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ABSTRACT

This article examines the roles and consequences of different approaches to 5G market design for innovation. The analysis is grounded in a conceptual framework that explicitly considers the complementarities among networks, applications, and services. Good policy arrangements align the legal and regulatory framework with the technical and economic characteristics of the sector and the broader, social visions for new technologies. Because the future development of 5G technology and markets is open-ended, policy has to be developed with incomplete knowledge and under conditions of uncertainty. These circumstances call for adaptive forms of policy and a focus on the creation of guardrails for market players, backed up by regulatory powers to intervene more directly if necessary. In the technologically dynamic 5G system, multiple stable policy constellations are feasible, but they likely will result in divergent outcomes and performance characteristics. Monitoring of the experience with different national and international developments will facilitate global learning and the incremental improvement of policy frameworks.

1. Introduction

Fifth generation (5G), sixth generation (6G), and emergent sub-THz wireless networks enable a broad range of innovative services and applications (Chaccour et al., 2021; Lehr et al., 2021; Saad et al., 2019). Whereas previous generations of wireless services primarily targeted the mass consumer market, many of the anticipated benefits of advanced wireless services will be associated with business and industrial use cases. Seeking to promote innovation and investment many countries are reviewing and adapting their policy approaches to 5G. This article analyzes the roles, trade-offs, and potential positive and negative effects, of different approaches to the regulation of 5G markets. It grounds the analysis in a framework that explicitly considers the complementarities among networks, applications, and services that are a characteristic feature of the advanced wireless ecosystem. Innovation is conceptualized as an experimental exploration of a space of technological and economic opportunities that is only partially known (Bauer & Knieps, 2018). Regulation influences the working of these interdependent markets and shapes the decisions and strategies of individual firms to explore the innovation opportunity space. Although other public policies, including spectrum policy and industrial policy, are also relevant for 5G markets, this article will focus on selected aspects of regulation that affect horizontal and vertical business relations among players.

In technologically dynamic systems, such as 5G, multiple stable policy constellations are feasible, but they likely will result in

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divergent outcomes. For example, alternative policy models may influence the direction of innovation or the equitability of infrastructure deployment differently. Good policy design aligns the legal and regulatory framework with the technical and economic characteristics of the sector and the broader, social visions associated with new technologies (Finger et al., 2005). Two primary sets of considerations influence the ongoing discussions about 5G policy. On the one hand, policy seeks to restrict the power of key players to manipulate markets and undermine competition. Although assessments of significant market power are part of the standard regulatory toolkit, the interdependencies among players in the 5G ecosystem raise new and unique challenges, such as how to delineate the relevant markets and how to deal with firms present in multiple related markets. Policy also seeks to select market designs that promote the innovative potential of 5G technology. Because innovation flourishes in a zone between contestability and temporary (but not structural) market power (e.g., Schumpeter, 1942; Shapiro, 2012), tensions exist between restrictive and promotional goals of regulation.

Because the future development of 5G technology and markets is open-ended, policy has to be developed with incomplete knowledge and under conditions of uncertainty. These gaps in knowledge are typically bridged with a combination of powerful images of an abundant 5G future and persistent past practices. Deliberately or tacitly, they become blueprints that inform the regulation of emerging technologies during their formative stages. However, there is evidence that reliance on prevailing approaches can result in the retention of inappropriate policies (Briglauer et al., 2019). Experience with the regulation of earlier generations of interdependent information and communication technologies (ICTs), such as the Internet or digital platforms, shows that most regulatory interventions have differential effects on players (e.g., Bauer, 2010). These effects are amplified in the emerging, highly interdependent 5G innovation system and ought to be considered in the design of regulation. This requires shifting the focus from local, partial effects to an examination of regulation in a broader framework that considers all adjustments by players in response to an intervention. In other words, it may require reconceptualizing regulation in a general equilibrium framework rather than in the prevailing partial equilibrium approach.

The remainder of the article is organized as follows. The next section explains the unique features that differentiate the 5G value system from earlier wireless technologies. Section three develops a conceptual framework to analyze desired and potential undesired effects of 5G policy on investment and innovation. Pros and cons of selected forms of 5G market regulation are discussed in section four. The article mainly examines the experience primarily in Europe and North America, but many of the insights are relevant to other national contexts. Section five integrates these different strands to develop an overall assessment and derive implications for robust 5G market design. Section six briefly recaps important insights.

2. The emerging wireless value system

Third generation (3G) and fourth generation (4G) wireless networks are function-oriented and often use dedicated hardware for the core and the radio access network. In contrast, 5G networks are designed as unified, enabling platforms that support a broad range of use cases. They will constitute an integral part of the future, converged, gigabit communication network infrastructure. Although technical and business details continue to evolve, 5G services will most likely support a differentiated architecture suited to facilitate diverse innovations. Technical attributes, such as high bandwidth and low latency, are expected to enable novel applications across many sectors with potentially far-reaching, economic and social impacts. Many experts envision three broad classes of services capable of supporting a plethora of use cases: (1) enhanced mobile broadband, (2) massive, machine-type communications, and (3) ultra-reliable, low latency communications (ITU, 2016).

Enabling a wide range of services will require network services that can support a heterogeneous quality of service (QoS). Software-defined networks (SDNs) and network virtualization will be critical to achieve such differentiation. In addition to innovative services for consumers, 5G is expected to support the Internet of Things (IoT) and allow the configuring of specialized services for sectors, such as smart manufacturing, smart transportation, and smart health care. Technological specifications allow the deployment of 5G across a wide spectrum of frequencies, from the 450 MHz band to millimeter waves in the 24.25–52.6 (and possibly higher) GHz range. This allows flexible configuration of technical, economic, and spatial propagation characteristics to achieve least-cost solutions for different deployment scenarios. For example, the “low” bands below 1 GHz are particularly suited to cover large areas at lower speeds; “mid” bands between 1 and 6 GHz offer less coverage but higher speeds; and “high” band services above 6 GHz achieve very low latency and high capacity in small cells. However, they require investment in many such cells to cover larger areas.

This has profound implications for the organization of the value system. Complementary, interdependent forms of innovation will be more important than in the current Internet. As an Internet Protocol (IP)-based network, 5G wireless will consist of distinct layers, including a physical network layer (comprising a passive and an active infrastructure layer), an enablement and development layer, and an application/services layer (e.g., Devlic et al., 2017). Building the 5G network infrastructure will require high investment in the physical network layers, even though business activities in higher applications and services layers promise higher revenues and profits. Therefore, all players, but particularly network operators, will have strong incentives to adopt business models that allow overcoming this potential bifurcation of costs and profits. Strategic responses include vertical integration across layers, network service and price differentiation, and mergers, which all may have undesirable consequences. Monitoring of market developments to safeguard competition and innovation therefore seems to be a prudent approach.

The organizational form in which 5G services are provided will co-evolve with innovation experiments, innovation successes, and failures. The regulatory model and the overall sectoral policy framework governing the sector will also influence sector organization. Because of the flexibility of 5G technology, firms have multiple options to build market presence. The legal and regulatory market design influences which models are feasible and sustainable. In a simplified form, Fig. 1 depicts several organizational options that the modular and software-defined architecture of 5G technology supports. Option (a) represents a vertically fully integrated organization.

Suppliers in this group offer network infrastructure, enablement tools, applications, and services in one organization to serve intermediate and end users, as is typical for traditional mobile network operators (MNOs). They may offer network slices as well as local industrial networks and services via separate subsidiaries.

Players with core skills in more than one layer may establish a presence across these areas (e.g., network infrastructure and enabling tools, enabling tools and applications/services). Option (b) represents an organization that focuses on active and passive network infrastructure layers. Options (c), (d), (e), and (f) represent players that specialize on one or two layer(s) in which they have core competencies and competitive strengths. New intermediaries (g), such as system integrators, will likely emerge to offer services to players that specialize on upper layers. Mobile Virtual Network Aggregators (MVNAs) and Mobile Virtual Network Enablers (MVNEs) are early examples of such players. End-to-end orchestrators will offer services to integrate components to create network slices and other specialized services across layers. The modular architecture of 5G will also open opportunities for decentralized entrepreneurial innovation, for example by allowing micro-entrepreneurs to gain a foothold in one or more of the layers (e.g., Knieps & Bauer, 2021; Walia et al., 2017). Moreover, the promulgation of the 5G New Radio Unlicensed (NR-U) standard further lowers entry barriers for entrepreneurs and users by offering a versatile option to deploy 5G services without the need to obtain a spectrum license or access to secondary spectrum.

In this differentiated multi-layer system, several concerns may arise, which policy might mitigate. The presence of significant market power is one concern. It may be abused to manipulate competition strategically, to extract super-normal profits from the network ecosystem, or both. For example, vertically integrated players may have incentives to discriminate against competitors that are only present on one layer. Integrated players could use strategies such as setting high access prices, reliance on tedious interfaces, or refusal to provide services (Beard et al., 2001). Such incentives are lower if effective competition prevails at each layer, if the services are complementary, and if the regulatory system allows internalization of such complementarities (Farrell & Weiser, 2003). Nonetheless, because of the cost structure of wireless networks and the spatial heterogeneity of wireless markets, there will likely be areas and market segments in which only one or two players can offer services economically. Limited access to rights-of-way (e.g., antenna sites, access to multi-dwellings and office buildings) may aggravate such problems.

