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Perspective

EXPERT INSIGHTS ON A TIMELY POLICY ISSUE

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America's 5G Era

Strengthening Current and Future U.S. Technical Competitiveness in 5G

Scientific and engineering achievements have the potential to reshape the global competitive landscape, repositioning companies and nations to dominate future markets. Accordingly, the capacity to harness emerging technologies has significant implications for the balance of military and economic power around the globe.

Like its predecessors, the fifth-generation telecommunications technology (5G) wireless communication has the potential to be a transformative technology and a fertile ground for disruptive innovation. 5G mobile technologies will increase the speed of data transfer, reduce latency, and fuel an expansive growth of mobile devices over the next decade. Emerging applications, such as artificial intelligence (AI), autonomous vehicles (AVs), and the Internet of Things (IoT) have enormous market potential and will rely heavily on next generation wireless connectivity.

Although innovation and technological achievements provide consumer products, patents, and other tangible metrics of progress, the full breadth of technical competition includes the supply chain, industrial base, presence in global standards committees, and more. Facing stiff foreign competition, American technological leadership has eroded in many of these critical segments over the past few decades. This erosion is a complex phenomenon without a single cause; it results from a large number of factors—including the economic development of other nations, internal and external demographic changes, differing policy and regulatory decisions between nations, and changes in the nature of key technologies themselves (e.g., the combination of increasing economies of scale and decreasing transportation costs). Reestablishing technical leadership will be the primary challenge for the United States in the 5G era, although no single group of U.S. actors will be able to achieve this by themselves. Through effectively partnering with allies, investing in advanced research, becoming more active in international standards-setting bodies, and helping protect against intellectual property theft, the United States can regain the technical leadership that it once

Abbreviations

3GPP	3rd Generation Partnership Project
5G	fifth generation
5GC	5G Core
AI	artificial intelligence
AV	autonomous vehicles
AWS	Advanced Wireless Service
CBRS	Citizens Broadband Radio Service
COVID-19	coronavirus disease 2019
DSS	dynamic spectrum sharing
eMBB	enhanced Mobile Broadband
FCC	Federal Communications Commission
Gbps	gigabits per second
GHz	gigahertz
GSMA	Global System for Mobile Communications Association
IoT	Internet of Things
LAA	License Assisted Access
LBT	listen-before-talk
LTE	Long-Term Evolution
Mbps	Megabits per second
MEC	multi-access edge computing
MHz	megahertz
MIMO	multiple-input multiple-output
mMTC	Massive Machine Type Communications
mmWave	millimeter wave
ms	milliseconds
NGMN	Next Generation Mobile Networks Alliance
NR	New Radio
NSA	non-standalone
NTIA	National Telecommunications and Information Administration
O-RAN	open radio access network
PCS	personal communications service
R&D	research and development
RAN	radio access network
RF	radio frequency
SA	standalone
SEP	standard essential patent
SMIC	Semiconductor Manufacturing International Corporation
telecom	telecommunications
TSMC	Taiwan Semiconductor Manufacturing Company
UE	user equipment
URLLC	ultra-reliable low-latency communications

enjoyed. Although these elements are not unique to 5G and will continue to play out over a broad variety of emerging technological fields, 5G will be a significant piece of the larger competition for global leadership.

This Perspective focuses on the technical aspects of 5G and discusses how the United States can remain a competitive technology player in advanced wireless communications. Our findings might be of interest to a broad variety of policymakers throughout the U.S. government, whether they are directly involved with promoting 5G technology (e.g., through spectrum licensing, export control policy, or research and development [R&D]) or they anticipate eventually benefiting from new 5G applications. We mostly focus on considerations for policymakers in the federal government, but also briefly touch on considerations for state and local governments.

Technical competition in the 5G era involves many different elements of the 5G ecosystem. This analysis will focus on spectrum availability, hardware and software components, and applications, and briefer discussions of patents and technical talent. The rest of this Perspective considers each of these elements, assesses its importance, and discusses U.S. competitiveness with other leading nations. Our main findings are summarized in the Conclusion section. This Perspective was completed in June 2020. Although 5G deployment has continued to advance since then, we believe that the issues raised here are still highly relevant today.

5G Technical Overview

The evolution toward 5G has been underway for several years. In 2015, the Next Generation Mobile Networks (NGMN) Alliance published a white paper articulating a vision for 5G as "an end-to-end ecosystem to enable a fully mobile and connected society."[1] A key takeaway from this early white paper is the emphasis on value creation through use-cases, customer experience, and business models, which laid the foundation for the formalized standards to come. In contrast, prior generations were predominantly driven by technological advances that delivered notable step changes in performance or coverage; use-cases then often followed. For instance, the first generation (retroactively termed *1G*) introduced cellular phones, in the analog form; 2G went digital and brought about significant improvements in security, quality, and delivered text messaging; 3G brought us online and enabled mobile data support for web browsing and video calls; 4G brought the full internet experience closer to the user, which was enabled by the arrival of smartphones. 4G would later go on to enable several disruptive services, including such photo- and video-sharing services as Instagram and TikTok, and such ridesharing services as Lyft and Uber. The improvements in each generation are depicted in Figure 1.

The early 5G vision first focused on families of use cases and the associated performance requirements, and second on developing and deploying the technological infrastructure and ecosystem to meet those needs. Of particular interest, beyond the enhanced mobile bandwidth demanded by the already pervasive video traffic,[2] were

- greater user mobility (including service for high speed vehicles [trains traveling 500 km/hr]) and broad coverage in remote areas (50+ Megabits per second [Mbps] everywhere)
- high density connections for dense urban environments, stadiums, and for large IoT deployments

FIGURE 1

Generations of Mobile Communication

1G	2G	3G	4G	5G
Analog Voice (1979)	Digital Cellular (1991)	Mobile Broadband (2001)	Long Term Evolution (2008)	5G New Radio (2019)
Standards • AMPS	**Standards** • GSM • CDMA	**Standards** • UMTS • CDMA2000	**Standards** • LTE • WiMAX	**Standards** • 5G NR
Capabilities • Analog Voice	**Capabilities** • Digital Voice • Encrypted Communication • SMS and MMS text messaging	**Capabilities** • Mobile Broadband (200 Kbps) • GPS Services • Multimedia Streaming • Global Roaming	**Capabilities** • High speed mobile broadband • IP-based packet switching • High definition Multimedia Streaming • Global Roaming	**Capabilities** • High speed mobile broadband • Ultra-low latency • Massive connectivity
	Extensions • GPRS (2.5G) • CDMA2000 (2.5G) • EDGE (2.75G)	**Extensions** • HSPA+ (3.5G) • EV-DO		
	Technologies • CDMA • TDMA	**Technologies** • W-CDMA • Beamforming • MIMO • QAM	**Technologies** • OFDMA • Extended MIMO • Carrier Aggregation (CA) • Higher QAM • Early virtualization	**Technologies** • Massive MIMO • Advanced Beamforming • Extended Spectrum Access (mid-band, mm Wave) • Small Cell Density • Network functions virtualization • Mobile Edge Computing • Advanced Channel Coding (LDPC)
Applications • Analog Voice	**Applications** • SMS and MMS text messaging	**Applications** • Early smartphone • Navigation services • Multimedia streaming	**Applications** • Smartphone • High definition mobile video • Wearables • Augmented Reality • Internet of Things (IoT) • Early Private Networks • Ridesharing Apps	**Applications** • Autonomous Vehicles • LoT • Edge Computing • Industry 4.0 • Others yet-to-be identified
				

SOURCE: RAND analysis based on Siemens, “Industrial 5G For the Industry of Tomorrow,” webpage, undated.

NOTES: CDMA = Code-Division Multiple Access; EV-DA = Evolution-Data Optimized; EDGE = Enhanced Data Rate For GSM Evolution; GPRS = General Packet Radio Service; GPS = Global Positioning System; GSM = Global System for Mobile Communications; HSPA = High Speed Packet Access; IP = internet protocol; LDPC = low-density parity-check; LTE = Long-Term Evolution; MIMO = multiple-input multiple output; MMS = Multimedia Messaging Service; mmWave = millimeter wave; OFDMA = orthogonal frequency division multiple access; SMS = Short Message Service; TDMA = Time-Division Multiple Access; UMTS = Universal Mobile Telecommunications Service; W-CDMA = Wideband Code-Division Multiple Access; WiMAX = Worldwide Interoperability for Microwave Access; QAM = quadrature amplitude modulation.

- extreme real-time communications for connected and autonomous vehicles, robotics, remote medical care, or a *tactile internet* with which people can remotely control objects in real time
- augmented and virtual reality
- reliable communications for emergency services, public safety, and critical infrastructure services.

Bringing these broad use-cases to fruition and providing an agile platform for future innovation requires a significant departure from prior generations. More specifically, standard-setting bodies have identified three primary areas for which 5G should provide meaningful advantages over existing wireless mobile networks and have articulated high-level technical performance requirements:[3]

- **eMBB (enhanced Mobile Broadband).** This will provide significantly enhanced bandwidth over prior generations with peak data rates of up to 20 gigabits per second (Gbps) downlink to devices (10 Gbps uplink from devices) and minimum user experienced data rates of 100 Mbps for rural, or network edge users, and a minimum 1 Gbps for urban users.[4]
- **URLLC (ultra-reliable low-latency communications).** Prior generations offered user plane latencies on the order of 10–100 milliseconds (ms);[5] technical requirements for 5G list 1 ms for URLLC-specific applications, 4 ms for general eMBB applications, and a significantly reduced packet loss rate for improved reliability.
- **mMTC (Massive Machine Type Communications).** Technical requirements demand a connection density of one million devices per square kilometer, which is an order of magnitude improvement over 4G LTE. Furthermore, mMTC requires support for massive IoT devices, which are low-powered and communicate sporadically.

These enhanced dimensions of cellular service set the stage for a futuristic vision that meets consumer demands over the next decade,[6] but also provides a flexible platform for a broad variety of applications yet to be devised.

Enabling Technologies for 5G

Achieving these goals requires a complete transformation of the mobile network. Delivering an efficient yet scalable and customizable network that meets the performance criteria and supports a wide variety of user equipment (UE) requires a confluence of existing and emerging capabilities; specifically, new devices and radio access technologies, expanded radio wave spectrum access, complete virtualization of the core network, and mobile edge computing.

The following section provides a brief overview of the essential technologies developed to meet the 5G performance requirements.

