, which classifies as a high degree of consolidation under the 2010 DOJ/FTC Horizontal Merger Guidelines. Retail-level competition is more extensive because of the existence of MVNOs that resell capacity purchased at wholesale from the MNOs which also compete with retail offerings of their own.

Figure 2 summarizes the various economic forces that helped create today's concentrated MNO industry structure, and later, we consider how the transition to 5G may be altering these economics.

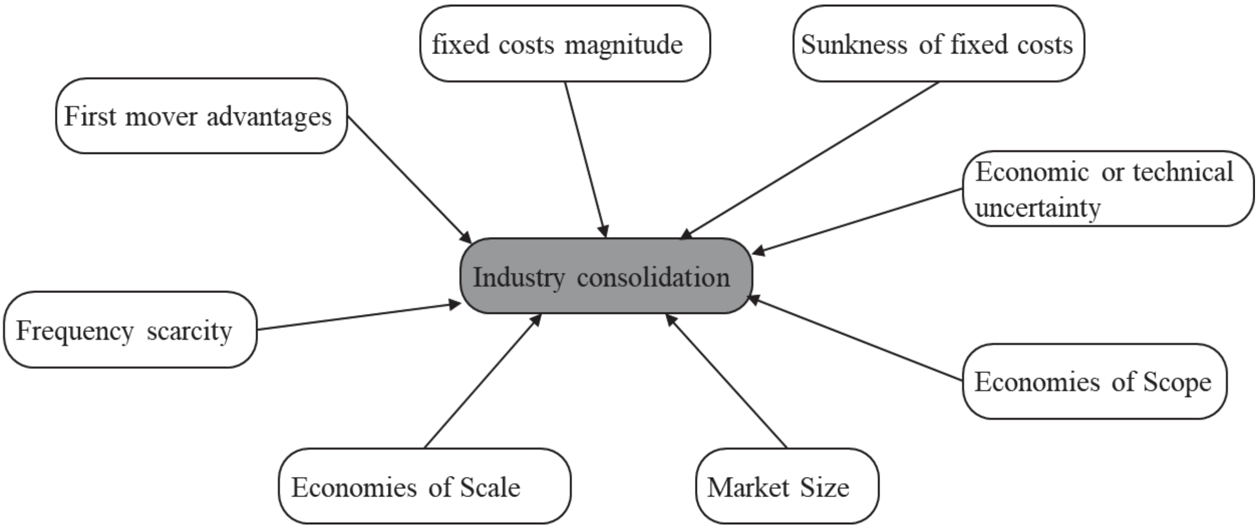

Figure 2: Economic forces behind the past MNO consolidation

3.1. Scale and Scope Economies

The first, and arguably one of, if not the most important factor, is the prevalence of extensive economies of scale. The fundamental challenge confronting MNOs is the need to first build out their network coverage in their target service area. Establishing their networks requires incurring significant fixed costs associated with acquiring the requisite spectrum licenses, antenna sites, and associated backhaul and core networks needed to provide end-to-end services (Nam *et al.*, 2009). Moreover, since the networks needed to be provisioned for peak capacity, much of the investment cost is fixed and does not vary with the actual number of subscribers or traffic that the MNO has to carry. In addition, there are significant non-network-related fixed costs associated with sales and marketing, customer service, and other back-office business functions. These fixed costs give rise to significant scale economies, which means that MNO unit costs decrease with a growing customer base, allowing fixed costs to be shared over a larger set of customers (Nam, Kwon, Kim, & Lee, 2009).

Because user traffic is not synchronized in time and end-to-end traffic does not originate or go to the same places, many users and services can share the same peak capacity and hierarchical routing can share high-capacity core network links. When the same capacity is shared over multiple services and users, the scale economies may be matched with scope economies. For example, mergers of fixed and mobile networks can realize significant scale and scope economies from being able to share backhaul and other network resources, as well as sales and marketing expenses (e.g., brand advertising, billing, customer service) and general administrative overhead expenses. A number of such mergers have been justified by the synergistic benefits of realizing such scale and scope economies.[54]

In rural markets, the principal challenge confronting MNOs is to ensure network coverage. Using low-frequency spectrum below 1GHz (with its longer-range propagation benefits) allows MNOs to most efficiently build out coverage since it allows a given area to be served by a smaller number of base stations than would be required if served with higher frequency spectrum (e.g., mid-band spectrum above 3GHz) (Lundborg, Reichl, & Ruhle, 2012). In urban areas, where subscriber density is larger and traffic loads are higher, the challenge for MNOs is to provide adequate capacity. Typically, capacity can be added to existing coverage networks in more scalable increments by upgrading the capacity of existing cell sites, or by splitting cell sites (i.e., moving toward smaller sized cells where each cell provides coverage over a smaller coverage area). The move to small cells facilitates spectrum reuse (a key bottleneck resource) and allows the full capacity of the cell to be shared by the smaller number of subscribers in the smaller coverage area.

Although coverage-constrained rural networks give rise to greater scale and scope economies than capacity-constrained urban networks typically, the need for MNOs to provide national coverage means that the rural and urban scale economies are shared.

The relevance of scale economies in driving industry concentration also depends on the size and growth rate for the industry and the pace of technical change. For example, ceteris paribus, a larger market can support a larger number of competitors, as can a market that is growing

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[54] Vodafone KDG (Vodafone acquired cable operator, Kabel Deuschland in 2013, see https://www.computerweekly.com/news/2240207149/Vodafone-completes-Kabel-Deutschland-acquisition); Vodafone acquired Liberty Global in 2019 (see https://ec.europa.eu/commission/presscorner/detail/lv/ip_19_4349); Telenet acquired the Belgian cellular provider, Base, in 2016 (see https://press.telenet.be/telenet-completes-base-company-nv-acquisition#); Vodafone acquired Spanish fixed broadband provider, Ono, in 2014 (see https://www.reuters.com/article/us-vodafone-group-ono/vodafone-agrees-10-billion-deal-for-spains-ono-idUSBREA2G08820140317); T-Mobile acquired the Dutch operations of Tele2 NL in 2018 (see https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6588); and Tele2 Swedish operator acquired the Swedish cable operator, Com Hem, in 2018 (see https://www.digitaltveurope.com/2018/11/05/tele2-com-hem-deal-closes/).

rapidly and is subject to rapid technical change (so that the fixed costs of upgrading to newer generations of technology need to be incurred repeatedly).

Rapid technical change has enhanced both the capacity and capabilities of cellular networks, while lowering the costs of providing services (measured on a $/GB transferred or $/Gbps of transmission capacity). Falling prices of bandwidth and IP transit services and for leased lines globally have enabled retail prices to fall also, which in turn, helped fuel the continued exponential growth in traffic. This was also fueled by lower prices and wider adoption of more capable end-user devices like smartphones (after 2007), tablets and more capable personal computers and by the growth in more data-hungry applications like streaming media and interactive multimedia applications like social media and on-line gaming. The exponential growth in traffic compelled MNOs to invest in expanding capacity, confronting anew the coverage-constrained rural and capacity-constrained urban build-out challenges with each successive generation of cellular traffic growth. From 1G to 3G, most of the challenge was in building out national coverage and then supporting the traffic growth from increasing subscriber penetration. With 3G and the transition to 4G, the challenge is more about adding capacity in order to meet the growing per-user traffic from a subscriber base that exceeds 100 percent penetration in many mature markets. Moreover, with the transition to 4G and the growth in multimedia traffic (principally streaming mobile video) and more capable end-user devices, the potential for per-device traffic to be locally bursty (i.e., for peak-to-average traffic ratios to increase) accentuates the peak-capacity provisioning challenge.

Although each new generation of cellular technologies delivered capacity improvements and lower costs per MB transmitted, the need to shift to ever higher frequency bands and shift to denser base station deployments meant that MNO investment costs remained high (Oughton & Frias, 2018; Oughton et al., 2019; Peltola & Hämmäinen, 2018; Schneir et al., 2019; Malandrino, Chiasserini & Kirkpatrick, 2017).

In the past decade, penetration rates grew continuously (Cisco, 2019), albeit at a slowing rate as penetration exceeded 100 percent in mature markets. However, the increase in penetration was not sufficient to offset the falling or stagnating ARPUs witnessed in most countries (Tefficient, 2018). Accordingly, the continued growth in traffic (and costs, albeit at a lower level per GB of capacity) coupled to the more sluggish growth in revenues contributed to the economic forces driving MNOs toward increased concentration.

The basic cost structure of constructing an MNO network necessitating the incurring of significant fixed andshared costs that give rise to significant scale and scope economies also pose significant cost-based barriers to entry (Buigues & Rey, 2004, p. 207; Moore, 2015; OECD, 2014). Moreover, because many of the costs are sunk, they pose a significant exit barrier, which serves to deter entry in the first instance. To compete with national scale MNOs, an entrant needs to incur large upfront investments to build out the network in the target coverage area, to acquire the requisite spectrum frequency rights, and to attract a critical mass of subscribers from established incumbents.

The combination of significant sunk, fixed and shared costs and the need to provision for peak capacity loads which can vary substantially over time and by location means that MNO operators generically have excess capacity that helps sustain significant competition among the MNOs, even when the prospect of new entry is limited. Additionally regulatory policies such as those mandating that MNOs offer services to MVNOs, provide roaming services, and support number portability contribute to sustaining vigorous retail competition.

