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5G and Mobile Broadband Disruption

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5G and Mobile Broadband Disruption

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Abstract

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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.² As the first large-scale deployments of 5G commercial

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² 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

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.³

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

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).

³ 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 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>).

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 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,⁴ 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

⁴ 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.

facilitating the replacement of specialized networking hardware with more generic IP hardware on the network side.⁵

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.⁶

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 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

⁵ 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.

⁶ 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.

broadband services that compete with MNOs.⁷ 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 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.

⁷ 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>).

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 it 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).⁸ The economic factors that have driven this industry consolidation have been several, including (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.

⁸ 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.

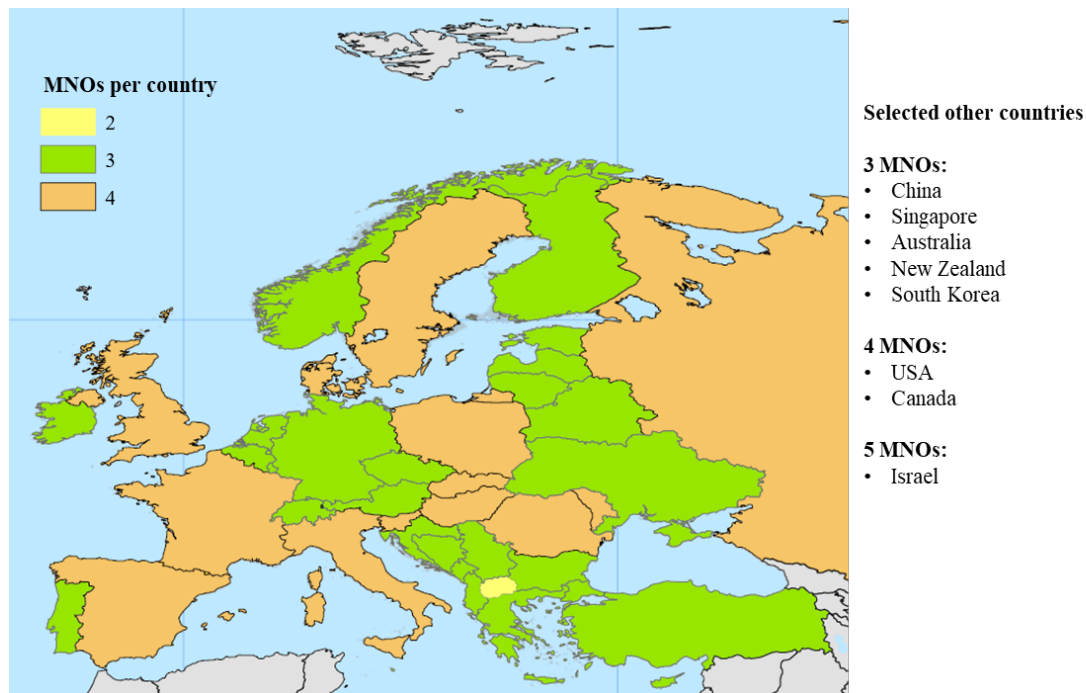


Figure 1: Mobile network operator per country. Source: own research based on (European Commission, 2018)

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.

