FUTURE OF BROADBAND COMPETITION IN A 5G WORLD

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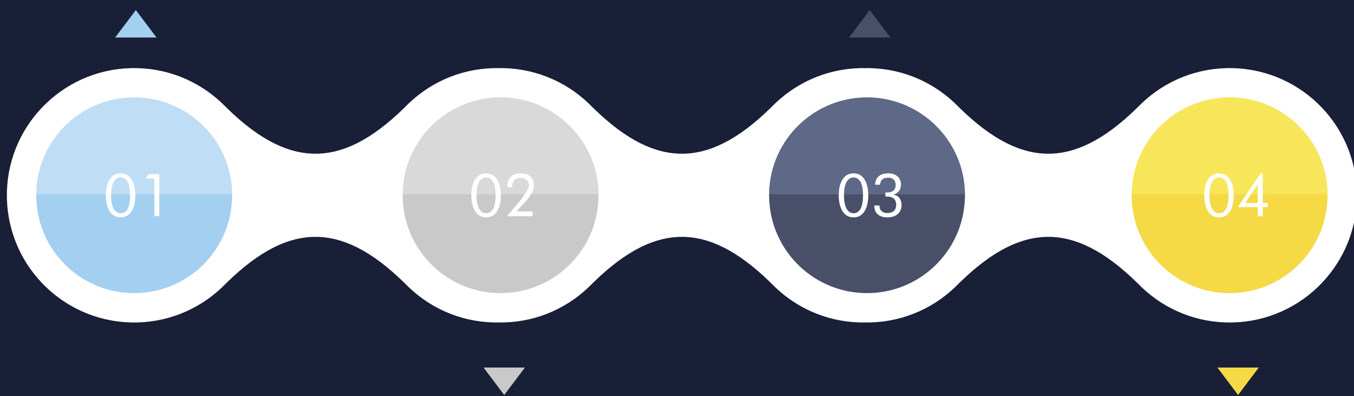
1. Executive Summary

This paper[1] explains how Mobile Network Operators ("MNOs") are transforming their networks to meet the 5G challenge and the implications this transformation has for the structure of the cellular industry and broadband competition more generally. It explores the requirements to support the wireless elements of 5G, which represents an order-of-magnitude improvement over 4G LTE. Meeting those performance targets will drive a number of important complementary changes in the design and operation of mobile networks that will have important economic implications. Among the many changes both large and small, the transition to 5G is driving MNOs to embrace: (a) agile management of diverse spectrum assets; (b) small cells; and (c) softwarization and virtualization.

Based on the scale requirements necessary to build 5G networks, I conclude the transactions that have occurred among facilities-based Commercial Mobile Radio Service ("CMRS") operators over the past decade are not only salutary but also likely to continue for the economic health of broadband and 5G—and the resulting consumer benefits—at least in the near term. I explain how the 5G Future will be a converged market in which promoting the survival of fewer but stronger MNOs will promote the healthy evolution toward 5G, which will contribute to promoting innovation and sustaining energized competition across the broadband ecosystem. Industry restructuring may happen in multiple ways, but the best way forward in terms of promoting prospects for robust competition is for there to be at least three national-scale facilities-based providers of comparable size.

These conclusions offer lessons for how regulators should assess the proposed merger between T-Mobile and Sprint to form a stronger MNO ("New T-Mobile").[2] The merger should be regarded as pro-competitive for the larger broadband ecosystem because it will contribute to accelerating the race to 5G and its accompanying economic transitions that will materialize sooner and improve consumer welfare. Accelerating the race to 5G, in turn, will help intensify competition within the larger ecosystem from four important directions.



01: Economies of scale for nationwide wireless operators are increasing with advances in network technology and architecture, which makes sustaining the pace of investment required to remain competitive with Verizon and AT&T more challenging for smaller operators.

02: The move toward 5G will further drive the convergence of fixed and mobile broadband, which will increase the potential for intermodal competition between fixed and mobile providers and among wireless networking technologies (*e.g.*, Wi-Fi and 4G-LTE-derived networks). The long-awaited convergence of fixed and mobile networking and the enhanced capabilities and localization of advanced wireless networking are creating new avenues for competition that increase the competitive pressure on the existing MNOs.

03: The transition to smaller cells and more dynamic/flexible and heterogeneous local networking requirements, coupled with advances in networking equipment and software solutions, will open opportunities for new types of local facilities-based wireless infrastructure providers. These opportunities will include venue networks and neutral host deployments.

04: The increased capabilities to virtualize every type of information communication technology ("ICT") resource (including network resources) and grow demand for customized networking services will lead to more vigorous Mobile Virtual Network Operator ("MVNO") competition.

Taken together, these factors—increasing scale economies and the efficiency of hybrid fixed-mobile deployments—add more pressure on MNOs to realize more efficiencies in network architecture and technology. Unless smaller MNOs—such as T-Mobile and Sprint—can achieve greater economies of scale to realize these efficiencies, the top-two MNOs might increase their entrenched positions, if either or both achieve 5G capabilities that smaller providers cannot match by virtue of their smaller scale or more limited access to high-cost fixed assets or both.

2. Introduction

The vision of "Pervasive Computing" is one of everywhere/always available ICTs to support the transformation to the Smart-X digital economy. Smart-X refers to a vision of the future in which all sectors of the economy and our social lives are better able to make use of embedded ICTs to enhance economic efficiency. Smart-highways, smart-healthcare, smart-energy grids, and smart supply chains are some of the examples of how ICTs are envisioned helping enhance economic decision-making across the economy. Making this possible will require significant investments in all aspects of our ICT infrastructures, including greatly expanding the performance, capacity, and capabilities of our wireless networks.

The 5G vision describes the network infrastructure that is required to fully enable the Pervasive Computing vision of Smart-X. For MNOs, it represents the next generation of wireless networking technology and establishes ambitious targets for order-of-magnitude performance improvements relative to the 4G LTE networks that MNOs are currently in the process of maturing. Realizing these capabilities will require MNOs to invest hundreds of billions of dollars, much of which is needed in any case to keep up with the exponential growth in traffic.[3] Forecasts of the potential for Smart-X to contribute to economic growth and productivity are in excess of multiple trillions of dollars.[4] Already, it is estimated that the digital economy accounts for 6.5% of GDP ($1.2 trillion in 2016) and MNOs added over $282 billion to U.S. GDP.[5] These are big numbers and staying on track to be at the forefront of the global digital economy transformation may determine how successful the U.S. is in sustaining economic growth and its competitive advantage in increasingly dynamic and competitive global markets. Ensuring that the U.S. has the wireless infrastructure it needs to stay on track is likely to depend on how successful we are in sustaining robust competition across the entire broadband ecosystem.

There is a lot of hype associated with 5G and a continuum of views regarding what 5G should mean, ranging from simply better mobile services than we have today (which might more appropriately be referred to as 4G+) to an order-of-magnitude improvement in the performance and capabilities of broadband networks along virtually every dimension. As with the vision of Pervasive Computing, realizing the most ambitious goals of 5G (and whatever may lay beyond) may best be understood as horizon goals,[6] but ones that are consistent with the trajectory of technical change and ICT-fueled economic growth that has been progressing in waves for decades.

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The proposed merger of T-Mobile and Sprint would create a third national MNO with the scale to sustain the maximal extent of facilities-based competition among MNOs that is likely to be economically feasible in the medium to longer-term.

The focus here will be on those more ambitious goals, since heading towards those goals offers the trajectory with the greatest promise of expanding market opportunities, innovation, and economic growth. The actual progress we realize toward achieving those goals will depend, in part, on how successful we are in promoting sustainable, robust competition on the road to 5G.

Realizing the 5G vision will have important implications for competition among MNOs and across the broadband ecosystem. For national MNOs, the challenge of scaling their network capacity and adding the network intelligence and capabilities to meet the 5G performance goals will compel each of the operators to invest tens of billions of dollars. Much of this investment will be directly associated with the need to transition to smaller, denser and hence more capital intensive network architectures. In addition to enabling the networks to support much faster data rates, lower latencies, and many more simultaneous connections, the investments will vastly expand the capacity of wireless networks. This capacity expansion is needed to meet the exponential growth in video traffic that is already happening, as well as to enable the new Smart-X services that are coming. In order for MNOs to manage this investment efficiently and to provide the flexibility and capabilities to offer customized, dynamic services to meet the needs of increasingly heterogeneous and demanding wireless applications and services, MNOs will be compelled to continue to implement softwarization and virtualization capabilities.

For the national MNOs, these complementary changes will increase their capital expenditure requirements and their potential to realize scale and scope economies required to operate a leading edge national-scale MNO. Although today there are four national MNOs, the scale of the top two gives them significant advantages in the effort to build nationwide 5G networks. The best prospect for longer-term competition among the MNOs is for the third and fourth ranked MNOs to merge: the proposed merger of T-Mobile and Sprint would create a third national MNO with the scale to sustain the maximal extent of facilities-based competition among MNOs that is likely to be economically feasible in the medium to longer-term.

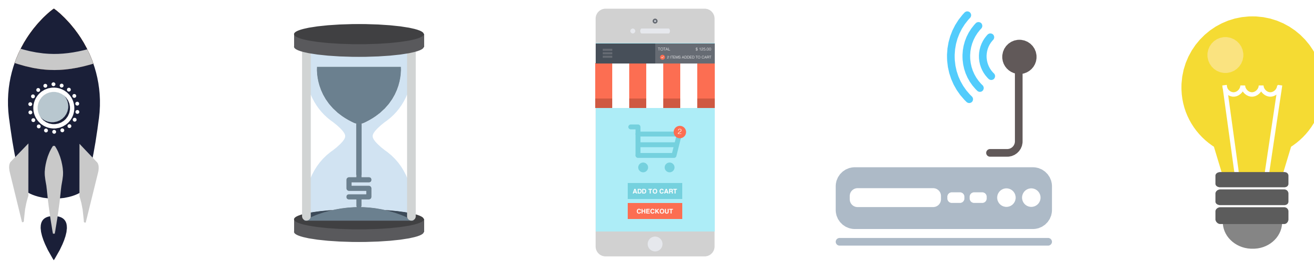
This paper explores the following areas of 5G growth and its implications: (1) the broadband 5G future vision; (2) what MNOs require to transition to 5G and to compete as national-scale, full-service providers; and (3) what a 5G future will mean for competition in the evolving broadband ecosystem of increasingly converged networks and services.

3. Broadband 5G Future Vision

Pervasive computing is a vision of *everything, always (24/7) and everywhere connect(able) to networked digital communication, computing, and storage resources wherever and whenever wanted.* Networking digital communications, computing, and storage capabilities create a powerful collection of resources that enhances the benefits of all three.[7] *Everything* means that individuals as well as "things" may be connected for any-to-any communications (*i.e.*, the Internet of Things or IoT).[8] The IoT future promises to link the virtual and real worlds, opening up new frontiers for deploying ICTs productively throughout the economy and society.[9] In such a world, much of the communications traffic may be between things (machine-to-machine or "m2m"). *Always and everywhere connect(able)* means that the networks will allow accessing the ICT capabilities wherever and whenever there is demand.[10] That implies that networked services are portable, mobile,[11] ubiquitously available,[12] and scalable.[13] The 5G vision is one of broadband networks capable of providing this sort of connectivity, one that requires significantly more wireless infrastructure, as well as many other complementary enhancements across the broadband ecosystem.

5G represents an important step toward achieving this vision, and relative to today's 4G LTE mobile technology, represents an order-of-magnitude improvement in performance along almost every dimension, including:[14]

Faster data rates	Reduced latency	Enhanced mobility	Massively increased connection density	Improved spectral and energy efficiency



- ***Faster data rates:*** Ten-fold increase in user experienced data rates, including 20-fold increase in peak data rates. Faster data rates are needed to support richer, interactive multimedia applications (including streaming higher resolution video) and to support faster and more robust content access.[15] Whereas 4G LTE offers user data rates that may be in the 10s of Mbps range today, the goal for 5G is to support data rates in the 100s of Mbps or more. Additionally, faster per-user data rates will drive the need for significant increases in area-traffic capacity to enable support for multiple users. Increasing the speed of mobile broadband services and the capacity of wireless access networks is necessary just to support the surging traffic associated with streaming mobile video.

- ***Reduced latency:*** Ten-fold reduction in latency from today's 10 ms norms to 1 ms latencies. Reduced latency is needed for near to real-time interactivity which is especially important when wireless networks are used for control (*e.g.*, managing autonomous vehicles on smart highways), as well as in highly interactive applications, such as virtual or augmented reality, including gaming.