3.2. Network Effects

In addition to the cost-based scale and scope economies, MNOs also realize significant demand-side scale effects commonly referred to as network demand externalities. The value to individual subscribers to a network service increase with the total subscriber base. Subscribers to a network with a larger subscriber base have more options of who to interconnect with and are likely to have deeper markets for complementary products and services like compatible equipment, applications, tech-saavy customer support, and related services. Moreover, with the transition to broadband platforms the MNO networks can benefit from becoming multi-sided platforms that may also realize indirect network effects. Those arise when increased subscribers on one side of the platform (e.g., providers of broadband content and applications) increase the value of subscribing to the platform for subscribers on the other side of the platform (e.g., broadband subscribers who are the consumers of the content and applications or the "eyeballs" that advertisers want to attract). The ability of multi-service broadband MNOs to operate across multiple markets with network effects further contributes to their demand-side scale benefits. Larger networks are more valuable as their subscriber base gets larger.

3.3. First Mover Advantages

First-mover advantages (FMAs) are another potential economic force impacting the competitive landscape confronting MNOs. There is strong empirical support for the importance of FMAs in mobile telecommunications (Atiyas & Doğan, 2007; Bijwaard, Janssen, & Maasland, 2008; Gomez, Lanzolla, & Maicas, 2016; Muck & Heimeshoff, 2012; Whalley &

Curwen, 2012). The FMAs arise from both the cost- and demand-side scale and network effects. Early movers that are successful in constructing their networks and attracting subscribers move down their average cost curve and build network effect advantages that allow them to compete more effectively against their smaller rivals. Moreover, the fact that a significant share of the network and non-network (principally, sales and marketing related) costs are sunk also provides a FMA for incumbents relative to would-be entrants. As already noted, to be successful, entrants need to build their own subscriber base and in a mature market that means attracting inframarginal subscribers from incumbents which earn large incremental operating margins on inframarginal subscribers. That provides incumbents with powerful incentives to invest in retaining subscribers. Nevertheless, churn among mobile broadband subscribers is relatively high (around 2% per month for many MNOs).

3.4. Regulatory Distortions

A final important factor that has contributed to the significant degree of consolidation among MNOs is the legacy of regulatory policies. Although the focus of cellular regulation in most markets was to engineer in industry competition from the start, regulatory policies have also helped the incumbents sustain their competitive advantages.[55] In the U.S., when cellular services were first introduced in the 1980s, the regulators allocated only two licenses per market with one of those licenses being granted to the wireline incumbent telephone company. Although this strategy made sense from the perspective of realizing the scale and scope economies already realized by the wireline telephone companies, it made it more difficult for new (non-wireline) competitors to enter. When auctions were introduced in 1995 and the spectrum allocated for mobile services was expanded significantly, additional national entrants were enabled and the number of network-based cellular providers in many markets increased to five or six. However, few of these were national providers and this was in an age of 2G cellular telephony services when the per-subscriber investment and network capacity needed to support cellular services was significantly less.

Indeed, the first waves of industry consolidation were driven by the need to establish national coverage footprints by merging adjacent wireless MNOs. The consolidated MNOs realized scale and scope economies as redundant retail and back-office operations could be consolidated and roaming costs could be reduced. Over time this lead to the creation in the U.S. of ultimately

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[55] See Anker, 2017.

four national scale MNOs, that with the merger of Sprint and T-Mobile, has become three MNOs.

Perhaps the single biggest regulatory distortion that has contributed to MNO industry consolidation and large entry barriers impeding new entry at scale is the artificial spectrum scarcity that is a byproduct of legacy spectrum management policies. All wireless operators need access to radio frequency spectrum resources. Historically, those have been allocated on the basis of frequencies dedicated to specific services and technologies and assigned to incumbent users with strong rights for interference protection. This includes both commercial telecommunications services as well as television and radio broadcasters; and significant shares of the spectrum are allocated for government (e.g., national defense) and other non-commercial uses (e.g., radio astronomy). The rules limit the transferribility of rights among users and impose significant costs on reallocating spectrum from low-value/low-utilization uses to high-value/high-utilization uses. Commercial demand for expanded spectrum for both licensed and unlicensed mobile broadband users has been a significant driver of spectrum policy reform, but the reforms take time.

In addition to spectrum, access to sites for cellular base station antennas and for siting backhaul facilities to connect antennas to the MNOs' networks are also bottleneck resources that are under regulatory controls that limit their supply and thereby limit the extent of facilities-based competition that can emerge.

4. The technology behind 5G

The evolution of mobile cellular standards from 1G analog networks to 4G LTE networks transformed mobile telephony from a niche service available along major highways into today's nearly ubiquitous wireless mobile broadband services that support mobile telephony as just one of many applications. The growth in capabilities, service penetration, and per-user traffic growth has allowed MNOs' networks to scale to handle the explosive growth of mobile data traffic during the last two decades (Clarke, 2014). The step from 4G to 5G promises to be more profound because it holds the promise of not only improving LTE´s performance but also is expected to come with a multitude of new functionalities and deployment options expanding the usage cases for cellular technologies beyond MNO legacy markets.[56]

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[56] Some of which were already introduced as part of LTE advanced 3GPP-releases, but will be herein referred to as 5G functionalities.

5G´s performance targets were chosen to reflect an order-of-magnitude improvement over 4G. As summarized in Table 1, 5G is intended to allow a 10 to 20-fold increase in data-rates, ten-fold latency reduction, enhanced mobility, increased connection density, and improved spectral efficiency. The plan for successive generations of mobile technologies to offer significant improvements in performance is in keeping with tradition, but the aspirations for 5G were even more ambitious.

Technical requirement	Target Value
Peak data rate	Download (DL): 20 Gb/s Upload: 10 Gb/s
Area traffic capacity	10 Mbit/s/km²
User plane latency	1 ms
Mobility	up to 500 km/h
Connection density	1,000,000 devices/km²
Peak spectral efficiency	DL: 30 bps/Hz UL: 15 bps/Hz

Table 1: IMT-2020 performance targets Source: (ITU-R, 2015)

From the outset, 5G´s ambition was to not only improve the LTE performance indicators but also to "acquire the same level of importance as access to electricity" (ITU-R, 2015, p. 10). To realize this goal, 3GPP developed 5G as a modular technology with the flexibility and capability to meet rigorous but different performance requirements for virtually any application requiring wireless network support. The modularity gives MNOs the flexibility to deploy features only if, where and when needed to satisfy the demand (ITU-R, 2015). This is different from the "one size fits all" paradigm underlying earlier generations of cellular technologies, and justifies viewing 5G more as a toolbox of capabiliites than a technology that is rigidly defined by a certain set of characteristics.

Another significant departure from earlier generations of cellular technologies is the participation in its design by firms outside the telecommunications industry, representing the needs and interests of vertical markets and complementary technologies and services, collaborating with the telecommunications firms that historically were chiefly responsible for developing earlier generations of cellular technologies (i.e., the vendors of network equipment, handsets, and MNOs). Within the 5G development process, multiple vertically-focused industry consortia participated, including the "5G for Connected Industries and Automation" (5G-ACIA) association[57] for the smart manufacturing vertical; the "5G Automotive Association" (5GAA)[58] for the smart-mobility vertical; "PMSE-xG"[59] for Program Making and Special Events; "European broadcasting union" (EBU)[60] for broadcast entertainment; and the "Public Safety Communication Europe" (PSCE)[61] for PPDR. Contributions from these associations as well as from individual firms within the verticals found their way into the 3GPP releases (3GPP, 2016) and translate into the features (5GPP, 2015) that are included in 5G.[62]

In the next three sub-sections we highlight feature sets, network functionality, and demand scenarios that exemplify how 5G goes beyond 4G and earlier cellular networks.

4.1. New Feature sets of capabilities enabled by 5G

5G will enable new sets of features, including Vehicle-to-Vehicle (V2V) networking; Mission Critical Push to Talk (MCPTT); Multimedia Broadcast Multicast Service (MCPTT); and Low Battery Consumption Mode. Each of these is discussed further below.

1. **V2V/V2N**: Advanced driving services such as semi- or fully automated driving require two types of wireless data connectivity. Vehicle-to-Network (V2N) connectivity allows the vehicle to communicate via the cellular wide-area network to acquire information about traffic conditions (e.g., traffic light status, accidents that may be disrupting traffic ahead, etc.) and to update databases such as live high-definition cloud-based maps based on the vehicle's sensor data. The V2N data transmission requirements for the air interface do not exceed the IMT 2020 performance targets (3GPP, 2016), even though significant investments in the cellular networks adjacent to the roads will be needed to handle the increased traffic. The second type of connectivity, Vehicle-to-Vehicle

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[57] See https://www.5g-acia.org/about-5g-acia/.

[58] See https://5gaa.org/.

[59] See http://www.pmse-xg.de/.

[60] See https://tech.ebu.ch/docs/techreports/tr044.pdf.

[61] See https://5gaa.org/.

[62] Although some of the fetures we highlight are officially part of 4G LTE-releases, we will include them in our discussion of 5G here.While this definition is inconsistent with the 3GPP-terminology, it reflects the reality that these features will only see wide-scale deployment in conjunction with or following 5G deployments. Furthermore, even the 4G-features are subject to continuous improvements in 5G releases, which further blurs the lines between successive generations of cellular technology.

(V2V),[63] brings new capabilities to allow such capabilities as vehicle platooning (i.e., when a collection of adjacent vehicles are jointly controlled) and real-time notification of collision or other danger situations. Enabling such capabilities would allow cars to travel much more closely at high speeds, and in the event of a need to brake suddenly, would ensure that the braking of individual vehicles in the platoon was coordinated to avoid a pile-up. For these V2V capabilities, extremely low latency performance is critical and precludes relying on the cellular network to mediate the communications between vehicles (Morgado, Huq, Mumtaz, & Rodriguez, 2018). The V2V feature addresses this requirement by enabling vehicles to broadcast data directly from a vehicle to other vehicles that are close to the vehicle (3GPP, 2017b). The V2V feature utilizes dedicated frequencies in a Direct-to-Direct (D2D) mode, either in a network-assisted or an off-network mode. Under the prior, a cellular network assists by assigning transmission channels and scheduling transmissions while the data is transmitted directly between the vehicles. In an off-network scenario, e.g., outside the geographic coverage of cellular networks, distributed algorithms decide on the frequency selection and scheduling and therefore ensure that vehicles still can communicate with each other even in the absence of a mobile network (3GPP, 2016).

