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Perspective
EXPERT INSIGHTS ON A TIMELY POLICY ISSUE

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America's 5G Era

Gaining Competitive Advantages While Securing the Country and Its People

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. Influential leaders from government and industry have argued that leadership in wireless communication is a crucial determinant of the country's economic success in the mobile technology era. The Defense Innovation Board stated,

> Historical shifts between wireless generations suggest that the first-mover country stands to gain billions in revenue accompanied by substantial job creation and leadership in technology innovation. . . . Conversely, countries that fell behind in previous wireless generation shifts were obligated to adopt the standards, technologies, and architectures of the leading country and missed out on a generation of wireless capabilities and market potential. (Medin and Louie, 2019, p. 2)

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The White House has made the case that leadership in wireless technology helps nations "win" in the information age, stating,

> In the information age, the nation that leads the world in wireless technology wins. To keep America's edge, we must accelerate our development and deployment of 5G. (Kratsios, 2018)[1]

and

> Fifth-generation wireless technology, or 5G, will be a primary driver of our Nation's prosperity and security in the 21st century. This new technology will provide consumers, businesses, and governments with remarkably fast network connections that will enable tens of billions of new devices to harness the power of the Internet, transforming the way we live, work, learn, and communicate. (Trump, 2020a, p. ii)

In its first week in office in January 2021, the Biden administration focused on 5G as well, raising a problem that threatens U.S. progress: spectrum constraints. In her confirmation hearing on January 26, 2021, then–nominee for Commerce Secretary Gina Raimondo stated,

> The race is on for 5G. I want America to win and lead, and that requires spectrum. . . . What we need to do is—and the president has been clear—is to step back and have a national strategy on spectrum, and look to make spectrum available from public and commercial uses. (Shields and Martin, 2021)

This Perspective was written as a policy primer for the 5G era and summarizes our observations from the RAND-Initiated Research project titled "America's 5G Era: Securing Its Advantages and Ourselves." As we assessed the 5G wireless ecosystem, we began to see the development of its markets and technologies as an enduring competition rather than a "race." A key observation from that project is that past technical or market leadership does not guarantee a lasting advantage. We also highlight important implications of 5G-era devices, networks, and services for securing data and protecting individual privacy.

Abbreviations

3GPP	3rd Generation Partnership Project
4G	fourth generation
5G	fifth generation
AI	artificial intelligence
COVID-19	coronavirus disease 2019
EU	European Union
FCC	Federal Communications Commission
Gbps	gigabits per second
GDPR	General Data Protection Regulation
GHz	gigahertz
HPE	Hewlett Packard Enterprise
IPO	initial public offering
kHz	kilohertz
LTE	Long-Term Evolution
Mbps	megabits per second
MHz	megahertz
mmWave	millimeter wave
ms	millisecond
NTIA	National Telecommunications and Information Administration
RAN	radio-access network
SEP	system-essential patent

The Organization of This Perspective

In this Perspective, we structure our discussion around a set of issues that we frame as "competitions":

- **economic competition:** How is the United States faring in key market segments, and is it well positioned for future success?
- **technical competition:** Are U.S. companies maintaining a technical edge in key 5G-ecosystem segments? How might uncertainties about market direction pose challenges? What other changes might put U.S. technical leadership at risk?
- **security competition:** What network security flaws have already been exploited by foreign entities? What new vulnerabilities might 5G systems introduce? How secure is the 5G supply chain?
- **competition between big data and individual privacy:** How is the United States—including its corporations, citizens, and regulators—balancing competing interests for information and privacy?

In each case, we also include observations on potential roles for policy to support U.S. interests.

What Is 5G?