Failures or deficits to achieve the necessary forms of coordination among the interrelated, complementary players are another concern. They refer to situations in which transactions needed to realize the complementarities among decentralized players do not emerge voluntarily, even though they would increase welfare. In 3G and 4G markets, market and non-market arrangements, such as model contracts, standards promulgated by industry bodies, and industry codes of conduct, have facilitated such coordination. However, the 5G value system is more complex and heterogeneous. Thus, effective coordination arrangements may not emerge, if the costs for decentralized players of organizing a market or the costs of transaction in a market are higher than the private benefits for these players. Coordination failure can also occur in the presence of benefits that are public goods, which are not considered by private actors in their investment and innovation decisions. Coordination deficits exist if the costs of decentralized, private coordination prevent the exploitation of innovation opportunities but policy interventions, such as open access and interoperability mandates, could lower the cost of coordination to overcome them. Thus, in addition to addressing market power issues, regulation and other forms of public policy may be justified if they reduce coordination problems in ways that promote innovation and generate positive net benefits for society.

3. Modeling the effects of 5G policy on performance

To address issues of market power and coordination effectively while protecting the unexplored innovation potential of 5G, this paper suggests grounding 5G policy in a framework rooted in innovation theory. Because only limited empirical data on 5G markets were available at the time of writing, this analysis must proceed at a conceptual level and draw, where possible and meaningful, on observations from earlier generations of wireless technology.

Innovation is traditionally defined as a new production process, product or service, organization, marketing method, or design (OECD, 2018; Stoneman, 2010). More generally, innovation can be conceptualized as a creation of novelty that contributes to sustainable efficiency increases and, hence, improves traditional measures of welfare (Antonelli, 2011). Digital technology greatly expands the role of software in the design of new products and services. More malleable than mechanical technology, it often accelerates the speed of change by reducing the cost of innovation. Because of its dynamic nature, digital innovation often unfolds in the presence of fundamental uncertainty. The models used in much of regulatory theory and practice, explicitly and implicitly rooted in static equilibrium economics, do not fully capture the factors that affect innovation decisions of entrepreneurs in the presence of such uncertainty.[1] Under these conditions, entrepreneurial decisions are often based on hunches and conjectures about the likely effects of a project on future firm values rather than on the maximization of profits at the margin (Janeway, 2018). Evolutionary economic theories of innovation (e.g., Nelson & Winter 1982) emphasize the trial-and-error processes that can lead to innovation and thus offer a promising route to analyze the potential effects of regulation and antitrust in the fast-paced 5G sector.

3.1. Innovation in the 5G system

Through a dynamic, evolutionary lens, digital innovation can be conceptualized as a succession of experimentation (typically a

[1] Regulation and antitrust continue to rely on perfectly competitive markets as a reference standard (e.g., Kahn 1970/71; Laffont & Tirole, 2000). This provides desirable analytical rigor but raises challenges for the design of the regulation of dynamic markets (e.g., Viscusi et al., 2018).

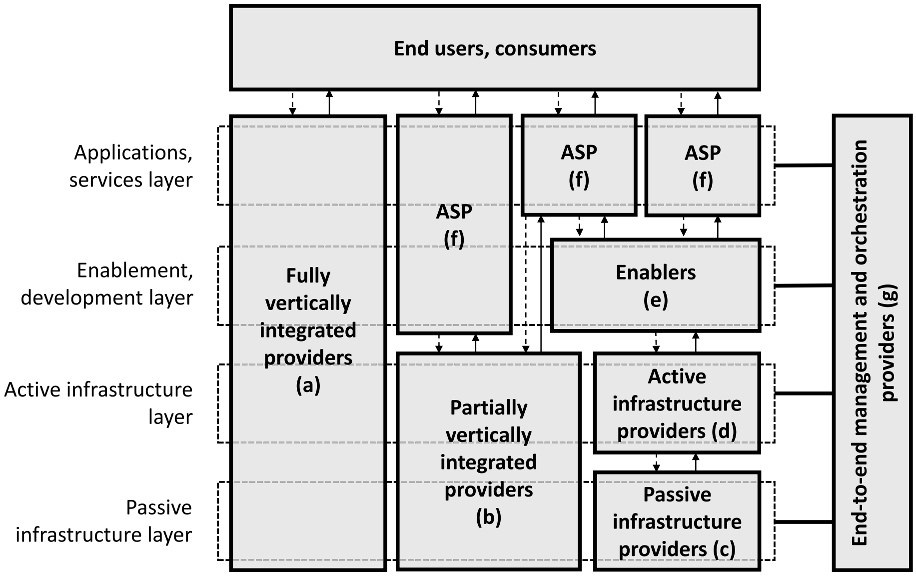

Fig. 1. A simplified view of the organization of the 5G value system. Players in the 5G value system will position themselves differently across the four main layers, depending on their core competencies and business strategy. Some players will be fully vertically integrated (a), and others will specialize on one or more of the layers (b, c, d, e, or f). New intermediaries will emerge to integrate components across specialized players (g). Arrows illustrate selected vertical transactions. Dotted arrows indicate requests by players at higher layers to players at lower layers; solid lines indicate delivery of services from players at lower layer to those on higher layers.

recombination of knowledge) and real-time feedback on what does and does not work, the selection of a successful idea in the marketplace or by other means (e.g., policy decisions), and its scaling beyond the experimental stage (Antonelli & Patrucco, 2016; Brynjolfsson, 2011). In this general framework, it is possible to identify common forces that shape innovation in 5G and other digital markets in which complementary innovation processes unfold (see Fig. 2). The innovation decisions of individual firms respond to the conditions faced in the relevant, often interrelated market segments. Particularly important are the competitive conditions (the degree of contestability), the technological and economic opportunities, and the conditions for the appropriation of rewards (rents) for taking the innovation risk. In addition, the complementarities with players in complementary activities and the costs of coordinating with them influence the innovation activities of a firm. The rate and direction of innovation at the sector level emerge from these interactions among individual players.

Fig. 2 depicts a stylized version of the factors that influence the rate and direction of investment and innovation in a multi-layer system with interdependencies and complementarities between players. To simplify, only two layers—infrastructure as well as application and service providers (ASPs)—are distinguished, but the model can be generalized to more layers. In each of the related layers, innovation is propelled by the contestability of the market, the opportunities for innovation, and the appropriability conditions. If the innovation activities in these layers are complementary, the conditions of players on related layers will influence innovation activity in addition to layer-specific factors. For example, innovation activities at the network layer that lead to the deployment of a broader range of functional capabilities will likely expand the innovation opportunities of ASPs (and vice versa). Moreover, the strength of the complementarities and the costs of coordinating the actions of players needed to realize them will be relevant. For example, the availability of standardized application programming interfaces (APIs) will benefit application developers, because it will reduce the cost of innovation compared to a scenario in which the developers must negotiate with individual service providers and adapt applications to multiple environments.

Innovation theory suggests that economic, technical, and regulatory innovation opportunities will be positively related to innovation activity, other things being equal. In a similar way, the improved appropriability of innovation rents also increases innovation activity. The relationship between contestability and innovation is more complicated and can be positive or negative. Joseph Schumpeter (1942) asserted that temporary monopoly power was conducive to innovations that require high upfront investment and a willingness to take large risks. In contrast, Kenneth Arrow (1962) argued that, for a firm in a monopolistic market position, an innovation only replaces existing profits (dubbed "replacement effect" by Tirole, 1997). In contrast, a firm under (perfectly) competitive conditions will be able to earn a positive profit by innovating (dubbed "escape competition effect" by Aghion et al., 2005). Consequently, Arrow concluded that competition was more conducive to innovation than monopoly.