2. **Mission Critical Push to Talk (MCPTT)** – Voice connections provided by 2G to 4G mobile networks are almost exclusively used for one-to-one calls[64] and require the call recipient to answer the call before a connection is established. This protocol fails to provide a critically important communication mode that first responders and public safety users depend on. The MCPTT-feature addresses these modes by enabling off-net D2D-communication between devices in direct proximity as well as group calls in which each user has the ability to gain access to the permission to talk in an arbitrated manner. The MCPTT enables public safety workers to listen and communicate effectively with the group that is assigned to the same task. Moreover, MCPTT provides an interface for administrators to organize and facilitate the communication by assigning users to groups and arbitrate between talk requests that are in contention based on prioritization rules (3GPP, 2019f).
3. **Multimedia Broadcast Multicast Service (MBMS)** – Over the air TV and radio distribution technologies have been separated from cellular technologies by one major

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[63] The same feature is also used for vehicle to infrastructure (e.g. roadside units) communication. We omit this part for the purpose of simplification.

[64] Group calls resemble an exception to this rule

difference. While past cellular technologies were optimized for upload and download unicast transmission (single sender and single receiver), broadcast TV and Radio technologies (e.g. ACTS or DVB-T) were designed for multi-cast (distribution of the same video or audio content to many receivers). The MBMS feature introduces efficient multicast broadcasting to cellular networks (3GPP, 2019g). Under MBMS APIs and interfaces are defined, which enables for standardized content delivery from the "content provider" and the network operator (3GPP, 2019b).

4. **Low battery consumption mode**[65] -- In earlier cellular generations, a key driver for the design of 3G and 4G was the need to cope with the exponential growth in traffic volumes, which were addressed by adopting computation intensive modulation schemes and energy intensive protocols, hampering the desire to reduce energy consumption and prolong battery life. 5G entails a low battery consumption mode in which transmissions are optimized for battery efficiency by using simpler modulation schemes and adapted protocols (e.g. longer idle periods). Thus, 5G is not only able to provide extremely high datarates for smartphone users but also supports connectivity to sensors that require battery lives of up to 10 years (Morgado et al., 2018).

4.2. 5G Network Functionality

In addition to the above novel feature sets that distinguish 5G, there are three key enhancements to network functionality: (1) Mobile Edge Computing (MEC); (2) Private network deployments (first defined in Release 15); and (3) Network slicing techniques. Each of these is discussed further below.

1. **Mobile Edge Computing (MEC)** is meant to bring computing and IT capabilities closer to the wireless network edge and hence closer to the end-user and the wireless device. Under MEC, Mobile edge servers (MES) at the network's edge provide storage and computing resources close to the consumer or device (ETSI, 2016). The physical proximity reduces latency, if compared to a centralized cloud model based on large-scale datacenters (3GPP, 2019a).

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[65] Network energy efficiency is technically speaking part of the IMT-2020 objectives. However, features such as BEST (Battery efficient Security for very low throughput Machine Type Communication Devices) (3GPP, 2019c) are essential enablers for such a low battery consumption mode.

2. **Private networks** expand the use of the 5G standard beyond MNO networks. 5G deployed in private networks can be fully independent of MNO networks, operating in different spectrum frequencies (unlicensed or licensed spectrum leased from whoever had the license). Private 5G networks allow the operator (private network owner) full E2E control and may offer customers seeking to deploy private wireless networks improved security (3GPP, 2017a; 5G ACIA, 2019).
3. **Network slicing** enables operators to virtually partition their network resources into separate, distinct logical networks with customized feature sets to support customer-specific performance requirements. These slices might be provided to support a private network or to enable the MNO to offer a shared service to many customers with similar needs (e.g. in a vertical industry sector). For example, a network slice might be optimized for sensors by utilizing the low battery consumption mode while another is optimized for high data rates, obviating the need for separate physical networks (3GPP, 2019d; Rost *et al.* 2017). Technologies like Software Defined Networks (SDN) and Network Function Virtualization (NFV) implemented in core networks allow MNOs much more dynamic granular control of network resources and support the realization of scale and scope economies (which are a byproduct of sharing resources) while also allowing greater capabilities to offer customized services on-demand.

Together, 5G’s key performance parameters, features and network deployment and operation concepts define the foundation for the 5G ecosystem and highlight the innovation potential 5G's technical vision brings. Figure 3 summarizes these key technological building blocks that comprise the 5G toolbox. The peak performance parameters provide the foundation, the new feature sets expand the ability of 5G to serve new demand scenarios, and the enhanced network operation and deployment concepts build in the needed adaptability and versatility.

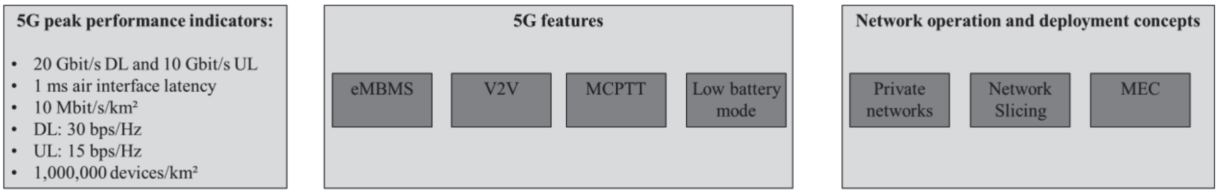

Figure 3: 5G technology building blocks

4.3. 5G and new demand scenarios

The improved performance capabilities and feature sets supported by the 5G toolbox make it feasible for MNOs to address new markets that were previously unserved or, if served, by niche networks.[66] Several examples that highlight the diversity of these markes include:

- Autonomous Vehicles (AVs) and Unmanned Aerial Vehicles (UAVs) will require wireless sensing and connectivity capabilities for environmental situational awareness (navigation, traffic conditions, crowd-sourcing information) and V2V and V2N communications. These applications will require the low-latency capabilities, frequency agility, and heterogeneous network support that 5G enables applications (see 3GPP, 2016, 2017b; Knieps, 2019; Park & Kim, 2019).
- Smart-Manufacturing, Smart-Cities applications will facilitate integrating machine-to-machine and Internet-of-things (IoT) devices for automated control of manufacturing, infrastructure systems (e.g., heating, cooling, lights), and other actitivities (see Bogue, 2017; Matinmikko, Latva-aho, Ahokangas, & Seppänen, 2018; Temesvári, Maros, & Kádár, 2019). These applications require wireless connectivity for potentially large numbers of end-points with heterogeneous Quality of Service (QoS) requirements for wireless service in a contiguous local area. This includes collecting data from sensors with limited data rate and QoS requirements, but with extreme battery efficiency requirements; while other use cases such as closed-loop manufacturing or augmented reality (AR) will need reliable, low latency and high bandwidth data transmission.
- Smart-Metering of electricity grids represents a vertical market opportunity with comparably homogenous QoS requirements. Utilities need connectivity for their smart meters deployed throughout residential areas and business locations, and the capabilities for collecting usage data, metering and controlling local grids will grow more complex as we shift to renewable energy sources. While some use-cases are not latency-sensitive, others, such as 2-way control are more challenging in that regard (NRG-5 Consortium, 2017). Generally, however, the data rates needed to communicate with the smart meters will be relatively low, but network security and reliability, especially if two-way control are enabled, will be key requirements.
- Public Protection/Disaster Recover (PPDR) network services are the mission-critical communication services used by first-responders and public safety providers such as the

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[66] E.g. GSM-R networks in railroad systems, TETRA (POL) networks for PPDR or DVB-T/ ACTS networks.

police, fire, and ambulance services. Historically, these needs were met by government-owned TETRA or TETRAPOL networks that provided nationwide voice connectivity and limited data transfer capabilities. Legacy PPDR-networks cannot support many of the services now being demanded by PPDR users such as support for two-way video, high-definition maps, and other more demanding applications. The next generation of PPDR-applications (e.g. body cameras or mobile CCTV-access) require reliable and secure data connectivity with moderate bandwidths, while MCPPT support is essential. Due to the mission-criticality of public safety services, networks need to provide a high-security level, extensive coverage and the ability to prioritize certain communications or data transfers(see 3GPP, 2019e; Höyhtyä et al., 2018; LS Telcom, 2019; Peltola & Hämmäinen, 2018).

- Broadcast media distribution is a vertical market that historically has been catered to by specialty technologies and services such as DVB-T (Europe, Africa and partly Asia), ATCS (North America), SBTVD-T (South America) and DTMB (China) provided by dedicated purpose-built networks (DTV Status, 2017; Hwang, 2009). These networks cover large areas with a comparably small numbers of base stations that have cell sizes of up to 100 km (Hwang, 2009)[67]. A large cell radius is also critical for the economic viability of dedicated broadcasting networks, while it becomes less relevant if MNOs address the broadcasting vertical as they can leverage their existing dense tower network. Throughput requirements are reduced (compared to unicast) by multicasting, whereas predictable and sustained QoS are a key requirement to ensure that consumers receive uninterrupted TV or radio signals as they are used to when consuming linear TV or radio services today (EBU, 2018; Gómez-Barquero, 2013). The multicast capabilities of 5G, and in markets where 5G base stations have been built out, will allow MNOs to address this market opportunity via network slicing.
- Enhanced mobile broadband services that take advantage of 5G's order of magnitude performance improvements will be able to support significantly more demanding smartphone applications such as mobile immersive AR and Virtual Reality (VR) experiences, 360-degree video or 4k video streaming (Yu, Lee, & Jeon, 2017). Although 4G LTE is offering many end-users a mobile broadband experience that is sufficient to induce them to substitute it for fixed broadband connectivity, so 5G will further enhance the mobile broadband user experience.