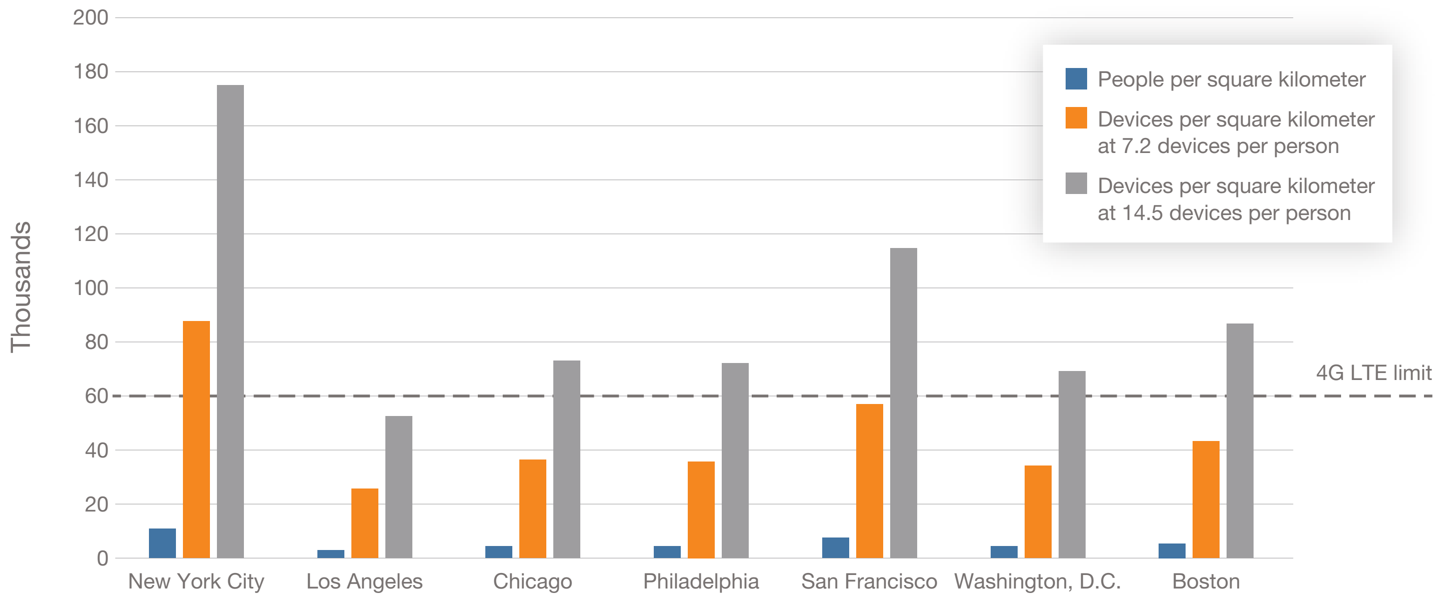
We begin by defining what we mean by *5G* and, more broadly, its environment (often called the *5G ecosystem*). 5G wireless networks include standards, hardware, and software that are intended to enable orders-of-magnitude improvements in the density of users, the data rates available to those users, and the latency of their communications. As we discuss in this section, the priority among these promised improvements varies by company, market segment, and host nation. Some companies might prioritize higher device density—for example, to expand the internet of things or to serve large groups of people, such as those in football stadiums or in Times Square on New Year's Eve. Other users might prioritize data rates for video streaming or low latency (the time between sending and receiving data) for autonomous vehicle navigation. Some countries might wish to trace coronavirus disease 2019 (COVID-19) contacts among their populations, while others might pursue large-scale monitoring of their people. Companies first to market with applications might reap rich rewards for themselves and their home countries—along with the benefits and detriments of the changes that these technologies bring to their societies.

To understand the changes 5G will bring, it is useful to compare its features with those of the prior-generation 4G systems (known as 4G Long-Term Evolution, or 4G LTE). From a demand-pull perspective, the 5G standard supports massive machine-to-machine communication. 5G increases the maximum density of devices from 60,000 per square kilometer (under the 4G standard) to 1 million devices per square kilometer.[2] Given the wide variety of devices that connect to wireless networks, it is interesting to estimate when user demand will exceed the ability of technologies adhering to 4G standards to meet that demand.

For example, if, on average, only one wireless device were connected to the 5G network per person, by 2030, even New York City would have, on average, 12,000 devices per square kilometer (the blue columns in Figure 1)—far below the 4G density limit of 60,000 devices per square kilometer.[3] But 5G-enabled applications are expected to drive an increase in the average number of devices simul-

FIGURE 1

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



SOURCES: Cisco, 2020; Maciag, 2017; K. Parker et al., 2018.

taneously connected to the cellular network on a per capita basis. Cisco has projected that, by 2023, the ratio of devices to people in North America will be more than 14 to 1 (Cisco, 2020). Cisco expects that half of these devices will be machines talking to other machines—and the devices' share of connections is growing at 30 percent per year, versus 7 percent for smartphones (Cisco, 2020).

If these rates of growth continue through 2030, the ratio in North America would be 29 devices connected to the internet for each person.[4] Cisco has estimated that 25 percent of North American devices will connect through wireless technologies (Cisco, 2020). New York City would then average 90,000 wireless devices per square kilometer (the orange columns in Figure 1)—causing 4G networks to exceed their device density limit of 60,000 devices per square kilometer.

But what if 50 percent of all devices in U.S. cities connect to the internet through wireless technologies in 2030 (like they do in other parts of the world in 2021)?[5] Then Chicago; Philadelphia; San Francisco; Washington, D.C.; and Boston would also exceed the device density supported by 4G (the gray columns in Figure 2), and Los Angeles would come close to the 4G limit.

Furthermore, the number of wireless devices simultaneously seeking connections will surge during the business day or for special events. During the weekday in Manhattan, for instance, 2.3 million commuters cause the average population to surge from 27,436 people per square kilometer to nearly 66,000 (see World Population Review, undated). If each commuter were simultaneously transmitting on just one cellular device, they would exceed today's 4G network capabilities.[6] Similar user-density surges likely happen in most cities, at professional sports venues, and during other special occasions (such as parades, festivals, and New Year's Eve celebrations).

It is also interesting to assess the technology-push aspects of 5G. At present, 4G systems operate in the low-band portion of the radio-frequency spectrum (typically at frequencies of 700 to 850 megahertz [MHz], with additional slices slightly above 1 gigahertz [GHz]).[7] The problem with the low-band frequency spectrum is that it is crowded—with many other users already occupying the spectral "real estate" around the frequencies allocated to cellular systems. Therefore, to grow the number of simultaneous users and their data rates, cellular providers need to move to higher frequencies that can provide larger chunks of repurposed or unused spectrum.[8] These include the midband (typically from 3 GHz to 7 GHz, sometimes called *sub–6 GHz*), and the high band (at millimeter wave [mmWave], above 24 GHz).[9] On the other hand, the great advantage of the 1-GHz band is that radio signals can travel long distances through the atmosphere—and through buildings, trees, and other obstructions.[10] The resulting trade-off between range and peak data rates and other features is shown in Figure 2.

