America’s 5G Era

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

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Spectrum

This appendix gives further information on the status of U.S. spectrum allocation for 5G as of June 2020.

Mid-Band Auctions

In early 2020, the Federal Communications Commission (FCC) opened up 1.2 gigahertz (GHz) of unlicensed 6 GHz WiFi spectrum and held two large millimeter wave (mmWave) auctions, freeing up the 24, 37, 39, and 47 GHz bands, as shown in Figure 3 of the accompanying Perspective.[1] In addition, two key mid-band auctions were slated for the second half of 2020; 70 megahertz (MHz) of licensed spectrum at the 3.5 GHz band (Citizens Broadband Radio Service [CBRS]) and 280 MHz of spectrum will be auctioned from the C-Band.[2] The FCC is also attempting to free up the 3.1 GHz band currently held by the Department of Defense, arguing that they could be more efficient with their spectral holdings.[3] Moreover, because relatively few fifth generation (5G)-capable devices have entered the marketplace as of June 2020, delayed mid-band spectrum allocation is unlikely to inflict significant economic damage. In addition, mobile carriers and application developers have been testing mid-band for some time and will be ready when spectrum comes available.[4] Ultimately, however, there remains the enormous challenge of infrastructure deployment, which is likely to be the more significant bottleneck; from the radio access equipment and fiber backhaul to property rights, infrastructure investments are costly and can take several years to accomplish.

Dynamic Spectrum Sharing, Military, and Citizens Broadband Radio Service

Because much of the 3–4 GHz range is occupied by military assets (as shown in Figure 3 in the accompanying Perspective), dynamic spectrum sharing (DSS) has been looked at as a means to share the lucrative spectrum with commercial operators. In April 2020, the Department of Defense set up a testbed at Hill Air Force Base

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1 FCC 'Spectrum Frontiers' auctions 102 and 103 were completed on May 28, 2019, and March 5, 2020, respectively. Federal Communications Commission, "Auction 102: Spectrum Frontiers—24 GHz," webpage, undated a; Federal Communications Commission, "Auction 103: Spectrum Frontiers—Upper 37 GHz, 39 GHz, and 47 GHz," webpage, undated b.

2 Auctions 105 and 107 are slated to take place in late July and December 2020, respectively. See Federal Communications Commission, "Auction 105: 3.5 GHz," FCC website, undated c; Federal Communications Commission, "FCC Seeks Comment on Bidding Procedures for December 8 C-Band Auction," press release, Washington, D.C., February 28, 2020a.

3 Michael O'Rielly, commissioner, Federal Communications Commission, letter to Donald Trump about the 5G midband spectrum, Washington D.C., April 8, 2020.

4 Monica Alleven, "Verizon Files to Conduct C-Band Tests," *FierceWireless*, May 18, 2020; Alan Weissberger, "AT&T Tests '5G' Transmission on Mid Band (Sub 6GHz) and Later Low Band (700 MHz) Spectrum," *Technology Blog*, Institute of Electrical and Electronics Engineers Communications Society, July 31, 2019.

in Utah with the intention of testing how well 5G networks can work in conjunction with military equipment (comms, radar, etc.).[5] In principle, this sharing scheme might operate similar to the current regulatory system employed at the CBRS, or 3.5 GHz, bands (see Figure 3 of the accompanying Perspective). Priority Access Licenses (PAL) will be given to military operators and lower tier licenses will be provided for commercial use.[6] This operating model represents a compromise between the existing spectrum holder (the U.S. Department of Defense) and commercial interests. The CBRS is managed by an automated frequency coordinator, known as a Spectrum Access System (SAS), which is a cloud-based piece of technology that scans the area to see if the military is using the frequencies in a given location; spectrum is then dynamically allocated, or denied, as appropriate.[7] However, one key limitation is that the CBRS also imposes power restrictions to limit interference. As a result, initial deployments might be limited to a few kilometers or indoors (such as private services in factories, stadiums, or office buildings).[8] Moreover, this system might pose challenges for applications that rely on high availability but do not have licensed bands to fall back on. Nevertheless, the CBRS model might offer a technological solution to the mounting challenge of spectrum congestion.

U.S. Mobile Carrier Spectrum Holdings

The sections that follow provide a brief overview for each major U.S. mobile carrier as of June 2020.

T-Mobile

Following the merger with Sprint, T-Mobile (which already claimed significant 600 MHz low-band holdings) obtained extensive swaths of spectrum in the mid-band (2.5 GHz)—something other carriers are lacking, as shown in Figure 3 of the accompanying Perspective. These holdings place T-Mobile in an excellent position to take the early lead into the 5G era. T-Mobile launched nationwide 5G services in late 2019, focusing primarily on upgrading radio units for low- and mid-band coverage, with some mmWave deployments. The 600 MHz bands have been in operation since T-Mobile went live in December 2019, and the 2.5 GHz will be part of a gradual re-farming process that will take some time.[9] In May 2020, T-Mobile became the first U.S. carrier to offer all three bands in select cities and claims it will start standalone deployments in late 2020.[10] The 600 MHz band, 2.5 GHz band, and 28 GHz mmWave, in addition to the License Assisted Access unlicensed spectrum, allows multiple layers of downlink options, which allowed T-Mobile to record gigabit speeds in select

5 Jared Serbu, "Pentagon Releases Last of Four Solicitations to Test 5G Technologies," *Federal News Network*, April 9, 2020.

6 Federal Communications Commission, "*3.5 GHz Band Overview,"* webpage, updated March 10, 2020b.

7 Bob O'Donnell, "CBRS vs. C-Band: Making Sense of Mid-Band 5G," *Forbes*, February 27, 2020.

8 Craig Schwechel, Marth Wilson, Lauren Buhl, and Tomislav Marcinko, "Mid-Band Spectrum Opportunities and Challenges: Balancing Coverage and Capacity for 5G Deployments in the US Market," inCode Consulting, technical paper prepared for Society of Cable Telecommunications Engineers 2019 fall technical forum, September 26, 2019; Mike Dano, "Anticipation Mounts for 3.5GHz Midband Spectrum Auction," *Light Reading*, January 13, 2020.

9 *Re-farming* refers to the process of repurposing spectrum assets that have been historically used for older technologies (i.e., 2G or 3G services) and making them available for newer technologies, such as Long-Term Evolution (LTE) or 5G (Shola Sanni, senior policy manager, Africa, "How to Implement Spectrum Re-Farming," briefing slides, Groupe Speciale Mobile Association, November 2017; Philip Michaels, "T-Mobile 5G Rollout: Locations, Phones, Price and More," *Tom's Guide*, May 11, 2020).

10 Bevin Fletcher, "T-Mobile Turns on 5G 'Layer Cake' in NYC with 2.5 GHz Integration," *FierceWireless*, May 5, 2020c.

areas of New York City.[11] Although nationwide 5G services have been marginally better than LTE services,[12] at this stage T-Mobile is out front of other U.S. carriers and is in a good position to claim much of the earliest economic value from the 5G era.