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[67] E.g. The German DVB-T operator Media Broadcast reaches 76% household coverage in Germany with only 63 tower sites (Media Broadcast, 2019).

5. Meeting the 5G Challenge

Although the technology exists to deliver the 5G capabilities and to offer the diverse services mentioned earlier, MNOs need to significantly change their networks in order to realize that potential. Here we discuss three important changes: (1) The transition to smaller cell network architectures; (2) Intelligent core networks; and (3) Shared Spectrum.

5.1. Small Cells

First, meeting the performance targets of 5G will require shifting to smaller-cell architectures.[68] The need to facilitate spectrum reuse (because spectrum resources are increasingly scarce), to take advantage of higher-frequency spectrum (e.g. in the millimeter bands above 30GHz), to enable mobile-edge-computing (which requires low-latency performance), and the need to support enhanced energy efficiency are compelling MNOs to build out wireless networks based on smaller cells. This includes splitting existing cell-sites as well as over-building with new small cells. Providing coverage for these small cells presents a large upfront investment cost and increases the per-subscriber capacity costs (since the potential peak traffic from a 5G customer is significantly larger than for earlier cellular technologies).[69]

Although building out the small cells poses a significant investment challenge, the transition to smaller cell architectures will have important benefits. When the cells are smaller, spectrum resources are more fungible. That is, large cells need low-band spectrum to provide connectivity to subscribers that are far from the cell site; but with smaller cells, the problems with longer-range propagation using higher-freqencies is less of an issue. Since smaller cells are better able to take advantage of higher-frequency spectrum which is both more abundant (less congested) and less costly, they are better able to sustain higher data rate services. Also, when operating at higher frequencies, the antennas can be much smaller and the entire base station can be less expensive (and more easily replaced) as compared to larger base stations.

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[68] See Lehr & Oliver, 2014.

[69] For example, some analysts have projected that 5G networks are expected to increase network costs by as much as a factor of 4-5 times relative to the costs of 4G (Wisely, Wang, & Tafazolli, 2018). Others have forecast that 5G capital costs will be 1.4-1.7 times the capital costs required to upgrade from 3G to 4G (see, Morgan Stanley, 2018).

Furthermore, when the cells are smaller, spectrum comprises a less significant share of the total cost of deploying and operating the small cell. The site, power, backhaul and other requirements for operating the small cell become relatively more important. With desktop-sized small cells, the question will be whether to professionally install the cells or to allow end-users to self-install the cells. With small cells, the costs of power, site-provisioning, and potentially the cost of the equipment may be shifted to end-users in the same way that fixed broadband providers often rely on their customers to self-provision the Wi-Fi routers that complement the fixed broadband services.

5.2. Intelligent Core Network

Enabling 5G is not just about changing the wireless components of the network. It also requires significant enhancements to the core network with technologies such as Software Defined Networking (SDN) and Network Function Virtualization (NFV). Both of these are about increasing the softwarization of networks, or equivalently, moving functionality into software that previously was instantiated in hardware and re-architecting the software systems to facilitate modularization. Once functionality is in software, it is more easily upgraded and facilitates the further realization of scale and scope economies that reduce operating costs for networks. Softwarization enables virtualization, which enables network resources to be partitioned or combined into distinct logical networks. Virtualization can partition a common resource such as a particular frequency band or computing resources for a single processer or aggregate diverse resources (e.g., multiple frequency bands or the processing power of multiple processers) to transparently support the applications making use of the underlying resources. This supports resource sharing which facilitates the realization of scale and scope economies. Softwarization and Virtualization also support the delocalization of control functions, or, separating the location of where a control decision is made and where the action takes effect. Delocalization further enables the realization of scale and scope economies. For example, delocalized software control allows billing systems and other back-end business systems to be consolidated at a single location to provide service for a national scale network. It also facilitates automating maintenance tasks and other operating functions, further reducing operating costs. Moreover, virtualization facilitates shifting from specialty and more expensive hardware-based network equipment to lower-cost commodity hardware. Increasingly, telecommunication networks have transitioned to all-IP networks, replacing legacy equipment and data networking technologies with the same data communications technology that supports the Internet.

The cost-saving benefits of switching to software intelligent core networks are sufficient to justify the transformation, however there are also important benefits in terms of the range and quality of products and services that MNOs can offer. Virtualization also allows MNOs to provide customized virtual networks and to dynamically provision those networks to meet the diverse needs of different applications, customers or networking situations. Virtualization can enhance service reliability (e.g., with automatic routing around network faults, load re-balancing, or automated cyber-attack responses) and facilitate seamless application support in the face of fluctuating availability of underlying network resources.

For MNOs, the implementation of NFV and SDN could be justified in terms of the cost-savings alone; however, it is also necessary in order for MNOs to deliver the enhanced legacy and new services that the 5G vision hopes to deliver. Although telecommunications network operators have been adding software-smarts or intelligence to their networks for years, enabling Mobile Edge Computing (MEC) and the slicing capabilities that 5G needs to support diverse operations places significantly more substantial demands on the MNO core networks that will support the expanded wireless connectivity promised by 5G.

5.3. Shared Spectrum

A final key element needed to enable the 5G future is expanded access to radio frequency spectrum resources for all spectrum users and uses, all of which envision futures with increased support for wireless access. This includes spectrum for commercial users, which includes both the MNOs for which spectrum is the key resource on which their services depend, as well as equipment providers for users of the unlicensed spectrum used by WLANs and many private networks. It also includes non-commercial uses of spectrum by governments and non-profit endeavors like basic research.

Although most of the focus of 5G for MNOs is on the provisioning of communication services, spectrum is also heavily used for remote terrestrial and space sensing applications like radio-astronomy and radar (including ground-penetrating radar and healthcare diagnostic applications).

The 5G future will be one of many heterogeneous wireless networks under the control of many independent operators that will need to co-exist in there use of the spectrum in the same locations and at the same times. In short, the 5G future will require end-users and their wireless networks and devices to much more extensively share spectrum among heterogeneous users, uses, and networks. This shared spectrum future will need to enable Dynamic Spectrum Access

(DSA) through smarter RF devices and radio networks, using technologies like Cognitive Radio and Software Defined Radios, to dynamically share spectrum on a much more granular basis in all possible dimensions (time, space, frequency, and context).[70]

For MNOs desirous of offering a wide-portfolio of 5G services, a portfolio of diverse spectrum resources are needed that span low-band to high-band spectrum. The low-band spectrum (below 1Ghz) is needed to provide coverage in coverage-constrained networking situations (e.g., rural areas), while the high-band spectrum (above 10GHz) is needed to meet the need for high-capacity connections for wireless backhaul and for high-speed connectivity to wireless devices (connected to small cells). The mid-band spectrum, and especially the spectrum between 2-4GHz, is key for supporting mobile broadband in today's 3G/4G networks and for the newer 5G networks. The mid-band spectrum is useful for mixed coverage/capacity-constrained situations and is key for supporting the operations of MNO networks which are still mostly reliant on large and moderate-sized cell architectures.

There are many ways to share spectrum. Unlicensed users share spectrum non-cooperatively in so far as access is open to any compliant user and users have no right to protection from the interference or spectrum congestion that may arise from the use of the spectrum by other unlicensed users. At the other extreme is the exclusive licensed spectrum on which MNOs have built their networks. With exclusively licensed spectrum, the MNOs manage spectrum sharing on behalf of their subscribers. Cellular roaming agreements and spectrum leases provide business arrangements by which spectrum may be shared among MNOs. In the case of roaming, one MNOs licensed spectrum, bundled with the network resources of that MNO, is used by the subscriber of another MNO. With spectrum leases, the rights to use the spectrum are transferred from the licensee to the lessee, another MNO to use for the duration of the lease.

The range of regulatory access regimes is much wider than just licensed and unlicensed, and spans a continuum of models. Of particular interest and indicative of the direction in which shared spectrum models may go is the new Citizen Band Radio Service (CBRS) that operates

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[70] Traditionally, radio frequency spectrum was shared on the basis of service and technology-specific frequency allocations. Carving up the spectrum in terms of frequencies significantly limits the number of users that can share the spectrum. Carving it up into time slices expands both the number of users who can share the spectrum and the ability to dynamically assign different qualities of service to the users. The transition to spread spectrum, where digital codes are used separate the signals of different users, shifts part of the burden of separating the signals to computing resources upstream from the radio front-ends and enables still further expansion of the capacity and capabilities for dynamically sharing the spectrum. Smart antenna systems that enable beam-forming or multi-input/multi-output (MIMO) techniques, new modulation schemes, and a host of other wireless technologies make it feasible to dynamically share spectrum on a much more flexible and granular basis.

in the 3.5GHz mid-band spectrum in the United States. The licensing framework for the CBRS is novel because it enables a three-tiered sharing arrangement, supported by a Spectrum Access System (SAS) that relies, in part, on a data base to keep track of who gets to use the spectrum when and at which locations. The three tiers include the incumbent users of the 3.5GHz band that have priority interference protection and include satellite earth stations and government naval radar. The CBRS was identified in 2010 as spectrum that could be shared by the incumbent users with commercial users. The other two tiers of the CBRS are the Priority Access License (PAL) users and the General Authorized Access (GAA) users. The PAL licensees have exclusive rights to use their spectrum when it is not being used by the incumbents (the first tier users) and are protected from interference from other users. The GAA users are able to use the spectrum when neither of the other two tiers of users are using the spectrum. The auctions for the PAL licenses only recently completed at the end of August 2020. The CBRS is important and illustrative for several reasons. First, it demonstrates the feasibility of a framework that shares spectrum between government (non-profit) and commercial (for-profit) users. Since much of the spectrum is currently tied up in legacy allocations to government users, enabling more extensive sharing of that spectrum represents an important direction for expanding the supply of spectrum resources for all wireless users. Second, the CBRS represents a framework for managing the sharing among more than just two-tiers of users with interference protection rights and includes the beginnings of the technology and institutional apparatus needed to manage the dynamic sharing of spectrum among legacy and new users, which will assist in spectrum refarming. The SAS can be updated with new license terms and capabilities for managing shared access over time and can be automated to support future more dynamic secondary markets in spectrum.