Radio Access Innovations

Three new radio access technologies are required to meet 5G performance requirements:

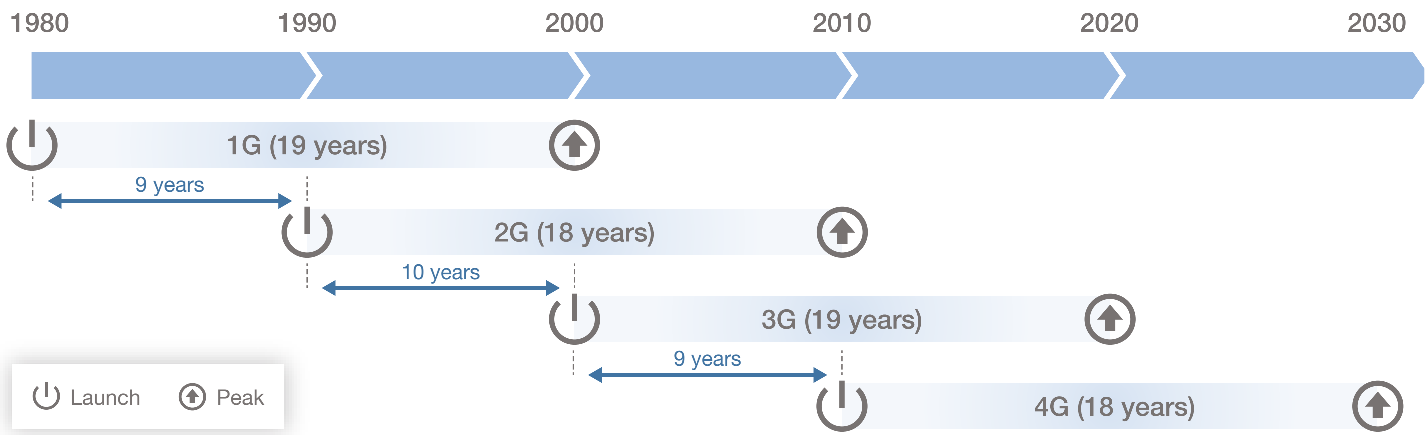
- *Expanded spectrum access and spectrum sharing—mid-band and mmWave*: Meeting eMBB requirements will require expanded spectrum access to the mid-band and high-band. Moreover, 5G New Radio (NR) will support several sharing techniques for making more efficient use of the limited spectrum.

- *Dense small cell network:* To improve coverage and alleviate congestion, a greater number of small cell base stations will be deployed. In addition, because higher frequencies travel shorter distances, coverage layers will be overlaid with micro-, pico-, or femto-cells, which will line street posts and building walls to ensure widespread coverage.
- *Massive multiple-input multiple-output (MIMO) and advanced beamforming:* Massive MIMO antennas increase throughput and capacity using a large number of antennas. Beamforming is a technique that is used to focus radio waves to a target rather than radiating in all directions, to extend range and signal clarity.

Virtualization of the Core Network

Prior generations of mobile communication technologies were largely built around voice and limited data services for mobile phones. However, the 5G era is expected to provide service to a broad variety of devices with unique requirements (e.g., wearables, IoT, autonomous vehicles). By virtualizing the core network and replacing several hardware elements with software installed on centralized cloud servers, the core becomes highly flexible and scalable to meet the needs of diverse 5G use cases. The virtualized core also enables *network slicing*, in which multiple distinct software-defined networks can operate more or less independently over the same physical infrastructure. In practice, this means that the telecommunications (telecom) operators will have the technological capability to offer

FIGURE 2
Timeline of the Deployment of Previous Generations of Telecom Technology



SOURCE: Groupe Speciale Mobile Association, *Understanding 5G: Perspectives on Future Technological Advancements in Mobile*, December 1, 2014. Used with permission.

individual end users an exclusive portion of the network with a guaranteed minimum quality of service regarding bandwidth, latency, and reliability tailored to meet the diverse requirements requested by a particular application.[7] These slices are then autonomously operated by an intelligent core network that can rapidly deploy or delete slice instances. This will allow network healing and intelligent load balancing.[8] Many of the emerging 5G applications would not be possible without network slicing and a cloud-native intelligent core.

Multi-Access Edge Computing

To meet the stringent 1 ms latency requirements of 5G, decisionmaking and other computations must be placed closer to the user. By extending compute power and data storage to the edge of the network, often at cellular base stations, distance and network congestion are significantly reduced, enabling a faster response time. In conjunction with network slicing and the cloud-native core, multi-access edge computing (MEC) enables such applications as large-scale AV intercommunication and emergency services that require instant feedback.

5G Deployment and Timelines

Historically, it has taken considerable time to fully deploy each new generation of wireless communication network. Incremental advances were made during the deployment of each generation, with the final set of features much improved over the initial offerings. A timeline of the deployment for previous generations of telecom technology and projections for their peak market saturation is shown in Figure 2.[9] Throughout the first four generations, there was a consistent lag of slightly less than 20 years from launch to peak, with each generation's launch roughly coinciding with the peak saturation of two generations earlier.

5G's three main technical innovations—eMBB, URLLC, and mMTC—will reach maturity at different times. Enhanced mobile broadband is the easiest to achieve technically and will arrive first, because it primarily requires upgrades to the RAN that connects end user devices to the core network. The 5G technology being deployed today, known as 5G NR, only replaces the RAN with 5G technology while the core network can continue to run on 4G LTE. The 5G NR RAN operates in what is referred to as non-standalone (NSA) mode, because it must connect to the 4G core network. The 4G LTE network core will eventually be replaced by a new 5G Core (5GC), which will allow the RAN to operate in standalone (SA) mode, in which the entire communication chain uses 5G protocols.

The time frame for the rollout of standalone 5G is not entirely clear. In 2019, some wireless service operators claimed to be aiming to start deployment in 2020,[10] but the NSA portions of the 5G standard (a part of Release 16) had not been finalized as of June 2020, having been delayed because of the coronavirus disease 2019 (COVID-19) pandemic.[11] Moreover, the replacement of the core network will be a massive project that will proceed gradually over the course of many years. The highest-performance 5G, including the URLLC and mMTC aspects, are unlikely to be feasible until the deployment of standalone 5G.[12]

The section that follows discusses the key factors influencing deployment, starting with spectrum allocation, followed by the equipment and devices that operate on it. Both are tightly connected and represent key metrics in the greater technical competition of the 5G era.

5G Spectrum Availability

At the heart of modern communication systems are the radio waves that wirelessly transmit information between devices and connect users to the internet. In recent decades, demand for wireless broadband has grown rapidly because of technological innovation and an increasing number of users accessing the internet. Because spectrum drives the overall capacity for wireless communication, it has become an increasingly scarce resource with several operators (AM/FM radio, television, satellite, cellular, etc.) all competing for a finite block of spectral real estate.

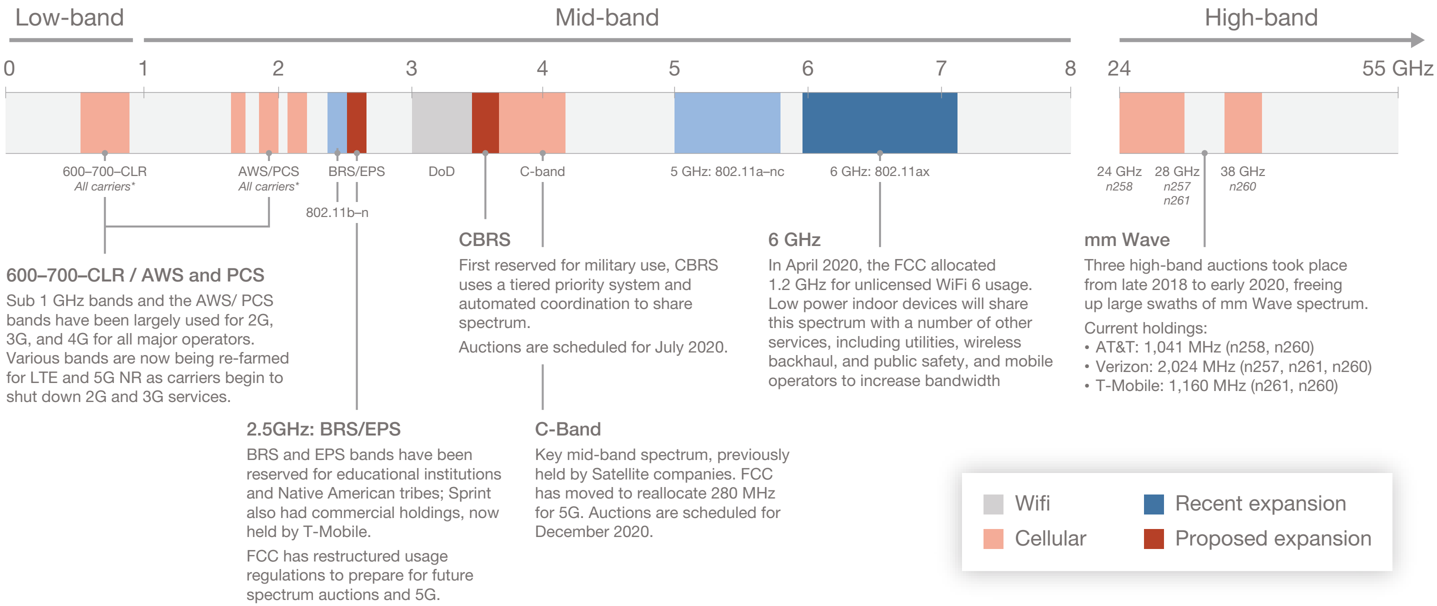
Moreover, not all radio wave frequencies are equivalent. Lower bands, such as those on the far-left end of Figure 3, have relatively long wavelengths, allowing them to travel longer distances and penetrate obstructions (such as walls or buildings)—all at the expense of a reduced data transfer capacity. Conversely, higher frequencies have shorter, more dense wavelengths and are better suited for high speed data transfer but have relatively poor barrier penetration. This trade-off is an unavoidable artifact of radio wave characteristics and is at the heart of the 5G spectrum debate, because no single frequency band will provide high bandwidth **and** expansive coverage. To support all of the requirements that 5G promises, multiple frequency ranges must be employed in tandem.