AT&T

5G deployments for AT&T began with a gradual rollout of commercial mmWave services in late 2018, followed by low-band services in the 850 MHz spectrum in November 2019.[13] As of June 2020, AT&T's network has expanded to 190 markets for low-band coverage and 35 cities for mmWave (5G+).[14] However, AT&T initially took a conservative approach to 5G by focusing on enterprise mmWave and fixed wireless (universities, stadiums, and factories). Many viewed this as a testing ground for mmWave because of some early challenges with deployments.[15] Hence, mmWave has only been available to the public since March 2020 on the 24 GHz and 39 GHz bands.[16]

In 2017, AT&T was awarded a $6.5 billion contract to build and manage FirstNet, a nationwide public safety broadband network dedicated to first responders and operated by the Department of Commerce operating on the 700 MHz band.[17] AT&T has been leveraging this contract to build out much of its 5G network, because there are cost savings to installing the FirstNet and 5G equipment on the same tower simultaneously. Hence, this contract has largely guided low-band deployment. AT&T has also reduced spectrum used in the 850 MHz band by its 3G and 4G services to make way for 5G services.[18]

As of June 2020, AT&T is said to be planning on deploying stand-alone 5G and DSS in the second half of 2020. This would allow 4G LTE and 5G New Radio (NR) services to exist on the same spectrum channel.[19] It is likely that AT&T will begin rolling out mid-band services around that time, as they have lower mid-band holdings in the Advance Wireless Service, Personal Communications Service, and Wireless Communications Service bands (see Figure 4 of the accompanying Perspective). However, the acquisition of Time Warner in 2018 and subsequent merger with Discovery Inc. a few years later, combined with the effects from the coronavirus disease 2019 (COVID-19) pandemic, have slowed 5G deployment. Investment in 5G and anticipated mid-band spectrum purchases later in 2020 might slow significantly as AT&T moves to reduce costs.[20]

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[11] Milan Milanovic, "How T-Mobile's Merger with Sprint is Changing the Game for 5G," *Speedtest*, May 28, 2020; Adrian Diaconescu, "T-Mobile Boasts Gigabit Milestone Paving the Way for Wide-Scale High-Speed 5G Service," *PhoneArena*, May 21, 2020.

[12] Michaels, 2020.

[13] Chaim Gartenberg, "AT&T's Faster Millimeter Wave 5G Network Launches on March 6th with the S20 Plus and Ultra," *The Verge*, March 4, 2020.

[14] Ed Oswald and Christian de Looper, "AT&T 5G Rollout: Everything You Need to Know," *Digital Trends*, May 27, 2020.

[15] Joan Engebretson, "AT&T Touts 5G for Business Market Plans, Including Fixed Wireless," *Telecompetitor*, January 22, 2019; Matt Kapko, "US Operators Encounter Limits of 5G on mmWave Spectrum," *SDxCentral,* March 27, 2019a.

[16] AT&T, "AT&T Bolsters Network with Enhanced Spectrum Position," press release, Dallas, Texas, March 31, 2020.

[17] AT&T, "AT&T Selected by FirstNet to Build and Manage America's First Nationwide Public Safety Broadband Network Dedicated to First Responders," press release, Dallas, Texas, March 30, 2017.

[18] Kelly Hill, "FirstNet is AT&T's Springboard to 5G," *RCR Wireless News*, March 13. 2019; Kelly Hill, "AT&T Reducing 4G Spectrum Use Ahead of Low-Band 5G Launches, OpenSignal Finds," *RCR Wireless News*, March 10, 2020.

[19] Bevin Fletcher, "AT&T to Deploy Dynamic Spectrum Sharing in Second Half of 2020," *FierceWireless*, May 28, 2020d.

[20] Bevin Fletcher, "AT&T Acknowledges Logistical Challenges in 5G Rollout Amid COVID-19," *FierceWireless*, April 22, 2020b.

Verizon

Because of limited low- and mid-band spectrum holdings, Verizon has largely focused solely on mmWave deployments (at the 28 GHz band). As of June 2020, mmWave is available in 34 cities and several large stadiums.[21] Although early mmWave deployments provided significant bandwidth, with speeds exceeding 800 megabits per second in some areas, deployments remain hampered by limited availability and interference.[22] In the low- and mid-band, Verizon is leaning heavily on DSS to share lower spectrum holdings. Although DSS is not ready, Verizon claims to be installing systems nationwide for deployment in late 2020.[23] The heavy focus solely on mmWave is risky; any delays—because of COVID-19 or technological issues with DSS—might leave a sizable amount of Verizon customers without 5G coverage. However, mmWave provides a significant boost over lower bands and, if delivered effectively, might be a strong competitive advantage for Verizon.

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21 Oswald and de Looper, 2020.

22 Bevin Fletcher, "5G a 'Mixed Bag' as Verizon Gets High Speeds, T-Mobile Offers Better Coverage—RootMetrics," *Fierce-Wireless*, March 11, 2020a.

23 Alan Weissberger, "Verizon to Double 5G mmWave Cities and Use DSS by End of 2020," *Technology Blog*, Institute of Electrical and Electronics Engineers Communications Society, February 14, 2020.

APPENDIX B

5G Ecosystem

This appendix provides a more detailed discussion of the 5G ecosystem described in Figure 5 of the accompanying Perspective.

User Equipment

Throughout the 3G era, and in the decades prior, radio frequency (RF) equipment makers such as Nokia and Motorola dominated the marketplace because they were able to leverage their hardware expertise to consistently deliver reliable devices that met consumers' needs.[1] However, the arrival of the smartphone shifted expectations from coverage and call reliability toward applications and internet access. Virtually overnight, user devices became internet-centric mobile computers rather than a portable telephone. Tech giants such as Google and Apple, working with advanced chipmakers, leveraged their software expertise to deliver an entirely new user experience. This trend largely continues today with Google and Apple controlling the entire mobile operating system (OS) market through Android and iOS, respectively.

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 mid-2020, only a handful of 5G phones are available in limited markets,[2] and early deployment is heavily dependent on network infrastructure availability, which remains fragmented and regional. For instance, Korean telecommunications (telecom) completed the world's first 5G network in early 2019, giving local handset makers (Samsung and LG) an early market.[3] In the same way, Chinese handset makers have attained some early success because of widespread domestic infrastructure deployment. However, true 5G device leadership will be difficult to gauge until all leading device makers enter the marketplace and global network operators achieve widespread 5G coverage, which might not happen for some time.

Mobile Chipsets

Central to user equipment operations are their mobile chipsets. Any discussion about device performance invariably involves the processor, or the digital brain of the device. Flagship smartphones use highly advanced integrated processors known as *Systems-on-a-Chip* (SoCs). These chips, often no larger than a thumbnail,

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1 Timothy M. Bonds, James Bonomo, Daniel Gonzales, C. Richard Neu, Samuel Absher, Edward Parker, Spencer Pfeifer, Jennifer Brookes, Julia Brackup, Jordan Willcox, David R. Frelinger, and Anita Szafran, *America's 5G Era: Gaining Competitive Advantages While Securing the Country and Its People*, Santa Monica, Calif.: RAND Corporation, PE-A435-1, 2021.

2 Mark Jansen, "Every 5G Phone Announced so Far so You Can Get a Faster Internet Connection," *Digital Trends*, May 12, 2020.

3 Catherine Sbeglia Nin, "How South Korea Built 5G, and What it's Learning," *RCR Wireless News*, September 12, 2019; Patrick Moorhead, "Who Is 'Really' Leading in Mobile 5G, Part 3: 5G Mobile Handsets," *Forbes*, June 27, 2019.

include the Central Processing Unit (CPU), a graphics processing unit for graphics-related tasks, a neural processing unit (NPU) for specialized artificial intelligence (AI) applications, and much more.[4]

Mobile chipsets are often designed in-house, as is the case with Apple, Samsung, and Huawei (through subsidiary HiSilicon), or sourced from other fabless suppliers such as Qualcomm or MediaTek.[5] Most mobile chipset designs are then sent to one of two foundries for manufacturing: Taiwan Semiconductor Manufacturing Company (TSMC) or Samsung. Both foundries are located outside the U.S. (in Taiwan and South Korea, respectively).[6]

Modem and Radio Frequency Front-End Chipsets

In addition to the primary chipset, there are two additional modules of critical importance for the 5G era: the *modem*, which demodulates wireless signals into data streams that the CPU can understand, and the *RF front-end*, which is generally defined as everything between the antenna and the digital baseband system, or modem.[7] To address the new challenges presented by 5G, innovative modem and RF solutions must be developed. For example, mmWave band signals can be blocked by the user's hands, have higher path losses, and require new antenna arrays to operate. Consequently, for 5G devices, antenna and transceiver modules are likely to be packaged with the RF front-end components to boost signal and minimize losses.[8] Then, in contrast to prior generations, three to four of such integrated RF modules will be placed along the edges of the device to avoid hand interference and ensure a clear line-of-sight to the base station.[9]

Qualcomm has long maintained leadership in modem and RF technology. Nearly half of all smartphones depend on Qualcomm modems,[10] and they are well positioned to continue this trend deep into the 5G era (see Standards and Patents section). Already in the second generation, the Snapdragon X55 Modem-RF system provides 4G/5G spectrum sharing, supports sub-6 GHz and mmWave frequencies for both standalone and non-standalone modes, and also supports DSS, multiple input multiple output, and beamforming.[11] Qualcomm also provides separate sub-6 GHz and mmWave RF modules, and, like earlier models, three to four

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4 Robert Triggs, "What is an SoC? Everything You Need to Know About Smartphone Chipsets," *Android Authority*, July 1, 2021.