Finally, the 5G future will not be addressed solely by the MNOs but also by other technologies such as the next generation of IEEE P802 standards that have given rise to the Wi-Fi family of WLANs that have already played such an important role in today's mobile broadband ecosystem. Indeed, 5G envisions private network deployments that could be supported by MNOs or deployed directly by end-users (e.g., for factory-automated networking). MNOs will be sharing the spectrum with each other and with other network participants in the 5G wireless future.

6. MNO Economics and 5G

In Section 0 we reviewed four of the key economic drivers that have sustained the MNO oligopoly through the first four generations of cellular technologies. And, in Section 0, we highlighted the order-of-magnitude improvements in 5G relative to earlier generations of cellular technology and the potential for those to open up new market opportunities for the deployment of network intelligence ever more widely throughout the economy and society (i.e., the realization of *SmartX*, where X includes electric power grids, cities, healthcare, manufacturing, buildings, etcetera). Altough earlier generations also delivered significant improvements and expansion of network capabilities, 5G's development process was different in so far as it embraced a wider range of stakeholders that included participants from vertical application sectors, outside of traditional telecommunications markets. Finally, Section 5 highlighted three important changes that commercial realization of the expanded market potential of 5G require of the ecosystem.

In this section, we bring these points together to identify ways in which the transition to 5G has the potential to disrupt and redefine the competitive dynamics for mobile broadband and wireless markets. Rapid technical change and each successive generation of cellular technologies raises the need to engage in significant investment (or re-investment) which has the potential to enable leap-frogging entry by new market participants and the reframing or redefining of market boundaries and the dynamics of competition.

5G has the potential to fundamentally alter MNO economics. Historically, MNOs invested first in expanding coverage with sufficient capacity to offer a predictable level of service for their core value proposition (mobile telephony for anywhere, always available, personal communication services). As already noted, industry consoldation via the merger of MNOs with adjacent, regional area networks and then the elimination of redundant core network and non-network resources to realize national scale and scope economies were key factors in the increased concentration of MNOs. However once coverage is provided, the MNOs next challenge is to add capacity to handle the growth in subscribers and per-subscriber traffic. Adding capacity is fundamentally a more localized challenge, especially in light of the transition toward smaller cell network architectures.

With the expansion in network capacity and the growth of complementary ecosystem developments like the proliferation of more capable end-user devices and the rich media applications and broadband content services, MNOs transformed from telecommunications service providers into broadband platform providers. With that transformation, MNOs have morphed from the provider of single silo-service to an general access platform. Furthermore, with the expanded implementation of network intelligence throughout MNO networks – from the core to the edges – to enable the provisioning of virtual slices and enable the flexible use of diverse spectrum resources (spectrum sharing) and interconnect heterogeneous networking technologies (wired and wireless backhaul, multiple radio technologies from bluetooth to GPS, from Wi-Fi to 4G, etc.), MNOs have greatly expanded their capabilities for sharing *all* network resources at finer granularity both in core and edge networks.[71]

The increased per-subscriber capital costs that MNOs need to incur to realize 5G's full potential confronts them with a choice. Provisioning the local peak capacity needed in any particular local area will be challenging for any single MNO, and if multiple MNOs each build out the requisite capacity, that will imply investing in significant excess capacity, and incurring the requisite fixed and sunk costs. The more excess capacity there is, the greater the incentive for MNOs to compete aggressively with each other for whatever revenues can be captured in each local market. Also, with extensive excess capacity, there will be ample capacity to enable MVNOs to enter, unless the MNOs are successful in denying that capacity to new retail entrants. In such a situation, MNOs may choose to consolidate still further, merging to reduce the numer of fully-capable MNO networks competing in each market, or they may elect to share local capacity more extensively. Historically, that was accomplished via roaming agreements which work well when the service that is being provided to retail customers is highly standardized (as was the case with mobile telephony). However, in a world of 5G, the MNOs will need more granular control of the underlying resources (spectrum, QoS traffic management, security, etcetera) to meet the needs of their diverse customers, and since intelligent software control enables more sharing options, it may prove easier to share resources. Having already built out national coverage networks, the challenge of expanding capacity offers fewer scale and scope economies (as noted earlier) and those that do arise are more likely to be associated with particular local markets in need of higher-capacity, smaller-cell network support.

Whereas in the past MNOs based their networks on macro-cells that utilized paired spectrum to support symmetric upstream and downstream voice channels, increasingly the needs of broadband platforms call for better support for traffic with more dynamic and potentially

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[71] Concurrent with the developments described herein, interconnection in the Internet and among IP networks has transformed from one based on a bifurcated, hierarchical model of peering and transit to a continuum of models involving ranging from paid-peering to partial-transit. In today's Internet, most of the IP traffic is carried on private IP networks that are not part of the public Internet and much more of the interconnection occurs close to the edge, delivered their by content delivery and other overlay networks (see Clark, Lehr, & Bauer, 2016; Lehr, Clark *et al.*, 2018; Stocker, Lehr *et al.*, 2017).

asymmetric channel requirements,[72] capable of using a mix of licensed and unlicensed spectrum in different frequency bands and increasingly reliant on unpaired spectrum. Meeting these challenges flexibly may call for diverse local strategies depending on where the subscribers are located (e.g., in urban v. rural areas, indoors v. outdoors, areas with different topological and environmental impediments to RF propagation). Additionally, the expanded spectrum and other resource sharing options that 5G enables may reduce the relevance of control of bottleneck resources, or may shift control of those to more decentralized local entities.

Furthermore, regulators, anxious to prevent even more consolidation among national MNOs may act to block further mergers, and are promoting infrastructure sharing as an alternative strategy for addressing the increased per-subscriber capital costs of building out 5G networks.[73]

Finally, the network demand externalities that contributed to enhancing the value of larger networks and helped deliver FMA to incumbents may be less relevant in a future world of 5G where a growing number of diverse users with heterogneous usage value the benefits of greater security and control afforded by network slicing and isolation of network traffic over the network externality benefits of interconnection to a wider network community (Vuojala *et al.*, 2019).

Thus, in the world of 5G, the trend toward small cells, intelligent core networks, and shared spectrum and the growth in Smart-X market opportunities and the new economics of small cell

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[72] On a broadband platform, subscribers may be using a mix of applications ranging from IoT applications requiring relatively low-bit rates but with variable latency requirements (e.g., meter reading may be asynchronous where real-time control of heating or electric power migh require low-latency control) to rich media applications that may be one-way (e.g. streaming entertainment media which is mostly downstream from the network to the end-user device such as a smart TV or tablet) or two-way (e.g., video-conferencing). Different subscribers may be engaging in these activities with variable frequency and at differing times. To support such traffic, variable length datagrams and potentially dynamically asymmetric upstream and downstream channels are often needed making unpaired spectrum potentially more useful than paired spectrum.

[73] This is the model adopted in Europe as part of the new European Telecommunications Regulatory Framework. European regulators, striving to promote the emergence of a single Digital Market and investment in next generation telecommunications infrastructure are encouraging MNOs to share network infrastructure. According to the European Commission, "the need to quickly and efficiently deploy new mobile networks triggered some operators to engage in different forms of network sharing agreements. Network sharing refers to a situation where two or more mobile network operators (MNOs) agree to share network infrastructure, typically with a view to reducing the cost of deployment and/or operation of the network. Network sharing can either cover only the "non-intelligent" part of the radio access network (RAN) such as sites, masts and antennas (passive network sharing), or also include the "intelligent" elements of the RAN such as base stations or controllers (active network sharing). Advanced forms of active network sharing include the sharing of radio spectrum. Network sharing has the potential to bring about significant efficiencies (see https://ec.europa.eu/competition/sectors/telecommunications/overview_en.html).

networks and local capacity provisioning may be offsetting the traditional forces of scale and scope economies, network effects, control of scarce bottleneck resources, and regulations that helped ensure MNOs remained an oligopoly.

Two additional potential disruptors are also apparent. First, there is the drive toward increased fixed-mobile convergence; and second, there is the potential for end-user self-provisioning. Both of these trends are enabled by the improvements in 5G wireless performance that renders mobile broadband a more viable competitor for fixed broadband services (since it increasingly can support similar levels of application performance for the most popular applications and services used by mass market subscribers), while simultaneously making MNOs more dependent on wired network service providers with dense-neighborhood wired infrastructure (of the sort that wired broadband providers need to support their retail services) for backhaul support for MNO small cells.

As noted earlier, most of the traffic from smartphones and other cellular-network connected devices is actually carried via Wi-Fi connected to fixed broadband services in the home or building since most wireless usage is actually indoors. The capabilities of Wi-Fi on one hand and the threat posed by MNOs to the core business of fixed broadband providers on the other are driving a growing number of fixed broadband providers to offer wide-area mobile broadband services. Services by Comcast's Xfinity or Google Fi take advantage of nearly ubiquitous Wi-Fi access points as the preferred mode of mobile broadband connectivity and then operate as MVNOs, leasing capacity from the MNOs, to provide coverage and high-speed mobility support when Wi-Fi access is not an option. For end-users, the tighter integration of fixed and mobile networks, wired and wireless technologies, enables better and more seamless service delivery, and potentially the added benefits of being able to take advantage of bundled service offerings. Telecommunications service providers have long recognized that subscribers with bundled services tend to churn less, and subscribers like the discounts and ease of dealing with a single provider when they purchase bundled services. Thus, the convergence of fixed and mobile services is driven from both the supply and demand sides of the market and that push will be greater in a 5G world.