Low-frequency bands are more effective than the higher-frequency bands in covering large areas, such as the middle of Texas County, Oklahoma, from a few sites. A well-equipped cell-tower base station (with six zones and two carriers per zone) operating at 700 MHz could serve up to 1,200 simultaneous voice calls at ranges up to 24 km (Baines, 2011). This is enough to cover a large rural area, as shown by the large circle on the left side of Figure 2. It might be possible to serve the whole of Texas County (population 19,983) (U.S. Census Bureau, undated b) with one or two such base stations, depending on how many inhabitants own cellular devices and use them at the same moment. As the number of simultaneous users increases, more such towers could be added. As long as the following conditions are met, 4G LTE protocols and standards would be adequate for these users:

- Peak data rates remain at or below 100 megabits per second (Mbps).[11]
- Users' applications can perform at a latency of 20 milliseconds (ms).
- The number of users remains below 60,000 devices per square kilometer.

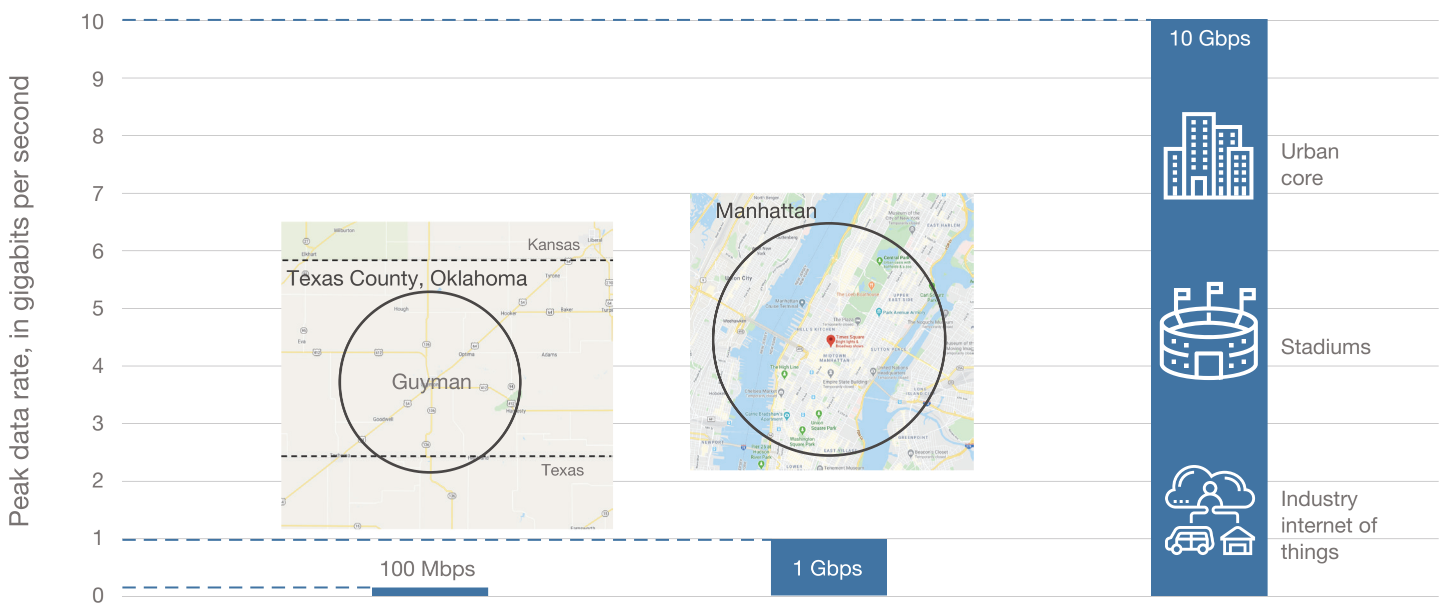
These towers could be upgraded to 5G if and when the 4G standards were no longer sufficient.

The business case for 5G standards and systems makes more sense in urban and ultradense settings, as shown in the middle and right-hand portions of Figure 2. For example, financial industry users in Manhattan might be willing to pay for higher data rates and lower latencies than 4G can provide.[12] At midband frequencies, 5G systems can offer peak data rates of up to 1 gigabit per second (Gbps), with latency as low as 1 ms. The trade-off is that each base

FIGURE 2

Comparison of 4G Networks, 5G Networks at Midband, and 5G Networks at High Band

	4G LTE (or 5G) low band	5G midband	5G high band
Maximum range, in meters	24,000	4,000	50–250
Maximum number of devices per square kilometer	60,000	1 million	1 million
Latency, in milliseconds	20	1	1
Best market	Rural	Urban	Ultradense



station will have a much shorter range—from 1 km to 4 km at the midband frequencies. Urban areas will require thousands of midband base stations both to make up for their shorter range and to serve their large populations—with each person likely to be within range of several base stations.[13]

As shown on the right-hand side of Figure 2, 5G standards might be even more attractive for ultradense applications, such as wireless networks supporting industrial facilities; concentrated venues, such as sports stadiums; or high-density events, such as Times Square on New Year's Eve. On a typical New Year's Eve, crowd densities at Times Square can approach 1 million people per square kilometer—well beyond the capability of 4G. At mmWave, 5G can also offer peak data rates of 10 Gbps.[14] The downside is that the range of mmWave base stations is limited to between 50 and 250 m—feasible for stadiums, factories, and urban core areas but much less attractive in the near term outside of these ultrahigh-density use cases. And although 5G is able to handle dense and ultradense applications, it will also require much more investment in new infrastructure.