This marks a significant departure from previous generations, in which coverage and reliability were primary considerations. Carriers largely deployed at the coveted frequencies below 1 gigahertz (GHz) (primarily in the 800-megahertz [MHz] band) or around 2 GHz (in the AWS/PCS bands shown in Figure 3), because these provided excellent coverage and building penetration for mobile devices. However, in the 5G era, emerging applications require both coverage and bandwidth, which makes this a multidimensional problem. Therefore, regulators and international standards-setting bodies have converged on three principal frequency ranges in which 5G will operate:[13]

- **low-band** (<1 GHz): Often described as the coverage layer, the low-band provides the furthest reach of the 5G layers, spanning hundreds of square miles,[14] and largely operates on the same spectrum as prior generations. Upgraded radio access equipment will boost download speeds and provide an improved user experience, but this band is best described as good 4G, because improvements felt by some users might be marginal (~20 percent).[15] However, because much of the low band builds on LTE infrastructure, it is likely to be among the earliest flavors of 5G deployed. Moreover, in many rural areas, the low-band might be the **only** form of 5G, because infrastructure costs could be prohibitive in the higher bands.[16]
- **mid-band** (1–6 GHz, or *sub 6 GHz*):[17] The mid-band balances coverage and capacity (called the goldilocks of frequencies) with a several-mile radius and a data rate of 100 to 900 Mbps. This flavor of 5G will cover large portions of suburban and urban areas, with licensed U.S. deployments primarily in the 2.5–4.0 GHz range.[18]
- **high-band** (24+ GHz, or *mmWave*): The high band provides peak data rates of nearly 10 Gbps with an antenna range of a few hundred meters. However, mmWave is highly sensitive to environmental obstacles and requires direct line-of-sight access; build-

FIGURE 3

Selection of Radio Wave Spectrum Highlighting Recent Federal Communications Commission Rulings and Upcoming Auctions



SOURCES: Adapted from Drew FitzGerald and Sarah Krouse, “5G Push Slowed by Squabbles Over ‘Sweet Spot’ of U.S. Airwaves,” *Wall Street Journal*, June 20, 2019; Halberd Bastion, “Mobile Networks,” webpage, undated; SignalBooster.com, “What Are the Cellular Frequencies of Carriers in USA & Canada?” webpage, undated; Mike Dano, “Anticipation Mounts for 3.5GHz Midband Spectrum Auction,” *Light Reading*, January 13, 2020a; Marguerite Reardon, “FCC Approves $9.7 Billion Payment to Free Up Satellite Spectrum for 5G,” *CNET*, February 28, 2020; Federal Communications Commission (FCC), “Auctions Summary,” webpage, updated November 26, 2019b; Jeremy Horwitz, “FCC’s Largest Spectrum Auction Nets $4.47 Billion for 5G mmWave Bands,” *Venture Beat*, March 12, 2020b; Bevin Fletcher, “AT&T Touts mmWave Spectrum Gains, but Verizon Still Has Nearly 2X as Much,” *FierceWireless*, April 1, 2020.

NOTES: AWS = Advanced Wireless Service (1700 and 2100 MHz); BRS/EPS = broadband radio service/Education Broadcast Service (2.5 GHz); CBRS = Citizens Broadband Radio Service (3.5 GHz); CLR = Cellular spectrum band (800MHz); PCS = personal communications service (1900 MHz); C-Band, n257, n258, n260, and n261 are electromagnetic spectrum frequency bands.

*Carrier Spectrum Holdings: AT&T: 700 MHz (FirstNet), 850 MHz (CLR, n5), 1700/2100 MHz (AWS), 1900 MHz (PCS), 2300 MHz (WCS), 24 GHz (n258), 39GHz (n260); Verizon: 700 MHz, 850 MHz (CLR), 1700/2100 MHz (AWS), 1900 MHz (PCS), 28 GHz (n257/n261), 39 GHz (n260); T-Mobile: 600 MHz (n71), 700 MHz, 850 MHz (CLR), 1700/2100 MHz (AWS), 1900 MHz (PCS), 2.5 GHz (BRS/EBS, n41), 28 GHz (n261), 39GHz (n260).

ings, trees, and even panes of glass cause significant attenuation or loss of signal. As a result, real world deployments require extremely dense networks of small cells to realize the full potential of mmWave bands.[19]

It should be emphasized that to harness all of the benefits that 5G promises, all three spectral layers must be deployed together—pursuing one band over the other would leave a sizable gap in coverage or capabilities. Although mmWave is optimal for dense urban environments (e.g., inner city, large events) and provides extremely high bandwidth, the mid-band spectrum is ideal for reliable coverage in metro areas, and the low-band provides broad nationwide coverage.[20] As a result, no single frequency band will become standardized over the others; rather, a layered solution will be broadly adopted—the exact nature of the spectrum and subsequent timeline of deployment will be a product of the complex regulatory processes and individual carrier decisions.

Spectrum Allocation

Although allocation varies widely around the world, at a fundamental level, spectrum is a scarce resource, tightly managed by governing bodies to avoid interference. In an era of increasing reliance on communication technologies (GPS, cellular, satellite communications, Radar, AM/FM radio, etc.) the radio wave spectrum has become highly congested, amplifying the prospects for interference. If a radio receiver attempts to interpret two different signals in the same place, at the same time, and on the same frequency, the device will become confused and relay unpredictable or scrambled messages.

To protect against interference, various entities must work together to ensure that signals are not transmitted on the same frequency in the same geographic area. This process is primarily handled through licensing, which grants exclusive rights to various operators and often comes with several intricate rules and regulations.[21] Licenses to operate on a portion of the radio frequency spectrum are either auctioned off (as is the case in the United States, South Korea, and much of Europe) or directly allocated (as is the case in China and Japan).[22] Spectrum allocation in the United States is administered by the FCC for commercial use and the National Telecommunications and Information Administration (NTIA) for government agencies. The FCC has released the 5G Facilitate America's Superiority in 5G Technology (5G FAST) plan, which outlines a comprehensive strategy to accelerate 5G deployment by easing infrastructure regulations and, more significantly, releasing more spectrum into the commercial marketplace.[23]

A significant challenge for U.S. allocation is the fact that much of the prime 5G spectrum is already occupied. The mid-band remains congested and highly fragmented with a broad variety of users, from the military and satellite operators to educational institutions and Native American tribes (see Figure 3).[24] The lengthy and often costly process of reallocation could be significant as incumbent users have already made large investments in complex radio systems scattered across the country. For instance, in light of the recent FCC decision to vacate the C-Band, incumbent satellite operators might be required to invest in fiber-distribution networks to make more efficient use of remaining spectrum holdings or deploy entirely new infrastructure to operate on different frequency bands.[25] In addition, military operators might be required to develop systems and protocols to securely share spectrum with the public.[26]

Although these allocation hurdles are not unique to the United States, they are noteworthy. In contrast, China—which relies on a more streamlined, top-down allocation approach—has already completed allocation of the mid-band spectrum to its four state-controlled 5G carriers.[27] Figure 4 provides a snapshot of current spectrum holdings.

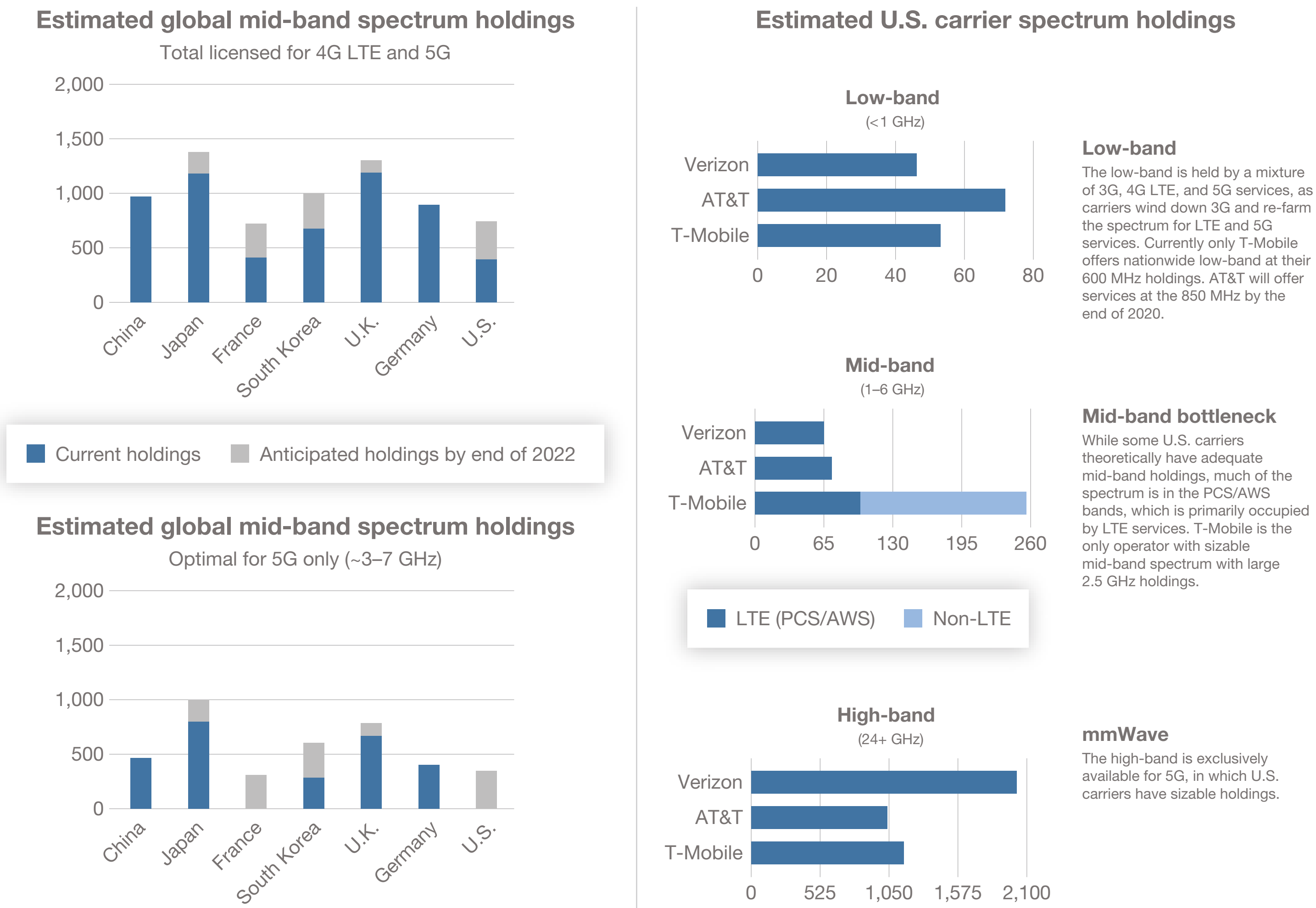
It is evident that although the United States has adequate mid-band holdings (Figure 4, top left), much of this spectrum is in the AWS/PCS bands (<3 GHz), which is currently reserved for LTE services. T-Mobile is the only operator with available mid-band spectrum on the large 2.5 GHz holdings obtained from Sprint, following the recent merger.[28] In the upper half of the mid-band (3–7 GHz), an area targeted for prime 5G deployment, the United States lags significantly behind peer markets, including China, Japan, and South Korea, as shown in the bottom left of Figure 4.[29] Claims of significant U.S. mid-band spectrum allocation for broadband wireless therefore exaggerate U.S. preparedness for 5G, because none of the deployed mid-band holdings are at the optimal frequencies for 5G. Although recent U.S. auctions have opened up large swaths of mmWave frequencies,[30] this mid-band deficiency might place the United States at a competitive disadvantage. The lack of an early nationwide mid-band rollout will be felt most at the application layer and by the consumer. Because the mid-band is anticipated to be a reliable source of high-speed broadband with adequate coverage for a wide variety of mobile applications, a delayed deployment might place U.S. companies in a difficult position to capture early economic value. Moreover, the development of various emerging application spaces, such as AVs, or the IoT, might be hindered, placing American industry leaders in a position to lose market share to foreign competition. However, despite a convoluted allocation process, the FCC has moved forward at a steady pace and has recently turned its attention toward the mid-band with several auctions scheduled. See Appendix A in the accompanying volume for more details on the upcoming auctions.[31]

Spectrum Sharing

In addition to the mounting problem of spectrum congestion, 4G and 5G technologies cannot natively operate on the same spectral band simultaneously. The spectrum block must be reserved or appropriately partitioned before switching between equipment.[32] Because 4G LTE is expected to remain the predominant workhorse for cellular communication for some time (as shown in Figure 2), with a gradual transition toward 5G over the next decade, this incompatibility issue further concentrates the limited spectral resources, forcing carriers to carve out blocks of precious LTE spectrum to deploy 5G services. This is the current predicament that U.S. mobile operators face in the mid-band. Aside from T-Mobile, which has sizable 2.5 GHz holdings, all available spectrum is dedicated to 4G LTE services (see Figure 4).