The second trend – end-user self-provisioning – is facilitated by the changes in MNO networks, the design of 5G as a modular toolbox, and the growth of complementary markets for consumer-grade and private-network equipment that is ever more capable and augmented with software to make the equipment easier to install and maintain. Business enterprises that are shifting more of their mission-critical operations into digitally controlled systems may opt for tighter control that private 5G networks or virtual slices may entail. At the same time, residential homes, shared tenant buildings and residential communities, retail centers and malls, corporate campuses and other institutions have increasingly been augmented with expanded local networking capabilities. These local islands of connectivity have the potential to be linked together as an alternative strategy for building out local last-mile connectivity. The network equipment and software to enable this is increasingly available in "big box" consumer stores that allow end-users to deploy wireless networking infrastructure directly, without requiring service provider assistance.

In summary therefore, the legacy business model of MNOs confronts a number of disruptive trends. Changing economics may be opening the door for new models of competition in legacy MNO markets while expanding the range of market opportunities MNOs may seek to pursue. Meanwhile, entry by fixed broadband providers into traditional MNO niches and the potential threat that end-users may opt to self-provision their last-mile access networks threaten MNOs traditional markets.

7. MNO Competitive Dymamics

In preceding sections we highlighted how 5G enables MNOs to significantly expand the scope of market opportunities they may address, while also noting the challenges they may confront in addressing both legacy and new markets. As general-purpose mobile broadband service providers, we expect that MNOs will continue to operate as full-service providers. And, it is quite possible that in spite of the challenges they will face, they may very well emerge as the dominant players in the wireless future. We are agnostic as to whether that will be the case or not since the outcome will depend on the confluence and co-evolution of multiple factors that cannot be perfectly forecasted. These include the rapidity with which different 5G applications will take off, the pace and direction of continuing wireless innovation (e.g., the speed with which millimeter wave spectrum is able to be exploited), and the outcome of regulatory policy-making. To better understand how the forces may play out, we focus on the following three market opportunities: (1) enhanced Mobile Broadband (eMBB); (2) wide-area coverage for niche applications; and (3) Local coverage and capacity markets.

It is worth noting that this tri-partite division is different than the standard division identified by the ITU in its 2015 characterization of usage scenarios for 5G (see Figure below).[74]

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[74] This is Figure 4, reproduced from the ITU (2015) report setting out the IMT vision. The ITU (2015) vision identified three class usage scenarios that helped motivate the performance targets that helped

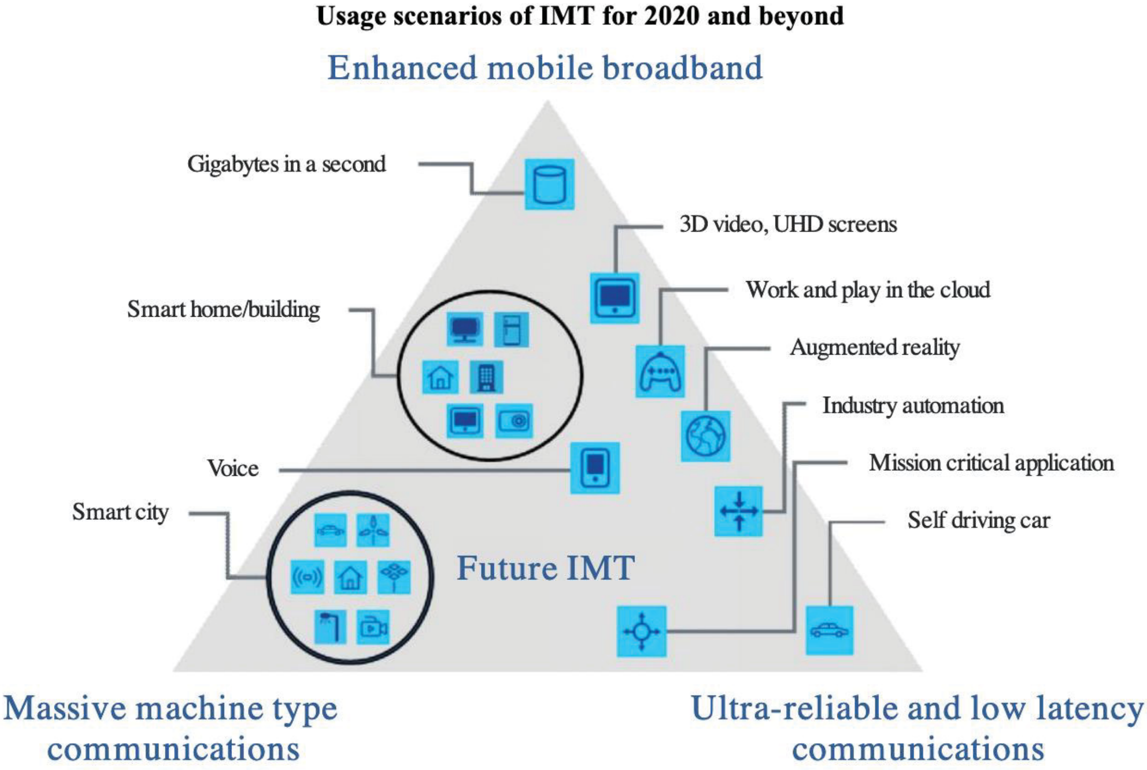

Figure 4: Usage Scenarios for IMT 2020

Earlier we discussed how 5G enables addressing these different usage scenarios. Here, our focus is on highlighting the challenges confronting MNOs and the competitive challenges they may face in pursuing each of these. Table 2 highlights each of these, which are explored further in the following sub-sections.

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frame the development of 5G: Enhanced Mobile Broadband (eMBB); Massive Machine Type Communications (MMTC); and Ultra-Reliable and Low Latency Communications (URLLC). We discussed each of these earlier.

5G-subsegment	**Supply models**	**Supplier class**	**Examples**
Enhanced Mobile Broadband (eMBB)	Dense WAN	MNOs	Verizon, AT&T, Vodafone, Deutsche Telekom
		New entrants	Rakuten, United Internet, Dish, TGP Singapore
Wide-area Coverage for Niche Applications (WAN vertical)	Dense WAN	MNOs	Verizon, AT&T, Vodafone, Deutsche Telekom
	Low-density WAN	Broadcaster	CBN, media broadcast
		Service provider	450 Herz, Sensus, Infrastructure Networks
		Self-supply	New York Power Authority
Local Coverage & Capacity Networks	Dense WAN, local private network	MNOs	Verizon, AT&T, Vodafone, Deutsche Telekom
		Self supply	Bosch, VW, BMW
		Vendors	Nokia, Huawei, Ericcson
		Specialised service provider	LS Telcom, Dortmund, Siemens,
		Cloud service provider	Microsoft

Table 2: MNO Market Opportunities

Each of these will be characterized in terms of their service model, key features of the network needed to support this model, and the key demand features they address (coverage, capacity, control) and the spectrum they will need. These are summarized in Table 3 below.

	Service Model	**Network Features**	**Coverage, Capacity, Control**	**Spectrum**
eMBB	Anywhere connectivity : (a) Uninterrupted connectivity for high-speed mobility; (b) Ubiquitous coverage Personal subscription service to provide mobile broadband access for mass market users exemplified by smartphones Penetration of subscriber base and rising per-user usage. Adding new services to sustain ARPUs. Connection growth increasingly multiple per person, and m2m (IoT).	National networks from highways to everywhere. Large macrocells, increasingly densified over time to add capacity. Full-service broadband platform for business and consumers. NFV, SDN in revamped core network with backhaul and global connectivity.	Coverage : wide-area Capacity: high, general-purpose mobile broadband access and networking platform to support full-range of services (QoS needs, mass market and vertical niches, retail and wholesale via MVNOs). Control: Service provider that can grant varying degress of control to end-users via slicing and VPNs ranging from full service outsourcing to private-network building blocks.	Licensed spectrum. Low & Mid-band for coverage, and increasingly high-band for local capacity. Off-loading to unlicensed. Next-gen allows standalone 5G LTE networks operating in licensed, unlicensed, and ashred spectrum.
Niche Wide-Area Networks	Anywhere connectivity for niche services such as IoT (connection-oriented) and broadcast (media distribution).	National or Regional, but with less-dense cell architecture and/or specialized technology for more limited service models (e.g., LPWA IoT network Specialized QoS may allow cost-savings relative to all-purpose MNO (e.g., LPWA or Broadacast) with former for IoT sensing and latter for media distribution. Niche technologies -- broadcast, satellite, LPWA technologies. Key is less dense cell architecture reduces network costs significantly.	Coverage : wide-area Capacity: Low and specialized QoS to allow lower cost network. Control: Service provider that can support MVNOs or end-user. Could be for large enterprise (e.g., natural resource company or electric utility)	Broadcast (dedicated, digital dividend), Satellite and unlicensed historically, but future may be shared (e.g., CBRS) Use a mix of low-band (coverage) and high-band (back-haul -- e.g., satellite) and mid-band (C-Band, getting cleared for MNOs).

Niche Local Area Networks	Local broadband access network to economize on costs of deployment (i.e., shared peak-capacity access via shared tenant services or community network) or for closed user community (Smart-X for X=manufacturer, hospital, etc.). Could be community network. Local deployment also has control benefits (own v. lease financial and control, shared government and commercial usage such as public safety and residential/local businesses	Private networks based on LAN technologies like WiFi and others can increasingly take advantage of 5G LTE as size of cells shrinks. 802.11x enabling management of multiple APs and ubiquitous coverage to compete directly with 4G/5G cellular technologies which may be deployed by MNOs or end-users (smart communities, enterprises).	Coverage : wide-area Capacity: high, general-purpose mobile broadband access and networking platform to support full-range of services (QoS needs, mass market and vertical niches, retail and wholesale via MVNOs). Control: End-user deployed private network that may be shared. Also shared tenant services (e.g., for MNOs to share).	Unlicensed and mostly in-doors. For campus/community environments with contiguous outside, may need shared (e.g., CBRS) or micro-licensed. Can use mid-high band since local area.