Shapiro (2012) reconciled the two positions, recognizing that contestability was critical in both cases, but that market concentration was less important. Thus, even a firm with high a market share might have strong incentives to innovate in a contested market to protect its future revenues and profits. Innovation incentives will be low, but not necessarily absent, in uncontested or only weakly contested markets (e.g., monopolies or tight oligopolies). Innovation incentives will likely also be low in ultra-contested markets because any innovation can easily be imitated by competitors. Only in the rare case in which a firm can escape intense contestability by

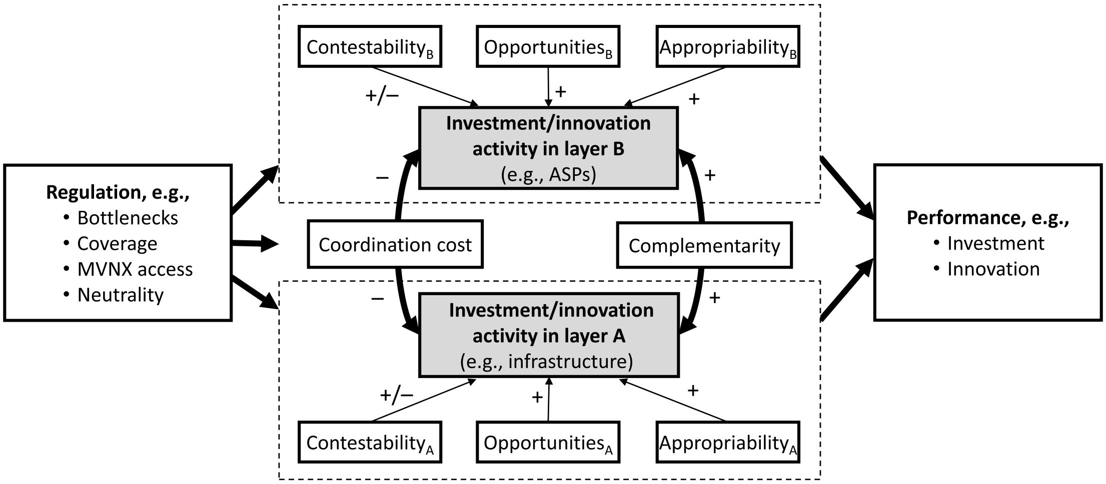

Fig. 2. Factors that influence complementary innovation processes.

pursuing a course of radical innovation may such markets stimulate strong innovation activity. This line of argument is compatible with empirical findings. Several studies have found an inverted, U-shaped relationship between contestability and innovation activity. As the intensity of competition increases, innovation initially increases. If the intensity of competition increases further, innovation incentives decline again. However, the strength and shape of these relations are subject to continuing debate (e.g., Aghion et al., 2005; Gilbert, 2020; Hashmi, 2013).

3.2. Complementarity and coordination

Recent contributions to research on innovation ecosystems suggest that interdependencies between players and systemic relations are exceedingly relevant in the digital economy (Fransman, 2018; Iansiti & Levien, 2004). Two factors are particularly influential for the course and direction of innovation: complementarities and coordination costs. Complementarities link the innovation activities of each layer, mainly by influencing innovation opportunities and appropriability conditions of players at related layers. A higher (lower) rate of innovation in one layer will have positive (negative) spill-over effects on innovation on players in related layers. Thus, the factors that influence innovation on one layer will, indirectly, also affect innovation on the related layers (and vice versa). For example, more rapid innovation in network technology that increases the variety and quality of network services will expand the innovation opportunities of players operating on related layers. In a similar way, a broader range of applications and services will likely increase innovation opportunities, appropriability, and possibly contestability on the network layer, thus providing additional stimulus for network innovation.[2] This interdependence likely works in both directions so that weak innovation activity on one layer may constrain innovation activity at a related layer.[3]

Coordination costs include transaction costs among players and possibly the costs of the adaptation of technology developed by one player to the requirements of the larger ecosystem. Because coordination costs reduce the expected gains from innovation (e.g., its impacts on profitability or firm value), they link innovation activities at interdependent layers in a negative feedback loop. Other things being equal, higher coordination costs reduce innovation activity, because they increase the cost of innovating, whereas lower coordination costs increase them. Coordination costs are not unique to the digital economy, but they are particularly relevant, given the increased number of interdependent players, the differentiation of the value system, and the need to produce a closely integrated, often synchronous service. They have resulted in numerous market and non-market arrangements that facilitate coordination and reduce these costs. Such arrangements include contracts between businesses, standards and protocols developed by public and private organizations (e.g., 3GPP), Internet exchanges, and digital platform companies, such as Apple and Amazon, which orchestrate entire innovation ecosystems.[4]

Spulber (2019) distinguishes market-making costs from market-transacting costs. Both types of costs matter in 5G markets: the former during the early stages of innovation and the latter in more mature stages. For example, market-making costs will occur in the form of negotiating and contracting efforts for rights of way, network quality of service (QoS), the development of application

[2] There is a counter argument to this logic. Because innovation sometimes is a solution to seemingly insurmountable constraints, there might be scenarios in which constraints beget additional innovation efforts. However, these effects are probably rarer than the negative effects of constraining conditions on the rate and direction of innovation.

[3] An early model of such innovational complementarities was formulated by Bresnahan and Trajtenberg (1995) in their discussion of general-purpose technologies (GPTs).

[4] Another matter that cannot be pursued here due to space constraints are cross-border services, such as autonomous vehicles. Standardization and harmonization work will be important to facilitate such applications.

programming interfaces (APIs), or the negotiation of MVNO agreements. Market transaction costs exist, for example, if ASPs need to negotiate with multiple MNOs to launch their services. Adaptation costs may arise if an application/service needs to be adapted to run on different network protocols, or if ASPs need to meet varying criteria required by different MNOs for partner arrangements.

There are reasons to believe that such coordination costs may be more pervasive in 5G markets, at least during the early phases of development and for certain innovations that require coordination among systems of systems (e.g., vertically integrated value systems in health care and automated vehicles). Private actors will succeed in coordinating their actions if the interaction is a common interest or a pure coordination game. They may not be able to find solutions in mixed interest games, in which one party may be able to gain at the expense of another (Friedman, 1994).[5] Similarly, decentralized actors may not find solutions if the coordination costs are prohibitively high, or some of the benefits have public good character.[6] There is evidence of the emergence of market solutions to address these issues. New intermediaries, such as Optiva and Transatel, help reduce the coordination costs for other specialized players and users. Technical architectures, such as Open Radio Access Networks (O-RAN), also help reduce coordination costs. Where market solutions do not emerge, regulation and public policy may contribute to reduced coordination costs, which improves the ability of firms to internalize innovation benefits. If successful, such measures can help increase the set of projects that promise positive net benefits and hence boost innovation.

3.3. *Regulation and innovation*

Regulatory interventions influence this innovation system directly and indirectly. Some regulations target the decisions of selected players directly (e.g., by requiring that MNOs put together a reference offer for access to network services to MVNOs) with the goal to improve performance of the system. These interventions typically also have indirect and second-round effects on innovation drivers (especially contestability, opportunities, appropriability, and coordination costs) and therefore influence outcomes (the rate and direction of innovation). For example, a mandate on infrastructure providers to offer MVNO access simultaneously increases the innovation opportunities for MVNOs and narrows the innovation opportunities of network operators. The net effect of these contradictory effects is contingent on the strengths of these two effects and the extent of the interdependence between the interrelated players. If relevant, the overall effect resulting from these forces may be non-linear and difficult to anticipate, requiring a different regulatory response, such as ex post regulation, as discussed in more detail below.

The innovation literature has recognized that different types of innovation processes − most importantly modular and architectural innovations − coexist in digital ecosystems (e.g., Baldwin & Clark, 2000; Bauer, 2018; Henderson & Clark, 1990). Modular innovations affect only one element of a system and can be carried out by one player. Improvements of individual modules stimulate additional innovations in related modules and initiate a virtuous cycle of innovation that percolates through the system. These improvements require agreement on an overall architecture and interfaces between modules but do not require explicit coordination among innovators. Modular innovation systems therefore are powerful engines of innovation, as demonstrated by the Internet. However, modularity has limits, and improving a system to a higher performance trajectory may require a restructuring of the system architecture once the opportunities for modular improvements have been exhausted (Yoo, 2016). Such architectural innovations require different types of coordination among the relevant players. For example, it may be necessary to agree on and implement a change in the overall structure and operational procedures of the system.

These innovation types coexist in the 5G system yet thrive under different conditions. Knowledge of these innovation opportunities is distributed and not necessarily internal to MNOs. Consequently, users will also be important drivers of innovation (e.g., von Hippel, 1988, 2005). They will be critical to explore the numerous use cases in industrial, government, and community applications. Many envisioned 5G innovations, for example, those supporting autonomous vehicles or advanced health applications, will likely require architectural efforts in addition to user innovation. They do not necessarily involve traditional MNOs and put high pressure on them to rejuvenate their business model. This innovation environment creates risks that players who have a wider control span over parts of the value system will sabotage more specialized players. Market and regulatory designs will provide important boundary conditions to channel competition in productive directions. They will also influence whether and at what rate these types of innovation will be explored. For example, an open network architecture and standardized connectivity platforms facilitate modular innovations. In contrast, a framework that allows the differentiation of network services, prices, and contractual arrangements will be better aligned with the requirements of architectural innovations. One of the challenges for forward-looking 5G policy, therefore, will be to design markets that support the pursuit of multiple types of innovation.

4. Current and emerging regulatory discussions

Competition policy and regulation affect innovation in regulated markets (Vogelsang, 2017). Regulation constrains and enables horizontal and vertical relations between players in the 5G system. It also delineates allowable transactions from those that potentially raise competitive or other policy concerns. In an interdependent system, regulations that are directed at a specific aspect of these relations (e.g., radio access network sharing, MVNO access) typically have indirect repercussions on related players. In this section, we discuss selected concerns that policymakers are currently discussing or that are emerging among experts and stakeholders (e.g.,

[5] An example of a mixed interest game is the interaction between a vertically integrated MNO and single layer OTT players.

[6] An example of high or even prohibitive transaction costs may be the need to negotiate rights-of-way (ROWs) with numerous municipalities and owners of buildings.