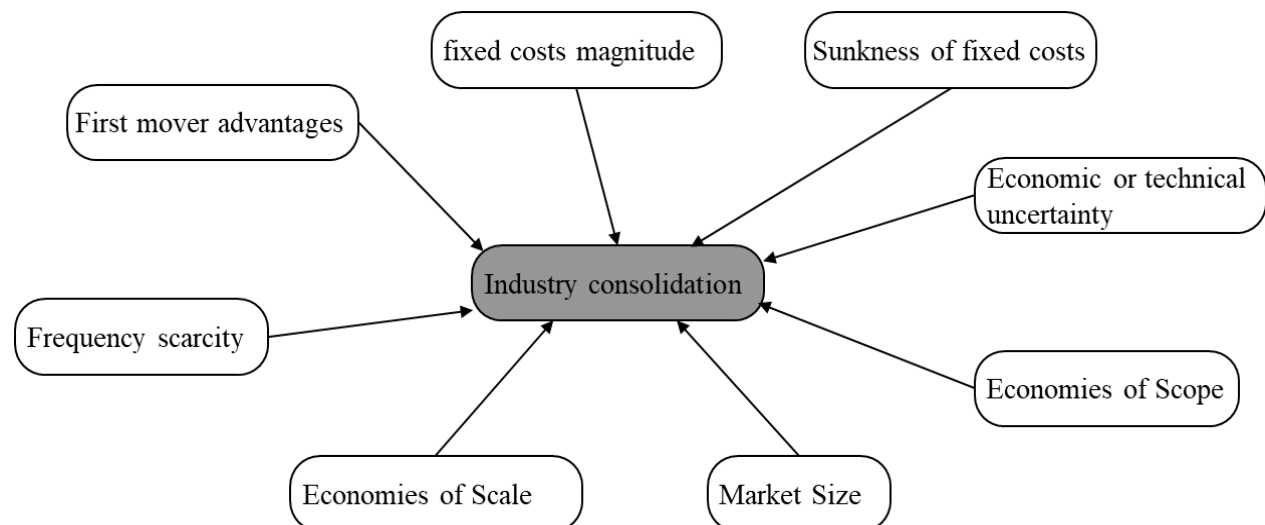


Figure 2: Economic forces behind the MNO consolidation

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.⁹

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 rapidly and is

⁹ Vodafone KDG (Vodafone acquired cable operator, Kabel Deutschland 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/>).

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 and shared 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-savvy 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.¹⁰ 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-

¹⁰ See Anker, 2017.

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 led to the creation in the U.S. of ultimately 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 transferability 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.¹¹

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

¹¹ Some of which were already introduced as part of LTE advanced 3GPP-releases, but will be herein referred to as 5G functionalities.

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/km ²
User plane latency	1 ms
Mobility	up to 500 km/h
Connection density	1,000,000 devices/km ²
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 capabilities 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) association¹² for the smart manufacturing vertical; the "5G Automotive Association" (5GAA)¹³ for the smart-mobility vertical; "PMSE-xG"¹⁴ for Program Making and Special Events; "European broadcasting union" (EBU)¹⁵ for broadcast entertainment; and the "Public Safety Communication Europe" (PSCE)¹⁶ 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.¹⁷

¹² See <https://www.5g-acia.org/about-5g-acia/>.

¹³ See <https://5gaa.org/>.

¹⁴ See <http://www.pmse-xg.de/>.

¹⁵ See <https://tech.ebu.ch/docs/techreports/tr044.pdf>.

¹⁶ See <https://5gaa.org/>.

¹⁷ Although some of the features 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

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 (V2V),¹⁸ 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 calls¹⁹ 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

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.

¹⁸ The same feature is also used for vehicle to infrastructure (e.g. roadside units) communication. We omit this part for the purpose of simplification.

¹⁹ Group calls resemble an exception to this rule

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 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**²⁰ -- 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).
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

²⁰ 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.

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.

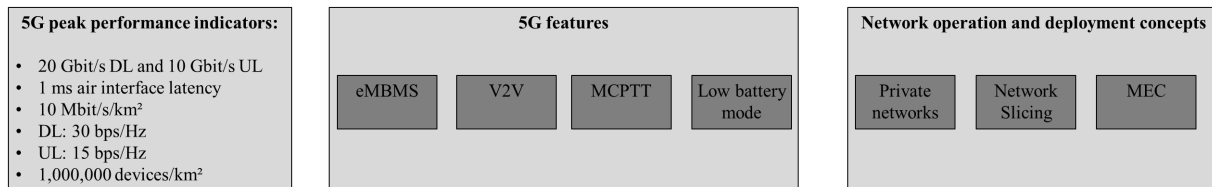


Figure 3: 5G technology building blocks

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.²¹ Several examples that highlight the diversity of these markets include:

1. 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).
2. Smart-Manufacturing, Smart-Cities applications will facilitate integrating machine-to-machine and Internet-of-things (IoT) devices for automated control of manufacturing,

²¹ E.g. GSM-R networks in railroad systems, TETRA (POL) networks for PPDR or DVB-T/ ACTS networks.

infrastructure systems (e.g., heating, cooling, lights), and other activities (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.