Table 3: Characterizing the Models

7.1. Enhanced Mobile Broadband (eMBB)

The core market for MNOs is exemplified by the typical mass-market 4G smartphone user that uses the smartphone as a universal, personalized broadband access device and digital appliance. The basic service model is for this device (or others like tablets, personal computers, and other post-PC devices) to provide personalized, portable anywhere/anytime high-speed connectivity that supports digital communication, computing, and storage to a suite of communication and cloud-based services, applications, and content.[75] The transition to 5G greatly expands the performance of such devices. The network needed to meet this demand requires national coverage and the other developments noted earlier (e.g., intelligent core network and a full-suite of backhaul and multiple connectivity options to connect to variety of wireless networks and resources).

The typical business model was to sell mass-market subscriptions for which users pay a fixed monthly fee and additional fees for features and usage-sensitive fees based on the monthly traffic usage. Since the market for human subscribers is saturated with penetration exceeding

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[75] For example, smartphones contain cameras and CPUs to locally store and process digital content. They contain multiple radios to support GPS, bluetooth, Wi-Fi, and multiple cellular protocols. Most include flashlights, multiple IO devices to input and display data, and other functionality to enable them to be used as personal appliances.

100 percent in many mature markets, further growth in subscriptions will depend on connecting things and enabling machine-to-machine communications. The need to provide a general purpose broadband network offering national coverage that can support the full range of capabilities means that the the network will need to support high-capacity communications.

With respect to control, the MNO will be able to grant varying degrees of control to end-users by exploiting network slicing. For less sophisticated users, the MNO will provide a bundle of full-managed services. For more sophisticated users (typically enterprises or other large users), the MNO may provide basic wholesale telecommunications services or virtual private networks (VPNs) that will allow end-users to customize the services and have more control over the operation and security of the network.

Both because of legacy considerations and the continuing need to have predictable spectrum access, MNOs will continue to want to rely heavily on exclusively licensed spectrum, but will also make use of unlicensed spectrum (e.g., Wi-Fi) to off-load traffic to less expensive spectrum when feasible.

Competing head-to-head with the national MNOs will require similar scale investments which poses a significant barrier to entry for most would-be entrants. The most likely competitors are the fixed broadband providers adding mobile broadband services as discussed above and MVNOs that may seek to take advantage of excess MNO capacity (acquired at low cost wholesale prices due to aggressive competition among MNOs) to compete with MNOs at the retail-level. In the U.S. today there are two fixed broadband network operators in each market -- the legacy fixed-line telephone company (e.g., Verizon, AT&T) and the legacy cable TV operator (e.g., Comcast, Charter) -- and three MNOs (Verizon, AT&T, and the new T-Mobile).[76] Since AT&T and Verizon are both MNOs and providers of fixed broadband services, one might consider the current market for national converged fixed-mobile broadband services as comprised of four or five national-scale competitors (i.e., AT&T, Verizon, T-Mobile, Comcast, and Charter). Although this is still an oligopoly, it suggests the potential for intensifying competition among MNOs.

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[76] In certain markets there are additional facilities-based regional competitors.

It is also conceivable that new global low-earth orbit (LEO) providers like Space-X or Amazon's planned Kuiper network could offer space-based broadband services that could rival terrestrial alternatives by being able to offer comparable speeds and potentially better latency.[77]

Although competing head-to-head with national MNOs confronts significant entry barriers, there are examples of facility based new entrants originating from a variety of backgrounds, including fixed operators (e.g. United Internet in Germany), MVNOs (Rakuten in Japan), Broadcasting companies (CBN in China), Satellite operators (Dish in the US), or MNOs expanding into other countries (Iliad in Italy).

7.2. Wide-area Coverage for Niche Applications

One niche that will expand in the market for 5G and the growth of IoT applications is the need for wide-area coverage with homogeneous service needs in a particular vertical niche. MNOs with 5G networks can address this opportunity via a network slice that is used to provide services to customers with that niche need. However, historically, these needs have been addressed in many cases by specialized providers operating purpose-built networks to address the niche requirements of a particular class of applications in a vertical segment.

Because coverage-constrained wireless networking confronts special cost challenges discussed earlier, there is the potential that a niche network provider might be able to compete with a full-service MNO, in spite of the scale and scope economies that an MNO is able to realize. The basic service model is to cater to the need for anywhere connectity (national coverage) for connection oriented services such as IoT or for broadcast media such as content distribution. In either case, generality is sacrificed to exploit benefits of lower cost, specialized network technologies.

This is another obvious opportunity for enhanced satellite broadband providers may be able to effectively address, taking advantage of advances in the design of VSATs and improved performance of high-throughput GEO and MEO satellites which offer the benefits of wide-area coverage, especially for IoT applications requiring connectivity in locations which are uneconomic for the deployment of terrestrial coverage (e.g, for asset tracking of ships-at-sea and remote areas).

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[77] While the potential for such services is great and significant investments have already taken place to make these a reality, we do not discuss satellite-based competition further here because their ability to compete directly with terrestrial broadband in well-served markets and the costs of operating LEO constellations remains uncertain.

Additionally, new terrestrial networks may be viable to compete for this demand. By sacrificing capacity (e.g., to support anywhere connections for low-bandwidth IoT devices), fewer base stations would be needed so macro-cell architectures could be utilized. Technologies like Low-power, Wide-area (LPWA) networks could be deployed. Potential applications may include natural resource companies or agriculture enterprises wishing to deploy IoT sensing for better irrigation or resource management for rural resourecs. Alternatively, broadcast applications that do not require symmetric two-way unicast communications may be able to exploit technologies that can deliver high-bandwidth applications less expensively than a full-service MNO network. For example, satellite-based broadcasting can deliver high-data rate media over wide coverage areas, obviating the need for costly terrestrial distribution infrastructure.

Whereas with eMBB, the focus was on providing a network offering both wide-area coverage and high capacity services, for the wide-area coverage for niche applications opportunity, the focus is solely on providing coverage. Once again, however, the basic model is a service-provider based model since it is unreasonable to expect individual end-users to rely on purpose-built private networks to meet this need. As with eMBB, control would be managed by the service provider on behalf of the end-user or the service provider could set up and manage a virtual private network on behalf of the end-user.

Historically, wide-area services have been provided in exclusively licensed spectrum because of the need to coordinate spectrum access over a wide area. In the case of satellite broadcasting, the coordination needs to be international because of the wide-coverage area of satellites. Currently, policymakers in the U.S. are looking into refarming spectrum previously allocated to satellite applications for use by terrestrial broadband operators. In the U.S., plans are to auction off 268 GHz of C-Band spectrum currently used by satellite providers starting in December 2020.

Also, for wide-area coverage, low-band spectrum is especially valuable. Historically, regulators in many countries have allocated low-band spectrum for wide-area coverage for niche users such as electric utilities.

Concurrently, several dedicated low density networks are being used to provide specialized connectivity to a vertical, including firms in the broadcasting domain, such as Media broadcast in Germany or Emitel in Poland[78] or CBN in China, the smart metering domain, e.g. Sensus[79]

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[78] https://www.emitel.pl/en/about-us/

[79] providing connectivity services to utilities http://www.aqua-metric.com/assets/ami-120-r-3.pdf

in the US or 450 Connect in Germany[80] or public safety networks operated by government institutions. Hitherto, these networks use dedicated technologies and address only one vertical. However, upgrading the existing networks to 5G and leveraging their already allocated licensed spectrum, may allow these firms to compete for the future connectivity demand in the vertical they currently serve or even expand their services to other verticals in competition with the MNOs.

7.3. Local Coverage and Capacity Markets

The third opportunity we focus on is the need for high-capacity broadband communications in a contiguous local area. That could be indoors or include the adjacent outdoors. The key is that the network is designed to serve the needs of a geographically contiguous group of end-users. The network could be publicly shared as in the case of a municipal network or the network for a residential community, industrial park, or shopping mall. Or, the network might be private and for use by a single enterprise such as in a factory or on a corporate or university campus. The literature and regulatory agencies refer to these networks under several terms, including local private 5G-networks, campus networks, locally operated networks (Matinmikko et al., 2018) or non-public local networks (5G ACIA, 2019).

In these cases, local providers (neutral hosts) or end-users may have an advantage over wide-area MNOs in terms of access to antenna sites, local distribution infrastructure such as conduit, and power. Moreover, local providers have the ability to exploit local scale and scope economies which may be more important in the world of bursty 5G traffic.[81] Additionally, local user communities may value the greater control and potential cost-savings that may be realized by self-provisioning their own network needs. The increased availability of high-performance, low-cost network equipment with software that assists self-configuration has the potential to enable users greater scope for self-provisioning. If adjacent private network providers wish, they can interconnect to aggregate their reach still further and increase the potential to take advantage of volume discounts for wider-area connectivity options and routing diversity (e.g., multiple connections to different wide-area service providers that can be used for load-balancing and fall-back in the event of a failure on one or another connection).

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[80] providing connectivity services to utilities https://www.450connect.de/ueber-uns

[81] Traffic is burstier when the peak to average data rate increases. Because of the higher potential peak capacity of 5G devices and connections, there is the potential for per-user and aggregate per-cell traffic to be burstier than with prior generations of cellular technologies.