BEREC, 2019; Cave, 2018; FCC, n.d.; GSMA, 2020b; Lemstra, 2018). The discussion focuses on four interrelated concerns: access to essential resources, achieving network coverage, how to safeguard access to network services, and concerns about non-discrimination and neutrality. In each of these areas, regulatory diversity currently seems to be on the rise (see Table 1, which provides a summary snapshot of the situation in selected countries). In section five, will reflect on the pros and cons of such increasing, regulatory differentiation.

4.1. *Access to essential resources*

Bottlenecks are essential resources that cannot be duplicated economically under the prevailing supply and demand conditions. In 5G networks, they may exist because it is uneconomic to roll out multiple access and backhaul networks to remote, sparsely populated, low income, or otherwise disadvantaged areas. Bottlenecks can be an outcome of the scarcity of physical assets (e.g., duct capacity), but they can also result from concerns about aesthetic, environmental, and the potential health impacts of structures such as antenna towers. Examples of inputs that might constitute essential resources include access to civil engineering infrastructure for antenna placement or the routing of cables, access to buildings, backhaul, and possibly access to electromagnetic spectrum. These situations require nuanced analyses and appropriate responses.

Limited space on civil engineering infrastructures is a potential bottleneck that may constrain network deployment to only one or a few operators. Hence, limited access to antenna space may constrain the number of players able to achieve cell densification. To some extent, whether bottlenecks arise is contingent on other policies, such as the laws and regulations that govern access to state and municipal infrastructure and the ability of wireless operators to assert eminent domain. In many countries, regulatory agencies do not have jurisdiction over these matters, even though they may have a voice. To reduce the cost of locally fragmented approaches, some countries, including the United States, have adopted federal regulations that provide a general framework within which local authorities must operate. Appropriate provisions that facilitate infrastructure co-investment, network sharing, and spectrum sharing, can reduce the risk that such bottlenecks may emerge.[7] These latter policies are typically within the remit of regulatory authorities.

Stakeholders have petitioned regulatory agencies in Europe and the United States to facilitate access to fixed and wireless backhaul services (e.g., BEREC, 2017), even though no specific regulations have yet been introduced for 5G. Residential and business 5G services will likely generate a high volume of data that require backhaul capacity from points closer to the edges of the network. Additional data traffic will mitigate concentration and facilitate competition in the market for backhaul services. Given the high capacity of fiber-optic backhaul, there will likely remain areas where backhaul can be provided economically by only one network operator. In these locations, facilities-based MNOs could use their presence in both the access and backhaul market segments to disadvantage competing mobile-only players. However, if the role of players is reversed in other locations, that is, access seekers in location A are access providers in location B and vice versa, self-interest will create incentives for the players to negotiate fairly and in good faith.

A third potential bottleneck arises in buildings, especially in multi-dwelling residential and commercial buildings. Developers may install ducts and provide room for electronic gear. In that case, multiple 5G licensees may be able to obtain access to a building. However, builders might prefer to contract with only one provider, or they might provision in-building, communications antenna systems themselves. In the latter two scenarios, sharing or access provisions may be needed to avoid an undesirable bottleneck. The experience with fiber-optical networks in Portugal, Spain, and France suggests that clear rules for access to buildings complement other policies and can boost rollout. All three countries have adopted legislation that requires the provision of information on building access, standardizes the types of access that must be provided, and establishes symmetric, sharing obligations (Godlovitch & Plückebaum, 2017). Similar frameworks would serve the 5G industry without requiring the imposition of more intrusive access or unbundling obligations.

A fourth area in which bottleneck-like problems might arise is in local access to electromagnetic spectrum. Many envisioned 5G services in smart manufacturing, smart agriculture, and similar applications require access to local spectrum, for example in a port or in an industrial location. A few countries, including the United Kingdom, Sweden, the Netherlands, and the United States, have started to issue highly granular local licenses in addition to national and regional ones (e.g., Matinmikko-Blue et al., 2021). Other countries have strengthened provisions that facilitate secondary spectrum market transactions, such as spectrum-leasing and spectrum-sharing arrangements. Secondary markets need careful design to generate sufficient liquidity (e.g., Gomez et al., 2019; Lehr, 2020). A few countries, including Italy, have introduced use-it-or-lose-it provisions to facilitate local spectrum access. Germany decided to set aside 100 MHz of spectrum for local industrial licenses to be issued on a first-come, first-served basis to industrial and other local users (GSMA, 2020a). Each of these solutions has potential advantages and disadvantages. Only experience will tell whether any model works better than others to support 5G investment and innovation (e.g., Knieps & Bauer, 2021).

Because of the high, technological dynamics of 5G services, traditional forms of price and access regulation to address these types of bottlenecks might lock in inefficient solutions. Thus, it would be desirable to find a different regulatory approach that avoids the complexities and potential pitfalls of applying traditional instruments of ex ante regulation in the presence of positive and negative feedbacks. Reliance on adaptive, agile forms of regulation to neutralize bottlenecks might avoid such disadvantages. These include general, symmetric obligations, such as most-favored nation clauses for access, a duty to negotiate spectrum and infrastructure-sharing arrangements in good faith, and empowering regulatory agencies to mediate where private negotiations fail. Thus, the emphasis of policy would shift from the design of precise, ex ante, regulatory interventions to the design of boundary conditions or a “constitution”

[7] A study of European 4G markets by Abate et al. (2020, p. 51) suggests that network and spectrum sharing have positive impacts on average download speeds in four player markets. However, rivalrous three-players without sharing outperform four-player markets.

Table 1
Diversity of 5G regulation in selected countries.

	Germany	Italy	Netherlands	United Kingdom	United States
Backhaul[1]	Fixed backhaul regulated if significant market power (SMP, Markets 3a, 3b, 4). Mobile backhaul not a separate SMP market	Fixed backhaul regulated if SMP (Markets 3a, 3b, 4). Mobile backhaul is not a separate SMP market	Fixed backhaul regulated if SMP (Markets 3a, 3b, 4). Mobile backhaul is not a separate SMP market	Fixed backhaul regulated, but no open access to ducts and poles to configure backhaul for mobile services	Regulated in very limited circumstances
Access to local spectrum users[2]	Set aside of 100 MHz for campus licenses; secondary market transactions	Operators holding at least 80 MHz in 3.4–3.8 GHz band are obliged to provide access to service providers to foster verticals; use it or lose it provisions	Some spectrum auctioned locally, no specific measures to support industrial 5G networks	Ofcom makes local, time-limited licenses available on a first-come first served basis in three bands (1800 MHz shared, 2300 MHz shared, 3.8–4.2 GHz)	Some licenses (e.g., CBRS) auctioned at county level; secondary market transactions
Coverage obligations in LTE and 5G[3]	2019 auctions include household, road, railway, ports, and underserved area coverage obligations	Coverage goals for population, underserved areas, roads, railroads, airports, ports	98% outdoor coverage of each commune, will be lifted in 2030	No coverage mandates but voluntary coverage commitments by four UK MNOs	Generally, no coverage obligations, except in reverse auctions intended to extend service to unserved areas
MVNO access[4]	MNOs need to negotiate non-discriminatory access conditions; no reference offer	No regulatory mandate to offer MVNO access; no reference offer	No regulatory mandate to offer MVNO access; no reference offer	No regulatory mandate to offer MVNO access; no reference offer	No regulatory mandate to offer MVNO access; no reference offer
Network neutrality	Mobile networks subject to neutrality regulation; reasonable traffic management permitted	Mobile networks subject to neutrality regulation; reasonable traffic management permitted	Mobile networks subject to neutrality regulation; reasonable traffic management permitted	Mobile network neutrality guidelines applied via self-regulatory approach, to be reviewed in 2021 by Ofcom	No mobile network neutrality provisions

Notes: CBRS … Citizen Band Radio Service in the United States (3350 MHz–3700 MHz).
Sources: Research by the authors. [1] BEREC (2017). [2] Sörries and Nett (2019). [3] Cullen (2020). [4] Cullen (2021); in Germany and Italy MVNO access commitments were negotiated as part of merger and antitrust cases.

of 5G markets. This approach is less intrusive and gives players entrepreneurial freedom to experiment with innovative, mutually beneficial solutions while providing non-discrimination safeguards.

4.2. Network coverage obligations

As fundamental, possibly general purpose, technologies 5G communication networks and services enable players on higher levels of the value system to create welfare-enhancing applications and services. However, the timeline of operators (whose decisions to invest in network coverage are driven by benefits they can internalize) and the socially optimal timeline of infrastructure rollout may deviate, especially in sparsely populated and low-income areas. To avoid undesirable spectrum warehousing and foster the development of ubiquitous infrastructures, licenses are often combined with interim milestones and performance targets for network coverage and supported speeds. Failure to meet such requirements typically leads to regulatory actions that range from fines to the reassignment of the spectrum to other users.

Setting such milestones requires a detailed, forward-looking understanding of market developments and a clear vision of how the private and social timeline of investment can be aligned. In many countries, coverage obligations are a substitute for missing universal service policies (e.g., Prado & Bauer, 2021). The widespread framing of the transition to 5G as a global technology race and the uncertainties surrounding its market potential create a high risk that policy will set unreasonable targets. Because of the complementary innovation system formed by 5G network and services, it is difficult to establish in advance which levels of network coverage and performance will further innovation. Goals set too high could threaten the sustainability of infrastructure coverage. In contrast, goals that are set too low could become focal points that inadvertently synchronize network operator decisions. Thus, overly modest aspirations could lock in low levels of infrastructure investment in some areas and impede complementary innovations in services and applications.