- ***Enhanced mobility:*** Seamless support for high-speed mobility across radio nodes, which is important for sustaining continuous performance while a user may be moving at highway speeds. This level of support becomes more important and challenging when mobility requires more frequent hand-offs across radio nodes because of smaller cell sites (a key feature of the future, as will be discussed further below) that may be operating with different Radio Frequency ("RF") spectrum resources.

- ***Massively increased connection density:*** Progressively, multiple devices per user are the norm, which in turn, drives the increase in the aggregate number of devices that need to be connected via the networks. With IoT, the connection density in any geolocation may increase substantially. Thousands of sensors may be embedded in the environment and built into our clothes and appliances to make them digitally enabled and allow them to participate in the online experience. Moreover, much of the communication in the 5G future will be m2m.

- ***Improved spectral and energy efficiency:*** Three-fold improvement in spectral efficiency and 100-fold improvement in energy efficiency. Spectrum and power are two critical inputs that are necessary for wireless devices to operate. Improving the efficiency with which these inputs are used helps lower costs and enhances usability in terms of portability, longevity, and capacity.

The benefits of realizing this vision are several. First, 5G will dramatically improve the capacity and capabilities of using ICTs to enhance economic efficiency in all of its dimensions.[16] ICTs allow us to collect, analyze, share, and act upon information. 5G will enable better real-time intelligence (*e.g.*, situation awareness with the assistance of AI and big data analytics[17]) and increase control of complex production systems with the assistance of sensors and automation. ICT augmented reality can enhance adaptability, flexibility, and responsiveness on a more granular and dynamic basis, facilitating real-time responsiveness and customization.[18]

From the perspective of the end-user's experience, ICT improvements mean that existing mobile broadband applications and services like streaming video or mobile video conferencing will work better with higher resolution, more stable performance, and easier portability and mobility across devices and usage environments.[19] Faster and more capable networks make it feasible to take greater advantage of faster and more capable complementary elements, such as end-user devices and applications that offer users a richer experience. Of course, as devices and applications are enhanced, they consume more network resources, driving growing demand for and increased investment in expanded capacity in the 5G ecosystem.

Providing the capacity and capabilities needed to serve the exponential growth in broadband traffic and enhancing the performance of legacy services provides a sufficient motivation for much of the investment in 5G. However, 5G's greatest promise is associated with its role in enabling the IoT future of Smart-X on which much of the hope for the digital economy rests. Examples include:

Smart healthcare can take advantage of networked, digitally-connected devices to allow continuous and remote health monitoring, earlier detection of health risks with crowd sourced data, and automated dispensing of drugs for real-time dosage management.

Smart agriculture and natural resource management can fine-tune irrigation, fertilization, and harvesting decisions to take account of local environmental conditions, as well as market prices.

Smart supply chains can enhance inventory management, production scheduling, and distribution control. This can enhance efficiency by enabling higher utilization rates of productive assets while supporting just-in-time, market-of-one demand customization. Costs can be lowered while customer satisfaction may be enhanced.

Smart finance and payments ("FinTech") can provide better fraud detection, enable more flexible and secure e-payments, and lower transaction costs.

Smart highways and vehicles (including autonomous vehicles) can contribute to safer roads, reduced congestion, and improved energy efficiency.

Smart energy grids boost greener power generation and usage. Addressing global climate change will require shifting to more renewable energy sources and using energy more efficiently. ICT-enabled smarter power management systems and distribution grids will be needed, from generation to consumption, to control when renewable sources can feed into the grid and to help manage consumption through AI-assisted management of HVAC and lighting in homes and businesses.

These are just some of the ways in which the transformation to Smart-X in the digital economy has the potential to open new opportunities for investment and economic growth across all sectors and layers of the economy. The world of 5G and Pervasive Computing expand options for embedding ICTs more deeply into the fabric of our economic and social lives—allowing virtually every aspect of economic production and markets to be ICT-empowered, from the distribution of final goods and services to the management of raw materials, from domestic commerce to international trade. ICTs enable just-in-time production, outsourcing, and market-of-one customization,[20] and in so doing help reorganize how markets and firms are structured and operate.

5G

3 million jobs

+ $500 billion to GDP

Although opportunities abound, some sectors are further along in upgrading their production methods and business processes to take advantage of ICTs. While it is uncertain precisely which Smart-X efforts will prove most successful, estimates of the potential benefits are huge. For example, a report from McKinsey & Co. forecasted the potential global impact of IoT to be $3.9 to $11.1 trillion per year by 2025, associated with smart cities, transportation, healthcare, retail, manufacturing, and other industrial sector applications.[21] Another report from Accenture forecasted that IoT could add $7.1 trillion to the U.S. economy by 2030.[22] In yet another study, Accenture forecasted that 5G could help drive $275 billion in telecommunications investment in making cities smarter, and that the investment could contribute to creating 3 million jobs and add $500 billion to GDP.[23] Of course, realizing the benefits of 5G will require more than just the successful deployment of 5G infrastructure, although that is certainly necessary. The transition to the digital "smart" economy will incur significant transition costs.[24] Workers, businesses, industry, and markets will confront disruptions and will need to experiment to determine how best to use ICT-smart processes in productive ways.

In the next section, I identify some of the important ways in which moving toward 5G will require MNOs to change the ways wireless networks are built and operate.

4. Economic Implications of 5G for MNOs

Each generation of mobile technology, from the analog 1G mobile telephone networks of the 1980s to today's 4G LTE mobile broadband networks, has propelled significant changes in how networks are designed and provisioned, with significant implications that resonated across the entire telecommunications and computer industries. The rise of mobile telephony, originally a luxury adjunct to fixed line telephony, eventually came to transform telephony into personalized "follow-me anywhere" service. The transition to digital with 2G and the addition of expanded data services with 3G expanded the modalities of mobile communications to include email, text messaging, chat, and other substitutes and complements to traditional voice telephony. With the advent of smartphones and the further expansion of wireless broadband platforms (including 3G, 4G, and Wi-Fi-enhanced fixed broadband services),[25] mobile wireless has been transformed into a general-purpose platform for broadband access to the Internet, cloud computing, and other services.

Driven by the exponential growth in broadband traffic these cycles of innovation have enabled, businesses across the broadband ecosystem have had to invest in expanded capacity. The rise of the smartphone application ecosystem, the growth of streaming media services, the expanded reach and use of social media, and the rise of the sharing economy are all due, in part, to the expanded coverage, capacity, and quality of our mobile broadband infrastructure. Such changes herald the restructuring of the digital economy.

The transition to 5G will be similar and potentially even more significant in its impact. Meeting the performance targets for 5G will require enhancements in all elements of the networking ecosystem from chips to services, from radios to core networks, from hardware and software to content and applications. The focus of this paper, however, is on what is required to support the wireless elements of 5G and the implications of those for MNOs. As explained earlier, moving to 5G represents an order-of-magnitude improvement over 4G LTE. Meeting those performance targets will drive a number of important complementary changes in the design and operation of mobile networks that will have important economic implications. Among the many changes, both large and small,[26] the transition to 5G is driving MNOs to embrace: (a) agile management of diverse spectrum assets; (b) small cells; and (c) softwarization and virtualization.[27]

In the following sub-sections, I first explain at a high-level of abstraction what these changes mean for the design and provisioning of wireless networks, and then identify some of the important economic implications of those changes.

4.1 5G's Demands on Network Design

Agile management of diverse spectrum assets

Enabling 5G will require MNOs to implement the capabilities required to support *agile management of diverse spectrum assets*. The growth in wireless traffic, the need to support wireless applications with diverse requirements, and the need to enable the desired always on/everywhere connectable, seamlessly mobile end-user experience will require MNOs to manage their diverse RF spectrum assets efficiently. Traditionally, MNOs have relied principally on exclusively licensed spectrum and have built up their portfolios of spectrum in different bands as legacy inheritances through purchases at auctions or other business transactions, including M&A activity. The result is that MNOs have different patchworks of spectrum resources (that differ in terms of the frequency bands and locations for which they hold licenses). Those spectrum licenses are valuable assets and acquiring additional licensed spectrum is not always feasible, and when feasible, is expensive.

Simply meeting the capacity requirements of exponential traffic growth is posing a massive challenge for MNOs. Cisco has forecasted that mobile data traffic is expected to grow at an annual rate of 46% per year.[28]

Softwarization

Refers to the replacement of traditional "hardware" solutions with software solutions. Once business and technical functionality is moved into software it is easier to modify and relocate. Virtualization refers to the capability, enabled by softwarization, of creating a virtual machine platform that can simulate the operations of different hardware and software environments and isolate those simulations from the underlying hardware and software on which it is deployed and from other virtual machines that may share those resources.

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Access to more spectrum bands will result in lower cost and higher quality. The transition to 5G with its order-of-magnitude improvements in performance will require MNOs to become even more agile in their ability to manage diverse spectrum resources on a fine-grained dynamic basis.

Although each generation of mobile technology has enabled significant improvements in spectral efficiency, demand for spectrum resources has continued to outstrip the increase in supply. The growth of mobile video is currently the key driver for aggregate and per subscriber traffic growth.[29] Advertising supported and subscription media content providers are competing aggressively for consumer attention and the rapidly growing market of subscribers interested in accessing streaming media content over the Internet. To retain fickle consumers, content providers are continuously enhancing the quality of the end-user experience[30] by expanding viewing options in terms of programming choices, the devices used to access the content (*e.g.*, new 4K and smart TVs, tablets, while still supporting legacy devices), and by providing better support for mobile access.

To meet the demand for additional spectrum resources, MNOs are expected to make use of shared spectrum that may be regulated as unlicensed (*e.g.*, in the 5 GHz band) or under a new framework such as the one recently established for the new Citizens Broadband Radio Service (3.5 GHz band). But even with these resources, spectrum is likely to remain scarce and MNOs will need to maintain diverse portfolios of spectrum assets. Furthermore, because the physics of RF propagation vary with frequencies and the challenges of supporting wireless communications varies with the local environment (*e.g.*, terrain, RF congestion and noise), spectrum assets are imperfect substitutes with complex implications for the costs of provisioning services using different spectrum.[31] Advances in wireless technology such as LTE have enabled MNOs to manage their spectrum assets on a more granular and dynamic basis. This allows MNOs more scope to mix-and-match spectrum resources (e.g., paired and unpaired, licensed and unlicensed, contiguous and non-contiguous) to support seamless mobility. Access to more spectrum bands will result in lower cost and higher quality. The transition to 5G with its order-of-magnitude improvements in performance will require MNOs to become even more agile in their ability to manage diverse spectrum resources on a fine-grained dynamic basis.

As explained below, although adopting these capabilities is increasingly essential for national MNOs to meet traffic demands and reduce their spectrum costs, the availability of these capabilities also enables new potential sources of competition. For example, it facilitates new models for niche or specialized regional competitors or competitors that may target a narrow class of applications or customer segments. This is in contrast to the full-service, national-scale MNOs. The technologies enabling these new capabilities are also creating new options for end-user self-provisioning.[32] These and other aspects of how the technical and market environment for mobile broadband are contributing to intensifying competition in mobile broadband.

Small cells

The need to shift toward smaller cell network architectures is a complementary development associated with the need to manage spectrum more efficiently.[33] Key to this transition is spatial reuse of scarce spectrum resources—splitting an existing cell into multiple smaller cells allows the same licensed spectrum to be used multiple times.

The shift to smaller cells also has a number of other important implications. It means that lower power is needed for radios to communicate with the base station; there are likely to be fewer radios operating in the smaller coverage area and hence fewer potential sources of interfering radio transmissions; line of sight issues are therefore likely to be less important. With smaller cells, higher frequency spectrum may have an advantage over lower frequency spectrum. Another important difference is that, while smaller cells are more expensive to provide area coverage, capacity can be added in smaller, more scalable increments.