What Is the 5G Ecosystem?

In this Perspective, we use the term *5G ecosystem* to include all of the enterprises that will participate in the markets and technologies that 5G devices and networks will enable, expand, or otherwise significantly influence. Four key segments of the 5G ecosystem are the focus of our analysis (as shown in Figure 3):

- At the highest level is the segment containing the **applications and services** that use the mobile network. In the United States, these include such dominant players as Alphabet (including Google), Amazon, Apple, Facebook, and Microsoft. They also include such companies as Netflix, Lyft, Uber, Twitter, Snap, Pinterest, Yelp, and other enterprises that depend on mobile users and devices for most of their markets.
- The next segment includes the **mobile- and backbone-network operators**. In the United States, this segment includes AT&T, Verizon, and T-Mobile/Sprint, as well as other internet providers and regional carriers. The mobile wireless radio-access networks (RANs) connect all of the necessary elements to deliver wireless services to the end user, link mobile devices to RANs, then connect to the core backbone networks, and so on to databases and servers around the country.
- Critical 5G **hardware and software components** include the chipsets for mobile devices, the mobile devices themselves, the RAN equipment (including base stations and any colocated switches and routers), and the core-network equipment. These components are the hardware and software of the 5G network backbone and the devices connecting to it.
- The **precursors**, necessary to design and build critical 5G hardware and software components, make up the most fundamental segment and include leading-edge manufacturing equipment (such as extreme-ultraviolet lithography machines); chip-fabrication facilities; instruction-set developers; and international agreements, such as standard setting and system-essential patents (SEPs) for hardware and software as established by international organizations, such as the 3rd Generation Partnership Project (3GPP).[15]

How Is the United States Faring Economically?

Viewed through the lens of market capitalization (the total value of the common stock shares issued by a given company), the United States is faring well in the 5G era, as shown in Figure 4.[16] U.S.-based companies in the application and service segment had a total market capitalization (or "cap") of nearly $4.5 trillion as of May 2019—more than