Local user communities may appropriately view the investment in next generation broadband connectivity solutions as long-term investments in small antenna deployments with associated power supply and last-mile fiber backhaul as real-estate, value-enhancing and may choose to fund such investments with long-term municipal bonds. Communities will need such networks for the use of their citizens as well as to support their government and anchor institutions, including public safety and schools. Much of the investment in such infrastructure is fixed and sunk (e.g., the conduit and outside structures, like the local roads and driveways to houses, are not relocatable for use in other markets). Concerns over the appearance and location of wireless antennas and excessive redundant investments in multiple small cell 5G networks in a community may lead municipalities to prefer to opt for a single shared infrastructure solution based on an open radio-access network that will meet the joint needs of local government, anchor institution, and residential and local business user needs for seamless local mobile broadband. An obvious solution for meeting this need is for the local community to issue Request for Proposals (RFP) for would be service providers to bid to construct and operate such a network on behalf of the community. In such cases, it is also logical to expect that MNOs will be leading bidders to answer this need. However, other providers might also seek to address this market opportunity, such as so-called neutral host providers. That may include antenna companies like American Tower or Crown Castle that provide many of the macro-cell antennas that are shared by MNOs. Such providers would offer local 5G infrastructure access that would be shared on a non-discriminatory basis among multiple MNOs or other users, obviating the need for MNOs to deploy their own dedicated 5G small cell infrastructure. Such neutral host providers could benefit from the local scale and scope economies noted earlier.

Additionally, companies are becoming more interested in these local private 5G-networks, because they satisfy the enterprises' stringent data security requirements (Walia, Hämmäinen, Kilkki, & Yrjölä, 2019).

Furthermore, in many cases, the enterprises want seamless indoor and (adjacent) outdoor connectivity which poses a challenge for MNOs since in many cases, cellular networks provide poor coverage indoors. In the markets for private end-user deployed local networks, the principal model has been to rely on unlicensed spectrum (because purchasing spectrum licenses was too expensive for users seeking to operate in a single local area) and WLAN equipment was often used (or other specialized wireless equipment). Inside factories and on campuses, it was easier for end-users to deploy Wi-Fi-based networks to address their wireless connectivity needs, and rely on wired broadband connections for wider-area connectivity. Thus, when it comes to such private network applications, 5G represents a new opportunity for MNOs which can seek to address this need via virtual slices on their wide-area networks.

However, for MNOs to address this market effectively, they will need to augment their mobile network by investing in complementary indoor small cell deployments (Ahokangas et al., 2016). As several countries made or are in the process of making licensed spectrum available for local private 5G-networks (see Matinmikko-Blue et al., 2019 for country case studies), an increasing number of enterprises may elect to self-provision their own private 5G networks (rather than relying on an MNO to offer those services). While some enterprises are building their own private networks (e.g. VW or Bosch[82]), others have partnered with equipment vendors (Lufthansa Nokia[83]) to meet their needs.

In addition to confronting competition from end-users self-provisioning private 5G networks, MNOs and cellular 5G will confront competition from the next-generation of the Wi-Fi technologies that have heretofore dominated in this segment.[84]

We anticipate that MNOs may see significant competition from new models of entry (e.g., municipal networks and self-provisioned networks by end-users) and new technologies (e.g., next-generation Wi-Fi), and may find it desirable to rely on neutral hosts for access to capacity in specific locations (e.g., stadiums, anchor institutions like schools and libraries, and other indoor facilities) where the high per-subscriber capital costs propel MNOs to rely on shared small-cell/local network infrastructures. Taken together, the potential for end-user deployed networks could significantly reshape how last-mile wireless connectivity evolves and disrupt the business models for MNOs.

7.4. Summing up the competitive dynamics for 5G

Although the future for mobile broadband competition remains uncertain, we expect to see intensifying competition which should deliver benefits to end-users and help drive further improvements in wireless performance as service providers and equipment providers seek to differentiate their offerings and respond to new 5G opportunities and the competitive responses of rivals.

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[82] https://www.bosch-presse.de/pressportal/de/en/bosch-applies-for-local-5g-licenses-203328.html

[83] https://pf.content.nokia.com/t004f2-private-wireless-airports/press-release-nokia-deploys-5G-private-wireless-network-lufthansa-technik

[84] See Oughton *et al.* (2020).

MNOs will compete in all of the market spaces since 5G networks will enable them to offer both wide-area coverage and capacity at national scale to both mass market consumers seeking general purpose broadband access as well as to niche vertical application markets with more specialized service requirements. However in addressing the markets, the MNOs will confront new competition.

In the MNO core market of providing eMBB services that offer both high-capacity and wide-area coverage for general purpose broadband, MNOs will confront new competition from MVNOs that are able to take advantage of the generic excess capacity that is likely to exist locally if multiple 5G networks are deployed in each area. There is also the potential for new entry from fixed broadband providers taking advantage of their national core networks, strong presence among mass market subscribers, and large-scale deployments of Wi-Fi enabling them to offer mobile broadband services. And, if ventures like Space-X or Kuiper are successful in deploying LEO constellations, satellite-based broadband competition may further expand the range of service-provider-based competition.

If last-mile access wireless connectivity bottlenecks are alleviated then other key concerns like security and control of network assets or the emergence of cloud or content-delivery-networks integrating into wide-area networking may pose significant challenges for MNOs. In pursuing new markets for vertical niches, other issues like vertical-sector domain expertise (e.g., in providing security or access to data) may prove more important than minimized the cost of supporting the basic wireless connectivity, opening the path for specialized MVNOs to operate in certain important vertical niches like healthcare, fintech, or smart supply chains.[85]

The markets for specialized networking services include both the wide-area niche application markets (e.g., low-power wide area services for IoT applications or on-demand services for first responder public safety providers) and localized networking contexts. In the former, MNOs have the potential to compete with specialized network slices. However, specialized providers operating purpose-built networks using lower-cost technologies optimized for coverage-constrained (wide-area) contexts may be able to compete with MNOs. When it comes to meeting the needs of local wireless connectivity for community (municipal) networking or for enterprises, the MNOs have a good case to make in bidding for the business, but also confront the potential of competition from new local competitors (e.g., neutral hosts) and end-users self-provisioning their own networks.

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[85] See Lehr (2019).

8. Policy implications

From a policy perspective, helping ensure the competitive potential for 5G is realized is important. Addressing that goal will require a range of initiatives.

First, policymakers should protect against incumbents seeking to foreclose competitive entry by alternative infrastructures and competitors. One of the most important areas there is to ensure adequate commercial acess to spectrum resources and to backhaul facilities. From a spectrum perspective, that means making sure there is an adequate supply of unlicensed spectrum available so that potential entrants are not foreclosed because an inability to access spectrum. Enabling access to smaller area licensed spectrum for potential providers to be able to offer an interference protected wireless service is also useful. The CBRS framework offers one way to do this. It is also important to promote the emergence of spectrum secondary markets to ensure that spectrum resources are priced at their opportunity cost and not rendered artificially scarce by legacy allocations.

For the viability of niche providers of wide-area solutions, it is necessary to ensure adequate availability of the low-band spectrum needed for coverage-constrained networking solutions. This is not an issue for local, high-capacity applications where small cells can more readily take advantage of less expensive and more abundant higher frequency spectrum. Because the low-band spectrum will remain scarce, the goal ought to be to make sure that it is appropriately valued at its true opportunity cost.

In addition to ensuring the availability of spectrum, it is also important to ensure access to other bottleneck resources such as conduit, rights-of-way, and antenna sites that are needed for small cell infrastructures. One way an incumbent might seek to limit the threat of end-user self-provisioning or other sorts of local competition threats (including neutral hosts) is to ensure that adequate backhaul, power, or interconnection options to wider-area networks are not available.

Finally, policymakers need to promote interoperable and open architecture technologies that enable network resource sharing and interconnection among heterogeneous networks. Adopting an open radio access network architecture for local small cell 5G networks offers one way that might be achieved. Realizing the potential of 5G should embrace both the 5G technologies specified by 3GPP and the P802.11 family of technologies, as well as other technologies such as satellite-based broadband and others that have yet to emerge.

To ensure that mass market end-users and niche applications have a wide range of 5G choices, it is important to protect the potential for MVNO competition. This is best achieved by making sure there is a robust and competitive market for wholesale 5G network services that can support a vibrant market in retail services.

Another tool that policymakers have in helping promote a healthy 5G future is its monopsony power. In most local markets, government users are the single largest source of demand for telecommunication services. Of special importance here and of relevance to realizing the ambitious performance goals of 5G is the need to provision next generation public safety networks. These will be supported with public subsidies and it is unreasonable to expect that we should built separate 5G networks for public safety (and other government needs like to support schools) and commercial users. The 5G networks should be shared by both commercial and non-profit users. As already noted, in many if not most cases, the best way to meet the needs of public safety and other government users is to rely on the services of commercial network providers such as MNOs. However, MNOs are not the only providers that may be able to address those needs and self-provisioning options, including investing in neutral hosts or municipal networks, should be part of the policy tool box for realizing the 5G future.

To ensure that MNOs and other options for deploying 5G remain viable, policymakers need to address regulatory impediments such as eliminating regulations that preclude local communities deploying their own networks for fear that those networks might compete with MNOs.

Because 5G involves much more than the last wireless connection, policymakers will need to remain vigilant to protect competition across the entire telecommunications value chain. Promoting open architecures, interoperability, and the option to efficiently share network resources from spectrum to physical infrastructure will be important, but the focus of policymakers should be on empowering market forces rather than favoring particular technologies or business models for addressing 5G opportunities.

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Eidesstattliche Versicherung

Ich, Herr Fabian Queder, versichere an Eides statt, dass die vorliegende Dissertation von mir selbstständig und ohne unzulässige fremde Hilfe unter Beachtung der „Grundsätze zur Sicherung guter wissenschaftlicher Praxis an der Heinrich-Heine-Universität Düsseldorf“ erstellt worden ist.

Düsseldorf, der 30. September 2020

Unterschrift