Cave and Nicholls (2017) maintain that spectrum auctions that include network coverage and other obligations have become very sophisticated so that these goals can be achieved without significant efficiency losses. It is not clear that this proposition, which is based on observations of earlier generations of wireless markets will also hold for 5G markets with their more complex and interdependent value system. Moreover, the growing diversity of detailed coverage obligations introduced by regulators risks reducing operational efficiencies by segmenting national and international wireless markets. These dynamic tradeoffs are typically not explored when deciding whether and how to implement coverage requirements. Given these conditions of 5G markets, it would be preferable to let entrepreneurs discover the sustainability of market-driven innovations in a trial-and-error process and then adopt corrective measures if necessary. Such interventions can rely on a broad set of tools, such as universal service programs and reverse auctions.

4.3. Access conditions for mobile virtual players

During the past decade, several types of mobile virtual players have emerged. Mobile virtual network operators (MVNOs) have been around since 1999, when Virgin Mobile started is operations. Although their business models vary, MVNOs typically do not hold spectrum licenses and do not own network infrastructure. In past generations of wireless, MVNOs often offered services similar to those of the networks upon which their operations were based (e.g., mobile voice, mobile data). MVNOs added value by differentiating prices, service quality, and other attributes. More recently, mobile virtual network aggregators (MVNAs) and mobile virtual network enablers (MVNEs), such as Optiva and Transatel, have entered the market. (We will collectively refer to all three types as MVNXs.) These newer intermediaries typically offer services that reduce coordination costs among other players, for example, between users and mobile network operators. MVNAs and MVNEs can be considered early instances of enablers whose importance will increase in 5G where they will provide coordination services to facilitate specialized network slices and other customized services.

In the much larger 5G innovation space, many experts foresee that MVNXs will be instrumental in the rapid exploitation of these opportunities, particularly in specialized services. This might include autonomous vehicles, logistics and transport, and health, often envisioned as uniquely configured "network slices" (Frias & Martínez, 2017). Regulated reference offers to grant MVNXs access to MNO resources may be justified if competition in the network layer is not workable or if there is reason to believe that vertically integrated MNOs may thwart the ability of MVNXs to offer services (e.g., by charging high prices for access or by strategically delaying negotiations). The need to engage in bilateral negotiations with multiple MNOs may also create coordination costs that reduce the level of ASP innovation. MVNAs and MVNEs emerged as a market solution to overcome these costs. By aggregating demand from smaller MVNOs and users, they can negotiate with MNOs more effectively than individual users and small MVNOs. For 5G market designers, the question arises whether policies are needed to facilitate the vertical business relations between network operators and higher-level MVNXs.[8]

Past experiences with MVNO regulation can provide some guidance, even though solid empirical studies are rare. Empirical observations corroborate that MNOs have strong incentives to open their networks for MVNOs during the early rollout stages, because they contribute to better utilization of the deployed capacity (Haucap, 2006; Lewin, 2001). This initial congruence between MNO and MVNO interests might revert later in the investment cycle if MNOs generate sufficient capacity utilization with their own customers. However, because of the direct and indirect effects discussed in the previous paragraph, mandates on MNOs to provide access to

[8] In past wireless generations, countries have adopted divergent paths regarding MVNO access. For example, in 2017, eight of thirty-two European countries had established regulated reference offers to grant MVNOs access to mobile networks, and several others had some form of regulatory intervention to facilitate MVNO access. In all other countries, MVNO agreements were negotiated commercially. See Cullen (2017).

MVNXs have ambiguous repercussions on the incentives of MNOs to invest in additional capacity. A study of 3G services by Kim et al. (2011) found that the regulation of MVNO access reduced MNO capital expenditures (capex) by about 17.1%. This suggests that, overall, the negative effects dominated the positive ones. Voluntary commercial agreements did not have a statistically significant negative or positive effect on capex.

Looking forward to 5G, it seems likely that commercially viable agreements will emerge in areas with strong, synergistic relations between MNOs and ASPs. Many new applications in industry, transportation, and health will require sector-specific knowledge and differentiated network support, some with high technical quality of service. The exploration and exploitation of these innovation opportunities will require collaboration among firms with specialized knowledge of the interrelated domains. A standardized access product offered by MNOs may be insufficient to explore these innovation spaces fully, but it might accelerate the rollout of initial applications and services. In general, even though it may initially entail higher transaction costs, a preferable strategy would be to allow negotiations among interested players that are safeguarded by ex post regulation and competition law.

Taken together, these observations suggest that it would be helpful to empower regulatory agencies to develop a market-monitoring framework. Oversight should be combined with a formalized appeals process to break impasses in private negotiations. This approach would protect entrepreneurial flexibility while providing safeguards against discrimination and sabotage of smaller players. Because of the very active standardization efforts by 3GPP and other players, it seems likely that, over time, de facto reference models and offers will emerge for standard and specialized network services. Other options exist to balance the competing and counteracting, dynamic interrelations in ways that support bottom-up market developments. One alternative approach is to generate a most-favored nation (MFN) obligation that would have the effect of reducing transaction costs over time. In this model, contractual conditions offered to one firm would have to be made available on a general basis to other, comparable firms in the 5G system. This allows entrepreneurial flexibility while building safeguards against strategic discrimination into the market design.

4.4. Non-discrimination safeguards

Digital markets have raised concerns about the ability of dominant players to manipulate competition in ways that competition policy would find difficult to detect (Crémer et al., 2019; Morton et al., 2019). There is widespread agreement among economists and engineers that QoS and price differentiation are efficiency-enhancing (e.g., Krämer et al., 2013). However, competition policy and regulation lack tools to analyze the ecosystem effects of competitive behavior or its effects on important social goals, such as end-user access to content of their choice. As a pragmatic safeguard, several countries have adopted network neutrality safeguards. An emerging debate on “full stack neutrality” explores whether neutrality precautions should be extended to devices, services such as search, and to data (e.g., ARCEP, 2018; Easley et al., 2018). Similar concerns have been articulated for 5G networks and services with the intention to reduce coordination and transaction costs with the goal to stimulate innovation (e.g., Lemstra et al., 2017).

Because the provision of differentiated services to specialized user groups is one key feature of 5G, designing non-discrimination safeguards is complicated. Network neutrality rules govern the relations between network operators and players on higher layers in the ICT value system. Although definitions are not completely standardized, "strict" neutrality typically implies that each datagram is treated equally, regardless of its origin, destination, service, and content. "Weak" neutrality permits differentiation of network services and pricing if they are offered to all other players on a non-discriminatory basis and not only to selected players (Bauer & Knieps, 2018). Network neutrality obligations affect the 5G complementary innovation system in two major ways that can affect overall outcomes positively or negatively: first, they influence the ability of players to appropriate rents from innovation; second, they influence the coordination costs of players. In the interconnected 5G ecosystem, these effects are asymmetric, dynamic, and difficult to evaluate ex ante. For example, other things being equal, network neutrality may weaken the innovation incentives for MNOs, but they may strengthen the innovation incentives of complementary ASPs (which in turn may increase the innovation incentives of MNOs).

Given the non-linear interdependencies in the ICT value system, it is not surprising that past research has found a range of possible outcomes (each reflecting different modeling assumptions and types of dynamic equilibria). Several scholars suggest that the imposition of strict net neutrality constraints on network operators will diminish short-term efficiency (e.g., Krämer et al., 2013). Briglauer et al. (2020) found weak negative effects of net neutrality regulation on investment in fiber networks. Depending on the specific model assumptions, some research suggests positive effects of strict neutrality on network investment and innovation, but others find a range of possible outcomes (e.g., Bourreau et al., 2015;Choi and Kim, 2010; Choi et al., 2018; Greenstein et al., 2016; Reggiani & Valletti, 2016). Choi et al. (2015) find that the effects of net neutrality regulation also depend on the business models of content providers.

Conceptual and empirical analyses suggest that the main effect of net neutrality (and by analogy, other forms of neutrality in the 5G system) is not to support or impede innovation. Rather, depending on how neutrality rules are specified, they will likely change the type of innovation activities and the resulting outcomes. For example, strict net neutrality policy will tend to favor modular innovations, possibly at the expense of architectural types of innovation. As envisioned by proponents of weak network neutrality, allowing differentiation while safeguarding non-discrimination and interoperability will likely constitute a more balanced approach that provides room for modular and architectural innovation. However, empirical research has not yet tested these conjectures.

Rather than locking in strict neutrality or other regulatory frameworks that force MNOs and/or other players in the stack to offer one set of conditions to all other players, this reasoning suggests that it would be preferable to allow the differentiation of network services while putting non-discrimination safeguards in place (Bauer & Knieps, 2018; van Schewick, 2010). This would free entrepreneurs to pursue a mix of integrated and modular innovations, which will offer more avenues to explore the innovation space of 5G. Such an approach would allow innovation processes that require network quality differentiation and integration across layers to coexist with those that thrive under conditions of openness and standardization. Strict net neutrality rules cannot reconcile the dual goals of differentiation and non-discrimination, but weak net neutrality, supported by competition policy and possibly ex post regulation, would allow it.