FIGURE 3

Key Segments of the 5G-Era Ecosystem

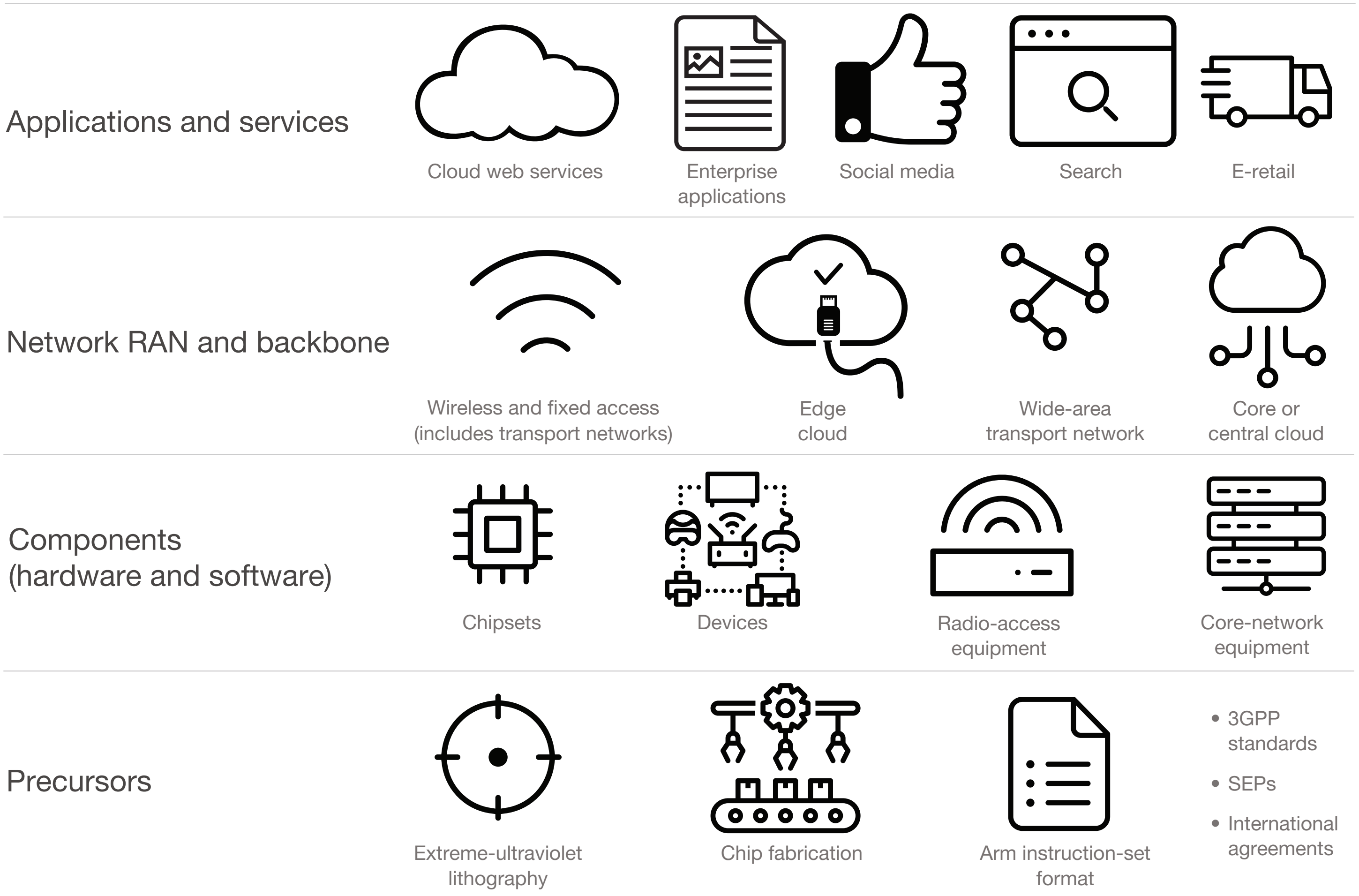
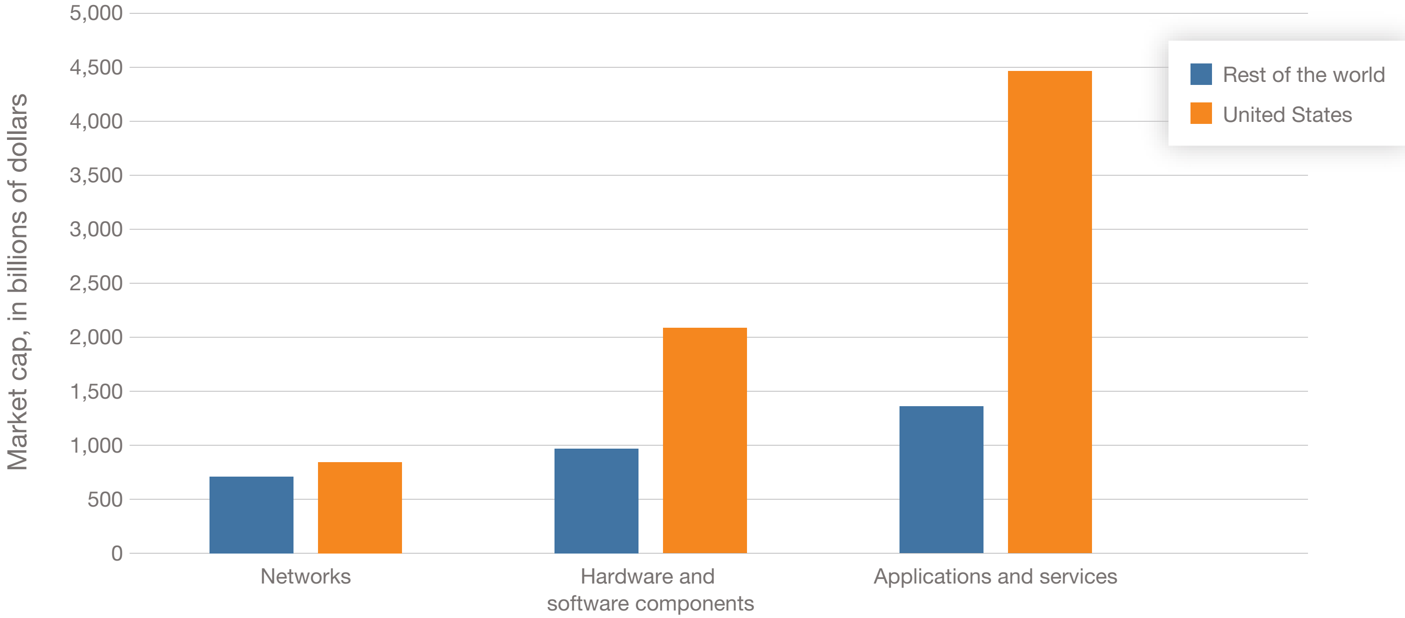


FIGURE 4

Comparison of Network, Component, and Application and Service Market Values in the United States and the Rest of the World



SOURCE: Forbes, 2020.

$3 trillion of which was contributed by Alphabet, Amazon, Microsoft, and Facebook alone. Hardware and software components added another $2 trillion of market cap (of which Apple accounted for nearly $1 trillion), and wireless networks added more than $800 billion.[17]

Significant benefits accrue to the United States from having these firms reside within it—including the economic impact of the jobs they create, the tax revenue they generate, and the ability to regulate and influence company policy and practices. The five most valuable 5G-ecosystem companies in the United States (Alphabet, Amazon, Apple, Facebook, and Microsoft) employed more than 1.2 million globally in 2019, with more than half of those employees in the United States.[18]

These big tech firms pay well, too. California's median household income is $75,277, but Facebook's median salary is $240,000 per year, which is high even among tech employers (van Romburgh, 2019). In Seattle, the median salary reached $93,000 in 2018, but Seattle-based Microsoft paid a median salary of $167,000 (Lerman, 2018). Median pay is lower at Amazon ($28,000 in 2018), largely because the workforce includes a large share of employees in less technical roles, such as packaging specialists and fulfillment-center associates (Fiegerman, 2018).