5 Spencer Chin, "Top-Tier Smartphone Makers Going to In-House Processors: Report," *FierceElectronics*, January 9, 2020. Mobile chipset designs are immensely complex and have rapidly evolved from general purpose CPUs into multi-core SoCs with various modules exclusively designed for specific functions (such as graphics or AI). These designs are generally reduced instruction set architectures (RISC) and are overwhelmingly based on ARM instruction sets (a UK-based semiconductor design firm); although the open-source RISC-V instruction set has garnered considerable attention in recent years. See "A New Blueprint for Microprocessors Challenges the Industry's Giants," *The Economist*, October 3, 2019. *Fabless* design firms outsource chip fabrication.

6 Samsung remains the only integrated device manufacturer (IDM) that designs and manufactures mobile chipsets.

7 This includes several amplifiers, filters, and switches required to convert information from the baseband to radio signals that can be transmitted or received over the air. See Qualcomm, "RF Front-End Explained in 101 Seconds," video, YouTube, September 20, 2017; Christopher Bowick, "What's in an RF Front End?" *EE Times*, February 4, 2008.

8 Mark LaPedus, "Challenges Grow For 5G Packages and Modules," *Semiconductor Engineering,* July 18, 2019; Prakash Sangam, "'Made for Each Other'—Why Integrated Modem–RF System Approach is a Must for 5G Device Supremacy (Analyst Angle)," *RCR Wireless News*, September 16, 2019b.

9 Ana Schafer, "5G Modems, RF and Antennas: Getting mmWave Data into the Device," blog post, Qualcomm Developer Network, November 7, 2019.

10 Sravan Kundojjala, "Intel Gives Up on 5G Modems While Qualcomm Scores Big with Apple," Strategy Analytics, April 18, 2019.

11 Qualcomm, "Snapdragon X55 5G Modem–RF System," webpage, undated.

RF modules might be included to avoid signal issues inherent to mmWave frequencies.[12] Other significant players in the market are: MediaTek, based out of Taiwan, which holds around 15 percent of the market share; Huawei, through subsidiary HiSilicon; Samsung; and Unisoc, a Chinese fabless semiconductor company based out of Shanghai.[13] Both Samsung and Huawei largely produce chips for their own smartphones.[14]

Because of the dispersed nature of the RF front-end architecture, there have been several competitors offering a variety of components. Although the prevailing trend in the 5G era is toward a more complex integration of the RF components, this is more expensive and might only find early usage in high-end mobile devices. Key players in the RF space are Murata, Broadcom, Skyworks, Qorvo, and Qualcomm, which primarily supply integrated RF modules to Samsung, Apple, Google, and LG and control most of the market. Alternatively, Huawei, Xiaomi, Oppo, and Vivo tend to source a higher number of *discrete* RF components from a wide variety of suppliers (including several emerging Chinese vendors) to keep the costs down.[15]

Core Network

As discussed in the accompanying Perspective, the *core* connects all parts of the network and aggregates data traffic from the endpoints. The 5G Core (5GC) has been designed to be *cloud native* with virtualized, software-based network functions (or services) at the core.[16] 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 multi-access edge computing (MEC), AI-driven automation, and self-healing for improved uptime.[17]

The standalone 5G network will consist of many different software-defined or "virtual" networks designed to be largely logically independent of the physical hardware that they operate on. These many virtual network slices might trigger many of the same issues as the current debate over net neutrality—the principle that telecom providers should not be allowed to offer different network capabilities to different users or different types of data, or more broadly to treat different users differently.[18] On the one hand, network slicing might prove critical for guaranteeing the quality of service necessary for groundbreaking new applications, including lifesaving ones such as remote surgery or autonomous vehicle collision avoidance. If so, regulations restricting network slicing could harm innovation in these applications. (And if other countries do not impose similar restrictions, the U.S. could be placed at a competitive disadvantage.) On the other hand, guaranteeing a certain quality of service to some customers but not others could be viewed as favoring some

12 Jeremy Horwitz, "Qualcomm Shows World's First 5G mmWave and Sub-6GHz Smartphone Modules," *Venture Beat*, July 23, 2018.

13 Kundojjala, 2019.

14 Intel was a player in this space, but recently sold their modem division to Apple for $1B in 2019. See Apple, "Apple to Acquire the Majority of Intel's Smartphone Modem Business," press release, Cupertino, Calif., July 25, 2019.

15 Cédric Malaquin and Antoine Bonnabel, "5G's Impact on RF Front-End Module and Connectivity for Cell Phones 2019," Yole Développement, August 2019.

16 Groupe Speciale Mobile Association, *Road to 5G: Introduction and Migration*, April 2018.

17 5G Americas, *5G and the Cloud: A 5G Americas White Paper*, December 5, 2019b; Guang Yang and Sue Rudd, "Complex Converged 5G Network Operations Demand Automation and AI," Strategy Analytics, September 2018.

18 Agam Shah, "10 Arguments For and Against Net Neutrality," American Society for Mechanical Engineers, March 22, 2018; Zoraida Frias and Jorge Pérez Martínez, "5G Networks: Will Technology and Policy Collide?" *Telecommunications Policy*, Vol. 42, No. 8, September 2018; Christopher S. Yoo and Jesse Lambert, "5G and Net Neutrality," in Guenter Knieps and Volcker Stocker, eds., *The Future of the Internet: Innovation, Integration and Sustainability*, Nomos, 2019.

forms of speech over others, which could stifle competition from up-and-coming rivals to the existing service providers, or lead to a disparity in user experience between those who can and cannot afford to pay for higher service.

Huawei and Ericsson are consistently ranked as top vendors in this space, followed by Cisco, Nokia, ZTE, and Samsung.[19] However, companies that provide server platforms (such as Dell EMC, HPE, and Amazon), are likely to play a significant role in the 5GC development as functions move to the cloud. The 5GC currently remains in its infancy with early deployments not scheduled until late 2020 at the earliest, as most 5G deployments remain in non-standalone mode as of June 2020.

Multi-Access Edge Computing and Cloud Computing

A significant departure from prior generations is the addition of MEC and cloud computing. The stringent low latency requirements of the 5G standard require data processing and decision making to be pushed closer to the network edge. Simultaneously, the virtualization of the 5G core allows several functions typically performed at the network edge to be centralized in a universal cloud environment. This enables more efficient, flexible, and intelligent core functions. Together, MEC and cloud computing enable many of the novel use cases outlined in early white papers through low latency, network slicing, AI-driven automation, and self-healing, the addition of which are a significant leap forward from prior generations.[20] MEC and cloud computing also bring about a higher degree of hardware disaggregation as network functions move from application-specific hardware to software on common servers. This new architecture affords more flexibility from a network control standpoint and also avoids vendor lock-in.

This space is largely undefined because these capabilities rely on standalone and 5GC deployment. However, cloud computing and software firms are likely candidates with several already positioning themselves for early leadership in the new battleground.[21]

[19] Dave Bolan, "5G Core: Are We Ready?" Dell'Oro Group, webpage, May 6, 2020; Matt Kapko, "Ericsson, Huawei Win Top Ratings on 5G Mobile Core," *SDxCentral*, October 31, 2019b.

[20] 5G Americas, "5G at the Edge," white paper, October 2019a.