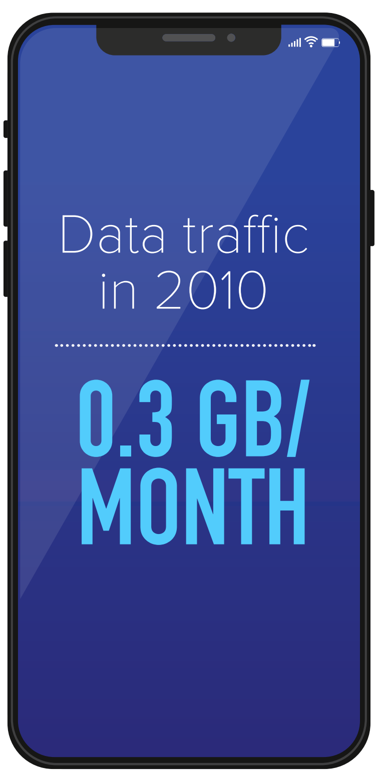
In addition to addressing the spectrum capacity and performance issues, the transition to 5G will drive the move to smaller cells because of the need to push the edge of the MNO network (and its embedded capabilities and intelligent resources) closer to the end-user.[34] 5G base stations will include computing and storage (caching) resources that will be needed locally to support the performance requirements of 5G (*e.g.*, 1 ms latencies) and efficiently manage network costs (*e.g.*, edge-based caching of popular content to avoid excess re-transmission costs). In the IoT future, many devices will be small and low power. Security and control considerations[35] may provide additional rationales for deploying small base stations closer to edge devices, to which the base stations provide communications and computing resources. For a national-scale MNO whose business model depends on providing a full-menu of service options that includes national coverage and interoperability across customers with legacy and new devices and applications, building out small cells required by 5G is likely to necessitate a significant increase in capital costs. While no one knows for sure, some analysts have forecasted that the cost of upgrading to 5G will be up to $200 billion per year in the U.S. alone over the next five to ten years,[36] while another study estimates that the cost will be $104 billion over the next ten years to upgrade networks.[37] The costs will depend on the strategies operators choose to pursue, but SNL Kagan estimates that the transition to 5G will require building aadditional 225,000 small cells by 2021.[38]

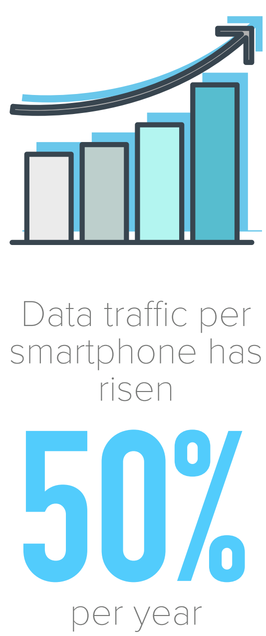
The cost of upgrading to 5G will be up to $200 billion per year in the U.S. alone over the next five to ten years, while another study estimates that the cost will be $104 billion over the next ten years to upgrade networks.

A slow approach would involve only rolling out 5G radios in markets where a strong business case can be made. However, analysts at Bain argue that "5G has the potential to scramble the competitive game board for all three classes of operators—mobile-only, fixed-only and converged" and operators "that opt to wait and see how the technology will evolve risk exposing themselves to disruption from competitors that are more aggressive."[39]

In a portent of things to come, it is worth considering how per-subscriber traffic continues to grow with 4G LTE networks. For example, data traffic per smartphone has risen 50% per year from 0.3 GB/month in 2010 to 5.2 GB/month in 2017.[40] With the faster speeds and enhanced applications enabled by 5G, the traffic per subscriber will continue to grow. A forecast from Ericsson predicts that data usage per smartphone will grow to 26 GB per month by 2022 for a total of 9.8 Exabytes of data traffic![41] McKinsey has forecasted that the total cost of network ownership would need to grow by 60 percent if data grows by 25% per year, and significantly faster if the traffic growth unleashed by 5G-enhanced access connections grows still faster.[42]

Meeting this challenge is one of the powerful market forces driving further industry restructuring among MNOs and elsewhere across the broadband provider ecosystem. At the same time, the technologies and architectures that small cells are enabling are opening up new models for niche facilities-based and other models for competition. To remain competitive in this environment, the national, full-service MNOs have to be even more aggressive in cutting costs and realizing scale and scope economies.





Virtualization

Refers to the replacement of traditional “hardware” solutions with software solutions. Once business and technical functionality is moved into software, it is easier to modify and relocate. Virtualization refers to the capability, enabled by softwarization, of creating a virtual machine platform that can simulate the operations of different hardware and software environments and isolate those simulations from the underlying hardware and software on which it is deployed and from other virtual machines that may share those resources.

Softwarization and Virtualization

Moving network functionality out of hardware into software has significantly enhanced the flexibility, customizability, and performance of modern communication networks. This *softwarization* of network functions has been driven in part by an effort to lower costs. By shifting from specialized to commodity hardware in 4G LTE, for example, MNOs separate the radio and data network functionality and thereby allow MNOs to move toward all-IP data networks and benefit from the cost-economies associated with commodity IP hardware. In the radio domain, advances in developing software and cognitive radios (*i.e.*, moving radio functionality from specialized hardware into software and adding ICT-smart features to radios to make them capable of adapting their operations in response to changes in their local environment) are another example of softwarization that render individual radios better able to interoperate in diverse wireless environments by, for instance, becoming frequency agile.

In addition to lowering costs, softwarization expands flexibility and functionality. For example, in networks, the rise of Software Defined Networking (“SDN”) and Network Function Virtualization (“NFV”) have allowed better control and partitioning of network functionality.[43] One benefit of this is that it facilitates *delocalization* of functionality, allowing remote control from where the actual function or service may be delivered. This increases opportunities for MNOs to realize scale and scope economies.[44] For example, a single softswitch can implement the signaling and control functions for multiple (lower-cost) IP switches in a VoIP network, substituting for multiple legacy local switches based on dedicated hardware. The ability to centralize (or decentralize) where functionality is provided can also enhance security and privacy. The move to SDN and NFV takes these capabilities to the next level, enabling more control over how services are provided and managed to be shifted to end-users (or not, as desired).

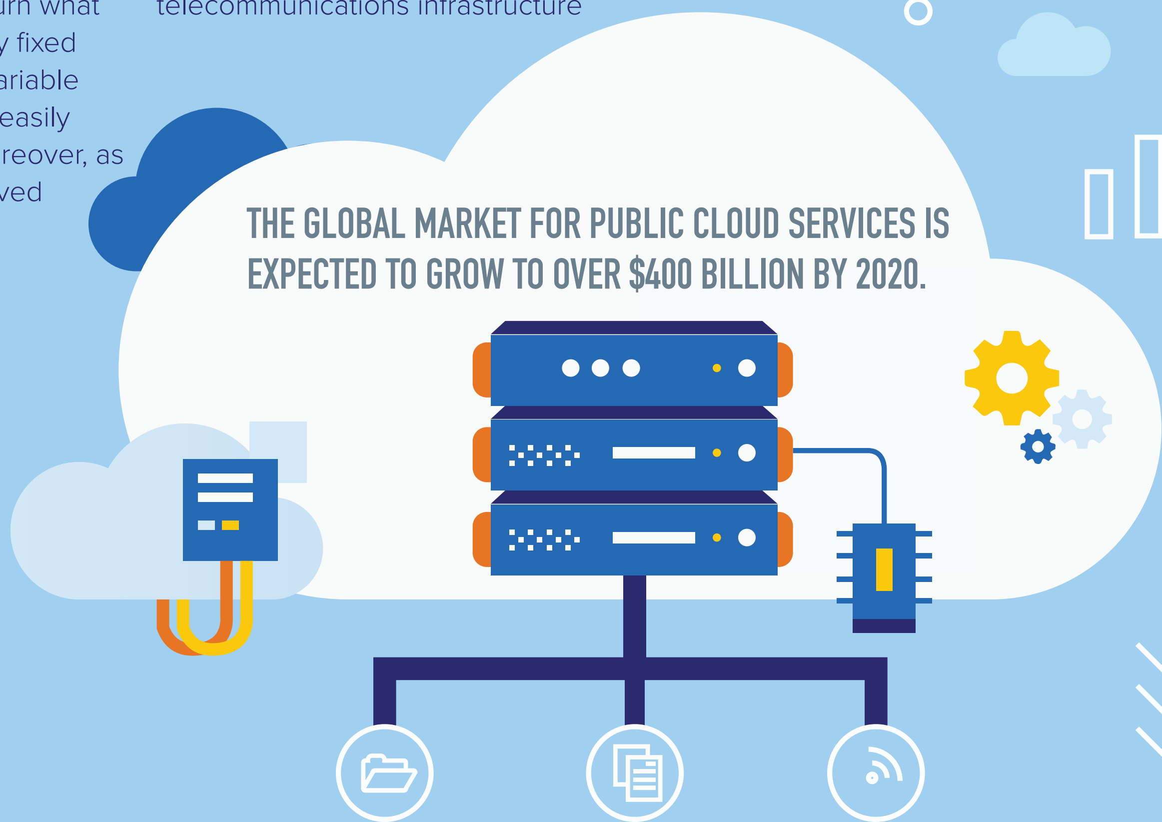
These capabilities facilitate *virtualization*. Virtualization allows resources to be combined or shared by multiple higher-level applications and services. It is a key capability enabled by a layered architecture and is important in enabling resources to be sliced and combined to meet the heterogeneous requirements of different applications and users. A computer operating system provides a virtual layer that enables multiple applications to run on a shared CPU.[45] In the 4G LTE architecture, separating the radio and IP network layers facilitates virtualization of the spectrum resources. Higher level applications do not need to know which frequency will be used to transmit the data over the wireless link, and diverse combinations of spectrum can be used in different locations and at different times to support communications.

Cloud services from providers such as Amazon, IBM, Microsoft, and Google offer end-users the flexibility to scale their demand for computing and communication services. Analysts often describe cloud services as being organized into three market segments: Infrastructure-as-a-Service ("IaaS"), Platform-as-a-Service ("PaaS"), and Software-as-a-Service ("SaaS"). As one goes from IaaS to SaaS, more of the ICT functionality is off-loaded to the cloud service provider.

The benefits of adopting cloud services are several. First, cloud providers can realize scale and scope economies not available to individual enterprises. These arise from limiting data center costs for equipment, power, ensuring reliability, and the backbone networking services needed to tie the data centers together and make it accessible to end-users. Second, by outsourcing the ICT to cloud service providers, businesses can reduce their maintenance costs and turn what otherwise might be lumpy fixed cost investments into a variable cost that can scale more easily with their user needs. Moreover, as cloud services have evolved to become more user-friendly, the specialized ICT expertise required to make use of them is becoming less important and an ecosystem of intermediary service providers (market research firms, consultants, business process providers) exists to expand direct and indirect access to cloud services to businesses of all sizes. At this point, cloud services have evolved sufficiently that analysts are talking about "Everything-as-a-Service," or "XaaS," which highlights the rich portfolio of specialized and general-purpose cloud services available to allow businesses to outsource virtually all ICT functions to the cloud, turning them from CAPEX investments to service purchases.[46] According to the Gartner Group, the global market for public cloud services was $260 billion in 2017 and is expected to grow to over $400 billion by 2020.[47]

The evolution of cloud services would not be possible without the growth of the Internet and the telecommunications infrastructure that supports it. Increased demand for cloud services is helping drive demand for 5G networks, since the two are complementary and progress in one helps drive progress in the other. By relying on virtualization to provide users slices to the shared resources, cloud services and the underlying 5G infrastructure enable the sort of shared access that makes on-demand XaaS possible.

All three of these developments are important and complementary changes in how broadband networks are being re-designed to address the 5G future. They are simultaneously being driven by the need to add cost-effective capacity and to support the order-of-magnitude enhanced performance requirements of 5G.



4.2 Network Changes Alter the Fundamental Economics of the Wireless Industry

The potential for 5G to unlock a wealth of opportunities for improved legacy and new mobile broadband services and to support the IoT future of Smart-X implies a need to support a growing range of heterogeneous wireless users and uses (from higher-resolution, interactive multi-media to IoT sensors). This will require expanded capacity for access and for core networks. It will also require the flexibility to customize services for diverse applications in varied usage environments. End-users will be using both fat and thin clients.[48] The 5G future will need to support both and having the flexibility to support both will expand opportunities for competition across the ecosystem, allowing device, application, content, and network service providers to tailor their solutions to best exploit their competitive advantages and appeal to the tastes of their target customers.

In addition to offering this functionality, the simple challenge of handling the continued explosive growth in mobile broadband traffic will compel MNOs to adopt more agile spectrum management, shift to small cells, and adopt softwarization and virtualization. These are responses to the rising shared, fixed, and sunk costs of provisioning smaller cell architectures associated with the move to 5G. These basic economics have characterized telecommunications networking from the start, but become more important with the move toward 5G.