The employment benefits to the United States extend past the full-time regular employees of these companies. For example, in 2012, Apple listed 72,800 full-time–equivalent permanent employees and 3,300 full-time–equivalent temporary employees (U.S. Securities and Exchange Commission, 2012). In that same year, Apple claimed to have directly or indirectly created a total of 514,000 jobs from "the engineer who helped invent the iPad to the delivery person who brings it to your door" (Guglielmo, 2012). In 2019, Apple stated that its "footprint" of direct and indirect employment had grown to 2.4 million U.S. jobs (Apple, 2019). Presumably, similar leveraging effects are at work for the other tech companies as well.

Furthermore, tech companies are a significant source of tax revenue. For example, Amazon and Apple paid $78 billion in taxes between 2015 and 2019, 68 percent of which ($53 billion) was paid to either U.S. federal or state governments (see Alphabet, 2020).

The application and service segment has grown rapidly in the United States, with Alphabet, Amazon, and Facebook going public in 1997, 2004, and 2012, respectively.[19] The value generated by application and service companies is related to data about people and enterprises—including their activities, preferences, relationships, and consumption behavior (both business–consumer and business–business transactions). In this segment, market values, like revenues, exhibit network effects—they increase exponentially with the number of users and their data. To date, the United States has dominated this segment, although some Chinese companies, such as ByteDance, owner of the trendy video-sharing social networking service TikTok, are rapidly gaining users and their data.[20] If the limits of 4G LTE networks begin to constrain the growth of the application and service segment, consumer demand might drive 5G deployment in the United States. But a late deployment in the United States could make application and service providers shift their attention to consumers in better-equipped countries.

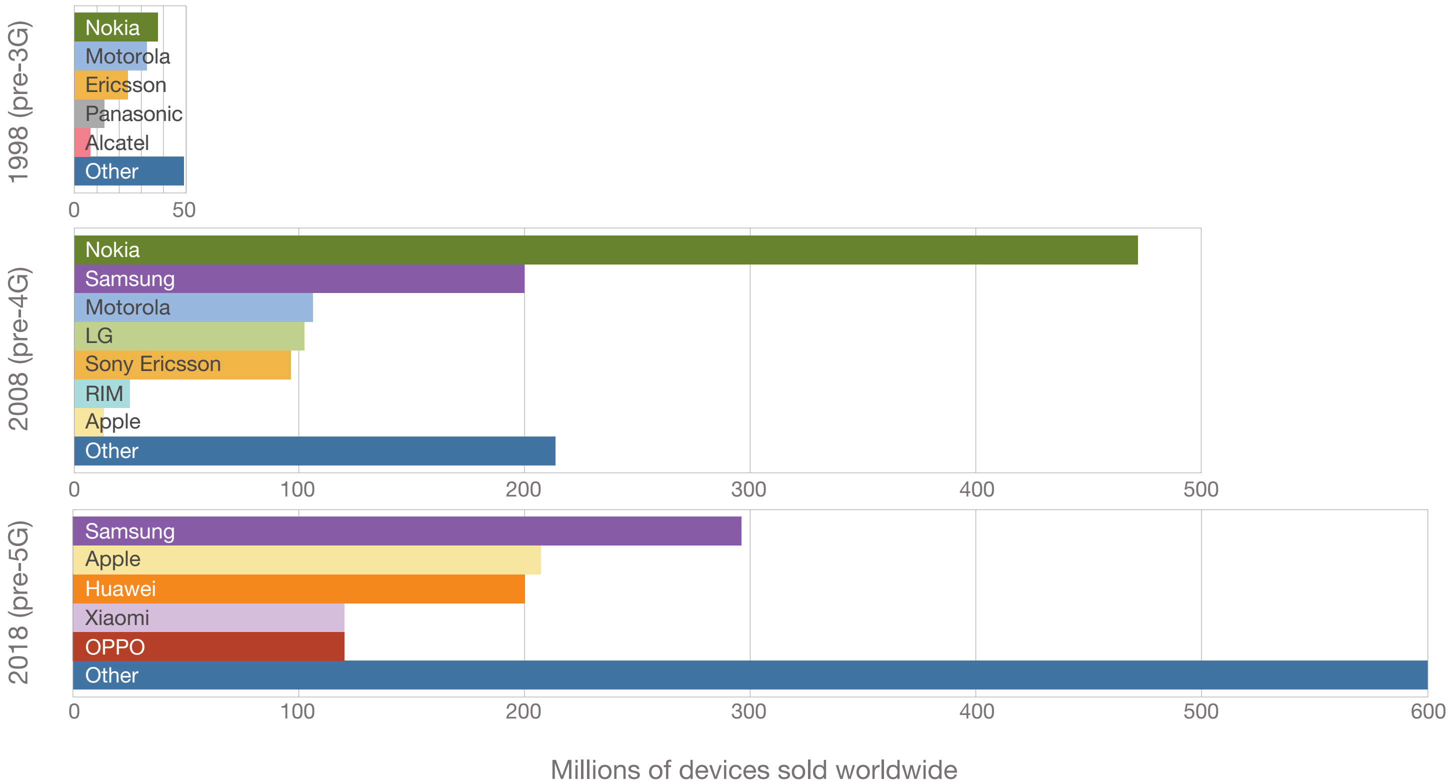
The hardware and software component markets of the 5G ecosystem appear to be highly dynamic and competitive. It is not clear that a first-mover advantage exists in this market segment—new firms have emerged and thrived, while established leaders often decline and occasionally become reinvigorated. For example, smartphones are among the most visible cellular components—and leadership of this market segment has changed hands dramatically in the past 20 years, as shown in Figure 5.