[21] Microsoft has made several acquisitions in recent months to fortify their 5G portfolio; Amazon has partnered with Verizon to deliver cloud and edge computing capabilities; Google's "Anthos for telco" is a scalable cloud computing platform developed for AT&T. See Mary Jo Foley, "Microsoft Buys Cloud Communications Software Vendor Metaswitch Networks to Bolster 5G," *ZDNet*, May 14, 2020; Sue Marek, "Verizon Partners with AWS to Bring More Power to its 5G Edge," *FierceWireless*, December 3, 2019; Maribel Lopez, "5G: The Next Battleground For Microsoft And Google," *Forbes*, April 6, 2020.

APPENDIX C

Export Controls

This appendix provides a more detailed discussion about export controls in relation to Chinese semiconductor ambitions.[1]

Export Controls

Export controls can be immensely effective if implemented in coordination with U.S. allies (Japan, the Netherlands, etc.).[2] Although Chinese firms have lured American companies into transferring advanced technology (as was the case with AMD in 2016),[3] overly restrictive controls might harm U.S. companies seeking access to lucrative Chinese markets and accelerate China's efforts toward developing a domestic supply chain. Moreover, strict controls place neutral parties (e.g., South Korea, Taiwan, or Europe) in a difficult position, forcing them to choose between the Chinese or American markets.[4]

Export restrictions issued by the Commerce Department on May 15, 2020, are aimed at the software and technology used to design and manufacture semiconductors abroad,[5] requiring all users seeking to export products with U.S. technology to obtain a license.[6] The move prevents TSMC and other advanced chipmakers from fabricating Huawei's designs. This type of low-level and highly precise export regime will deal a significant blow to Huawei's 5G capabilities and to China's greater semiconductor ambitions.

However, the full ramifications of these new rules will not be immediate. Recent teardowns have indicated that China has the capability of releasing 5G devices without U.S. modem and RF technology, depending heavily on Japanese, South Korean, and various domestic firms as replacements.[7] This is significant

1 Although this perspective was completed in June 2020, there have not been major changes in export control policies between the Trump and Biden administrations as of August 2021. The Biden administration has slightly tightened restrictions by more explicitly prohibiting the export of components for Huawei 5G devices, thereby increasing the uniformity of the ban. Eric Martin, "U.S. Imposes New 5G License Limits on Some Huawei Suppliers," Bloomberg News, March 12, 2021.

2 Alexandra Alper, Toby Sterling, and Stephen Nellis, "Trump Administration Pressed Dutch Hard to Cancel China Chip-Equipment Sale: Sources," *Reuters Technology News*, January 6, 2020.

3 Kate O'Keeffe, Brian Spegele, "How a Big U.S. Chip Maker Gave China the 'Keys to the Kingdom,'" *Wall Street Journal,* June 27, 2019.

4 Will Knight, "The Newest US Sanctions on China's Huawei Could Backfire," *Wired*, March 31, 2020.

5 U.S. Department of Commerce, "Commerce Addresses Huawei's Efforts to Undermine Entity List, Restricts Products Designed and Produced with U.S. Technologies," press release, Washington, D.C., May 15, 2020.

6 Prior efforts were largely directed at preventing Huawei from purchasing U.S. chipsets, not at the equipment and software required for manufacture. Most designers use electronic design automation software sold by Cadence and Synopsis, which are both U.S. firms. Replacing this software will not be an easy task.

7 Notable replacements are in the RF modules, critical for 5G (Murata [Japanese] and various Chinese firms have replaced Qualcomm). See Atsushi Takano, "Inside Huawei's First 5G Phone: Teardown Reveals Rush to Innovate," Nikkei Asia, October 23, 2019; Fumie Yaku, "Huawei Teardown Shows US Ban Made Company Turn to Chinese Parts," Nikkei Asia, May 14, 2020.

because RF components require entirely different manufacturing processes and do not scale like logic or memory chipsets. In this, China has shown the ability, or at least the early stages of, designing and fabricating several RF components domestically (through foundries Semiconductor Manufacturing International Corporation [SMIC] and United Microelectronics Corporation, and design firms Unisoc RDA, Airoha, Richwave, etc.).[8] Although China remains heavily dependent on Japan and South Korea, these moves are evidence of significant progress, because they will still be able to produce 5G-capable devices, even in the face of U.S. sanctions. Hence, there remains a path forward. Moreover, China is unlikely to allow Huawei to fail and will continue issuing state-sponsored loans to ease the financial strain and increase research and development (R&D) efforts. The large domestic market and state subsidies might keep Huawei afloat until they can devise a solution via international partners (such as Japan and South Korea), through loopholes, theft, innovation, or a potential deal with the United States.

However, in the longer term, without access to Qualcomm's modems, TSMC's cutting-edge chipsets, or a way to circumvent U.S. restrictions,[9] Huawei will look toward SMIC to produce the bulk of their domestic chipsets. SMIC's capabilities remain several generations behind and they are also dependent on U.S. software and equipment technology, so it will take time and considerable resources to independently produce lower-end chipsets. Huawei will then be forced to produce lower-tier devices and equipment (or continue releasing older devices). Even with a strong domestic market, Huawei will no longer be able to compete with Samsung or Apple devices and is likely lose substantial market share to foreign and domestic rivals.[10] The same applies to Huawei's telecom equipment business, which heavily relies on high-end application-specific integrated circuits (ASICs) to be competitive. Without TSMC's manufacturing capabilities, Huawei will be placed at a significant disadvantage and will likely lose market share to Ericsson, Nokia, and Samsung (Table C.1).

8 Mark LaPedus, "RF SOI Wars Begin," *Semiconductor Engineering*, May 17, 2018; Malaquin and Bonnabel, 2019.

9 Interestingly, Huawei may look toward Samsung. "Huawei Said to Ask Samsung, SK Hynix for Stable Supply of Memory Chips," *South China Morning Post*, May 25, 2020.

10 Cheng Ting-Fang and Lauly Li, "China's Oppo Steps Up Chip Ambition as US Ban Hits Huawei," Nikkei Asia, May 27, 2020.

TABLE C.1

Global Market Share Held by Semiconductor Manufacturing Equipment Firms in 2018

Company	Country	Market Share (Percent)
Applied Materials	U.S.	17.7
Tokyo Electron	Japan	15.0
Lam Research	U.S.	14.0
ASML	Netherlands	12.1
KLA-Tencor	U.S.	4.4
Screen Semiconductors	Japan	2.2
Hitachi High Tech	Japan	1.8
ASM International	Netherlands	0.9
Rudolph Tech	U.S.	0.4
Nova Measuring	Israel	0.3
Nanometrics	U.S.	0.3
Top 10, Total		69.1
Others		31.1

SOURCES: Adapted from John VerWey, “Chinese Semiconductor Industrial Policy: Prospects for Future Success,” Journal of International Commerce and Economics, August 2019, p. 5; Thomas Alsop, “Global Market Share Held by Semiconductor Equipment Manufacturers in 1Q’17 and 1Q’18,” Statista, March 2019.
NOTE: Totals may add up to more than 100%, due to rounding.

APPENDIX D

Standards and Patents

This appendix provides additional background information on the global 5G standards and patents competition.

Influence of Patent Holders

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 standards (between the U.S. 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. Two notable cases are

- *Global System for Mobile communication (GSM) versus Code Division Multiple Access (CDMA):* Throughout the 2G and 3G eras, two standards were in a heated competition. GSM was a standard mandated by law in Europe in 1987, and CDMA was a standard developed by Qualcomm. In the U.S., Sprint and Verizon chose CDMA, while AT&T and T-Mobile chose GSM, along with most European countries.[1] This competition split the U.S. and European markets, isolating various segments which nearly led to a trade war and is often cited as a contributing factor to the decline of the domestic telecommunications industry.[2] Ultimately, a compromise was reached, after nearly a decade of disputes and considerable financial strain.[3]
- *WiMAX versus LTE:* In 2009, just before LTE became commonplace, Intel committed to WiMAX as the presumed 4G standard, while Qualcomm prioritized LTE.[4] Once AT&T and Verizon sided with the LTE standard developed by the 3rd Generation Partnership Project [3GPP], WiMAX began to decline rapidly. Both Intel and Sprint (a key U.S. carrier backing WiMAX) had invested considerable resources into WiMAX and took significant losses as a result. This placed Intel at a disadvantage for quite some time and is viewed as a contributing factor in the loss of Intel's mobile chip business.[5]

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1 Sascha Segan, "CDMA vs. GSM: What's the Difference?" *PCMag*, April 7, 2020.