A telecommunications network is a shared network. It needs to be provisioned to handle the expected peak loads that result from the aggregate behavior of all of the users who want to make use of the network at the same time. Because users do not perfectly coordinate their usage in time, location, or what they are trying to do,[49] the same resources can be shared by multiple users for mixed uses. Sharing reduces the total costs of providing capacity, since the aggregate peak capacity can be shared and allows capacity to be used at higher utilization over time. However, because traffic needs are stochastic and uncertain, MNOs need to be able to scale and adjust capacity on a finer-grained, more dynamic basis.[50] Moreover, as we move toward further integration of the virtual and real worlds, the ICT systems are becoming more complex, involving more industry participants across multiple levels. The technical, market, and policy uncertainty is increasing. In this environment, the benefits of flexibility, adaptability, and intelligence increase.

Virtualization and softwarization (enabling delocalization) accentuate the potential to realize scale and scope economies for MNOs, and are increasingly important for national-scale, full-service MNOs. For example, a single, larger network operations center ("NOC")[51] can be both more capable and lower cost than multiple smaller NOCs.

> **The necessity to move to smaller cell architectures for 5G means that the capital costs of providing wide-area coverage and expanding aggregate capacity are increasing.**

A single customer account management center for bill processing, customer provisioning, and customer service can provide support for an MNO across multiple states, consolidating what may previously have been multiple facilities. This reduces the costs of operating an MNO, and the opportunity to take advantage of these cost reductions increases with scale.

A byproduct of the movement from 3G to 4G was the convergence of the major MNOs on a common technology, LTE, which increasingly can be supported using commodity IP networking equipment. The adoption of a common technology platform has helped realize industry-wide scale and scope economies, reducing the per-MB costs of supporting mobile broadband network services. At the same time, common technology helps intensify competition among MNOs by making their network services closer substitutes. Meanwhile, more capable end-user devices and more aggressive competition among content and application providers (to control the customer-relationship) are helping to reduce customer switching costs.[52]

The necessity to move to smaller cell architectures for 5G means that the capital costs of providing wide-area coverage *and* expanding aggregate capacity are increasing.[53] The increased fixed, shared and sunk costs in scale and scope economies combine to increase the scale required to sustain a national facilities-based, full-service network.

Today, we have four national scale, facilities-based MNOs, each of which offers a portfolio of services: Verizon, AT&T, T-Mobile, and Sprint.[54] According to the FCC 20th CMRS, as of the end of 2016, these four were providing the underlying service (on a wholesale or retail basis) to 99% of the 417 million connections (which is more than the population because many subscribers have more than one device with a cellular subscription).[55] By way of comparison, in 2005, these same top four operators provided service to 80.7% of the 213 million subscribers, whereas in 1997, the top four operators were different (AT&T, SBC, Bell Atlantic, and BellSouth) and provided service to only 38.7% of the 55.3 million subscribers.[56]

These data points illustrate several important features. First, MNOs have experienced tremendous growth in subscribership as mobile services have approached saturation across the population. The number of subscribers has grown 816% from 1997 to 2016, and the volume of traffic has grown significantly more.[57]

This growth was enabled first by the cellular operators building out national networks. The largest MNOs built their national coverage networks by sustained high levels of investment and through mergers and acquisitions to consolidate regional carriers, who in many cases had complementary coverage networks.

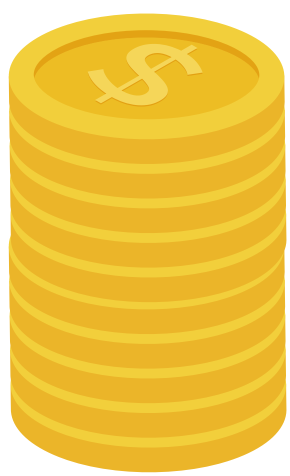
In the early days (before 2000), there were numerous mobile telephony networks across the country, subscribers had to roam across multiple networks in order to use their cell phones nationwide, and many parts of the country lacked cell coverage because network infrastructure had not yet been deployed.

By 2005, the industry had substantially consolidated with the aforementioned top four mobile providers providing service to over 80% of combined retail and wholesale subscribers. The consolidation of the cellular industry is a natural outcome of the underlying economics confronting the industry. The market barriers to establishing a full-service, national coverage mobile network are substantial and beyond the reach of all but very large enterprises, such as the major cable and Internet companies. The annual investment requirements to operate a national MNO network run to the billions if not tens of billions of dollars per year, and the scale and scope economies associated with larger size are substantial, as already noted. Building out coverage and then adding capacity and expanding capabilities to enhance legacy services and add new services, while keeping up with the rapid pace of technical change, induced the operators to invest approximately $205 billion from 2010 to 2016,[58] which was when operators were completing their build-out of 3G and deploying 4G networks.

Although the top four MNOs are competing aggressively across the entire U.S., there are big differences between the top two MNOs. Based upon the data available from the FCC 20th CMRS, Verizon was #1, with a 37% share of all connections, and AT&T was #2, with a 33% share of all connections and the next two (#3 T-Mobile, with a 15% share of connections, and #4 Sprint, with a 13% share of connections).[59]

The size difference is also apparent in the different pace of investment the firms have been able to sustain. From 2010 through 2017, Verizon and AT&T have each averaged close to $10 billion per year in CAPEX, while Sprint and T-Mobile have each averaged closer to $4 billion. *See infra* Table 1.

Verizon and AT&T
have each averaged close to $10 billion per year in CAPEX,



$10 billion

Sprint and T-Mobile
have each averaged closer to $4 billion

$4 billion

Table 1: Capital Expenditures for Top Four MNOs ($ Millions)[60]

Year	Verizon	AT&T	Sprint	T-Mobile	Total
2002	$4,414	$5,302	$2,640	$1,700	$14,056
2003	$4,590	$2,774	$2,123	$1,734	$11,221
2004	$5,633	$3,449	$2,559	$2,138	$13,779
2005	$6,484	$7,475	$3,545	$5,045	$22,549
2006	$6,618	$7,039	$5,944	$3,444	$23,045
2007	$6,503	$3,745	$4,988	$2,667	$17,903
2008	$6,510	$6,021	$1,789	$3,603	$17,923
2009	$7,152	$5,924	$1,161	$3,687	$17,924
2010	$8,438	$8,593	$1,455	$2,819	$21,305
2011	$8,973	$9,764	$2,702	$2,729	$24,168
2012	$8,857	$10,795	$4,199	$2,901	$26,752
2013	$9,425	$11,191	$7,136	$4,025	$31,777
2014	$10,515	$11,383	$4,828	$4,317	$31,043
2015	$11,725	$8,697	$7,193	$4,724	$32,339
2016	$11,240	$8,384	$3,798	$4,702	$28,124
2017	$10,310	$7,870	$4,692	$5,237	$28,109
Cumulative	$127,387	$118,406	$60,752	$55,472	$362,017
Average 2010-2016	$9,935	$9,585	$4,500	$3,932	$27,952

Sprint and T-Mobile have also historically experienced substantially higher churn rates than either Verizon or AT&T.[61] Their smaller size means they are unable to realize the same level of scale and scope economies of the larger two firms.

In spite of these disadvantages and in part motivated by those disadvantages, T-Mobile has pursued an aggressive strategy of retail innovations to disrupt the market with novel pricing plans and new services. T-Mobile was the first to abandon subscriber termination fees and long-term contracts, making it easier for customers to switch carriers (which can result in higher churn rates). T-Mobile also innovated with new transparent pricing models, Wi-Fi calling, and programs to drive heavier mobile broadband data usage without risking exceeding data caps.

While this demonstrates the ability of smaller providers to impose significant competitive pressure on much larger rivals, this does not mean that it is likely that either Sprint or T-Mobile could significantly disrupt the dominant market position of the top two MNOs, which has remained remarkably stable for over a decade.

In addition to lacking the scale of either Verizon or AT&T, both Sprint and T-Mobile suffer from additional important deficiencies that prevent them from competing as peers with the top two MNOs. First, Verizon and AT&T are both part of larger companies with wired networks and with significant investments in media content. The wired networks make it easier for Verizon and AT&T to offer their customers a converged, seamless broadband experience. Moreover, with their substantial wired core and access network infrastructure, both Verizon and AT&T have easier access to the back-haul transmission resources that are critical for connecting base stations into the backbone network. The costs of backhaul are a significant component of the costs of operating a mobile network.

In the move toward 5G, any MNOs that succeed in deploying 5G networks would have a significant advantage relative to other providers operating less advanced and less capable networks. Since most of the costs of building out the network will be shared, fixed or sunk, the 5G provider will have relatively low forward-looking incremental costs should it find it necessary to confront a rival. Consequently, if any national provider builds a 5G network, the other providers who want to compete on a level footing with that provider will also need to build 5G networks.

AT&T and Verizon have demonstrated in the past their capability to sustain the levels of investment that are required to keep pace with the leading edge of mobile technologies, and both have the scale to invest aggressively to deploy 5G networks. Hence, whether and how fast they choose to deploy 5G networks will be strategic choices. The same cannot be said for T-Mobile or Sprint as standalone MNOs.

In contrast, however, New T-Mobile would have both the resources and incentive to compete even more aggressively with AT&T and Verizon on quality-adjusted prices and would have stronger strategic incentives to more rapidly deploy its 5G network.

> **“New T-Mobile would have both the resources and incentive to compete even more aggressively with AT&T and Verizon on quality-adjusted prices and would have stronger strategic incentives to more rapidly deploy its 5G network.**

1.

First, New T-Mobile would be able to realize comparable scale and scope economies and would have the network, financial, and other business resources to compete head-to-head with Verizon and AT&T in a race to build out 5G networks.

2.

Second, merging the networks (and operations) of Sprint and T-Mobile will require significant new investment and reconfigurations, costs which compare with upgrading to 5G, replacing radios, etc., and possibly may prove to be a major incentive for New T-Mobile to rapidly move forward with 5G upon merging. This cost-based justification would dovetail with the strategic benefits of being able to offer the enhanced services that having a 5G network portends. Moreover, the fact that Sprint and T-Mobile have quite complementary spectrum resources would help facilitate coverage and capacity for a joint network. T-Mobile has relatively lower frequency spectrum for expanding national coverage, whereas Sprint has relatively higher frequency band spectrum that is especially valuable for adding capacity and supporting faster data rate services. Pooling their spectrum will provide an easier transition path toward 5G while protecting the user experience of 4G LTE subscribers during the transition.[62]

3.

Third, New T-Mobile also will have strong incentives to compete aggressively to add new customers to its new 5G network. Indeed, New T-Mobile will try to use all of its network capacity by capturing the high value customers who currently are served by AT&T and Verizon.

Rapid deployment by New T-Mobile of its 5G network would put added strategic pressure on AT&T and Verizon to accelerate their deployments of 5G. If either or both chose to sit on the sidelines, they would be taking significant risk that could jeopardize their current market positions. The pattern of follow-the-leader innovations in networks and service offerings has been an enduring characteristic of the history of competition among MNOs since 1G.

In short, the move to 5G will amplify the economic forces that have led to the increased size of MNOs. Those forces first drove the industry to combine to create national MNOs that have become dominant over time. Those forces resulted in an industry structure that is concentrated in traditional HHI terms with two leading firms of comparable size and two much smaller firms, also of comparable size. Although the industry has been concentrated for quite a while, there is ample evidence that the industry is highly competitive based on numerous performance metrics. Taking the next step to build nationwide 5G networks will require a level of investment that is feasible for the top two MNOs but unlikely for those ranked third and fourth. The merger of those providers to create a national, full-service MNO, with the scale to compete on comparable terms with the dominant two MNOs, is a pro-competitive response to the changing conditions in the market. Prospects for more rapid deployment of 5G networks *and* more aggressive quality-adjusted price competition among the national MNOs is likely if T-Mobile and Sprint are allowed to merge.

Likewise, European regulators have recently concluded that the substantial annual investments required to operate national scale MNOs supports consolidation, particularly in light of the growing investment needs in 5G networks. The French electronic communications regulatory authority, ARCEP, which formerly opposed several telecommunication mergers and even encouraged the introduction of a fourth operator in 2012, has now relaxed its opposition toward further consolidation in light of the benefits it has seen from the large investments by operators already (*e.g.*, €9.6 billion spent in 2017) and the need for substantial additional investment to deploy 5G networks across France.[63] Similarly, in an assessment of the future of telecom infrastructure, the British government concluded that "[a]s far as the Government is concerned, there is no magic number of mobile network operators. Each merger control case should be assessed on its own merits."[64] Indeed, "analysis suggests there is no significant difference in industry-level investment between four and three player markets."[65] There is concern in both circumstances that efforts to protect against hypothesized increases in retail prices in the short term will create substantial disincentives to allow for the large capital investments needed to promote robust and cost-efficient national wireless networks.