3. 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.
4. Public Protection/Disaster Recover (PPDR) network services are the mission-critical communication services used by first-responders and public safety providers such as the 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 MC-PPT 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; Höyhty et al., 2018; LS Telcom, 2019; Peltola & Hämmäinen, 2018).
5. 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)²². 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

²² E.g. The German DVB-T operator Media Broadcast reaches 76% household coverage in Germany with only 63 tower sites (Media Broadcast, 2019).

base stations have been built out, will allow MNOs to address this market opportunity via network slicing.

6. 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.

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.²³ 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).²⁴

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-frequencies 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.

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

²³ See Lehr & Oliver, 2014.

²⁴ 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).

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 processor or aggregate diverse resources (e.g., multiple frequency bands or the processing power of multiple processors) 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 their 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).²⁵

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

²⁵ 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 to 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.

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 MNO's 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 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 3 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 4, 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). Although 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 consolidation 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.²⁶

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

²⁶ 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).

may choose to consolidate still further, merging to reduce the number 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 asymmetric channel requirements,²⁷ 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.²⁸

²⁷ 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 might 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.

²⁸ 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).

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 heterogeneous 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 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 Dynamics

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).²⁹

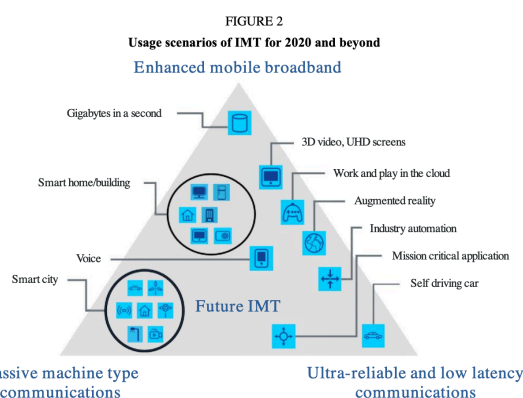


Figure 4: Usage Scenarios for IMT 2020

²⁹ This is Figure 2, 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 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.

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.

Table 2: MNO Market Opportunities

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, Ericsson
		Specialised service provider	LS Telcom, Dortmund, Siemens,
		Cloud service provider	Microsoft

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.

Table 3 : Characterizing the Models

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

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.³⁰ 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 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 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).³¹ 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

³⁰ 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.

³¹ In certain markets there are additional facilities-based regional 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.

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.³²

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 connectivity (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).

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 resources. 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.

³² 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.

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 Poland³³ or CBN in China, the smart metering domain, e.g. Sensus³⁴ in the US or 450 Connect in Germany³⁵ 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).

³³ <https://www.emitel.pl/en/about-us/>

³⁴ providing connectivity services to utilities <http://www.aqua-metric.com/assets/ami-120-r-3.pdf>

³⁵ providing connectivity services to utilities <https://www.450connect.de/ueber-uns>

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.³⁶ 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).

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

³⁶ 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.

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 Bosch³⁷), others have partnered with equipment vendors (Lufthansa Nokia³⁸) 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.³⁹

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.

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.

³⁷ <https://www.bosch-presse.de/pressportal/de/en/bosch-applies-for-local-5g-licenses-203328.html>

³⁸ <https://pf.content.nokia.com/t004f2-private-wireless-airports/press-release-nokia-deploys-5G-private-wireless-network-lufthansa-technik>

³⁹ See Oughton *et al.* (2020).

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.⁴⁰

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.

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 access 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

⁴⁰ See Lehr (2019).

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 build 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 architectures, 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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