5. Implications for 5G policy

As the discussion thus far shows, the legal and regulatory framework for 5G services will have to be developed with incomplete knowledge. Marcus (2017) warned that claims for or against regulation cannot be refuted easily, because of the uncertainty surrounding many aspects of 5G. This section offers a framework that can be employed when designing a 5G market and regulatory order. Given the interrelated value system of 5G services, three effects are at work. Even though they may vary from case to case, there is a recurring pattern: (1) direct effects, typically affecting interrelated players differently; (2) indirect, second-round effects due to their competitive interactions; and (3) systemic effects (see Fig. 3). In all scenarios, the total (net) effect of regulatory interventions is contingent on the relative magnitude and direction of these three effects.

5.1. Direct, indirect, and systemic effects of regulation

These regularities can be illustrated using the four policy issues discussed in section four (see Table 2). An intervention motivated by facilitating access to essential resources, such as regulated access to backhaul service, has three consequences. First, it has direct effects on the player forced to grant access at regulated conditions (typically the MNO) and on the player, who is seeking access (e.g., a provider without backhaul facilities). These direct effects typically affect players in opposite directions. For example, more stringent regulation of backhaul services reduces the opportunities of the MNO to appropriate returns from innovation in such services, but it reduces the costs and therefore improves the incentives of an access-seeking player to invest and innovate in complementary activities

Second, the regulatory intervention has indirect effects related to the interdependence of players. Indirect effects are typically positive and mutually re-enforcing. This is self-evident if players are in a complementarity relation, for example, it more innovation by one player enhances the innovation opportunities of related players. It also holds if players offer substitutes and are in a competitive relation, because competition increases the pressure players exert on each other to improve performance. Third, regulatory interventions have systemic effects by influencing the coordination costs between players and as feedbacks from sector outcomes to the behavior of players and of regulators. Regulations that reduce coordination costs will typically stimulate innovation because they reduce the cost of innovation. Feedback effects from outcomes to player behavior can be positive or negative.

Similar effects can be identified for other types of regulations. Coverage obligations have direct effects that may improve or impede the performance of infrastructure providers. On the other hand, they typically have a positive effect on complementary players, because improved coverage increases their innovation opportunities. However, this effect can be reduced of overcompensated if the direct effect on infrastructure providers is strongly negative. An intervention such as mandated, regulated MVNX access, typically affects MNOs negatively and MVNXs positively. Finally, non-discrimination regulations have similar direct effects on players at different layers of the ecosystem. For example, strict net neutrality rules will affect network operators negatively while enhancing the opportunities of players at related layers. In all these scenarios, direct, indirect, and systemic effects co-exist. The overall effect of an intervention depends on the direction and magnitude of the component effects.

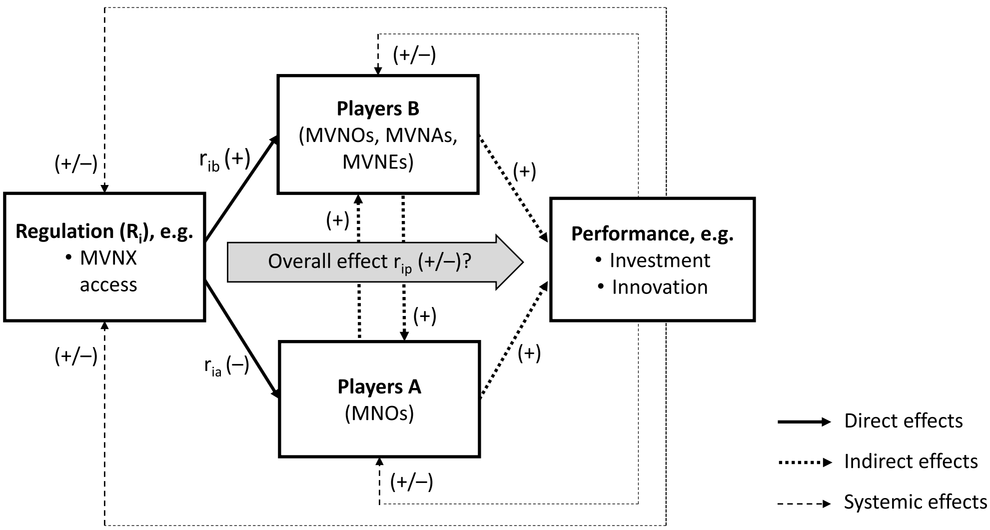

Fig. 3. An illustration of direct, indirect, and systemic effects of regulation. In a dynamic, interrelated system, a regulatory intervention, such as mandated MVNX access, has direct effects (r_{ib}, r_{ia}, solid lines), indirect effects (thick dotted lines), and higher round, systemic effects (thin dotted lines). Plus (+) and minus (−) signs indicate the direction of the effects. For example, more stringent MVNX regulation (+) will increase incentives for MVNXs (+) but decrease incentives for MNOs (−). The overall effect of regulation on performance will depend on the relative size of these component effects and could be positive, negative, or negligible.

Table 2
Direct, indirect, and systemic effects of regulatory intervention (simplified).

Regulatory measure	Direct effects	Indirect effects	Systemic effects
Essential resources, ex ample backhaul regulation	Constrains opportunities of infrastructure providers to extract profits and hence reduces innovation incentives; reduces the cost of innovation for local and complementary players and hence increases their innovation incentives	Innovation activity by local and complementary players provides additional incentives for MNOs to invest and innovate; reduced investment and innovation activity by MNOs may constrain local and complementary players	Successful local and complementary innovation may create a virtuous cycle with backhaul and other infrastructure investment; however, failure to innovate may introduce a negative feedback process
Coverage obligations	Shape deployment strategies of MNOs typically reducing profit opportunities; increase innovation opportunities of complementors; (possibly reduce auction revenues)	Coverage goals increase opportunities for complementary innovation; rollout mandates may create mismatch between market needs and network availability hence reduce complementary innovation	Additional complementary innovation may create a virtuous cycle with infrastructure investment; potential mismatch between market needs may weaken or erase these synergies
Regulated MVNX access	Constrain opportunities of players to negotiate contracts, reducing the ability of MNOs to extract profits and hence reduce innovation incentives; reduce the costs of innovation for MVNXs and hence increase their innovation incentives	Increased MVNX innovation may provide additional incentives for network investment and innovation; regulated MVNX offers may constrain the negotiation of more efficient agreements and stifle innovation by MVNXs and infrastructure providers	Reduced transaction costs and coordination costs may provide an additional stimulus to the players in the complementary innovation system; regulated access may discourage the entry of new intermediaries that could coordinate more efficiently
Non-discrimination safeguards	Strict non-discrimination safeguards will reduce innovation incentives of affected players; will increase innovation opportunities of complementors; weak non-discrimination safeguards will put fewer constraints on innovation, improve QoS for complementors, but possibly increase the cost of innovation	Additional innovation by higher-level players may stimulate additional infrastructure investment and innovation; non-discrimination requirements may stifle innovation experiments and slow infrastructure investment and innovation	Additional innovation may lead to overall faster rate of innovation and growth of the digital ecosystem; strict non-discrimination may stifle differentiation and the emergence of heterogeneous services and solutions

Source: Author construct.

These direct, indirect, and systemic effects typically work in both directions in the interdependent value system, even though they may not be symmetric. For example, other things being equal, deregulation of backhaul will increase the opportunities for rent appropriation by MNOs but may reduce the innovation incentives of access seekers. Fewer complementary services will slow innovation in the related layers, and lower coordination costs will increase innovative activities, other things being equal. Matters are further complicated by the potential divergence of short-term and long-term effects. For example, in the short run, the availability of a regulated, MVNO reference offer may benefit players needing wholesale access, because it reduces the transaction costs of such agreements. It may be challenging to define the (virtual) elements and bundles of elements that should be offered on a regulated basis. A bigger concern, however, is that such short-term benefits may turn into longer-term liabilities. Reference offers may become focal points around which market players organize. This may deter further innovative differentiation and the development of contracts and bundles of functions that better support the increasingly heterogeneous needs of MVNOs.

5.2. Lessons for market design and regulation

These considerations offer two lessons for 5G market design and regulation. First, they may require a modification of prevailing practices. In addition to assessing the rationale for a policy intervention, regulators and policy analysist should routinely gauge the potential strengths of direct, indirect, and systemic feedback effects. If the indirect and systemic effects are negligible or small, they can likely be ignored:. Existing approaches are capable of yielding valid, abstract models of 5G challenges. Moreover, the prevailing practices of regulation can be adapted and are capable of addressing the policy issues. However, if these feedbacks are non-negligible, good regulatory design will have to assess them explicitly and incorporate them into market and regulatory design. Few models and robust practical tools are currently available to make these assessments with confidence. Many of the challenges could be addressed with computational tools, such as dynamic simulations and agent-based modeling. Quantitative and qualitative scenarios, long a tool of technology assessment, can be modified to assist in the development of regulatory policy. These approaches are already informing policies in some areas, including infrastructure planning (e.g., Oughton & Frias, 2018) and spectrum policy (e.g., Milgrom, 2017).