In 1998, just before 3G networks began to be deployed, global cell-phone sales exceeded 160 million units, and Nokia, Motorola, and Ericsson were the dominant competitors—together capturing nearly 60 percent of the market ("GartnerGroup's Dataquest Says Nokia Became No. 1 Mobile Phone Vendor in 1998," 1999).

By 2008, at the dawn of the 4G era, total global cell-phone sales had increased by nearly an order of magnitude, to more than 1.2 billion units. Nokia's sales had shot up to nearly 500 million units—making it the clear leader in mobile cell phones. Motorola had also tripled its annual sales with the razr, but even that was not enough to keep pace with Nokia or a surging Samsung (Schonfeld, 2010). However, all of these phones remained principally voice and text devices—just when the market was beginning to shift to smartphones with integrated applications. Apple had just begun to offer its iPhone, which would reshape

FIGURE 5

Global Cell-Phone and Smartphone Market Leaders and Growth



SOURCES: "GartnerGroup's Dataquest Says Nokia Became No. 1 Mobile Phone Vendor in 1998," 1999; Schonfeld, 2010; Counterpoint Research, 2020.
NOTE: RIM = Research in Motion.

this market forever, and, among the 2008 market leaders, only Samsung managed to catch this technology wave by embracing Google's Android platform—resulting in its subsequent sales surge (Schonfeld, 2010).

In 2018, as networks and nations began to prepare for the emergence of 5G, total global smartphone sales had increased to more than 1.5 billion units (Counterpoint Research, 2020). (Although market analysts still tracked sales of voice- and text-only cell phones, the emphasis had clearly shifted to smartphones after 2008.) Samsung and Huawei, both using the Android operating system, and Apple occupied the top three slots. More recently, Huawei has been banned from U.S. suppliers (Rodrigo, 2021). While Huawei continues to appeal this ban, it has developed its own Harmony operating system—although it appears to largely ride on top of Android (Whitwam, 2021).

Nokia, Motorola, Ericsson, and others either disappeared, merged, or struggled for survival within the growing category of "other," which consisted of 600 million unit sales in 2018 (Counterpoint Research, 2020).

The leaders in each of the components of the wireless market, along with their market shares, are shown in Figure 6. Although they are strong in some components, U.S. companies have exited the radio-access equipment market and several precursor segments of the market. As mentioned, Samsung led smartphone device hardware through the end of 2018 with a 19-percent market share, although Apple has led sales in some quarters since that time (Counterpoint Research, 2020). The operating-system market is dominated by U.S.-based firms, with Google's Android running 85 percent of smartphones at the end of 2018 and Apple iOS running just under 15 percent of devices (Statista, undated b).[21]

The RAN equipment segment, consisting of cell towers and base stations, is almost entirely served by foreign entities. Huawei commands the largest share of the market, at 31 percent, followed by Ericsson (27 percent) and Nokia (22 percent) (Téral, 2019). However, although Huawei appears to be thriving and poised to grow further, both Ericsson and Nokia have lost market share, and Nokia might be struggling to remain competitive ("Ericsson and Nokia Are Now Direct Rivals," 2018; Hammond et al., 2020; Milne, 2019). China's ZTE and South Korea's Samsung round out the five RAN equipment makers with the largest market share, which collectively hold 96 percent of this market segment (Téral, 2019).

U.S.-based companies have prominent positions in the key core-network equipment markets. Cisco had almost half of the ethernet switch market through the middle of 2020, with Huawei a distant second at about a 2-percent share ("Leaders in Switch and Router Market in Q3," 2020). In 2019, Dell had 17 percent of the server market, and a joint venture of Hewlett Packard Enterprise (HPE) and China's H3C (now New H3C) captured 16 percent of the market (International Data Corporation, 2019), although, by 2020, HPE might have pulled slightly ahead (Haranas, 2020; International Data Corporation, 2019).