Dynamic spectrum sharing (DSS) might provide a technological workaround, because it "enables a mobile operator to flexibly allocate existing spectrum across low-, mid-, and high-frequency bands, by dynamically switching between 4G LTE and 5G NR coverage based on traffic demand."[33] This allows mobile operators to leverage much of the 4G LTE infrastructure to create a gradual transition

FIGURE 4
Estimated Spectrum Availability for Mobile Broadband Services



SOURCE: Stewart, Nickerson, and Lewis, 2020.

NOTES: As of July 2020, only 70 MHz will be available by the end of 2020 following the CBRS auction. Later C-Band auctions will free up additional spectrum for late 2021, after incumbent satellite operators vacate.

toward 5G. However, DSS is a relatively late-stage addition to the 5G standard.[34] Consequently, DSS development remains in the early stages (as of June 2020) and might come with a price in performance. The additional network management overhead might also consume additional bandwidth, with consequences for the user experience.[35] Notably, T-Mobile has claimed that DSS has performed poorly and is behind schedule.[36] However, all major U.S. carriers plan on using some form of DSS, particularly in early deployments. The extent to which DSS is used will likely depend on spectrum availability. See Appendix A in the accompanying volume for a further discussion about prioritized spectrum sharing involving military operators and the CBRS band.

Unlicensed Spectrum

The final venue for alleviating congestion is through utilizing unlicensed spectrum. This is currently accomplished by offloading data traffic onto unlicensed 5 GHz Wi-Fi spectrum through the License Assisted Access (LAA) protocol. A key feature of the LAA is a listen-before-talk (LBT) protocol which is a required technique that allows Wi-Fi and LTE systems to coexist on the same spectrum to avoid interference and to identify free channels in which to operate.[37] LAA and other variants have been in operation since 2014 and have become more efficient. LAA is now a key part of carrier aggregation, which allows operators to use multiple channels to deliver enhanced bandwidth.[38]

In April 2020, the FCC allocated 1.2 GHz of the 6 GHz band for unlicensed Wi-Fi 6 (Institute of Electrical and Electronics Engineers 802.11ax) usage. Although this spectrum is currently held by cable operators, utilities, wireless backhaul, public safety, and more, by opening up the spectrum for unlicensed usage, the FCC also places several limitations on its usage to avoid interference, including low power emissions to limit signal propagation and requiring devices to have LBT capabilities to synchronize with others. However, opening up such a large swath of spectrum will immediately alleviate congestion in the lower bands—particularly because there will be limited mid-band spectrum available for some time.[39] Carriers will be able to access channels in the 5 and 6 GHz bands to supplement LTE and 5G services in congested areas via small cell deployments, which is currently the case for many operators.

U.S. Mobile Carriers

Following the merger of Sprint and T-Mobile,[40] the United States has three tier-one mobile service operators, each investing billions in next-generation networks and taking significantly different spectrum pathways toward 5G deployment. Estimates place capital expenditures through early 2020 at nearly $20 billion for each carrier, largely distributed among equipment upgrades, cell densification, and fiber.[41] For comparison, rough estimates put Chinese investment at $25–$40 billion USD per carrier, for a projected total of ~$218 billion between 2020 and 2025.[42] (China was estimated to have outspent the United States on 5G capital expenditures by $24 billion between 2015 and 2018.[43])

However, incentives for such heavy investment remain somewhat unclear. As we will later discuss in more detail, the “killer” 5G apps have yet to be identified. As it stands, margins remain thin, with operators actively looking for ways to monetize 5G services and recover the substantial infrastructure investments.[44] In recent years, over-the-top services (such as television and streaming platforms) have opened new fronts for competition and a means for generating revenue.[45] In the short term, growth might be achieved by increasing bandwidth and replacing fixed broadband for customers looking to consolidate services, but further customer use cases are uncertain (although future sources of revenue might reside in enterprise solutions).[46] For a more detailed breakdown of each carrier's investment strategy and spectrum holdings, see Figure 4 and Appendix A in the accompanying volume .

U.S. Competitiveness

Aside from the 2.5 GHz band held by T-Mobile, limited mid-band spectrum is currently available with only a handful of domestic deployments underway. Because the mid-band has been deemed the sweet spot for most 5G applications (because it balances bandwidth and coverage), U.S. operators might be unable to collect much of the economic value from 5G for some time. Simultaneously, because of the significant infrastructure costs, uncertainty related to the COVID-19 pandemic, and several recent acquisitions (including spectrum via FCC auctions), U.S. carriers are taking on considerable risk and have little incentive for an overly aggressive 5G rollout.

Operators are still expanding 4G LTE coverage (to keep up with demand in the short run), maintaining or winding-down 3G networks (which still have millions of customers), and are pinning down considerable precious spectral resources.[47] Furthermore, mobile carriers are often bound to geographic regions and are highly dependent on local regulations, government support, and spectrum access, so although there are several global network operators,[48] competition is largely regional. Hence, from a global strategic competition perspective, mobile carriers are primarily enablers of 5G but currently face considerable challenges competing globally, particularly in a mature and highly consolidated industry.

Without more spectrum, or a much better way to share, it will be very hard to continue a high quality of 4G LTE service while deploying 5G. Either fewer simultaneous users could be supported, data rates would need to be rationed (or a steeply progressive pricing regime imposed), 5G delayed, or a combination of these and other measures imposed.

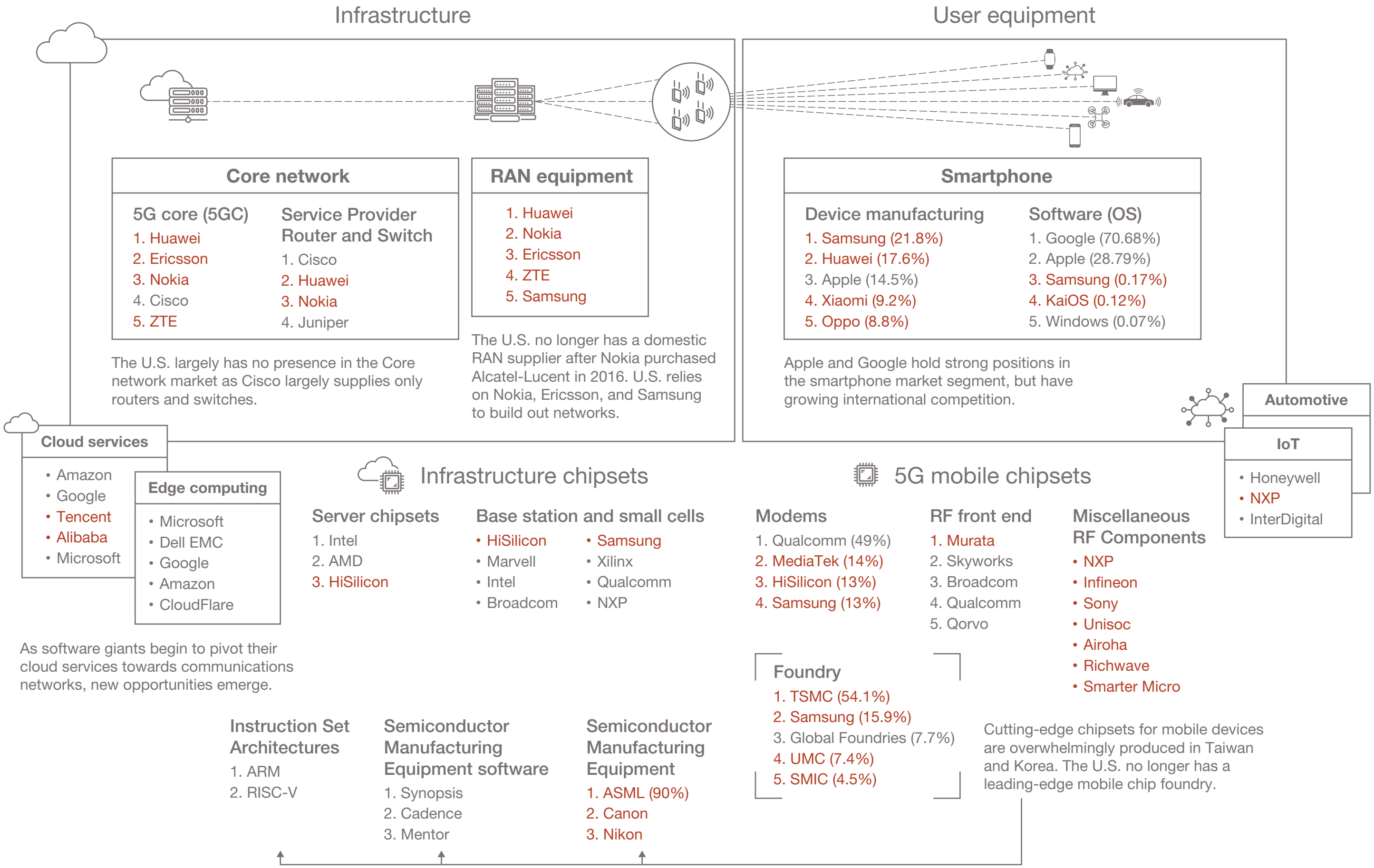
Conversely, allocating mid-range spectrum will enable early adoption of 5G in all geographic areas, and will be particularly crucial for users in rural areas or remote locations. Allocating high-band spectrum will be especially necessary to enable 5G use in dense urban areas and other locations that concentrate people and IoT devices.

5G Hardware and Software Components of the 5G Ecosystem

The wireless communications ecosystem is expansive and continually evolving—encompassing network service providers, equipment vendors, device design and manufacturing, system integration, testing, and more. As more capabilities arrive, a new class of key industry players are expected to join the list, opening up new battlefronts in an already highly competitive landscape.