2 Zen Soo, "How US Went from Telecoms Leader to 5G Also-Ran Without Challenger to China's Huawei," *South China Morning Post*, April 2, 2019; Michael Murphree, Jung P. Shim, and Kevin Love, "National Approaches to Technology Standards for Mobile Telecommunications," 2013 Wireless Telecommunications Symposium, 2013.

3 Seth Schiesel, "'Holy War' Over the Future of Wireless," *New York Times*, February 15, 1999; Svenolof Karlsson and Anders Lugn, "A New Fight," Ericsson, undated; Jacques Pelkmans, "The GSM Standard: Explaining A Success Story," *Journal of European Public Policy*, Vol. 8, No. 3, 2001.

4 Jim Duffy, "LTE vs WiMAX," *Network World*, June 7, 2010.

5 Vlad Savov, "Intel's New Smartphone Strategy Is to Quit," *The Verge*, May 3, 2016.

5G Standard Essential Patents

3GPP is one of the primary standards organizations that develops protocols for mobile communication systems. 3GPP is composed of representatives from seven regional technical standard-setting organizations that hold standards setting authorities in different regions of the world.[6] During the past several years, 3GPP has been working to develop 5G NR specifications, with release 16 planned as soon as June 2020. These specifications will then be coordinated with various other international organizations (such as the Institute of Electrical and Electronics Engineers, for instance) and then passed on to the International Telecommunications Union, a United Nations agency that handles information and communications technologies for approval. Then, the technical workings effectively become global standards and enable 5G system vendors to develop products that can be sold in any part of the world and integrated into 5G networks.[7]

3GPP working groups are responsible for defining technical standards for specific parts of the architecture. The 3GPP delegates who serve on these committees are technical experts in the technologies relevant to specific parts of the 5G technical architecture and typically represent the interests of the companies they work for. Technical standards are defined in a consensus-building process, in which members can submit candidate technologies and intellectual property from their own companies. Working groups then deliberate over the technical concepts (such as a solution or an algorithm). Specific technologies or intellectual property and patents might be associated with these features and functions. Next, the working group distills the winning ideas into a working document, which is published for the larger organization and various companies to review. The document goes through continuous review cycles until it is approved by 3GPP.

The solutions to various technical challenges often lead to patents. If the patent is deemed essential to build a standard compliant product, then the patent is declared a standard essential patent (SEP), which is highly valuable. Alternatively, nonessential patents are declared non-SEPs, as they might be relevant but not necessary for basic functionality. 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 determined by market forces and agreements between device makers and patent holders.[8] SEPs also require licensing on fair, reasonable, and nondiscriminatory terms and royalty rates must abide by these rules. However, not all SEPs are created equal. Some patents play minor roles while others might go on to define an entire era of mobile connectivity.[9] Moreover, it's nearly impossible to track value of individual patents as they are generally packaged as part of a SEP portfolio held by a specific company.[10] For a more complete discussion on patents and standards, see the companion piece to this Perspective.[11]

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6 These seven partners are ETSI (Europe), ATIS (USA), ARIB and TTC (Japan), TTA (South Korea), CCSA (China), and TSDSI (India). See 3GPP, "Partners," webpage, undated.

7 Guang Yang, "Who Are the Leading Players in 5G Standardization? An Assessment for 3GPP 5G Activities," Strategy Analytics, March 2020.

8 For instance, for mobile phones, patent portfolios cost roughly 2–5 percent of the product price. Mike Dano, "Qualcomm to Charge Up to $16.25 in Royalties for Every 5G Phone, More Than Ericsson's $5/Phone," *FierceWireless*, November 28, 2017.

9 Mark A. Lemley and Timothy Simcoe, "How Essential Are Standard-Essential Patents?" *Cornell Law Review*, Vol. 104, No. 607, 2019.

10 Prakash Sangam, "Demystifying Cellular Patents and Licensing Part 2: Patents Are a Monetization Tool for Innovators," *RCR Wireless News*, April 12, 2019a.

11 Daniel Gonzales, Julia Brackup, Spencer Pfeifer, and Timothy M. Bonds, *Securing 5G: A Way Forward in the U.S. and China Security Competition*, Santa Monica, Calif.: RAND Corporation, forthcoming.

APPENDIX E

5G Application Case Studies

This appendix describes three case studies of possible future 5G applications and the questions that they will raise for policymakers.

Case 1: Autonomous Vehicles and Traffic Control

Autonomous vehicle navigation might seem like an unlikely 5G case study for two reasons: First, vehicle manufacturers want to equip their vehicles to be truly autonomous without needing command guidance from centralized controllers. Second, progress toward fully autonomous driving has been slow—so it might be years before this case has immediate relevance.

But within these issues might lie important opportunities for vehicle-to-everything (V2X) communications. New applications such as autonomous parking (e.g., in automated parking structures) and vehicle beckoning require some form of *X2V* (everything-to-vehicle) communications. Today, Tesla makes use of X2V with its summoning feature. To the degree that such features distinguish some brands over others, vehicle makers might begin to compete on the basis of ever-more-sophisticated V2X/X2V communications.[1] And, X2V communications requirements might be imposed by municipalities to safely move automated vehicles through urban streets choked with pedestrians, other vehicles, and construction or other obstacles. 5G communications can shine in each of these situations, so we briefly consider their applications to autonomous vehicles in this section.

The potential advantages of autonomous vehicles include freedom from controlling a vehicle when a driver would rather attend to something else, enabling disabled persons to enjoy the autonomy of personal vehicles, reducing accidents and injuries, improving economy, and reducing traffic congestion. Leading autonomous vehicle companies (such as Tesla, Waymo [owned by Alphabet], and Aurora), and traditional automotive manufacturers are developing technologies to enable vehicle autonomy. These include a suite of sensors that feed a sophisticated onboard computer system able to maintain control of the vehicle in a wide variety of driving situations. Although it is unclear if any of the current onboard systems *learn* while operating, automotive companies have been improving successive releases with data from road tests and simulations of especially challenging hazards.[2]

1 For example, Tesla's car summoning feature experiences challenges in the presence of pedestrians and other vehicles. X2V communication "pings" from every person, vehicle, and obstruction might make this feature function more efficiently. Matthew Skwarczek, "Tesla's Smart Summons Doesn't Work So Well," *MotorBiscuit*, September 30, 2019; Shelby Bracho, "Man's Tesla Crashes into Pole Using 'Smart Summon' Valet Feature," FOX26, July 25, 2021.

2 Sean O'Kane, "How Tesla and Waymo are Tackling a Major Problem for Self-Driving Cars: Data," *The Verge*, April 19, 2018.

Although this approach offers some relief from the drudgery of driving, no system has yet demonstrated the ability to operate unattended—e.g., without a hand on the wheel—in all driving environments.[3] Fully autonomous vehicles face the greatest challenges in urban areas where they must operate safely in the presence of pedestrians, bicycles, construction zones, and vehicle densities of up to 4,300 per square kilometer.[4]

Fully autonomous vehicles appear to be years away, and most designs currently under development hope to operate independently without real-time network connection.[5] And, as long as autonomous vehicles (AVs) are sharing the roads with a large number of human-driven vehicles without 5G networking, they will need to be able to safely operate without widespread vehicle-to-vehicle networking. Therefore, it is not clear that the deployment of AVs will be tied to 5G in the near future.

However, 5G capabilities would be needed if communications between the vehicle and fixed objects, pedestrians, bicycles, and other vehicles is a requirement for fully autonomous driving control. The premise is that such V2X communications could provide awareness of proximity among these entities and early warning of potential collisions. One application of such communications would be to improve auto safety—ideally achieving zero auto-related accidents.[6] More broadly, communications between autonomous vehicles and a centralized control system might be necessary to manage overall traffic conditions and relieve congestion. Both V2X and centralized traffic control would require wireless communications.