> **Rapid deployment by New T-Mobile of its 5G network would put added strategic pressure on AT&T and Verizon to accelerate their deployments of 5G.**

5. 5G Increases Competition in the Broadband Ecosystem

The preceding discussion has focused on the prospects for competition among MNOs, ignoring the implications of 5G for the larger broadband ecosystem. As I will explain further below, the transition to 5G is likely to intensify competition within the ecosystem. Additional competition from other vectors will alleviate remaining concerns over the shift from having four unbalanced national MNOs to three balanced MNOs. In the following subsections, I describe three likely sources of intensified competition: (1) increased intermodal competition because mobile will be a more competitive substitute for fixed; (2) increased competitive pressure from a more robust market of MVNOs; and (3) new competition from local facilities-based providers that are expected to emerge with the transition to 5G.

5. 1 Intensified Intermodal Competition Between Fixed and Mobile Operators

If the services offered by mobile and fixed broadband were identical, then they would be perfect substitutes and part of the same market from the perspective of competitive analysis. Nevertheless, the merging of fixed and mobile broadband services has been underway for some time, and the transition to 5G accelerates this convergence.

Historically, fixed and mobile broadband services were not close substitutes either in terms of the user experience (demand) or in terms of the costs of providing the service (supply). Fixed broadband services tend to be significantly faster, with more predictable performance, but lack the mobility associated with cellular broadband services. Mobile broadband services have tended to offer much more variable performance with average data rates that are typically below the speeds delivered by fixed broadband services. Fixed broadband is typically shared by all of the users in a household, whereas mobile broadband services are more personalized.[66] In addition, mobile services have been more expensive on a per-Mbps or per-MB basis and have been subject to monthly data caps or thresholds for most subscribers. For these reasons, for most subscribers, fixed and mobile broadband services have been viewed as complementary services rather than as substitutes, in the sense that most consumers want both.[67] Furthermore, the opportunity to take advantage of Wi-Fi-offloading to improve the price/quality of the user experience when using cellular broadband services provides yet another reason for many subscribers (who can afford it) to want both fixed and mobile broadband services.

With continued improvements in the data rates, coverage, and capabilities of mobile broadband services, the performance of mobile services is getting sufficiently better for a larger segment of the population (even in markets where fixed broadband speeds and pricing on a per MB basis may continue to be better). The question for many subscribers is how much speed and performance is enough and whether it will remain necessary to have both mobile and fixed broadband subscriptions. With telephony, we have seen a substantial number of customers choosing to cut the cord and switch to mobile-only telephony. As of 2016, the majority of households in the United States were wireless-telephone-only.[68] The cord cutting began when mobile telephone calling quality was not as good or reliable as fixed telephony, but today, mobile telephony or VoIP is often as good if not better than traditional wired telephony.[69] When it comes to comparing mobile and fixed broadband performance on a price/quality basis today, the services appear to be imperfect substitutes. Yet, we are seeing a growing trend toward mobile-only subscribers.[70] The movement to 5G accentuates the capabilities of mobile broadband services, rendering mobile broadband (and fixed wireless broadband) an even stronger competitor for fixed broadband services.

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Changes in the markets for upstream applications are also driving the convergence of broadband services. The shift toward delivering entertainment media (especially television and movies) via the Internet in order to take advantage of faster broadband services is inducing a growing number of households to consider cutting the cord to their traditional Multichannel Video Programming Distributor (“MVPD”). Historically, most customers of fixed broadband services purchased a bundle of services from their telephone or cable provider. That bundle included broadband, television services, and often, telephone services as well. Wired broadband providers like to sell bundled services because it reduces their costs, enhances their subscriber revenues, and improves retention.

With more and more entertainment media becoming available via the Internet, customers are learning to appreciate the flexibility that over-the-top services provide (for instance, access to user content wherever the customer has a broadband Internet connection and on the device of the customer’s choosing), and over-the-top may also be less expensive, depending on a subscriber’s consumption habits. Traditional cable and telephone providers have been responding with their own services for accessing subscriber content via the Internet. As the range of Internet-available content and applications expands, and the broadband performance of mobile networks improves, more entertainment consumption can shift to mobile services. The expansion in viewing options and platforms is driving content and application providers to expand their distribution options to compete for viewer attention and to explore new ways to monetize their content assets. The shift from legacy MVPD models toward broadband-based models increases the potential for competition between mobile and fixed broadband access options.

At the same time that the mobile broadband user-experience is approaching the experience that previously was only available via fixed broadband services, fixed providers are adding mobile capabilities. Cable and DSL broadband providers recognized relatively early that allowing their subscribers to connect their broadband modems to Wi-Fi enhanced the usability and value of fixed broadband services within the home by allowing localized mobility. With the maturation of Wi-Fi and the proliferation of Wi-Fi services, Wi-Fi is increasingly seen as a substitute for mobile in many usage modalities that do not require support for high-speed movement. The wide-spread availability of Wi-Fi connectivity outside the home has prompted a number of new mobile offerings such as Google’s Project Fi,[71] Google’s mobile telephone offering that uses Wi-Fi in place of cellular service when available. Google purchases the cellular service as an MVNO wholesale from the MNOs. Comcast already offers its customers Xfinity Wi-Fi access via its installed base of Wi-Fi-enabled subscribers and recently launched a new mobile service.[72]

In the small cell world of 5G, the capabilities of LTE and Wi-Fi are increasingly comparable, all else equal.[73] Nomadic roaming (moving into the coverage area of a base station and then remaining stationary) is often well-suited for many attention-intensive broadband applications, which makes LTE and Wi-Fi better able to support comparable user experiences.[74] Additionally, in the small cell world, the economics of wired and wireless providers become increasingly similar since a greater share of the infrastructure is sunk in particular local locations (just as last-mile fiber has to be close to the end-users, so too do small cells). Providing the sort of local area-coverage required of 5G is analogous to the challenges of providing fiber to a town: the costs go up with the area covered, rather than with the number of subscribers. With earlier generations of mobile technology, it was easier to scale capacity with demand by starting with large cell sites and then adding sites as demand warranted.

Finally, the desire for a converged, seamless broadband experience is contributing to the convergence of wired and wireless services. Both providers are moving closer in terms of the capabilities they need to offer—wired and mobile providers are implementing SDN and NFV capabilities and connecting to cloud service providers and, in doing so, are becoming increasingly alike.

This assimilation is comparable to that which occurred with the first generation of broadband. Before broadband, telephone and cable television providers operated networks that were designed for distinct applications. Although both had wired infrastructure deployed to homes across the United States, the telephone-provider networks were designed for narrowband, two-way telephony while cable television networks were designed for one-way television distribution. With the move toward broadband platforms, the network architectures and the capabilities of the legacy telephone providers and cable television companies have coalesced. Today, Comcast and Verizon are more alike from a cost and product portfolio perspective than were the cable television and telephone companies of the 1980s. In an analogous process, the move to 5G will further drive convergence between wired and wireless network operators.

> **Providing the sort of local area-coverage required of 5G is analogous to the challenges of providing fiber to a town: the costs go up with the area covered, rather than with the number of subscribers.**

5.2 Stronger Competition Among MVNOs

The drive toward stronger MVNO competition will come from multiple sources. First, the increased capacity of the facilities-based networks will make it more likely that the networks will be able to support new sorts of MVNOs models and provide assurance that robustly competitive wholesale markets for capacity will be available to support the MVNOs.

Second, the intensifying competition among content (especially entertainment media providers noted earlier) and edge providers to offer more attractive offerings and to expand their control of the customer experience will create incentives for some to self-provision and manage more of the network functionality associated with the delivery of their products. The rise of CDNs, cloud services, and robust markets for the technologies that enable 5G will make self-provisioning a more viable option for the larger edge providers. This will create demand for MVNO strategies by larger content or application providers. In addition, increased retail market competition will provide increased opportunities for customer-segment-focused MVNOs (*e.g.*, focusing on a particular class of programming or customer segment, etc.). The entertainment and media industries are important economic sectors, and their intensifying competition will drive competition at the network and services level to support their growing demand for network capacity.[75]

Third, the potential to enable Smart-X opportunities will also contribute to expanded demand for MVNO business models. The greatest promise of 5G to contribute significantly to resurgent productivity and economic growth rests with these Smart-X opportunities, and because Smart-X applications are likely to have quite a bit of domain-specificity to them, meeting the ICT needs of Smart-X is likely to expand opportunities for specialized MVNO providers. Thus, although there will obviously be similarities between the telecommunication services that Smart-healthcare and Smart-agriculture will require (e.g., both will want users to make telephone calls), there are also likely to be important differences. For example, the cybersecurity requirements or the need to support particular types of IoT deployments may be quite different across application domains. When Smart-X takes hold, domain-specificity will be mission-critical for the businesses that are involved. In many contexts, that will make adopters anxious to retain significant control, especially when the Smart-X applications are deeply embedded within their business processes. 5G networks are intended to enable the sort of functionality and flexibility to allow enterprise customers to assume more direct control over how their enterprise networks are provisioned and managed. The largest enterprises may elect to operate their own in-house MVNOs, while smaller enterprises may opt to purchase services from domain-specific MVNOs.

Additionally, it is reasonable to expect that there may be benefits of scale, scope, or learning economies associated with some business functions (*e.g.*, potentially some aspects of ePayments clearing or support for a cryptocurrency like Bitcoin) that may lead the providers of such services to operate purpose-built networks. In the world of Content Delivery Networks ("CDNs"), the largest content providers (Netflix, Google, Facebook) have opted to build their own customized CDNs rather than continue to rely exclusively on third-party CDN providers.[76]

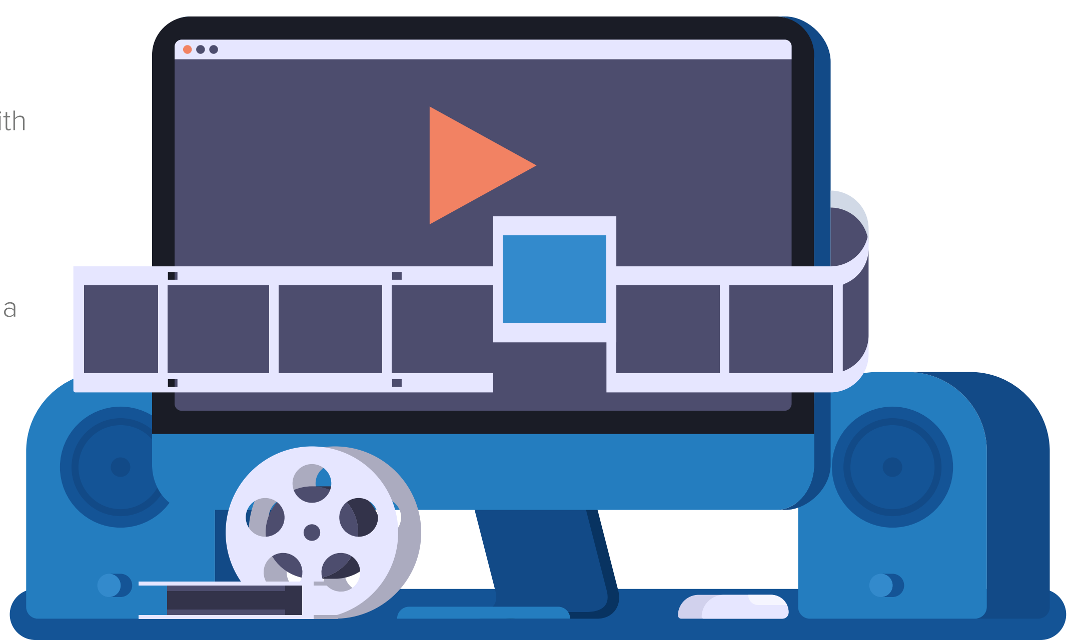
These demand considerations suggest that the market for specialized MVNOs that are either directly integrated with the application providers (*e.g.* Facebook or Netflix becomes an MVNO for their customers, or a Smart-healthcare or Smart-agriculture MVNO emerges that caters to the customized needs of its focus sector) will increase. In many cases, the MNOs may choose to pursue such vertical market opportunities by integrating forward with their own specialized operations. However, such efforts are not without problems. They can lead to channel conflicts when the MNO finds its retail operations competing directly with its wholesale operations that are selling to competing retailers.