Second, 5G policy may benefit from a reconceptualization of how it interacts with the value system of players. It would require altering the role of policy and regulation as a set of rules that define constitution—the "order"—of 5G markets. Within these boundaries entrepreneurs and market forces can flourish. Given the many complementarities between innovation at the network level and players at higher levels, there are strong endogenous mechanisms to align the interests of the players. For example, unless MNOs are myopic or overestimate their capabilities to develop vertical market slices themselves, they will negotiate mutually beneficial arrangements. Premature, ex-ante regulation of these conditions will unduly reduce the space of potential innovation opportunities and the innovation rate. Absent such an experimental approach, many innovations may remain unexplored and unexploited. This is not to assert that all will work out just fine in a laissez faire model. Rather, in addition to offering guardrails, policy and regulation may need to be invoked if the market does not develop as anticipated.

This requires an approach in which market design and adaptive, agile regulation complement each other. Market design establishes the broad rules for players, which allow differentiation and heterogeneity while providing safeguards against discriminatory strategies. An additional important design feature is to encourage institutional diversity. This can be achieved, for example, by allowing different types of players to enter the market and by encouraging local entrepreneurial and policy experiments. For regulation to respond to outcomes in an adaptive way, continuous market monitoring is necessary. This requires an appropriate framework for collecting and curating data about market developments. Although this requires resources, it is a precondition for securing the efficient working of increasingly dynamic and complex, high technology markets. Moreover, regulation must be enabled to respond quickly, if needed. The existing framework of regulatory forbearance offers a rudimentary example of ex post regulation and an example of how this could be achieved. This approach to 5G markets will create a policy learning environment in which boundary conditions and regulation can evolve and improve organically in a framework of overall regulatory stability.

6. Conclusion

In the dynamic environment of 5G services, it will be important to consider the direct, indirect, and systemic effects of policy and regulation. The overall effects of these often counteracting, positive and negative forces on 5G investment and innovation are difficult to assess ex ante. This paper provides a detailed analysis of the potential effects of selected, regulatory interventions that are currently in place or considered. In contrast to earlier research, the discussion in this paper relies on an approach inspired by innovation economics that considers the strong complementarities between networks, applications, and services explicitly. Innovation is conceptualized as an experimental exploration of a space of technological and economic opportunities that is only partially known. Players across the entire value system engage in activities to discover and co-create new applications and services. Non-myopic network operators and players at higher layers of the value system will recognize these complementarities and embed them in their business decisions, but myopic players may manipulate competition in undesirable ways. Regulatory obligations and interventions influence these decisions and hence affect the rate and direction of innovation and investment of individual firms and the sector.

This paper illustrates that traditional, regulatory approaches that focus on the direct effects of regulation on the regulated entities may result in a 5G market design that does not support its full innovative potential. Rather, it will be necessary to adopt a broader perspective that assesses, in a first step, whether indirect and systemic effects are relevant. If they cannot be ignored, policy will have to respond by adopting appropriate analytical tools, such as dynamic models, general rather than partial equilibrium lenses and computational methods. Moreover, higher level rules, referred to as the order or constitution of 5G markets, will have to be designed to provide guardrails for the players in the 5G market. This would be a more radical departure from current practices but would constitute a superior option that is better aligned with the new technological and economic conditions of 5G. These guardrails should allow entrepreneurial flexibility while providing safeguards against unwarranted discrimination. The diversity of approaches to 5G regulatory market design across Europe and the United States can be seen as a real-world laboratory to explore workable and non-workable approaches. As more empirical observations become available, it will be important to assess the outcomes of these experiments and learn from successes and failures.

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References

Abate, S., Castells, P., Bahia, K., & Sivakumaran, M. (2020). *Mobile market structure and performance in Europe: Lessons from the 4G era*. London: GSMA.

Aghion, P., Bloom, N., Blundell, R., Griffith, R., & Howitt, P. (2005). Competition and innovation: An inverted-U relationship. *Quarterly Journal of Economics, 120*(2), 701–728.

Antonelli, C. (Ed.). (2011). *Handbook on the economic complexity of technological change*. Cheltenham, UK; Northampton, MA: Edward Elgar.

Antonelli, C., & Patrucco, P. P. (2016). Organizational innovations, ICTs and knowledge governance: The case of platforms. In J. M. Bauer, & M. Latzer (Eds.), *Handbook on the economics of the Internet* (pp. 323–343). Cheltenham, UK; Northampton, MA: Edward Elgar.

ARCEP. (2018). Smartphones, tablets, voice assistants. *Devices, the weak link in achieving an open Internet*. Paris: Autorité de Régulation des Communications Électroniques et des Postes (ARCEP) Accessed on https://www.arcep.fr/uploads/tx_gspublication/rapport-terminaux-fev2018-ENG.pdf. (Accessed 31 July 2021).

Arrow, K. J. (1962). Economic welfare and the allocation of resources for inventions. In R. R. Nelson (Ed.), *The rate and direction of inventive activity* (pp. 609–625). Princeton, N.J.: Princeton University Press.

Baldwin, C. Y., & Clark, K. B. (2000). Design rules. In *The power of modularity* (Vol. 1). Cambridge, MA: MIT Press.

Bauer, J. M. (2010). Regulation, public policy, and investment in communications infrastructure. *Telecommunications Policy, 34*(1–2), 65–79.

Bauer, J. M. (2018). Regulation and digital innovation. In G. Knieps, & V. Stocker (Eds.), *The future of the Internet–innovation, integration and sustainability* (pp. 58–88). Baden-Baden, Germany: Nomos.

Bauer, J. M., & Knieps, G. (2018). Complementary innovation and network neutrality. *Telecommunications Policy, 42*(2), 172–183.

Beard, T. R., Kaserman, D. L., & Mayo, J. W. (2001). Regulation, vertical integration and sabotage. *The Journal of Industrial Economics, 49*(3), 319–333.

BEREC. (2017). BEREC Report on the convergence of fixed and mobile networks. *BoR (17) 187. Riga, Latvia: Body of European regulators for electronic communications*.

BEREC. (2019). Report on the impact of 5G on regulation and the role of regulation in enabling the 5G ecosystem. *BoR (19) 245. Riga, Latvia: Body of European regulators for electronic communications*.

Bourreau, M., Kourandi, F., & Valletti, T. (2015). Net neutrality with competing Internet platforms. *The Journal of Industrial Economics, 63*(1), 30–73.

Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies: 'Engines of growth'? *Journal of Econometrics, 65*(1), 83–108.

Briglauer, W., Camarda, E. M., & Vogelsang, I. (2019). Path dependencies versus efficiencies in regulation: Evidence from "old" and "new" broadband markets in the EU. Available online 21 May 2019. Telecommunications Policy https://doi-org.proxy2.cl.msu.edu/10.1016/j.telpol.2019.05.001.