Historically, the United States has enjoyed broad telecommunications industry leadership though a thriving

FIGURE 5
Key Players in the 5G Ecosystem



SOURCES: James Andrew Lewis, *How 5G Will Shape Innovation and Security: A Primer*, Washington, D.C.: Center for Strategic and International Studies, December 2018; Canalys, "Global Smartphone Market Q4 and Full Year 2019," January 30, 2020; "Mobile Operating System Market Share Worldwide," *Statcounter*, April 2020; Stefan Pongratz, "The Telecom Equipment Market 2019," Dell'Oro Group, March 2, 2020; Sravan Kundojjala, "Intel Gives Up on 5G Modems While Qualcomm Scores Big with Apple," Strategy Analytics, April 18, 2019; Cédric Malaquin and Antoine Bonnabel, "5G's Impact on RF Front-End Module and Connectivity for Cell Phones 2019," Yole Développement, August 2019; Mike Robuck, "Cisco Tops Huawei, Nokia and Juniper in Q3 Service Provider Router Rankings—Report," *FierceTelecom*, December 5, 2019; Thomas Alsop, "Global Market Share Held by Semiconductor Equipment Manufacturers in 1Q'17 and 1Q'18," Statista, March 2019.

NOTE: Non-U.S. companies are listed in red. IoT: Internet of Things; RAN = Radio Access Network private sector and a deep history of innovation,[49] from the famed Bell Laboratories, or the introduction of the first cellular phone by Motorola, to the successful commercialization of the smartphone, which immediately transformed the wireless industry into a data-centric ecosystem bringing tech giants Apple and Google into the fold as future industry leaders.[50] In each successive generation of wireless technology, U.S. companies were at the forefront of innovation with a strong presence in all aspects of the value chain. However, as key market segments reached maturity and the wireless ecosystem expanded, U.S. dominance began to decline. Although the United States maintains broad leadership in several segments, it faces stiff competition in others. Figure 5 breaks down the key physical components of the 5G ecosystem and highlights market leadership. The section that follows provides an overview of critical market segments. For a more detailed breakdown, see Appendix B in the accompanying volume.

User Equipment (UE)

The most tangible elements of the 5G era are the mobile devices that connect users to the 5G network. Currently the most anticipated 5G-capable device is the smartphone, although 5G technologies will soon encompass a plurality of devices as the number of internet-connected gadgets continues along its expansive trajectory. Although early 5G smartphones provided limited support for 5G frequency bands and were plagued by overheating issues,[51] recent iterations have largely addressed these concerns and provide support for sub-6 GHz and mmWave bands, and DSS.

Global leadership in the hardware space is largely held by Samsung, Huawei, and Apple, with flagship devices in the Galaxy, P-series, and iPhone, respectively. As of June 2020, only a handful of 5G phones are available in limited markets,[52] and early deployment is heavily dependent on network infrastructure availability, which remains fragmented and regional. From a mobile device software perspective, Google and Apple hold dominant positions with more than 95 percent of the market (see Figure 5).

The key to realizing advanced mobile devices are the chipsets, which have a vast and immensely complex supply chain. In this space, the United States has historically strong leadership in advanced chipset design, with dominant leaders in Qualcomm, Broadcom, and Apple. However, these chipset designs are then sent overseas for manufacturing, because the United States no longer has a domestic mobile chipset foundry. For a more detailed discussion on mobile chipsets and key players, see Appendix B in the accompanying volume.

Radio Access Network

In the simplest of terms, the RAN is a system of antennas and base stations that provide access to the core network. Mobile devices are wirelessly connected through antenna arrays to RAN base stations; wireless signals are then routed on to the core. With the introduction of 5G, the RAN will experience the most visible changes. To meet the low latency requirements and accommodate poor wave propagation at higher frequencies, significantly more base stations (including small and pico cells) will be deployed in urban environments (on street lamps, buildings, etc.).[53] These base stations also bring new capabilities, including spectrum sharing, massive MIMO, and beamforming, which allow for base stations to communicate with more end user devices simultaneously.[54] In addition, significant aspects of the RAN are expected to be virtualized in later deployments, with the potential for this to be the case for the entire network. This means that the software and hardware will be decoupled, and much more of the processing will be performed through software (potentially at offsite servers) instead of by dedicated purpose-built hardware. This will provide support for network slicing and bring about multivendor compatibility at reduced costs, as equipment will be vendor-agnostic commercial off-the-shelf hardware.[55]

As shown in Figure 5, the United States has no domestic presence in RAN equipment providers and must rely on suppliers from other nations to build the most critical elements of the wireless communication infrastructure.[56] Competitors in this space are Ericsson, Huawei, Nokia, Samsung, and ZTE, with Huawei and Ericsson widely seen as the leaders. However, if multipurpose hardware becomes standard, other players could enter the market, such as Cisco, Dell EMC, HP, and Lenovo.[57]

Early RAN deployments will be NSA, relying on the existing 4G LTE core and sparing network operators from the sizable costs of building out an entire network from the ground up. This also brings about a key point for RAN infrastructure: vendor incompatibility. RAN market share positions are unlikely to meaningfully change in the 5G era, because replacing legacy systems requires a network overhaul rather than an upgrade, leading to potential vendor lock-in;[58] once a vendor's network is in place, dislodging them is immensely difficult.[59] Although switching vendors might be easier for later standalone deployments, because it does not rely on legacy infrastructure, there remain several benefits to retaining a single vendor for network operators.[60] In addition, low margins and high R&D costs prevent other competitors (such as Cisco or Oracle) from entering.

Core Network

The core connects all parts of the network and aggregates data traffic from the endpoints. The core also authenticates user devices, routes calls and data packets, performs various higher-level functions, and acts as a gateway to the broader internet. Although the 5GC will ultimately perform similar functions to its predecessor, the 4G LTE Evolved Packet Core, the underlying principles are significantly different.[61] The 5GC has been designed to be *cloud native* with virtualized, software-based network functions (or services) at the core.[62] This provides the inherent flexibility and efficiency required to deliver 5G use cases at scale. The virtualized 5GC enables network slicing, continuous software updates, higher degrees of hardware disaggregation to reduce costs, and support for a multitude of emerging capabilities, including MEC, AI-driven automation, and self-healing for improved uptime.[63] See Appendix B in the accompanying volume for an extended discussion on the 5G Core and MEC.

Huawei and Ericsson are consistently ranked as top vendors in this space as of June 2020, followed by Cisco, Nokia, ZTE, and Samsung.[64] However, companies that provide server platforms (e.g., Dell EMC, HPE, Amazon), are likely to play a significant role in the 5GC development as functions move to the cloud. The 5GC remains in its infancy as most 5G deployments remain in NSA mode.

Broader Supply Chain Assessment

As is evident from Figure 5, key segments of the 5G ecosystem are under increasing pressure from foreign competition—or have already ceded U.S. leadership entirely. Chinese companies, led by Huawei and ZTE, are actively seeking to displace competitors across 5G the ecosystem. Moreover, China has a long track record of stealing intellectual property and using state subsidies and unfair trade practices to undercut competitors. [65]

Although U.S. companies maintain strong leadership in critical segments, leaving China heavily dependent on U.S. technology (particularly radio frequency [RF] components) (see Appendix B in the accompanying volume), there are strong indications that China is rapidly moving to fix this, with export restrictions accelerating the split.[66] For instance, a teardown of Huawei's high-end Mate 30 smartphone revealed rapid innovation on key components to cut nearly all U.S. dependencies. The 5G Mate 30 breakdown showed unsophisticated design work, but it was assembled and released on time, using less than 1 percent U.S.-made components; down from 11 percent in the Mate 20 (other Chinese vendors use up to 38 percent of U.S. components, for comparison).[67] This indicates that Chinese device makers are capable of developing 5G capable devices and forging new supply chains in short order to survive without U.S. technology. And although these devices have a tough road ahead and might not compete in the top tier,[68] lower price points and a large domestic marketplace will deliver high volumes and consistent growth, further fueling efforts toward independence.

However, the long-term goal is to completely sever all dependencies on U.S. technology, as part of the Made in China 2025 (MIC 2025) plan announced in 2015.[69] This is particularly true for semiconductors—an Achilles' heel for China, which imports nearly 85 percent of their chipsets.[70] Although China continues to invest billions of dollars developing a home-grown semiconductor industry, meeting their goal of producing 40 percent of the semiconductors it uses by 2020 and 70 percent by 2025, as outlined by MIC 2025, will be a significant challenge. Top Chinese foundries, such as Semiconductor Manufacturing International Corporation (SMIC) or United Microelectronics Corporation, remain several technology nodes behind, which might take nearly a decade to catch up to global leaders.[71] Moreover, the majority of the advanced semiconductor manufacturing equipment comes from the United States, Japan, and the Netherlands (see Table C.1 in Appendix C in the accompanying volume), and export controls have slowed the pace of Chinese domestic chip efforts.[72] However, China has placed technology at the forefront of its strategic goals and will not allow significant dependencies on Western intellectual property to undermine these plans in the long run and will continue investing heavily in semiconductor technology.[73]

Appendix C in the accompanying volume contains a detailed discussion of export controls as they pertain to China. Japan and the Netherlands are among the most important U.S. allies regarding the coordination of these exports controls, and in order for the controls to be effective, these nations will need impose them with precision, aiming at the fundamental elements of the semiconductor supply chain. In addition, the United States should consider only restricting sales of cutting-edge chipsets while keeping current low-level semiconductor equipment limits in place. Commodity logic or memory chipsets, or even slightly outdated chipsets, retain considerable value abroad and need not be overly restricted. This would allow U.S. firms to protect their market share while mitigating the consequences of China's push toward semiconductor independence.[74]

U.S. Competitiveness in the 5G Ecosystem

The United States remains dominant in the *fabless* (fabrication-less) mobile chipset design space, with several industry leaders residing in the United States (e.g., Qualcomm, Apple, Skyworks, Broadcom, Qorvo). However, fabrication is overwhelmingly dominated by Taiwan and Korea, as the United States no longer has a leading-edge foundry for mobile chipsets.[75] This amounts to a severe loss of industrial leadership in an area that U.S. companies began and dominated for decades, and the lack of a leading-edge mobile chip foundry also presents national security concerns.[76] Heavy reliance on Asian partners leaves the door open to nefarious circuitry backdoors inserted into chipsets used in critical U.S. infrastructure, which could lead to surveillance or eavesdropping by adversaries. Furthermore, numerous defense systems are highly dependent on advanced chipsets; exploited vulnerabilities might lead to unpredictable behavior or unexpected outcomes.[77]

Because semiconductor fabrication facilities are among the most sophisticated fabrication facilities in the world, costing billions of dollars in capital expenditures and requiring years of cutting-edge R&D, an experienced work force, and highly specialized equipment, rebuilding a domestic industry is unlikely. However, the recent announcement that Taiwan Semiconductor Manufacturing Company (TSMC) intends to build a facility in the United States might provide a middle ground toward developing a trusted foundry.[78] Although this facility is unlikely to be at the leading edge by the time it enters production, this deal could provide a pathway toward manufacturing advanced chipsets with the level of assurance required by U.S. government agencies.