Although Bluetooth or WiFi might be potential substitutes for V2X, neither are likely to be as suitable for centralized traffic control. The 5G standard as planned would offer the low latency required for real-time collision avoidance and traffic control, and 5G NR cellular communications will offer significantly improved capabilities to maintain continuous contact with vehicles as they travel distances of many kilometers through urban areas. Such traffic control networks have been proposed as a feature of smart city initiatives, which would use wireless communications to improve a wide variety of city-provided services.[7]

Several challenges remain for fully autonomous vehicles operating in urban areas:

- It is unclear what standard of acceptable risk autonomous vehicles must meet.[8] Several vehicles have suffered or caused fatal accidents, and the total accumulated travel miles are not yet sufficient to establish whether or not these autonomous vehicles have less accidents than their human-piloted counterparts. Is "as good as the average human" good enough, or must autonomous vehicles be better? If better, then how much better (e.g., how many standard deviations above the distribution of human drivers)? And how many miles must they drive in urban conditions before they have accumulated enough miles to demonstrate this level of performance?[9]

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3 Daphne Leprince-Ringuet, "For Self-Driving Cars, Winter Is Coming," *ZDNet*, March 5, 2020.

4 ETSI, "5G: Service Requirements for Enhanced V2X Scenarios (3GPP TS 22.186 version 15.3.0 Release 15)," technical specification, 3rd Generation Partnership Project 5G, July 2018; Laura Fraade-Blanar, Marjory S. Blumenthal, James M. Anderson, and Nidhi Kalra, *Measuring Automated Vehicle Safety: Forging a Framework*, Santa Monica, Calif.: RAND Corporation, RR-2662, 2018; Marjory S. Blumenthal, Laura Fraade-Blanar, Ryan Best, and J. Luke Irwin, *Safe Enough: Approaches to Assessing Acceptable Safety for Automated Vehicles*, Santa Monica, Calif.: RAND Corporation, RR-A569-1, 2020.

5 However, this might simply reflect the current lack of network connections that deliver 5G's quality of service.

6 Liisa Ecola, Steven W. Popper, Richard Silberglitt, Laura Fraade-Blanar, *The Road to Zero: A Vision for Achieving Zero Road Deaths by 2050*, Santa Monica, Calif.: RAND Corporation, RR-2333, 2018.

7 Francesca Baker, "The Technology That Could End Traffic Jams," *BBC Future*, December 12, 2018.

8 See National Highway Traffic Safety Administration, U.S. Department of Transportation, "NHTSA Issues First-Ever Proposal to Modernize Occupant Protection Safety Standards for Vehicles Without Manual Controls," press release, Washington, D.C., March 17, 2020.

9 Nidhi Kalra and Susan M. Paddock, *Driving to Safety: How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability?* Santa Monica, Calif.: RAND Corporation, RR-1478-RC, 2016; Timothy B. Lee, "New California

- It is not clear which approaches will be included in the standards of performance that are ultimately established. Will Tesla's combination of sonar and optical cameras be sufficient once the operating systems has been taught to avoid the causes of recent crashes? Or will Waymo's more expensive combination of LIDAR (Light Detection and Ranging), RADAR (radio detection and ranging), and cameras be necessary? And would any purely autonomous system be allowed unfettered operation in urban areas, or would they be required to respond to a centralized traffic control system?
- If a centralized traffic control system is needed, who is going to pay to develop, construct, and operate it? Will users, taxpayers, or entrepreneurs be willing to fund it in exchange for rights to user data? Residents, taxpayers, and companies that build and maintain roadside infrastructure will resist a mandate to install 5G internet-enabled devices unless they are given an economic incentive to do so, which could slow the deployment of these devices.
- What rights do individual users have to opt out of central traffic control? For example, do users have the right to revert to manual control in exchange for maintaining their right to privacy? Or is their choice narrowed to submit to central control (and, perhaps, give up your data) or keep your car out of this city?

Setting-appropriate regulatory policy will be a central challenge for these devices. Regulators will need to ensure that these devices are safe to use while understanding that excessive regulation could push the center of innovation toward other countries with looser requirements. A similar dynamic is already playing out within the U.S., where most autonomous vehicles are designed and built in California, but much of the testing has occurred in Arizona because of its looser regulations and earlier moves to encourage AVs.[10] Striking the right balance here will be key to ensuring U.S. technical competitiveness.

If high-bandwidth and low-latency 5G allows for significant increases in safety, then this could raise challenging ethical and political questions as different areas adopt 5G at different rates. In particular, if dense networks of mmWave base stations do not prove to be economical in sparsely populated areas, as some experts have suggested,[11] then this could further increase the disparity in outcomes between urban and rural areas. For example, networked autonomous vehicles would ideally communicate over vehicle-to-vehicle communication systems that are fully self-contained and work anywhere. But it might also turn out that the bandwidth and latency requirements for safe navigation can (at least initially) only be met through communication via fixed infrastructure, which would raise difficult questions for policymakers about where this infrastructure should be deployed.

Finally, devices such as connected vehicles and drones will likely move much faster than cell phones do today and connect to small cell mmWave base stations with much shorter ranges. Together, these two developments would require a large increase in the frequency of handoffs between adjacent base stations: for example, an AV moving at highway speeds through a series of mmWave base stations spaced 1 kilometer apart would need to reauthenticate with a new base station every 34 seconds. Managing such a rapidly changing network will pose both technical challenges and cybersecurity challenges, as every new handshake between a device and a base station could pose an opportunity for a malicious actor to enter the network.[12] It will also raise questions for regulators regarding safety requirements for how rapidly moving systems will

Driverless Car Data: Waymo and GM Miles Ahead—Literally," *Ars Technica*, February 1, 2018.

[10] Andrew J. Hawkins, "The Self-Driving Car War Between Arizona and California is Heating Up," *The Verge*, March 2, 2018.

[11] Jon Brodkin, "Millimeter-Wave 5G Will Never Scale Beyond Dense Urban Areas, T-Mobile Says," *Ars Technica*, April 22, 2019.

[12] The companion perspective (Gonzales, Brackup, Pfeifer, and Bonds, forthcoming) explores in detail the challenges that 5G poses to cybersecurity.

be required to respond in the event that they lose a connection with the base stations, because of a variety of limitations or signal interference (including from deliberate jamming).

The questions raised in this case study are not traditionally considered to be 5G policy issues, and they do not all need to be resolved before 5G is rolled out. But, in the longer term, the widespread deployment of 5G might enable applications that raise a host of broader questions that policymakers—including those not directly involved with telecom regulation—should begin considering before they become urgent.

Case 2: Large-Scale Public Surveillance

Tracking people and using automated facial recognition applications are among the most anticipated and most controversial applications of wireless communication technologies. Although some applications are available now over 4G devices, and some functions can be performed over WiFi, the emergence of 5G data rates and device density will enable such uses to increase by orders of magnitude. The issues raised below already exist today, but this huge acceleration in usage will make them much more urgent for policymakers to address. Policymakers should begin considering these questions before events overtake any meaningful policy action.

Data from Fitbit and other wearable movement trackers is already collected. The *New York Times* has published the aggregate data of millions of people moving around New York, the Pentagon and its neighboring municipalities, and other locations.[13] If these tracks are cross-referenced with other data in the public domain, individual data could be de-anonymized.

Law enforcement agencies already correlate movement data from tracking devices with the times and places at which crimes have been committed. Although companies such as Google make some attempt to notify users before revealing their identity to police departments, it remains up to the individual to maintain awareness of such requests and then contest release.[14]

At the same time, the numbers of cameras and facial images in the public domain are increasing rapidly. Since 2007, the year the iPhone first was introduced, over 11 billion smartphones with embedded cameras have been sold worldwide.[15] In addition, mobile cameras connected to communications devices are embedded in tablets, computers, and cars and worn by law enforcement and sports enthusiasts. Such cameras can be bought at very low cost—with wholesale prices in 2015 ranging from $7 apiece to as little as $1.79 apiece.[16] It has been estimated that one billion cameras will be deployed specifically for public surveillance by 2021—half of which are expected to be placed in China.[17]

The accumulating numbers of private and public surveillance tools can accumulate enormous amounts of personal information; at least one company claims to have downloaded more than 3 billion pictures from Facebook and other social media platforms.[18] That company, *Clearview AI*, claims to have more than 600 law

13 Stuart A. Thompson and Charile Warzel, "Twelve Million Phones, One Dataset, Zero Privacy," *New York Times*, December 19, 2019.