Briglauer, W., Cambini, C., Gugler, K., & Stocker, V. (2020). *Net neutrality and high-speed broadband networks: Evidence from OECD countries*. Unpublished manuscript. 31 December 2020. Available at: https://lnkd.in/dafieAy.
Brynjolfsson, E. (2011). ICT, innovation and the e-economy. EIB papers, ISSN 0257-7755, European investment bank (EIB). *Luxembourg, 19*(2), 60–76. Available at: https://www.econstor.eu/bitstream/10419/54668/1/682754064.pdf.
Cave, M. (2018). How disruptive is 5G? *Telecommunications Policy, 42*(8), 653–658. https://doi.org/10.1016/j.telpol.2018.05.005
Cave, M., & Nicholls, R. (2017). The use of spectrum auctions to attain multiple objectives: Policy implications. *Telecommunications Policy, 41*(5–6), 367–378.
Chaccour, C., Soorki, M. N., Saad, W., Bennis, M., Popovski, P., & Debbah, M. (2021). *Seven defining features of terahertz (THz) wireless systems: A fellowship of communication and sensing*, Article 07668v1. arXiv:2102.
Choi, J. P., Jeon, D.-S., & Kim, B.-C. (2015). Net neutrality, business models, and Internet interconnection. *American Economic Journal: Microeconomics, 7*(3), 104–141.
Choi, J. P., Jeon, D.-S., & Kim, B.-C. (2018). Net neutrality, network capacity, and Innovation at the edges. *The Journal of Industrial Economics, 66*(1), 172–204.
Choi, J. P., & Kim, B.-C. (2010). Net neutrality and investment incentives. *The RAND Journal of Economics, 41*(3), 446–471.
Crémer, J., de Montjoye, Y.-A., & Schweitzer, H. (2019). *Competition policy for the digital era*. European Commission, Brussels: Prepared for the Directorate-General for Competition.
Cullen. (2017). *Regulatory basis for MVNOs*. Brussels: Cullen International.
Cullen. (2020). *Coverage requirements. By dieter kronegger*. Brussels: Cullen International.
Cullen. (2021). *Regulatory basis for MVNOs. By celine senay*. Brussels: Cullen International.
Devlic, A., Hamidian, A., Liang, D., Eriksson, M., Consoli, A., & Lundstedt, J. (2017). NESMO: Network slicing management and orchestration framework. In *IEEE International Conference on Communications Workshops (ICC Workshops)* (pp. 1202–1208). https://doi.org/10.1109/ICCW.2017.7962822
Easley, R. F., Hong, G., & Krämer, J. (2018). From net neutrality to data neutrality: A techno-economic framework and research agenda. *Information Systems Research, 29*(2), 253–272.
Farrell, J., & Weiser, P. J. (2003). Modularity, vertical integration, and open access policies: Towards a convergence of antitrust and regulation in the Internet age. *Harvard Journal of Law and Technology, 17*(1), 85–134.
FCC. (n.d.). FCC 5G FAST Plan. Available at: https://www.fcc.gov/5G. Accessed 23 August 2019.
Finger, M., Groenewegen, J., & Künneke, R. (2005). The quest for coherence between institutions and technologies in infrastructures. *Journal of Network Industries, 6*(4), 227–259. https://doi.org/10.1177/178359170500600402
Fransman, M. (2018). *Innovation ecosystems: Increasing competitiveness*. Cambridge, UK: Cambridge University Press.
Frias, Z., & Martínez, J. (2017). 5G networks: Will technology and policy collide? *Telecommunications policy*. https://doi.org/10.1016/j.telpol.2017.06.003.
Friedman, J. W. (1994). *Problems of coordination in economic activity*. Boston, MA: Kluwer Academic Publishers.
Gilbert, R. J. (2020). *Innovation matters: Competition policy for the high-technology economy*. Cambridge, MA: MIT Press.
Godlovitch, I., & Plückebaum, T. (2017). *Access to ducts, poles and in-building wiring: Practicalities and implications. Bad Honnef*. Germany: WIK Consult.
Gomez, M., Weiss, M., & Krishnamurthy, P. (2019). Improving liquidity in secondary spectrum markets: Virtualizing spectrum for fungibility. *IEEE Transactions on Cognitive Communications and Networking, 5*(2), 252–266.
Greenstein, S., Peitz, M., & Valletti, T. (2016). Net neutrality: A fast lane to understanding the trade-offs. *The Journal of Economic Perspectives, 30*(2), 127–150.
GSMA. (2020a). *5G IoT private & dedicated networks for Industry 4.0*. London: GSMA.
GSMA. (2020b). *Realising 5G's full potential: Setting policies for success*. London: GSMA.
Hashmi, A. R. (2013). Competition and innovation: The inverted-U relationship revisited. *The Review of Economics and Statistics, 95*(5), 1653–1668. https://doi.org/10.1162/REST_a_00364
Haucap, J. (2006). *Competition policy and MVNOs*. Mainz: Paper presented at the ITU/BNetzA Joint Workshop, 22 June 2006.
Henderson, R., & Clark, K. B. (1990). Architectural innovation: Th reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly, 35*(1), 9–30.
von Hippel, E. (1988). *The sources of innovation*. New York: Oxford University Press.
von Hippel, E. (2005). *Democratizing innovation*. Cambridge, MA: MIT Press.
Iansiti, M., & Levien, R. (2004). Strategy as ecology. *Harvard Business Review, 82*(3), 68–78.
ITU. (2016). *Emerging trends in 5G/IMT2020*. Geneva, Switzerland: International Telecommunications Union.
Janeway, W. H. (2018). *Doing capitalism in the innovation economy*. Cambridge, UK: Cambridge University Press.
Kahn, A. E. (1970/71). *The economics of regulation: Principles and institutions*. New York: Wiley.
Kim, J., Kim, Y., Gaston, N., Lestage, R., Kim, Y., & Flacher, D. (2011). Access regulation and infrastructure investment in the mobile telecommunications industry. *Telecommunications Policy, 35*(11), 907–919.
Knieps, G., & Bauer, J. M. (2021). *Internet of Things and the economics of 5G-based local industrial networks*. Unpublished manuscript. Michigan: Freiburg im Breisgau, Germany; East Lansing.
Krämer, J., Wiewiorra, L., & Weinhardt, C. (2013). Net neutrality: A progress report. *Telecommunications Policy, 37*(9), 794–813. https://doi.org/10.1016/j.telpol.2012.08.005
Laffont, J.-J., & Tirole, J. (2000). *Competition in telecommunications*. Cambridge, MA: MIT Press.
Lehr, W. (2020). Economics of spectrum sharing, valuation, and secondary markets. In C. B. Papadias, T. Ratnarajah, & D. T. M. Slock (Eds.), *Spectrum sharing: The next frontier in wireless networks* (pp. 361–388). Hoboken, NJ: John Wiley & Sons.
Lehr, W., Queder, F., & Haucap, J. (2021). 5G: A new future for mobile network operators, or not? *Telecommunications Policy, 45*(3), 102086.
Lemstra, W. (2018). Leadership with 5G in Europe: Two contrasting images of the future, with policy and regulatory implications. *Telecommunications Policy, 42*(8), 587–611.
Lemstra, W., Cave, M., & Bourreau, M. (2017). *Towards the successful deployment of 5G in Europe: What are the necessary policy and regulatory conditions?* Brussels: CERRE.
Lewin, D. (2001). *MVNOs - competition policy and market development*. Paper presented at the ITU workshop on 3G mobile. *20*, 2001. September.
Marcus, J. S. (2017). *High expectations for 5G confront practical realities*. Retrieved from http://bruegel.org/2017/03/high-expectations-for-5g-confront-practical-realities/.
Matinmikko-Blue, M., Yrjölä, S., Ahokangas, P., & Hämmäinen, H. (2021). Analysis of 5G spectrum awarding decisions: How do different countries consider emerging local 5G networks?. In *Paper presented at the 2021 ITS biennial conference*. Gothenburg, Sweden.
Milgrom, P. (2017). *Discovering prices: Auction design in markets with complex constraints*. New York: Columbia University Press.
Morton, F. S., Bouvier, P., Ezrachi, A., Jullien, B., Katz, R., Kimmelman, G., … Morgenstern, J. (2019). *Report. Committee for the study of digital platforms. Market structure and antitrust subcommittee*. Chicago, IL: University of Chicago, Stigler Center for the Study of Economy and State.
Nelson, R. R., & Winter, S. G. (1982). *An evolutionary theory of economic change*. Cambridge, MA: Belknap Press of Harvard University Press.
OECD. (2018). *Oslo Manual 2018. The measurement of scientific, technological and innovation activities*. Paris: Organisation for Economic Co-operation and Development.
Oughton, E. J., & Frias, Z. (2018). The cost, coverage and rollout implications of 5G infrastructure in Britain. *Telecommunications Policy, 42*(8), 636–652.
Prado, T. S., & Bauer, J. M. (2021). Improving broadband policy design using market data: A general framework and an application to Brazil. *Telecommunications Policy, 45*(4), 102111.
Reggiani, C., & Valletti, T. (2016). Net neutrality and innovation at the core and at the edge. *International Journal of Industrial Organization, 45*, 16–27.
Saad, W., Bennis, M., & Chen, M. (2019). A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Network, 34*(3), 134–142.
van Schewick, B. (2010). *Network neutrality: What a non-discrimination rule should look like*. Stanford Public Law Working Paper No. 1684677, Stanford Law and Economics Olin Working Paper No. 402, available at: SSRN: https://ssrn.com/abstract=1684677.
Schumpeter, J. A. (1942). *Capitalism, socialism, and democracy*. New York: Harper.

Shapiro, C. (2012). Competition and innovation: Did Arrow hit the bull's eye? In J. Lerner, & S. Stern (Eds.), *The rate and direction of inventive activity reconsidered* (pp. 361–404). Chicago, IL: University of Chicago Press.

Sörries, B., & Nett, L. (2019). *Frequenzmanagement: Lokale/regionale Anwendungsfälle bei 5G für bundesweite Mobilfunknetzbetreiber sowie für regionale und lokale Betreiber unter besonderer Betrachtung der europäischen Länder sowie von China, Südkorea und den Vereinigten Staaten von Amerika* (p. 452). WIK Diskussionsbeitrag Nr.

Spulber, D. F. (2019). The economics of markets and platforms. *Journal of Economics and Management Strategy, 28*, 159–172.

Stoneman, P. (2010). *Soft innovation: Economics, product aesthetics, and the creative industries*. Oxford, UK: Oxford University Press.

Tirole, J. (1997). *The theory of industrial organization*. Cambridge, MA: MIT Press.

Viscusi, W. K., Harrington, J. E., Jr., & Sappington, D. E. M. (2018). *Economics of regulation and antitrust*. Cambridge, MA: MIT Press.

Vogelsang, I. (2017). The role of competition and regulation in stimulating innovation-telecommunications. *Telecommunications Policy, 41*(9), 802–812. https://doi.org/10.1016/j.telpol.2016.11.009

Walia, J. S., Häimmäinen, H., & Matinmikko, M. (2017). 5G micro-operators for the future campus: A techno-economic study. In *Paper presented at the 2017 Internet of things business models, users, and networks conference*. Copenhagen, Denmark.

Yoo, C. S. (2016). *Modularity theory and Internet regulation* (Vol. 2016). University of Illinois Law Review (1).