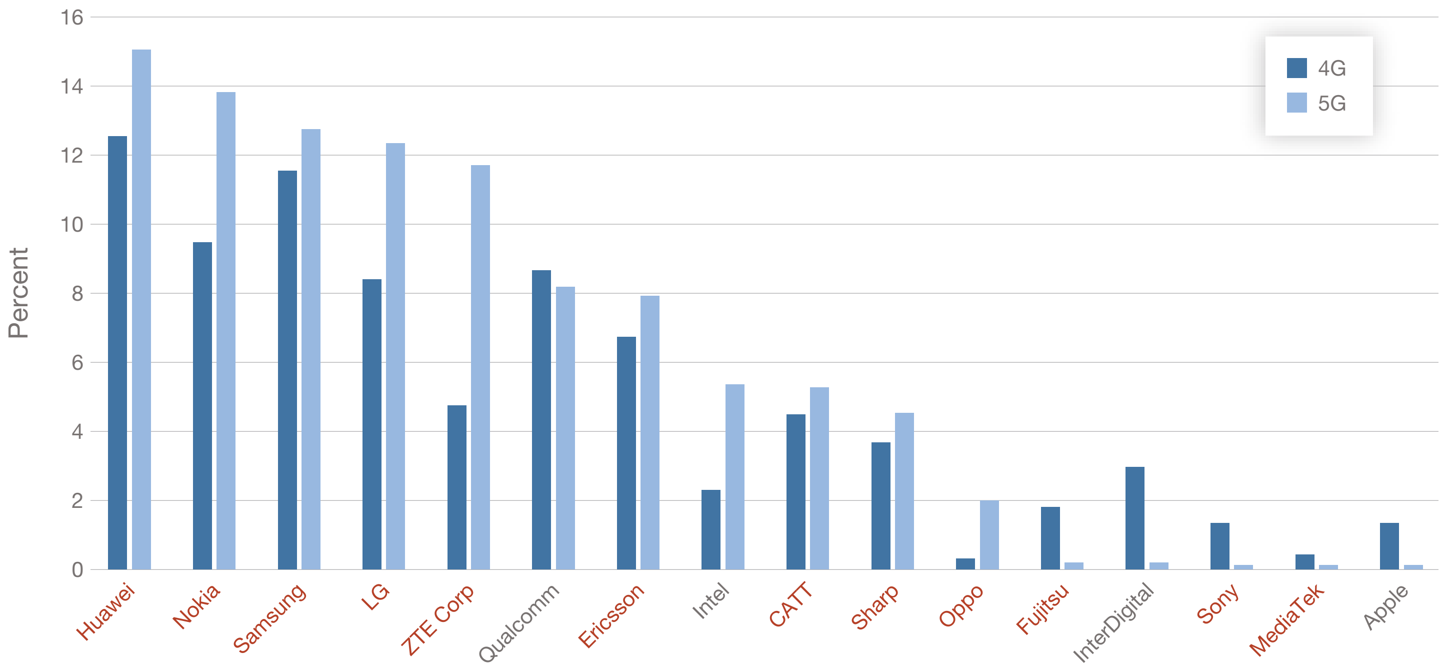
In the broader telecom infrastructure market, four companies (Ericsson, Nokia, Huawei, and ZTE), account for the majority of global 5G contracts, with Huawei regarded as a strong leader technologically and in terms of market share.[79] The United States has not had a presence in network infrastructure since 2015, after Nokia acquired Alcatel-Lucent.[80] The absence of a major U.S. alternative to foreign suppliers creates a critical dependency on allied partners and leaves a key portion of the 5G network beyond U.S. control. Moreover, if one of the European partners were to exit the market, this would leave a single trusted supplier for the entire U.S. communications infrastructure.[81] Nokia, for instance, is reportedly under financial strain, having halted dividend payments in 2019, then subsequently taken on increased debt and announced leadership changes shortly thereafter.[82] As of June 2020, Nokia is rumored to be fending off a hostile takeover.[83] Although some potential alternative RAN equipment suppliers might exist in the United States (such as Cisco, which is a world leader in routers and switches but does not compete in the radio access market), there are higher barriers to entering the RAN marketplace, because of vender lock-in and low margins.[84]

Unlike other elements of the network, which more easily benefit from common hardware (such as the core, for instance), the RAN remains proprietary and accounts for a large share of an operator's capital expenditures. The open radio access network (O-RAN) is a concept gaining momentum that allows for white-box hardware and open source software elements from different vendors.[85] This would allow significantly more interoperability between equipment and additional players to enter the marketplace, which might lead to a more-competitive and innovative ecosystem with reduced costs.[86] Several operators have begun exploring O-RAN–compliant 5G equipment as a way to introduce more diversity in the supply chain, but the field remains immature with few implementations worldwide.[87]

Standards and Patents

Ownership of critical patents that have been broadly adopted by the primary standards-setting bodies will have a significant long-term effect on the 5G ecosystem and the broader competitive landscape. Throughout the generations of mobile communication technology, patent holders have held considerable influence over the direction in which mobile technology evolves, allowing them to become market leaders. Alternatively, conflicting stan-

FIGURE 6
Percentage of Standard Essential Patents



SOURCE: RAND analysis of data from Akito Tanaka, "China in Pole Position for 5G Era with a Third of Key Patents," Nikkei Asia, May 3, 2019.
NOTE: Non-U.S. companies are listed in red. CATT = China Academy of Telecommunications Technology.

dards (between the United States and Europe, for example), have historically led to fragmentation and costly turf wars between major players, resulting in significant shifts in the global competitive landscape.[88]

The 3GPP—one of the primary standards organizations that develops protocols for mobile communication systems—is setting a unified global standard for 5G to avoid such large scale make-or-break scenarios. However, there are clear competitive advantages for those with the most significant and valuable portfolio of patents.

Although the 3GPP patent development process is highly complex (see Appendix D in the accompanying volume for a more detailed discussion), at the most fundamental level, the solutions developed to meet various technical challenges often lead to patents. If the patent is deemed to be essential to build a standard compliant product, then the patent is declared as a standard essential patent (SEP) and is then highly valuable (although the system is often abused).[89] If a device-maker wishes to build a standard compliant device, they must use such SEPs and are required to pay royalty fees to the SEP holder (the value of which is largely determined by market forces).

Figure 6 shows the current 5G SEP leaders, solely based on patent filing quantity. However, all patents are not created equal, and the quantity of 5G related contributions is insufficient to gauge SEP leadership. A broad range of metrics should be used, including submitted papers, chairmanship positions and working group representation, and the overall effects of the contribution in relation to the overall 5G standard. For instance, in various assessments of these metrics, Huawei is considered the largest contributor, but not necessarily the most consequential.[90]

Ultimately, the key to maintaining competitiveness in global standards and patents comes down to the quantity and quality of SEPs and representation on the international standard-setting bodies that determine the direction of the greater 5G standard.

5G Applications

Potential Killer Apps for 5G

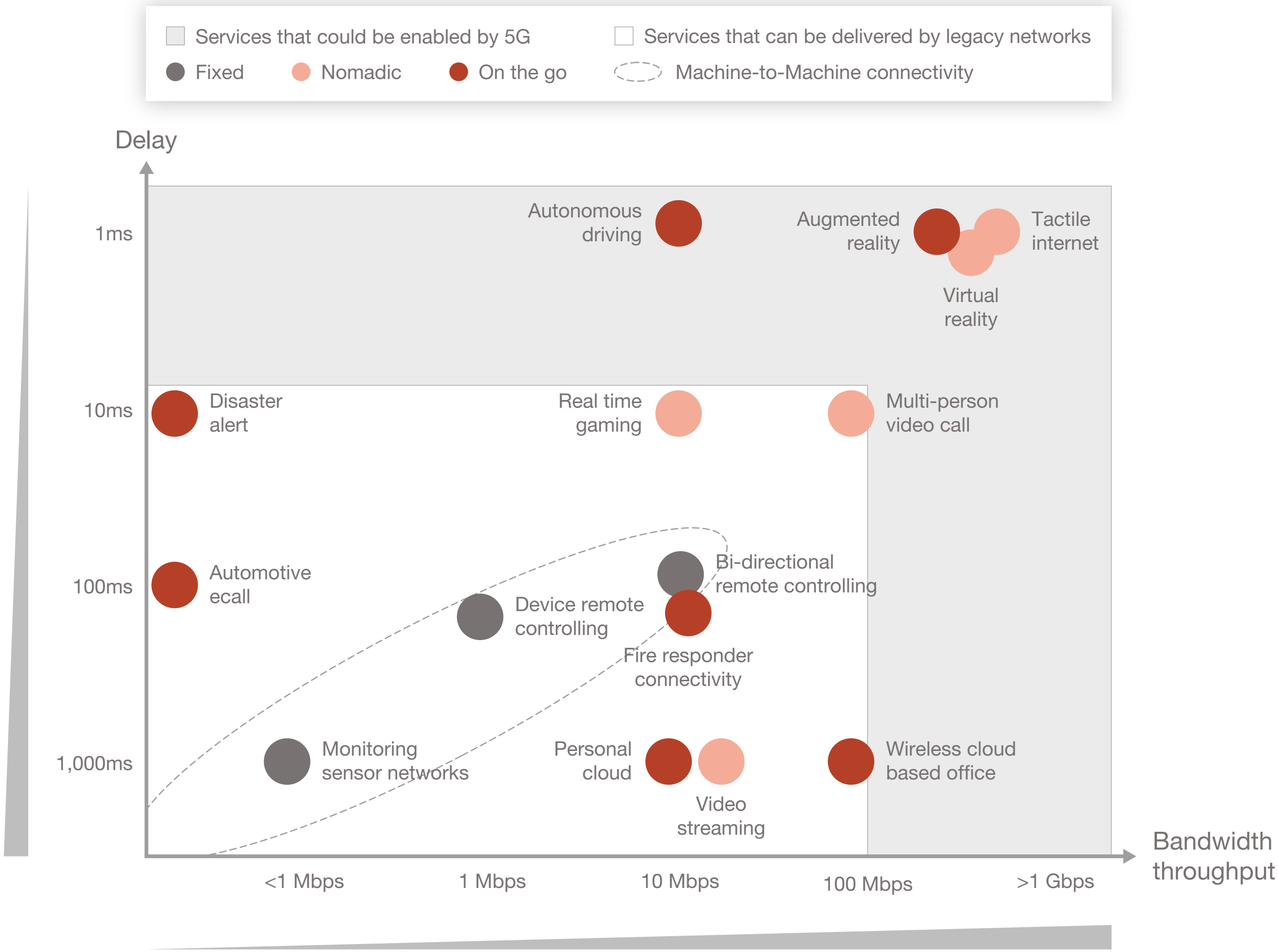
One of the biggest questions facing the rollout of 5G is what will be the killer apps (if there are any) that most transform society and provide enough value to justify the expensive R&D and enormous infrastructure investments that 5G requires. As of yet, there is no clear answer.

As Figure 7 illustrates, most currently known wireless technology applications can be technically supported with sufficiently dense networks of 4G base stations. Augmented and virtual reality fundamentally do require the bandwidth and latency that 5G will provide, and their applications might spread from their current use—primarily games—to many new areas, such as aiding surgery,[91] or training police and soldiers,[92] but it is far from clear that augmented reality and virtual reality will generate enough value to justify 5G infrastructure investments.