14 Jon Schuppe, "Google Tracked His Bike Ride Past a Burglarized Home. That Made Him a Suspect," *NBC News,* March 7, 2020.

15 Simon O'Dea, "Number of Smartphones Sold to End Users Worldwide From 2007 to 2020," Statista, February 28, 2020.

16 Robert Triggs, "Who's Who in the Smartphone Camera Business," *Android Authority*, July 10, 2015.

17 Elly Cosgrove, "One Billion Surveillance Cameras Will Be Watching Around the World in 2021 a New Study Says," CNBC, December 6, 2019.

18 Donie O'Sullivan, "This Man Says He's Stockpiling Billions of Our Photos," CNN Business, updated February 10, 2020.

enforcement agencies and financial institutions using its AI-based facial recognition software and database. The FBI is also reported to have their own database with 641 million images.[19]

So how might tracking, ubiquitous cameras, facial recognition technologies, and instant communications be combined and used now and in the future? Brick-and-mortar stores want to track customer purchases and identify their most loyal customers for special treatment.[20] Law enforcement agencies in the United Kingdom use automatic number plate recognition (ANPR) to "help detect, deter, and disrupt criminal activity at a local, force, regional, and national level, including tackling traveling criminals, organized crime groups, and terrorists."[21] Law enforcement agencies in the state of Utah have partnered with an artificial intelligence company to monitor data streams from traffic cameras, CCTV and public safety cameras, 911 emergency systems, location data for state-owned vehicles, and social media posts to alert police to suspicious activity.[22] Other law enforcement authorities in the United States have begun to use fitness-tracking apps to identify people who might have visited a location where a crime occurred.[23]

China is using facial recognition as part of a broader surveillance system to monitor its population and identify threats to its ruling regime. The COVID-19 pandemic has given Chinese authorities an opportunity to test the effectiveness of this system on a nationwide scale.[24]

Case 3: COVID-19 and Contagion Control

A particularly salient use case might be contagion control—such as minimizing one's exposure to a disease outbreak. Several applications have been designed to track potential exposure to COVID-19 infection, including one disseminated within the People's Republic of China. These applications had fairly limited functions, including:[25]

1. using a map application to mark areas within a town or city in which people with confirmed infections were located
2. tracking the user's location and alerting the user if her/his movements are approaching or have entered proximity to people or areas in which the infection was present
3. assessing the user's risk of exposure, and judging whether that risk is "green" (low), "yellow" (moderate), or "red" (high)
4. providing risk judgement to individuals to advise them whether they should now avoid uninfected areas or seek medical attention, and indicating that status on that individual's device
5. providing the same risk judgement to police to alert them to potentially infected people for quarantine purposes.

[19] Lane Brown, "There Will Be No Turning Back on Facial Recognition," *New York Intelligencer*, November 12, 2019.

[20] Coranet, "Commercial Applications of Facial Recognition," webpage, July 16, 2019.

[21] Metropolitan Police, "Automatic Number Plate Recognition," webpage, date unknown.

[22] Jason Koebler, Emanuel Maiberg, and Joseph Cox, "This Small Company Is Turning Utah into a Surveillance Panopticon," *Vice,* March 4, 2020.

[23] Lopez, 2020.

[24] Liza Lin, "China Marshals Its Surveillance Powers Against Coronavirus: Officials Use Big Data To Track the Movements of Infected Individuals," *Wall Street Journal*, February 4, 2020.

[25] Paul Mozur, Raymond Zhong, and Aaron Krolik, "In Coronavirus Fight, China Gives Citizens a Color Code, With Red Flags," *New York Times*, March 1, 2020.

The effectiveness of these applications is limited. They do not perform any diagnoses on individuals—they simply estimate whether an individual has come close to an area where infected people are believed to exist. Whether that individual has remained within a vehicle or taken other precautions is not known. On the other hand, that same person could have come into contact with one or more infected people outside areas marked as affected. An application subsequently developed by Google and Apple added a feature using Bluetooth to determine how close individuals came to others.[26] When all those coming close to each other have this app, each could then record and track the previous exposure and subsequent infection status of the others.[27]

Future applications could be augmented by sensors operated by humans or placed in portals through which people enter buildings, subways, and other crowded places. The sensors might monitor all people entering buildings, identify individuals with an elevated temperature or coughing, and cross-index their symptoms with diagnostic programs for known diseases.[28] People showing some symptoms could be notified of their possible condition, advised to seek medical treatment, and denied entry. A more intrusive action would be to notify the individual's employer (or building occupants, if the person is a visitor), family, and medical provider that they are showing signs of a particular illness.

A host of issues attend the kinds of health applications outlined above. First, highly personal information is involved, and it is unclear what protocols will be needed to anonymize and otherwise protect this data while employing it as part of a large sample base. And contact-tracing systems based only on proximity of Bluetooth devices could be expanded to include facial-recognition, geolocation, and other technologies.[29] Other entities—including product manufacturers and law enforcement agencies—might be interested in this same information. Agreement should be reached among individuals, health providers, government agencies, and lawmakers as to how much sharing should be allowed and how much protection is required.

Second, an application that identifies diseases might help people seek treatment—but might expose those same people to harm. For example, people falsely testing positive might be placed with and infected by those having the diseases, while people falsely testing negative might then infect others. More serious misuses are conceivable in times of panic.

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[26] Leo Kelion, "Coronavirus: First Google/Apple-Based Contact-Tracing App Launched," BBC News, May 26, 2020.

[27] Microsoft and others argue that this app would only be effective for people owning and carrying smartphones. See Ben Lovejoy, "Apple Contact Tracing Has 'Blindspots' as Companies Mull Badges and Wristbands," *9to5 Mac*, April 27, 2020.

[28] Marc Weber Tobias, "AI and Medical Diagnostics: Can a Smartphone App Detect COVID-19 From Speech or a Cough?" *Forbes*, May 5, 2020; Jared Newman, "Smart Cameras Will Soon Check If You're Social Distancing and Wearing A Mask," *Fast Company*, May 13, 2020.

[29] Kirsten Grind, Robert McMillan, Anna Wilde Mathews, "To Track Virus, Governments Weigh Surveillance Tools That Push Privacy Limits," *Wall Street Journal*, March 17, 2020.

APPENDIX F

Innovation Test Beds and Sandboxes

One possible approach that policymakers could take to boost the U.S.'s competitive advantage in 5G would be the establishment of test beds or *sandboxes* for innovation in 5G. These might take the form of areas in which a significant amount of 5G infrastructure is built out, in which start-ups, government laboratories, academic groups, and others are encouraged to experiment with innovative new deployments of 5G (potentially through direct investment, or though changes in taxes and regulations within those areas). These sandboxes could provide a relatively controlled area in which innovators could experiment with new 5G infrastructure and applications and could take advantage of the presence of other innovators to combine ideas and form formal or informal collaborations. Ideally, they would incorporate a variety of different environments and use cases, such as indoor and outdoor environments over a variety of scales (some with large amounts of metal obstacles), areas for testing the rapid deployment and removal of temporary networks, networks with a variety of security and access levels, etc. Although there are already numerous (mostly small-scale) testbeds for specific applications such as autonomous vehicles, there are few large-scale ones that span multiple categories of applications.[1]

The Department of Defense operates four 5G testbeds exploring military applications of smart warehouses and logistics, dynamic spectrum sharing, and augmented and virtual reality,[2] and the fiscal year 2020 National Defense Authorization Act orders the establishment of at least two more testbeds (including a Major Range and Test Facility Base at the Nevada Test and Training Range). This is a promising step, but these test beds will be focused on primarily military applications. Policymakers might want to consider encouraging additional test beds that focus on private-sector or public-private technology experimentation as well, given the important role that 5G will play in the overall U.S. economy. The recently announced testbed at the University of Colorado Boulder, which will be jointly operated by the National Telecommunications and Information Administration Institute for Telecommunication Sciences and CU Boulder, is a promising first step, and the Institute for Telecommunication Sciences should consider allowing private companies to participate as well.[3]

In some ways, these sandboxes might somewhat resemble the smart city innovation hubs that have recently been established, such as the former Sidewalk Toronto,[4] the Smart Docklands District in Dublin, Ireland,[5]

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1 Aschkan Omidvar, Clark Letter, and Lily Elefteriadou, "An Overview of Existing Pilot and Testbed Activities to Advance Connected and Autonomous Vehicle Technology: Common Threads and Future Priorities," paper presented at Transportation Research Board 97th Annual Meeting, 18-05854, January 2018.