The history of long distance telephone competition provides a ready example of how this can work to the benefit of those in favor of robust retail competition. In the 1980s, there were three national facilities-based wired telephony providers of long-distance service: AT&T, MCI, and Sprint. In addition, there were a large number of resellers that varied from partial facilities-based providers (*e.g.*, ones that may have operated a few switches) to pure resellers (*i.e.*, those who fully outsourced their network operations to one of the facilities-based providers and only managed the customer-facing retail operations).

These long distance resellers were able to offer significant competitive discipline, including significant price competition, because there was an active and competitive market for wholesale long distance services. Each of the three large facilities-based providers had to have excess capacity in order to meet peak traffic needs, and because capacity in facilities-based telecommunication networks has to be added in lumpy increments. If there were only one facilities-based provider, it could have priced its wholesale services to extract the resellers' surplus, denying them the ability to offer competitive discipline.

With three facilities providers, there was excess capacity available, and the incentives of selling this to resellers helped ensure that the national long-distance network operators could not collude to cartelize the wholesale market. The competitive market for wholesale long-distance telephone capacity contributed to ensuring a competitive market for resellers, which in turn, helped ensure aggressive competition in retail long distance services.

In the world of Content Delivery Networks ("CDNs"), the largest content providers (Netflix, Google, Facebook) have opted to build their own customized CDNs rather than continue to rely exclusively on third-party CDN providers.



Indeed, a reason the FCC concluded it was appropriate to deregulate markets for business telephone services in the 1990s (thereby helping advance the movement from legacy public utility regulation of telephone service toward market-based competition) was because of the widespread availability of bulk wholesale transport services in long-distance markets.[77]

In today's world of 3G/4G MNO competition, MVNOs already are playing an important role in sustaining robust retail service competition. MVNOs are especially relevant in the markets for discounted and pre-paid mobile services. With the transition to 5G, the scope of options for MVNO competition and their importance in the competitive landscape is expected to increase.

Moreover, the softwarization and virtualization capabilities noted earlier will make it easier for MNOs to offer MVNOs customized slices of their networks. These capabilities will make it feasible to support a robustly competitive wholesale market for the MNO services needed to support a robustly competitive ecosystem of MVNOs. Although the MNOs will be compelled to implement the softwarization and virtualization to lower their costs and to enable them to appeal to the increased demands for customized and enhanced services from ever-more-demanding end-users in order to compete against other MNOs, these same capabilities will make it harder for MNOs to collectively avoid the intensifying competition that will come from MVNOs.

5.3 Increased Competition From Specialized or Local Facilities-Based Entrants

A final vector for competition will come from local facilities-based entrants. In the 5G world of small cells and Smart-X environments, the potential for small, localized providers are greater. To the extent that high frequency spectrum in the millimeter wave bands (above 20 GHz) becomes important for 5G, making use of this spectrum will require small cells. The siting of small cells requires a lot of complementary infrastructure (site access, power, management of interconnection to wider-area networks) that may make more sense to manage locally where the spectrum is actually being used.

For many of the Smart-X applications (such as Smart cities), the natural manager and deployer of much of the 5G infrastructure may be the city or municipality. The city may be able to justify the investment costs on the basis of specialized applications such as IoT for public safety (*e.g.*, using sensors to detect gunshots and enable faster responses), for traffic management (*e.g.*, to reduce congestion, improve public transportation, and manage parking), or for monitoring critical infrastructure (*e.g.*, repair statuses of roads and bridges). In stadiums, factories, malls or other venues, the owner of the venue may be well-suited for deploying the infrastructure.

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In today's world of 3G/4G MNO competition, MVNOs are already playing an important role in sustaining robust retail service competition.

In addition to the above business models, there is growing interest in so-called “neutral hosts” business models. The case for these is to take advantage of the natural monopoly elements of much of the local 5G infrastructure by enabling the infrastructure to be shared. Softwarization and virtualization techniques that are used at the core of the networks can also be used in edge components, allowing those to be shared. A base station’s resources could be reconfigured to support multiple MNOs or sliced to provide MNOs with on-demand access to local 5G capabilities. MNOs have demonstrated their willingness to outsource components of their networks and share those with other MNOs already in the case of large coverage area cell sites. Historically, MNOs built out their mobile telephone networks by building their own cell towers. Today, most of the macrocell towers are owned by third parties who lease space on the towers to multiple MNOs. The towers support multiple base station radios. In a world of software radios, the towers can be smaller and the radios themselves can be shared.

The increased incidence of end-user enabled Wi-Fi roaming (campuses and venues providing free Wi-Fi access, home-owners sharing Wi-Fi) is another example of how end-user provided local networking infrastructure can offer a new vector for competition that is only conceivable in the world of wireless. With the improvements in support for seamless mobility which 5G promises, additional technical barriers to end-users in venues and communities are falling, creating competitive alternatives to MNO services.

While 5G is likely to enable new models for wholesale and retail local or otherwise specialized wireless facilities-based providers, these business models will not displace the need for national-scale MNOs, nor will they be likely to provide a sufficient platform for a wholesale market for facilities that would allow national scale MVNOs to survive without relying on the wholesale offerings of the national MNOs.

“With the improvements in support for seamless mobility which 5G promises, additional technical barriers to end-users in venues and communities are falling, creating competitive alternatives to MNO services.

6. Conclusion

The future of the global economy is digital. Remaining competitive and sustaining robust economic growth requires sustaining our critical ICT infrastructure's capacities for continued growth. Mobile broadband networks are key components of our national ICT infrastructure.

In the first four generations of their evolution, MNOs have been dominated by cellular networks. The fundamental economics of constructing and operating a national-scale telecommunications network implies that the industry structure will be oligopolistic but can also contribute to conditions for intense competition with a small number of facilities-based providers. Today, we have four national cellular MNOs that are competing aggressively against one another. Collectively, for over a decade, these four MNOs have sustained a record of performance that includes expanding capacity and falling quality-adjusted prices. The MNOs have sustained exponential growth in traffic and contributed significantly to national economic growth and the increased vibrancy of the entire Internet ecosystem.

With the transition to 4G LTE, of which we are still in the midst, the MNOs have finally consolidated on a common technology platform that makes them better able to flexibly manage diverse spectrum assets on the radio side, while allowing them to make use of a unified IP-platform on the data network side.

This sets the stage for closer convergence between fixed and mobile network providers and brings us one step closer to realizing the future of always and everywhere connectivity that is part of the vision of Pervasive Computing and the Smart-X future of converged real and virtual worlds. From an MNO network perspective, 5G represents the next round of order-of-magnitude improvements and investment that will be required to advance this vision and enable the potential for economic growth that Smart-X promises. However, even without Smart-X, MNOs need to continue to invest significantly in order to expand capacity and reduce the costs of carrying exponential growth in mobile broadband traffic. Most of this traffic growth in the near-term is associated with the explosion in entertainment video traffic, as more content shifts from traditional delivery platforms to broadband-based platforms, including increasingly mobile broadband.

Addressing exponential traffic growth cost-effectively while enabling the enhanced service management capabilities that 5G requires (and are being demanded by today's more demanding 4G MNO enterprise and consumer customers), MNOs are being compelled to adopt more agile spectrum management capabilities, softwarization and virtualization network architectures, and small cells all at the same time. For the national MNOs that want to remain full-service providers, this is contributing to the potential and need to realize ever-larger scale and scope economies. The scale necessary for operating a national-scale MNO is increasing, rendering it less viable for smaller MNOs (like T-Mobile or Sprint) to sustain the pace of investment required to remain competitive with the largest two MNOs (Verizon and AT&T).

At the same time, market and technical trends are driving the convergence of fixed and mobile networking and the enhanced capabilities and localization of advanced wireless networking are creating new vectors for competition that further puts pressure on legacy national MNOs. The best prospect for sustaining robust competition among national MNOs is via the merger of T-Mobile and Sprint to form New T-Mobile. The merger represents a pro-competitive response by two providers with synergistic reasons for combining to better address the challenges of remaining a viable competitor in the 5G future.

The future of broadband and 5G is uncertain, but the success of robust competition and demand for 5G holds the promise of significant economic growth. Wireless networks of all kinds will be important if the 5G vision is to be realized. A merger of T-Mobile and Sprint offers important benefits in terms of helping to ensure sustainable and viable facilities-based competition among MNOs in the near to middle-term, and in promoting aggressive investment across the entire broadband ecosystem directed at enabling the 5G vision. Additionally, realizing the 5G vision will expand options for new vectors of competition from MVNOs, local providers, and more intense intermodal competition among fixed and mobile network operators.

About the Author

Dr. William Lehr is an economist and industry consultant. He is a research associate in the Computer Science and Artificial Intelligence Laboratory at the Massachusetts Institute of Technology, currently working with the Communications Futures Program, which is an industry-academic multidisciplinary research effort focused on road mapping the communications value chain. Previously, Dr. Lehr was the associate director of the MIT Research Program on Internet & Telecoms Convergence, and was an associate research scholar and assistant professor on the faculty of Columbia University 's Graduate School of Business. Dr. Lehr's research focuses on the economics and regulatory policy of the Internet infrastructure industries. He teaches courses on the economics, business strategy, and public policy issues facing telecommunications, Internet, and eCommerce companies, and is a frequent speaker at international industry and academic conferences.

He has published articles on such topics as the impact of the Internet on the structure of the communications infrastructure industries, telecommunications regulation, and the pricing of Internet services. He is currently engaged in research on the convergence of the Internet and telecommunication services and the implications for corporate strategy and public policy.

In addition to his academic research, Dr. Lehr provides litigation, economic, and business strategy consulting services for firms in the information technology industries. Dr. Lehr has advised information technology companies on strategic marketing, pricing, financial planning, and competitive strategy; and government agencies in the United States and abroad on telecommunications policy matters. Dr. Lehr has prepared expert witness testimony for both private litigation and for regulatory proceedings before the FCC and numerous state commissions.

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SOURCES

[1] The author would like to acknowledge the support of T-Mobile in preparing this white paper. All views expressed herein are the author's own.

[2] The merger was announced April 30, 2018, and applications were filed with the FCC to transfer control on June 18, 2018. *See* Drew FitzGerald, Dana Cimilluca & Dana Mattoli, *T-Mobile Agrees to Buy Sprint in $26 Billion Deal,* Wall St. J. (Apr. 29, 2018), https://on.wsj.com/2HBQwd6; *Commission Opens Docket for Proposed Transfer of Control of Sprint Corporation to T-Mobile US, Inc*., Public Notice, DA 18-625 (rel. June 15, 2018), https://bit.ly/2AQaBJq.

[3] See Morgan Stanley, *Telecoms Send Mixed Signals on 5G Wireless* (Nov. 9, 2017), https://mgstn.ly/2vLY07U.

[4] For example, McKinsey & Co. forecasted the potential global impact of IoT to be $3.9 to $11.1 trillion per year by 2025. *See* McKinsey & Co., *The Internet of Things: Mapping the Value Beyond the Hype 3* (June 2015), https://mck.co/2gyPezB ("Value Beyond the Hype").

[5] *See* Kevin Barefoot et al., Bureau of Econ. Analysis, Dep't of Commerce, Defining and Measuring the Digital Economy 3 (Mar. 15, 2018) (working paper), https://bit.ly/2Lcov8O; Roger Entner, *The Wireless Industry: Revisiting Spectrum, The Essential Engine of US Economic Growth*, Recon Analytics LLC 8 (Apr. 2016), https://bit.ly/2mCOEE0.

[6] If and when we actually achieve the 5G performance targets identified in the ITU specifications (*see* Int'l Telecomm. Union, *Recommendation ITU-R M.2083-0: IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond* (Sep. 2015), https://bit.ly/2bl8QU2) ("IMT Vision"), then we may choose to identify the next steps forward as "6G."

[7] Networking allows resources to be accessed, combined and shared. A networked computer is much more useful and powerful than a standalone computer. Moreover, networked computing, storage and communications (transport) resources can act as substitutes, expanding the productive potential when used together. For example, in telecommunication networks, transmission capacity needs (and hence, costs) and traffic loads may be reduced using computation (video compression) or storage (content caching). Such resource flexibility and substitutability expands options for load balancing and customizing service offerings.