Another proposed killer app for 5G is industrial automation. Highly networked industrial systems might eventually use 5G's ultra-low latency for safety-critical industrial control systems, or use its scalability to eliminate existing wiring or greatly expand the use of system monitoring and tracking individual items as they move through the manufacturing process.[93] Although 5G will very likely deliver a much higher quality of service than the existing

FIGURE 7

Bandwidth and Latency Requirements for Various Network Applications



SOURCE: Groupe Speciale Mobile Association, *Understanding 5G: Perspectives on Future Technological Advancements in Mobile*, December 1, 2014. Used with permission.

Wi-Fi standard, the new Wi-Fi 6 standard appears to offer quality of service comparable to 5G for most indoor applications, and it remains unclear whether 5G will deliver capabilities significantly beyond Wi-Fi 6.[94] Although Wi-Fi 6 does not list quantitative latency requirements, latencies as low as 6 ms have been demonstrated and future improvements might match 5G's 1-ms target.[95] However, Wi-Fi 6 cannot accommodate rapid handovers between base stations for devices that move over long distances, so there might be certain industrial contexts in which 5G will be necessary (e.g., such large outdoor areas as ports, airports, and construction sites).

If 5G does end up enabling new industrial applications, then many facilities might prefer to work with the telecoms to set up their own private networks, because these networks would give the users more control, customization, security, and possibly allow them to avoid using untrusted components in the telecom infrastructure. Several German automakers have already begun installing such networks, but the United States has not offered 5G spectrum licenses to industrial companies (as of June 2020).[96] The FCC could encourage experimentation for industrial applications by moving as quickly as possible to offer licenses for smaller bands of spectrum to companies beyond the major telecoms for use in specified facility boundaries.

New Types of Applications That Could Be Enabled or Expanded by 5G

A broad variety of wireless devices and services are being contemplated or developed to take advantage of the 5G network features discussed in this Perspective. Many applications of 5G technology will be beneficial and widely welcomed, while others might be controversial. Some applications have the potential to be extremely detrimental in a democratic society like the United States. It should be noted that we are not advocating for any of the applications discussed in this analysis. Rather, our aim is to point out both potential opportunities and dangers among the applications and emerging use-cases. This analysis will also identify questions for policymakers to consider in preparation for the development of 5G technology.

Today, the prototypical wireless connected device is the smartphone: a sophisticated, relatively expensive device whose motion and functionality are tightly associated with a single person. The development of 5G could significantly change this paradigm to one in which the number of connected devices in a given region is much larger than the number of people, and most devices primarily communicate with other devices while only occasionally delivering information to a human. 5G could enable the proliferation of two fundamentally different types of devices, which might be much less tightly connected to any particular person.

The first category consists of high-power, relatively expensive devices in motion, which includes smartphones but also new devices, such as aerial drones, AVs, smart agricultural equipment, and augmented or virtual reality goggles. These are the devices which will require the high bandwidth and low latency established by the eMBB and URLLC of the 5G standards. The top and right-hand portions of Figure 7 illustrate some of these applications. Many of these applications that require ultra-low latency are safety-critical, including AVs and some industrial control systems.

The second category of connected devices that 5G will enable is extremely low-power devices (such as simple sensors) deployed at massive scales. Individually, each device is relatively simple and equipped for basic functionality. However, when deployed in massive numbers, IoT networks have enormous data collection capabilities.[97] These devices generally have loose latency requirements and consume little bandwidth individually. Some of these devices must be mobile (e.g., for tracking vehicle fleets), while others are fixed in position but would be too expensive to individually connect to the network with fixed cable, particularly over long distances. In the near future, everything from teapots to bathroom scales might have an internet connection, and the recipients of that information could be largely beyond the device users' control. To more completely depict the space of technical requirements for new 5G-enabled applications, the axes of bandwidth and latency shown in Figure 7 would need to be supplemented by a third axis of *scalability*, which incorporates such measures as cost, power requirements, and ability to avoid or mitigate spectrum interference.

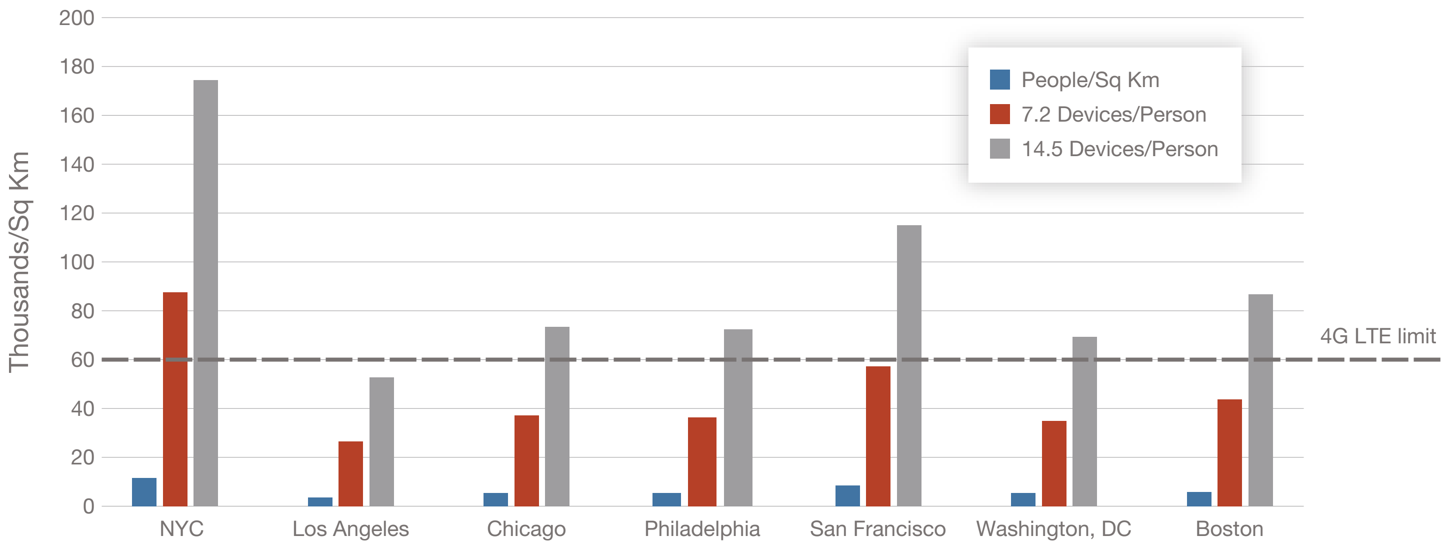
The regulatory and policy challenges for IoT devices deployed at massive scale generally revolve around questions of privacy and data ownership. Many of these technologies lend themselves to ubiquitous surveillance from which there is often no meaningful way to opt out. New products such as the Ring doorbell camera have already led to large growth in the number of wireless cameras, which will only continue with the onset of 5G.[98] Appendix E in the accompanying volume considers large scale public surveillance, and the special case of COVID-19 tracking, as case studies in this category of applications.

Part of the need for scalability in 5G applications simply comes from technical and economic requirements: the billions of edge devices connected to the network must be cheap and low power enough to be both practical and economical, and must avoid interfering with each other's transmissions. Another critical aspect is that many mobile applications depend critically on *network effects*, in the social and technological sense—that is, success is achieved only if a critical mass of people use them. (The competitive advantage of a large social network such as Facebook is not necessarily the sophistication of its technology, but rather the sheer size of its user base.) For these types of applications, a large potential user base will itself be a major competitive advantage.

If there were, on average, only one wireless device connected to the 5G network per person, then even New York City in 2030 would have only 12,000 devices per square kilometer (blue column in Figure 8)—far below the 4G density limit of 60,000 devices/km^2.[99] But 5G-enabled applications are expected to drive an increase in the average number of devices connected to the cellular network on a per-capita basis. Cisco projects that by 2023 the ratio of devices to people in North America will be over 14 to 1.[100] Cisco expects half of these devices will be machines talking to other machines—and their share of connections is growing at 30 percent per year, versus 7 percent for smartphones.[101]

If these growth rates continue through 2030, the ratio in North America would be 29 devices connected to the internet for each person.[102] Of these, Cisco estimates that 25 percent of North American devices will connect through wireless technologies.[103] New York City would then average 90,000 wireless devices per square kilometer

FIGURE 8
Projected 2030 Population and Device Density in U.S. Cities



SOURCE: RAND analysis based on Maciag, 2017 and Parker et al., 2018.

(the orange column shown in Figure 8), causing 4G networks to exceed their device density limit of 60,000 devices per square kilometer.

What if, in 2030, the proportion of devices in U.S. cities connected to the internet through wireless communications is not 25 percent, but 50 percent, as seen in other parts of the world?[104] Then Chicago, Philadelphia, San Francisco, Washington, D.C., and Boston would also exceed the device density supported by 4G (gray column in Figure 8) with Los Angeles approaching the 4G limit as well. At this point, 5G will need to be well into its mature deployment to meet the plausible demand for device density.

Implications for U.S. Competitiveness

Today, American dominance of worldwide network applications delivers economic benefits, but past market leadership is not a guarantee of a lasting advantage. The United States has been extremely successful at producing network applications with global appeal, while Chinese applications like Weibo are ubiquitous in China but generally fail to attract users in other countries. However, the rise of Chinese-developed applications like TikTok might indicate that this is changing: TikTok had become quite popular in the United States by 2019, and even more so in India.[105] Furthermore, the rapid growth of network connections in developing countries worldwide could open up new markets with billions of people with no preexisting affinity for network applications created in the United States.

Network effects and economies of scale are especially important for applications powered by machine learning—which in recent years have been some of the most transformative applications. For many machine learning applications, the creativity or technical skill of the designers is less important than the sheer volume of data used to train machine learning applications and intelligent agents. For these applications, countries that are able to amass large amounts of data will have a major competitive advantage. As illustrated in the case studies in Appendix E in the accompanying volume, 5G could enable data-gathering on an unprecedented scale and thereby drastically improve the power of these machine learning applications.

It is not yet clear to what extent the United States will hold the advantage or disadvantage here. Such countries as China obviously have much larger populations than the United States, but the United States currently draws on a much more global user base. However, such countries as China and Russia can collect data and deploy machine learning in ways that would be morally or societally unacceptable in the United States (for example, through ubiquitous surveillance systems like those found in the Chinese region of Xinjiang),[106] which has helped China become the world leader in facial recognition technology.[107] Countries with lower costs or standards of labor than the United States might be able to leverage much larger numbers of native low-wage workers to label large sets of training data, which could give them a competitive advantage. For some applications, the United States will similarly be able to farm out the labeling of training data to lower-wage countries. But this option will not always be open to the United States for data sets that are national-security sensitive, business proprietary, or violate U.S. ethical norms.