2 Billy Mitchell, "DOD Kicks Off Procurement for 5G Prototypes," *FedScoop,* updated December 10, 2019.

3 National Telecommunications and Information Administration, U.S. Department of Commerce, "NTIA Signs Agreement for Wireless Test Bed Study in Partnership with University of Colorado Boulder," press release, Washington, D.C., April 12, 2018.

4 Sidewalk Toronto was a collaboration between Alphabet's Sidewalk Labs and the city of Toronto, but as of June 2020 it is no longer moving forward. See Sidewalk Labs, "Sidewalk Toronto," webpage, undated.

5 Smart Docklands, homepage, undated.

and the Curiosity Lab (a 5G smart city testbed collaboration between Spring and the city of Peachtree Corners, Georgia).[6] China has opened similar innovation hubs, such as a flying drone innovation center in Shanghai's Jinshan district with loosened regulations.[7] As these examples indicate, all levels of government can take action to encourage 5G innovation, not just the federal level.

The rollout of these early innovation hubs has not gone entirely smoothly. For example, Alphabet was forced to greatly scale back its projects in Toronto after disagreements over the governance of the huge amount of data that they would generate on Toronto residents.[8] (The economic crisis triggered by the COVID-19 pandemic later caused Alphabet to completely cancel the entire Sidewalk Toronto project,[9] but the popular backlash was likely also a contributing factor.) Data governance will continue to be a sticking point as further innovation hubs develop, but this might allow political debates to play out on a contained scale, which could allow for experimentation with data practices, and the development of compromises and best practices that could be a model for the rest of the nation before 5G technology reaches maturity nationwide. On the other hand, if countries with more authoritarian cultures and governments than that in the U.S. are able to roll out test beds such as these without concern for public opinion, then that might give them an edge up on technical competitiveness. This certainly does not call for the U.S. loosening its commitment to privacy rights and community accountability, but policymakers should be aware of this potential technical advantage, and might want to monitor for evidence that other countries are moving forward with such applications that would be socially unacceptable in the U.S.

There is an inherent challenge in the testbed model for 5G innovation. As discussed above, many 5G applications will be inherently network applications that only become useful with a critical mass of users, sensors, data sources, etc. A service like Uber or a new social network is unlikely to work in a single neighborhood, or possibly even in a single city. Some 5G applications are likely to only be feasible when deployed on a national or even global scale, which will make it difficult to test them in a controlled setting before they catch on. In one regard, this fact limits the usefulness of testbeds for 5G applications, as it is difficult to scale them up large enough to be useful. However, because small companies have difficulty demonstrating and testing new network applications without a large preexisting infrastructure, such testbeds could level the playing field and help smaller companies compete with larger ones that can afford to build their own testbeds. A large, shared testbed could also allow different companies to leverage each other's innovations and produce synergies, as occurs in the real world.

The fact that networked applications can suddenly explode in popularity and usefulness as they achieve a critical mass poses an additional challenge for policymakers trying to think through their policy implications. Policymakers should prepare to be regularly surprised as new applications suddenly take off with little warning as they reach a critical scale and become self-sustaining.

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6 Curiosity Lab at Peachtree Corners, homepage, undated.

7 Marco Margaritoff, "China's New Drone Innovation Center in Shanghai Will Boost Developing Technologies," *The Drive*, August 31, 2018.

8 Matt McFarland, "Alphabet Scales Back its Smart City Project in Toronto After Backlash," CNN Business, October 31, 2019.

9 Daniel Doctoroff, "Why We're No Longer Pursuing the Quayside Project—and What's Next for Sidewalk Labs," *Medium*, May 7, 2020.

National Postures in Science, Technology, Engineering, and Mathematics (STEM) Talent and Research and Development

As of mid-2020, the U.S. leads the world in a variety of metrics including total R&D investment and the number of highly cited research articles, and its technical workforce is still growing.[1] Moreover, undergraduate computer science majors in the U.S. substantially outperform those in China, Russia, and India, both when comparing the average and the top students.[2]

However, China is rapidly catching up on a variety of fronts. In 2016, China produced 1.7 million bachelor's degree equivalents in science and engineering—more than twice the U.S.'s 800,000 and well over the E.U.'s one million. Since 2007, China has produced more doctoral degrees in natural science and engineering that the U.S. (with 32,000 in China and 30,000 in the U.S. in 2015). The U.S. leads the world in total R&D spending (25 percent of the world total in 2017), but China is rapidly catching up (23 percent of the world total in 2017), and might well soon pass the U.S., if it has not already.[3]

The U.S. remains an attractive location for international talent. Thirty percent of U.S. workers in science and engineering occupations were born abroad, and more than half of doctoral degree holders in engineering, computer science, and mathematics were also born abroad. More international students studied in the U.S. in 2016 than in any other country (19 percent of all students studying internationally), much higher than the number of international students studying in China, but this percentage has declined since then, particularly in engineering.[4]

By some metrics, foreign interest in technology jobs in the U.S. has held steady in recent years,[5] but interest in other nations, such as Canada, has increased significantly.[6] The primary driver of this shift is likely recent policy changes regarding skilled immigration: denial rates for the U.S. skilled immigrant H-1B visas quadrupled between 2015 and 2018 and application procedures have toughened, while the Canadian government has recently streamlined the process of immigration for skilled workers. Some U.S. tech companies have

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1 National Center for Science and Engineering Statistics, National Science Board, National Science Foundation, *2020 National Science Board Science and Engineering Indicators: The State of U.S. Science and Engineering*, NSB-2020-1, January 2020.

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responded to this policy changes by moving to Canada.[7] Meanwhile, the U.S. is experiencing a shortage of skilled workers in technical fields,[8] and many business leaders have urged the government to ease the path to immigration by skilled workers.[9] Rising wages have the potential to alleviate some of this shortage, but not in the immediate term. China, on the other hand, has made a concentrated effort to recruit top technical talent from other countries, particularly through its controversial Thousand Talents program (which some U.S. officials believe encourages corporate espionage of foreign intellectual property, including 5G technology).[10] Although there do not appear to be very large numbers of researchers actually moving to China from abroad, the program has successfully recruited some top-tier U.S. talent; one of the foremost U.S. research scientists was recently arrested for concealing participation in the Thousand Talents program.[11]

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Abbreviations

3GPP	3rd Generation Partnership Project
5G	fifth generation
5GC	5G Core
AI	artificial intelligence
AV	autonomous vehicles
CBRS	Citizens Broadband Radio Service
COVID-19	coronavirus disease 2019
CPU	central processing unit
DSS	dynamic spectrum sharing
FCC	Federal Communications Commission
GHz	gigahertz
LTE	Long-Term Evolution
MEC	multi-access edge computing
MHz	megahertz
mmWave	millimeter wave
NR	New Radio
R&D	research and development
RF	radio frequency
SEP	standard essential patent
SMIC	Semiconductor Manufacturing International Corporation
SoC	system-on-a-chip
telecom	telecommunications
TSMC	Taiwan Semiconductor Manufacturing Company
V2X	vehicle-to-everything

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