[8] The world of IoT includes individuals talking to appliances and machines talking to other machines ("m2m"). The appliances and machines may be big (*e.g.*, HVAC system in a building, factory machine tool, or mainframe computer) or small (*e.g.*, a sensor/actuator embedded in a pet or in the environment). In a 5G world of Pervasive Computing, the availability of networks and computing resources should not be limiting constraints on who or what is able be digitally networked.

[9] The vision of Pervasive Computing expressed here is optimistic in so far as it describes how ICTs can expand the productive frontiers of the economy; however, this does not mean that we will succeed in operating at the productive frontier or that there will not also be problems or that everyone is or should be happy with the prospect of living in a world where computers and electronic communications are more ever present than already. Such normative considerations are beyond the scope of this paper.

[10] Choice in connection modalities is important for many users and applications. For example, privacy and cybersecurity considerations call for nuanced control and support for multiple options over how end-users (whether individuals or devices) are digitally connected in the 5G future.

[11] Mobility can mean a range of things: services should be sustained at both high speeds (*e.g.*, while flying in a plane or driving down the highway) and low speeds (*e.g.*, sitting at a café or walking through a mall). Indeed, fixed location services are just a special case of a mobile service. Portability is a form of mobility and implies the ability to move a service across platforms or to new locations or contexts (*e.g.*, accessing television services from multiple devices). Enabling seamless mobility allows end-users or their applications to connect via multiple devices and to have a predictable and satisfactory experience that is supported as they move through the environment where the movement can occur in any dimension (*e.g.* geo-space, time, or context). Ensuring seamless mobility presents a significant challenge since individual flows have to be protected from congestion and other network disruptions.

[12] Ubiquitously available means everywhere in geospace (*e.g.* inside buildings, in the city and in the woods) and with sufficient capacity to meet demand over time whenever, wherever demand arises.

[13] Since demands will naturally fluctuate as individuals and their devices change what they are doing, capacity and services will need to adapt in real-time, scaling as needed.

[14] These performance targets are based on the ITU-2020 requirements. *See* IMT Vision.

[15] Faster data rates provide additional head-room to accommodate fluctuations in performance. For example, faster-than-real-time delivery of content can feed buffers that can be used to smooth temporary congestion. This also contributes to lowering costs by enabling more efficient network management since increased tolerance for temporary congestion reduces the peak capacity provisioning requirements, allowing the network to be operated closer to full utilization.

[16] *Productive efficiency* means that goods and services are produced at the lowest resource cost; *allocative efficiency* means that scarce resources are devoted to their most valuable, welfare-maximizing uses; and *dynamic efficiency* means efficiency is preserved over time.

[17] ICT-enhanced business intelligence can help improve forecasting, enable real-time monitoring for rapid response to changes, and empower operational management.

[18] Network or application performance can be customized on a more granular and dynamic basis with respect to time, geo space, or context. This allows services to adjust as user needs change over time (*e.g.*, to accommodate fluctuating needs for faster data rate support based on what the user is actually doing), by location, or by context (*e.g.*, accommodating different traffic management or security requirements depending on the nature of the application). Finer granularity means customizations can occur over shorter time-scales (real-time), smaller geographic areas (personal-space wireless networks), and more complex (rich) contexts. Enhanced ability to customize services to supply-and-demand conditions unlock economic surplus (customer value and cost-saving opportunities). For example, the ability to respond automatically to faults (*e.g.*, re-route traffic, send alerts) can enhance the robustness and reliability of services, better managing risks and enabling more predictable services.

[19] Users can control which device to answer a video call on and trust that the service will provide a good and predictable experience wherever they are (in town or in the country, indoors or outdoors, at home or at a concert, etc.).

[20] *ICTs* allow richer, faster, and more flexible communications and decision-making by enabling electronic communication, information gathering, computation and control at a distance. This makes it feasible to reorganize economic activities to make them more responsive to changes in local conditions. *Just-in-time* production enables faster inventory turnover, higher factory utilization rates, and closer matching of market supply and demand, which helps businesses lower costs. Such capabilities have become increasingly necessary for firms to compete in the digital economy. *Market-of-one* customization refers to the ability of ICTs to allow economic decisions to be customized on a more granular basis, from real-time-control of factory production to on-demand manufacturing of custom-fit blue jeans.

[21] *See* Value Beyond the Hype. Other analysts have produced similarly large estimates: Bain forecasts 2020 annual revenues for IoT could exceed $470B; General Electric predicts investment in industrial IoT to top $60 trillion over the next 15 years (*see* Louis Columbus, *Roundup Of Internet Of Things Forecasts and Market Estimates*, *2016*, Forbes (Nov. 27, 2016), https://bit.ly/2Lw3ie0). For additional estimates, *see* Adam Thierer & Andrea O'Sullivan, *Projecting the Growth and Economic Impact of the Internet of Things*, Mercatus Center, George Mason Univ. (June 15, 2015), https://bit.ly/2O7Reyd.

[22] *See Accenture, Winning with the Industrial Internet of Things* 3 (2015), https://accntu.re/2mynldl.

[23] *See Accenture, Smart Cities: How 5G Can Help Municipalities Become Vibrant Smart Cities* 1 (2017), https://bit.ly/2pMuM4y.

[24] For example, the digital transformation will require workers with the appropriate digital skills and automation will reduce demand for labor in many traditional tasks. Acquiring the requisite skills is shifting education toward lifetime learning (something that eLearning solutions can help with). Within industries, some firms are more successful than others in adapting to the new digital

economics, and the new digital capabilities are creating new markets and redefining market boundaries. The uneven growth can contribute to Digital Divides along many dimensions. A number of authors have pointed to the need for national strategies to help coordinate policies across all sectors of the economy in order to realize the benefits of investments in ICTs. *See, e.g.*, World Bank, *World Development Report 2016: Digital Dividends* (May 2016), https://bit.ly/2werCaF; Nagy K. Hanna, *Mastering Digital Transformation: Towards a Smarter Society, Economy, City and Nation* (2016).

[25] The fact that mobile users often access broadband data and other cellular services via Wi-Fi demonstrates how entwined the worlds of fixed and mobile broadband have become. Indeed, the ability to off-load cellular traffic to fixed broadband networks via Wi-Fi has enabled cellular traffic to scale faster than would have been possible if all of the traffic had to be carried with existing cellular capacity. For a discussion of the benefits of Wi-Fi off-loading, *see* Richard Thanki, *The Economic Significance of License-Exempt Spectrum to the Future of the Internet* 36-40 (June 2012), https://bit.ly/2LeGzEi.

[26] Some of the advanced technologies that 5G will need to make use of include RF in millimeter wave bands (above 30 GHz), massive MIMO (using multiple antennas to allow disambiguation of digital signals that follow different paths from the transmitter to the receiver), beamforming (antenna technology to provide fine-grained focusing of radio signals), full duplex (enabling the same frequency for simultaneous reception and transmission which eliminates the need for paired frequencies for upstream and downstream channels), and small cells (to expand spectrum capacity, take advantage of smaller/portable base stations with lower power and smaller antennas, etc.). For a layman's description of these technologies, *see* Amy Nordrum & Kristen Clark, *Everything You Need to Know About 5G*, IEEE Spectrum (Jan. 27, 2017), https://bit.ly/2OV1Dhh.

[27] *Softwarization* refers to the replacement of traditional "hardware" solutions with software solutions. Once business and technical functionality is moved into software it is easier to modify and relocate. *Virtualization* refers to the capability, enabled by softwarization, of creating a virtual machine platform that can simulate the operations of different hardware and software environments and isolate those simulations from the underlying hardware and software on which it is deployed and from other virtual machines that may share those resources. *See, e.g., What is Virtualization?*, Red Hat, https://red.ht/2nINDAn (last visited Aug. 8, 2018).

[28] *See* Cisco, *Cisco Visual Networking Index: Forecast and Methodology, 2016-2021* (Sep. 15, 2017), https://bit.ly/2mxglxY ("Cisco VNI Sept 2017").

[29] In 2016, video already accounted for 60 percent of traffic. *See* Cisco, *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021 White Paper* (Mar. 28, 2017), https://bit.ly/2vu69MQ. By 2020, Cisco forecasts that Internet video traffic will be 82 percent of all consumer Internet traffic in 2020, up from 73 percent in 2016 (*see* Cisco VNI Sept 2017).

[30] Audio and video offerings are being offered with differing degrees of resolution (but increasingly those options include higher-resolution options) and access to expanded libraries ("infinite" digital libraries). Providing access to ever-larger libraries of content imposes additional challenges on the underlying network infrastructure. For example, encoding content incurs a computation cost. For popular content that is to be viewed many times by multiple consumers on multiple devices (each requiring different resolution), it may be optimal for the content provider to incur the fixed encoding cost once and then incur the costs to cache multiple copies close to the consumers (to reduce access latency and transport costs). For rarely viewed content, the provider may elect to store the content at more remote servers, encode the content on the fly, and rely on faster (potentially real time) network delivery to get the content to the consumer so that the consumer has a responsive, high-quality experience regardless of what selection the consumer is making from the provider's digital archives. Meeting the more demanding requirements of content and application providers requires the MNOs to upgrade their networks. Failing to do so risks the largest content providers integrating forward to provision their own customized delivery networks, something that is also happening as I discuss further below.

[31] Radio networks operating in different bands and local environments have quite different design and operating constraints. For example, lower frequency spectrum is less abundant (there is only 1 GHz below 1 GHz but lots more spectrum above that), more crowded, but has better non-line-of-site ("NLOS") propagation and requires fewer cell sites per area to provide coverage and is better at penetrating walls and other obstructions (*e.g.*, leaves). Higher frequency spectrum is more abundant (offering more bandwidth capacity), the antennas are smaller (good for multiple antennas and smaller radios), but it is less capable of penetrating obstacles and supporting NLOS connectivity. However, advances in radio technologies from signal processing (e.g., new modulation schemes and MIMO) to antenna design (*e.g.*, arrays) have allowed radio networks to better address the challenges posed by operating with different spectrum resources.

[32] The same equipment and software solutions that the large national MNOs are using to more efficiently manage their large and diverse portfolios of spectrum assets are providing would-be competitors new options for overcoming asymmetric spectrum access costs.

[33] For further discussion of what the transition to smaller cell architectures will mean *see* William Lehr & Miquel Oliver, *Small Cells and the Broadband Ecosystem* (25th European Regional Conference of the International Telecommunications Society, conference paper, June 2014), https://bit.ly/2OmczmL ("Small Cells and the Broadband Ecosystem").

[34] *See* Cisco, *Fog Computing and the Internet of Things: Extend the Cloud to Where the Things Are* (2015), https://bit.ly/2eYXUxj; Tuyen X. Tran et al., *Collaborative Mobile Edge Computing in 5G Networks: New Paradigms, Scenarios, and Challenges*, IEEE Comm., Apr. 2017, at 54-61, https://bit.ly/2nvF5Y1.

[35] Not all 5G devices and networks will be connected to MNO networks or be globally accessible via the Internet. Privacy, cybersecurity, cost, market strategy or other concerns may provide a basis for end-users or 5G service providers to control how devices connect. For example, application developers for home, factory, or office automation may wish to deploy 5G sub-networks downstream of firewalls or even as isolated, standalone (sand-boxed) networks. Even if such networks never connect to MNO's networks, they will be part of the 5G wireless ecosystem and contribute to the aggregate demand for 5G technology.

[36] *See* Olga Kharif & Scott Moritz, *Upgrade to 5G Costs $200 Billion a Year, May Not Be Worth It*, Bloomberg (Dec. 18, 2017), https://bloom.bg/2Bb8nnK.

[37] *See* Diana Goovaerts, *iGR Study Forecasts $104B Cost to Upgrade LTE Networks, Build Out 5G Network*, Wireless Week (Dec. 7, 2015), https://bit.ly/2mBjHjk. Another study by Deloitte Consulting estimates that an additional $130 to $150 billion in fiber investment will be required over the next five to seven years to support the transition to 5G. *See* Deloitte, *Communications Infrastructure Upgrades* (July 2017), https://bit.ly/2LJ9JY0.

[38] SNL Kagan forecasts that there will be 138,000 small cells by the end of 2018 and 363,000 by the end of 2021. The SNL Kagan forecast is reported in an Accenture strategy report, *see* Accenture, *Impact of Federal Regulatory Reviews of Small Cell Deployment* 3 (Mar. 12, 2018), https://bit.ly/2JKXkRC.

[39] Herbert Blum et al., *Why the 5G Pessimists are Wrong*, Bain & Co. 4 (June 28, 2018), https://bit.ly/2Mblday.