On the economic front, the fact that there are currently no obvious killer apps for 5G certainly does not imply that there will not be any. Investment in telecom infrastructure has often preceded the understanding of its eventual applications. For example, the enhanced bandwidth that 4G LTE began delivering in 2010 led to a variety of such unexpected applications as Uber and Instagram, which then transformed entire industries. As discussed, previous generations of telecom technology have generally taken almost 20 years from their launch to their peak. 5G will similarly take many years of continuous improvement to reach maturity, and so we might not know its eventual killer apps for years.

Not only is there no single 5G application that will offer reliable near-term value, even if such an application does arise, it is not clear how much of that value will actually flow to the telecom companies that make most of the physical infrastructure investments. The network telecoms only received a small portion of the substantial revenues generated throughout the 4G era, with most of the value going to producers of end user–applications.[108] Network telecoms will be reluctant to make risky (and expensive) infrastructure investments in 5G, in case the same proves true again. Moreover, mobile carriers do not seem to be rushing to deploy infrastructure: even before the COVID-19 crisis spread worldwide, multiple 5G markets seemed to be slowing down rather than speeding up their infrastructure deployment.[109] Market investments in 5G do not seem to be matching the hype around near-term profitability. Appendix F in the accompanying volume discusses one possible approach that policymakers could take to support U.S. innovation in applications: encouraging the development of large-scale shared 5G testbeds where the private sector could experiment with various potential 5G applications.

China's competitive position is quite different from that of the United States and other allied countries, because the Chinese government views 5G as a source of geopolitical advantage and revenue. To further its geopolitical goals, the Chinese government has given Huawei alone an estimated $75 billion in subsidies,[110] allowing it and other Chinese firms (e.g., ZTE) to greatly undercut the prices offered by unsubsidized firms in the United States and Europe. Moreover, as discussed above, many of Huawei's technological advances are believed to have resulted from intellectual property stolen from other nations.[111] The United States should not respond in kind by copying the Chinese strategy of subsidies and intellectual property theft, but policymakers at all levels of government might want to consider innovative approaches toward encouraging infrastructure investment, such as encouraging private-public partnerships to build 5G infrastructure (as already exist in Europe).[112]

Maintaining the current advantage will involve complicated trade-offs and thoughtful policy for United States industry and for national policymakers. Policymakers should closely monitor network applications developed by potential adversary nations that appear to be gaining widespread popularity in the United States. The collection and use of large amounts of data by such applications might be of particular concern. At the least, increased popularity of foreign-built applications could signal the beginning of a major realignment in international soft-power influence.

Research and Development Ecosystem

This section discusses national R&D postures in the telecom sector. Appendix G in the accompanying volume discusses postures in the overall technical sector, which could shape the development of the applications that 5G will enable.

The United States leads the world in private-sector R&D in the telecom industry as of 2020,[113] but China is catching up rapidly. In 2016, the United States spent $98.1 billion in corporate telecom R&D. China followed with $48.8 billion, the European Union spent $34.4 billion, South Korea spent $26.5 billion, Japan spent $20.5 billion, Taiwan spent $16.8 billion, and Canada spent $3.0 billion. However, between 2015 and 2016, private telecom R&D increased by 15.6 percent in China, 8.6 percent in South Korea, 7.6 percent in Taiwan, and 7.1 percent in the United States—while it only grew by 4.0 percent in the European Union and shrank in Japan and Canada.[114]

Given the rapidly changing nature of the software development industry, the companies that dominated 4G app development might not necessarily dominate 5G as well. The past decade has shown a relative movement of app developers away from the United States and Europe and toward East Asia. As of 2016, there were 1,567 commercial mobile app development firms in the United States, followed by 776 in China, 456 in the United Kingdom, 395 in South Korea, and 351 in Japan. However, because of the winner takes all nature of app development, U.S.-developed apps were estimated to capture more than three times as much revenue as Chinese-developed ones in 2016. Every country showed a preference for apps developed domestically, but third countries disproportionately like to use apps developed in the United States and other Western countries rather than those developed in China, possibly because of language barriers.[115]

The fact that English is much more widely spoken worldwide than Mandarin might be an important boost to U.S. technical competitiveness in mobile application development. However, the number of Chinese app users is growing fast: China represented nearly 50 percent of global app downloads in 2018, and Chinese downloads increased 70 percent between 2016 and 2018 versus just 5 percent growth for the United States (with other developing countries showing large growth)—so the relative advantage of English-language apps is probably eroding.[116]

Conclusions

The United States has a strong technical position in key segments of the 5G ecosystem. However, some threats to U.S. technical competitiveness are emerging. To sustain and protect U.S. technical strengths, U.S. policymakers should speed some actions and prepare to take others as needed. We conclude with a short summary of some of the most important issues along several dimensions.

Spectrum

As of June 2020, the United States remains significantly behind many other countries on spectrum reallocation and licensing, particularly in the mid-band. 5G will need a significant amount of dedicated mid-band spectrum to achieve its full technical potential. U.S. spectrum allocation is based on a competitive auctioning process that must be responsive to many different interests, while strategic competitor nations with more centralized decisionmaking processes have determined that 5G is a national priority and have moved more quickly to open up spectrum. The FCC has begun the process of setting up mid-band license auctions, but has not yet licensed any meaningful amount of mid-band spectrum, while other countries are moving ahead much faster. DSS technology is unlikely to solve this problem by itself, but it might help ease the transition of spectrum to 5G networks and is worth exploring.

However, it is incorrect to frame a 5G spectrum strategy as a choice of whether to compete in the high-band or the mid-band. A mature national 5G network will require 5G spectrum in all of the high-, mid-, and low-bands for different environments and population densities, and eventually every major country will use 5G bands in all three sets of frequencies. It is vital that U.S. policymakers seek ways to accelerate the pace of spectrum auctioning in all frequency bands for the development of 5G networks and their applications. Although most of these networks will likely be built by the major mobile telecom operators, led by Verizon, AT&T, and T-Mobile, policymakers should consider granting other organizations the right to use mid- and high-band spectrum in the boundaries of specified facilities and usage conditions.

Supply Chain

The supply chain for 5G hardware has become increasingly globalized, complex, and interdependent. Several U.S. companies are major players in the 5G supply chain, and U.S. companies dominate many of the mobile applications, services, and IoT devices that comprise a major part of the market value that 5G will generate. However, the United States will not be able to dominate all segments of such a massive and rapidly changing supply chain.

Despite its global scope and complexity, the 5G supply chain has grown worrisomely consolidated at certain points. In particular, the majority of the highest quality fabrication facilities for mobile device semiconductors are located in Taiwan, with about half of the global value from these semiconductors produced by a single corporation (TSMC) in a limited number of factories. These companies supply microchips to both Chinese companies and companies in the United States and allied nations. A natural disaster, disease outbreak (such as a resurgence of COVID-19), or military action involving China could massively disrupt the global supply of mobile device chipsets. Another concern is that the United States no longer has domestic companies building RAN equipment—which could force the United States to turn to currently restricted equipment if China's Huawei and ZTE were to drive Ericsson and Nokia out of this market. Any form of supply chain consolidation is worth monitoring, but critical markets that are consolidated into a few companies in allied nations are likely to pose a very different set of risks than markets that are consolidated in such strategic competitor nations as China.

Science, Technology, Engineering, and Mathematics Talent

The United States remains a world leader in most aspects of technological innovation; it produces the highest-value software applications and maintains a skilled science, technology, engineering, and mathematics (STEM) workforce. Moreover, the United States is much more closely integrated with the rest of the world than China is, and it faces lower cultural and language barriers.

However, this competitive advantage is not guaranteed to last indefinitely. STEM talent inflows in the United States are decreasing, in contrast to China's aggressive effort to court foreign talent amid increasing investment in telecom R&D. Policymakers have several possible options for keeping the United States technically competitive on the talent front; for example, ensuring that the United States remains (in the short term) both attractive and accessible to foreign talent and (in the longer term) strengthening U.S. STEM education and domestic workforce development.

Data Access

Regarding 5G applications, the United States still holds a strong competitive position. However, looking further into the future, the United States faces both cultural and political barriers to the centralized mass collection of data that such nations as China do not. This might give these other countries a competitive advantage, in the sense that they are free to develop applications that do not align with U.S. values (e.g., applications for mass surveillance).[117] Similarly, they might be able to leverage their access to larger and more-centralized databases of information to train machine learning algorithms that outperform those developed in allied nations. If 5G-enabled applications (as opposed to infrastructure) developed in strategic competitor nations achieve widespread adoption outside their country of origin, then that might also signal that

U.S. competitive advantage in application development is eroding.

Research and Development and Use Cases

Despite the urgency that surrounds much of the public discussion, 5G technology is still very much under development as of June 2020, both in terms of technical standards and applications. There remains considerable uncertainty about their eventual use, how much value they will generate, and who will capture that value. Moreover, these questions will take many years to answer. Previous wireless generations took well over a decade to reach maturity, and major parts of the 5G technical ecosystem (such as the 5G Core) have not yet been fully standardized, let alone built out. Although deployment efforts are proceeding at a steady pace, the COVID-19 pandemic has added additional uncertainty to the timelines and could result in either an acceleration or a deceleration of deployment.[118] The eventual winners and losers from 5G are very difficult to predict today. Policymakers should therefore continue to support 5G R&D in a broad fashion and avoid getting locked into any assumptions about the course of either 5G's infrastructure deployment or its eventual applications.

Although the deployment of 5G infrastructure is just beginning and could take decades, there has already been some early discussion of 6G (although no formal standard-setting).[119] 6G will presumably continue the current trends of ever-higher connectedness among an increasingly heterogeneous array of edge devices. As with 5G, this will pose great opportunities for new technology applications, but also new risks to privacy and to the United States' economic and technical competitiveness.

Notes

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[4] The International Telecommunication Union defines *user experienced data rates* as "the 5% point of the cumulative distribution function (CDF) of the user throughput" or the data rate that is achieved over a large coverage area for the majority of mobile users.

[5] *User plane latency* is the time required for the source to send a packet to when the destination receives it (in ms).

[6] Internet traffic is anticipated to grow between 10- and 100-fold by 2030 with the number of connected devices projected to reach 50 billion. See Radiocommunication Sector, International Telecommunication Union, *IMT Traffic Estimates for the Years 2020 to 2030*, Report ITU-R M.2370-0, July 2015.

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About This Perspective

The latest generation of wireless networks, called 5G (for "fifth generation"), has launched with great expectations and amid significant concerns. A theme running through discussions of the 5G era is that this is a race, that first movers will dominate all others, and that this dominance will provide enduring economic and technical benefits to those first movers' home countries and populations.

This Perspective serves as a companion piece to the Perspective "America's 5G Era: Gaining Competitive Advantages While Securing the Country and Its People" published in May 2021. In this analysis, we examine the technical underpinnings of America's 5G ecosystem, assess its critical strengths and weaknesses, and identify actions that policymakers in government could consider to help secure America's 5G future.

This research was completed in 2020. Although subsequent events have changed the 5G ecosystem and its major players to some degree, the major findings and conclusions of this perspective remain relevant to policymakers.

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