[40] Sprint Corp. and T-Mobile US, Inc., Joint Application for Consent to Transfer Control of International and Domestic Authority Pursuant to Section 214 of the Communications Act of 1934, as Amended, Declaration of David Evans, WT Docket No. 18-197 at 41 (June 2018), https://bit.ly/2Lt25Ex ("Evans Decl.").

[41] An Exabyte is a billion Gigabytes ("GB"). Ericsson, *Ericsson Mobility Report*, at 14, 33, 35 (June 2017), https://bit.ly/2szKfGz.

[42] *See* Ferry Grijpink et al., *The road to 5G: The inevitable growth of infrastructure cost*, McKinsey & Co. Telecomm. (Feb. 2018), https://mck.co/2uUn2he.

[43] *See* Balamurali Thekkedath, *Network Functions Virtualization for Dummies* (2016) https://bit.ly/2Ldi6iu; Kathy Pretz, *The 'Softwarization' of Telecommunications Systems*, IEEE: The Institute (July 20, 2016) https://bit.ly/2bdClpM; Naoki Oguchi et al., *Virtualization and Softwarization Technologies for End-to-end Networking*, 53 FUJITSU Sci. Tech. J. 78-87 (2017), https://bit.ly/2AT6H2v.

[44] Oughton and Frias (2017) estimate that the transition to SDN and NFV can significantly reduce operating costs (63%) and capital costs (68%) relative to traditional cost models. *See* Edward Oughton & Zoraida Frias, *The Cost, Coverage and Rollout Implications of 5G Infrastructure in Britain*, Telecomm. Policy 3 (July 29, 2017), https://bit.ly/2L4ScIV.

[45] *See* Craig Mathias, *What is Virtualization?,* Network World (Oct. 26, 2017), https://bit.ly/2zRdAgr; *What is virtualization?*, Red Hat, https://red.ht/2tZDa43 (last visited July 1, 2018).

[46] *See* Charles McLellan, XaaS: *Why 'Everything' is Now a Service*, ZDNet (Nov. 1, 2017) https://www.zdnet.com/article/xaas-why-everything-is-now-a-service/.

[47] *See* Press Release, Gartner Inc., *Gartner Forecasts Worldwide Public Cloud Services Revenue to Reach $260 Billion in 2017* (Oct. 12, 2017), https://www.gartner.com/newsroom/id/3815165. Public clouds are distinguished from private cloud services. Public clouds are accessible via the Internet and are shared infrastructure.

[48] Fat clients are more substantial user applications running on more capable edge-devices like personal computers or higher-end tablets or smartphones that have on-board computing and storage capabilities to support a high-degree of functionality on the end-user device. Thin clients are less substantial and need to rely more heavily on network-hosted cloud resources and services for computing, storage and other communications functionality. Thin clients may run on high-end, capable devices (a question of application design) or on much less capable devices, such as digital appliances (sensors) that lack the on-board capacity to support fat client applications. Peer-to-peer computing (associated in the mass market with the rise of personal computing) is associated with fat clients, whereas client-server architectures are often associated with thin clients, and now with cloud architectures. The choice of fat or thin client involves a choice of where to put ICT smarts and has implications for power utilization, management control, security, reliability, and virtually every other aspect of computer system design.

[49] The communications capacity of RF is limited by the ability of receivers to disambiguate the information in the signals they want to receive. The signals from other transmitters appear as noise to a receiver. Technology allows signals associated with different transmissions to be separated in many ways—in time, space (separate the transmitters and receivers in geo-space or by the direction in which the signals move through the air), in code (use digital codes to identify packets of information destined to particular receivers), or some other dimension in which RF waveforms may be modified. The limits of receiver technology and wireless network infrastructure limit the effective capacity of our spectrum resources.

[50] With certain types of traffic (*e.g.*, legacy voice telephony), well-known probability distributions (*e.g.*, Erlangs) can be used to model the stochastic behavior of traffic. However, in the rapidly evolving markets for wireless services, no one has a perfect crystal ball to forecast how the mix of traffic will evolve and the expanding matrix of players with control over traffic flows (from end-users to CDNs, from device manufacturers to ISPs) renders traffic planning inherently uncertain. This increases the need for the network flexibility and rapid scalability of 5G networks and cloud services that is supported by the fundamental trends discussed earlier.

[51] Typically, for network critical functionality for a large network, redundant "hot" facilities are needed, which means two network operations centers, each with the capability of assuming control of the functionality in the event that one of the NOCs goes down. The need to provision for highly reliable services further increases the costs of network provisioning. *See* William Lehr, *Reliability and the Internet Cloud* (June 2012), https://bit.ly/2O9Arul.

[52] As will be discussed further below, these are forces helping to propel the drive toward more extensive MVNO and niche competition.

[53] As noted earlier, with small cells it is easier to target capacity investments to local hot spots, enabling more fine-grained management of capacity expansions (rendering such investments less lumpy and more scalable); however, the significant growth in aggregate traffic volumes continues to require substantial investments in expanding capacity across the network.

[54] It is worth noting that the enterprise offerings of T-Mobile and Sprint are much more limited than those available from AT&T and Verizon.

[55] *See Implementation of Section 6002(b) of the Omnibus Budget Reconciliation Act of 1993, Annual Report and Analysis of Competitive Market Conditions with Respect to Mobile Wireless, Including Commercial Mobile Services*, Twentieth Report, 32 FCC Rcd 8968, Table II.B.1 (2017) ("FCC 20th CMRS"). The FCC 20th CMRS only provides data on combined MNO retail and wholesale connections. The FCC does not provide data separately for retail and wholesale connections.

[56] *See Implementation of Section 6002(b) of the Omnibus Budget Reconciliation Act of 1993, Annual Report and Analysis of Competitive Market Conditions with Respect to Mobile Wireless, Including Commercial Mobile Services*, Fourth Report, 14 FCC 10145, Table 4 (1999) ("FCC 4th CMRS") (for 1997 data); *Implementation of Section 6002(b) of the Omnibus Budget Reconciliation Act of 1993, Annual Report and Analysis of Competitive Market Conditions with Respect to Mobile Wireless, Including Commercial Mobile Services*, Eleventh Report, 21 FCC Rcd 10947, Table 4 (2006) ("FCC 11th CMRS") (for 2005 data). In 2005, AT&T had not yet acquired BellSouth (renamed Cingular Wireless), which occurred in 2006. *See Cingular Merger Timeline,* AT&T, https://soc.att.com/2KyezYh (last visited Aug. 1, 2018).

[57] Subscribership has grown from 46,375,849 (1997) to 378,554,642 (2016) (*see* Table III.A.ii in FCC 20th CMRS). Wireless data use has increased from 388 billion MB (2010) to 13.7 trillion MB (2016) (*see* app. 1, Chart 1, FCC 20th CMRS).

[58] See Evans Decl., Tables 4 and 16.

[59] *See* FCC 20th CMRS, Chart II.C.1 (2016 Revenue Shares). As discussed above, the FCC 20th CMRS does not provide data that would allow one to present shares separately on the basis of retail connections.

[60] The data for this table is reproduced from Evans Decl., Exhs. 8-9.

[61] *See* FCC 20th CMRS, Chart II.B.6. Higher churn rates imply higher customer acquisition costs and other operating costs, adding to the challenges that T-Mobile and Sprint must confront.

[62] Sprint and T-Mobile are using their spectrum to support their 4G LTE customers and the need to continue providing service to those customers during the transition limits the spectrum and other resources available to build out their 5G networks.

[63] The French government presented a roadmap for deploying 5G networks across France on July 16th. *See* Sandrine Cassini, *Sebastien Soriano: Sur la consolidation dans les télécoms, la porte de l'Arcep s'entrouvre*, Le Monde (May 22, 2018), https://lemde.fr/2Lmcu5v.

[64] See Dep't. for Digital, Culture, Media and Sport, *Future Telecoms Infrastructure Review*, July 23 2018, ¶ 190, (July 23 2018), https://bit.ly/2OPAZ8m.

[65] *Id.* ¶ 191.

[66] The personalization of mobile services has benefits and costs—it gives individuals potentially better control over how their service is used but it may make it difficult to share resources with others. The ability to use cellular services as mobile hotspots (allowed under many subscriptions) or to pool data allowances can mitigate those differences.

[67] For subscribers for whom the performance of mobile broadband is good enough or who are budget constrained, on a quality-adjusted price basis, mobile broadband may be a sufficiently good substitute to induce those subscribers to cut the cord. In economic terms, however, mobile and fixed are likely to be substitutes in-so-far as an increase or decrease in the price of one is likely to result in an increase or decrease in the demand for the other. *See* William Lehr, *Mobile Broadband and Implications for Broadband Competition and Adoption,* Social Science Research Network 23-24 (Nov. 2009), https://bit.ly/2KFMo8p.

[68] The data from the July-December 2016 survey found that 50.8% of the households in the U.S. were wireless-only (*see* Stephen J. Blumberg & Julian V. Luke, Nat'l Ctr. for Health Statistics, *Wireless Substitution: Early Release of Estimates from the National Health Interview Survey, July-December 2016* 1 (May 2017), https://bit.ly/2pC9LZ7).

[69] Fixed line telephones have been declining for years. For quite a while, the need for dial-up Internet access, fax, and second lines for children drove many households to subscribe to multiple fixed telephone lines. With the rise of Voice over Internet Protocol (VoIP) telephone service, a growing number of subscribers started using their broadband access connections to support their telephone service. Today, providers like Comcast and Verizon provide their telephone service via VoIP, but do not route it via the broadband access service. Although increasingly, most who offer basic VoIP telephone service also offer an Internet application to allow their subscribers to use their fixed line telephone service as a mobile service wherever the subscribers have a broadband access connection.

[70] *See* Aaron Pressman, *Why cord cutting is spreading to broadband Internet subscribers*, Fortune (Oct. 5, 2016), https://for.tn/2OV3HWv. Pew Research surveys found that 20% of adults do not use broadband at home, but have smartphones, which is up from 8% in 2013 (*see* Pew Research Center, *Mobile Fact Sheet* (Feb. 2018), https://pewrsr.ch/2inUJzB).

[71] *See* Andrew Martonik & Joe Maring, *What is Project Fi, how does it work, and why do I want it?*, Android Central (Aug. 15, 2018), https://bit.ly/2OpZIWp.

[72] *See* Mari Silbey, *US Cable WiFi Hotspots Near 17 Million, Light Reading* (July 6, 2016), https://ubm.io/2LsBQOt; *see also* Klint Finley, *Comcast's New Mobile Service is a Good Deal, But Maybe Not Good Enough*, Wired (Apr. 6, 2017), https://bit.ly/2o04jfA.

[73] *See* Small Cells and the Broadband Ecosystem.

[74] For example, a user who wants to review a spreadsheet or watch a movie is unlikely to want to do that when driving a car (although the passengers may wish to). Moreover, seamless lower-speed service hand-offs are increasingly able to be supported in Wi-Fi networks (*e.g.*, keeping a telephone call connected while moving from one Wi-Fi access point to another at walking speeds).

[75] Although the changing dynamics of competition in the entertainment industries will drive additional economic growth, much of the economic impact will be associated with shifting revenues and profits among industry players rather than creating new economic opportunities. For example, the movement of video entertainment to Internet platforms accessed via broadband access results in revenues being displaced from traditional subscription cable and satellite TV services to new channels rather than the creation of wholly new revenue streams. For further discussion, *see* William Lehr & Douglas Sicker, *Would You Like Your Internet With or Without Video?*, 2017 J. of L., Tech. & Policy 73-140, https://bit.ly/2A0nNLl.

[76] *See, e.g.*, Volker Stocker et al., *The Growing Complexity of Content Delivery Networks: Challenges and Implications for the Internet Ecosystem,* 41 Telecomm. Policy 1003-1016 (2017), https://bit.ly/2Ol8AH8.

[77] In 1991, the FCC found the outbound business services market segment to be "substantially competitive" based principally on its finding "that the business services marketplace is characterized by substantial demand and supply elasticities." *Competition in the Interstate Exchange Marketplace*, Report and Order, 6 FCC Rcd 5880 ¶ 36 (1991). That finding was reaffirmed (*see AT&T Corp.*, Order, 11 FCC Rcd 3271 ¶ 89 (1995)) and a similar finding was made with respect to inbound (*i.e.*, 800) services in 1993, once 800 numbers were made portable (*see Competition in the Interexchange Marketplace,* Second Report and Order, 8 FCC Rcd 3668 ¶ 10 (1993)).

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