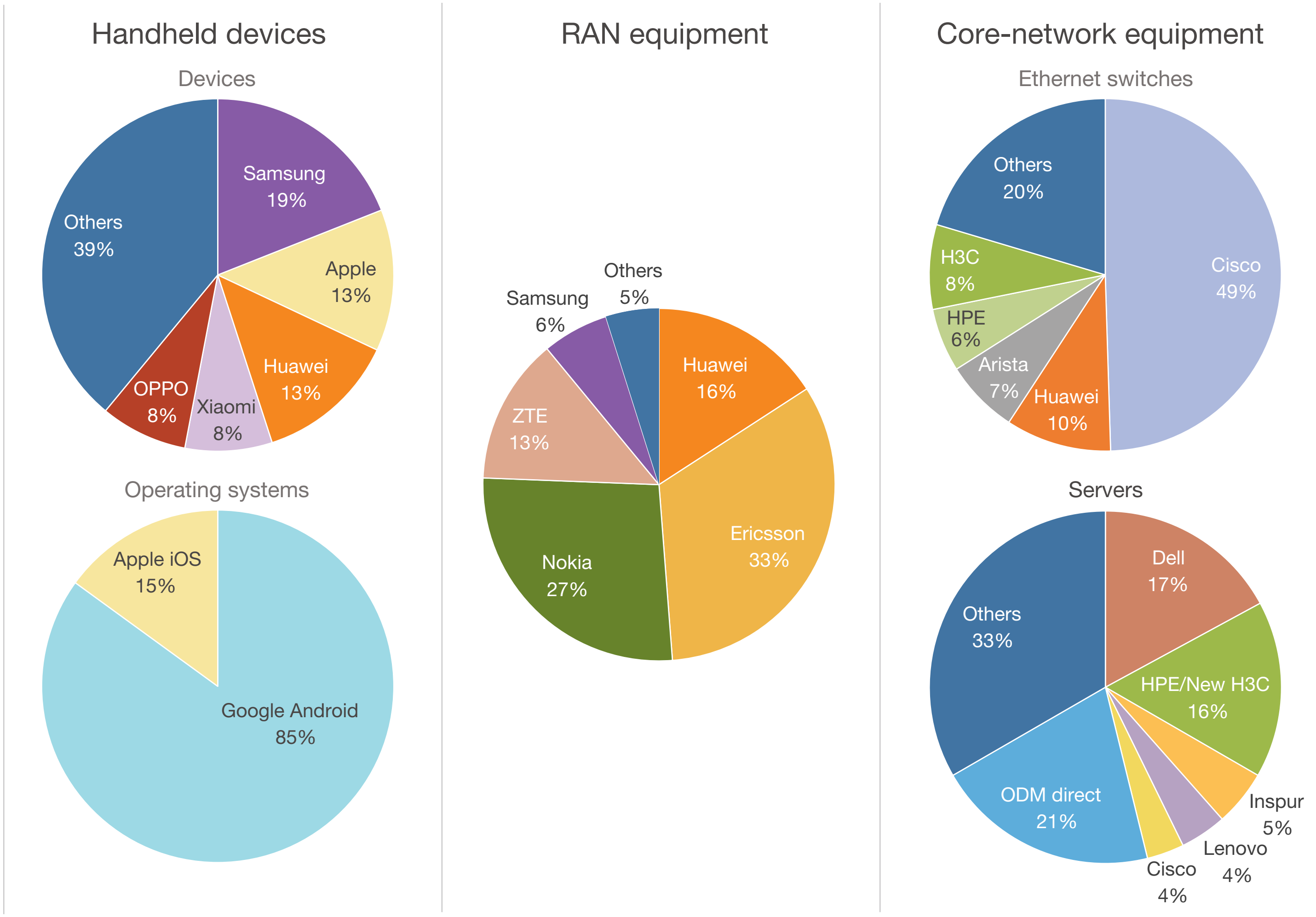
The market for the new 5G ecosystem in the United States appears to be strong, as measured by the number and projected market value of U.S.-based "unicorns."[22] A unicorn is typically a company offering a new product or service, funded with venture capital, and projected to be worth $1 billion or more when it holds its IPO of stock. At present, the United States has more and more-valuable unicorns than any other country. However, the promise of future technologies and markets that unicorns offer can be dimmed if they are bought out and their innovations stifled by entrenched interests (Wen and Zhu, 2019).

Are Companies Based in the United States Maintaining a Technical Edge?

The United States maintains strong technical leadership across several key segments. As we discussed earlier, U.S. tech companies provide the largest share of applications and services today, led by Alphabet (Google), Amazon, Apple (with an integrated ecosystem of devices and ser-

FIGURE 6

Market Leaders and Share in the Device, Radio-Access Network Equipment, and Core-Network Equipment Segments



SOURCES: "GartnerGroup's Dataquest Says Nokia Became No. 1 Mobile Phone Vendor in 1998," 1999; Schonfeld, 2010; Counterpoint Research, 2020; Statista, undated a; Téral, 2019; "Ericsson and Nokia Are Now Direct Rivals," 2018; International Data Corporation, 2019.

NOTE: ODM = original design manufacturer. *ODM direct* refers to sales directly from that manufacturer to the customer.

In recent years, U.S. technological leadership has eroded in several key segments, often giving way to foreign competition.

vices), Facebook, and Microsoft. U.S. companies provide most smartphone operating systems (with Android and Apple iOS) and are strong competitors in smartphone devices (Apple) and core-network switches and servers (Cisco, Dell, and Hewlett Packard).[23] And U.S. companies have strong mobile chip designers in Qualcomm, Skyworks, Broadcom, Qorvo, and others.

However, in recent years, U.S. technological leadership has eroded in several key segments, often giving way to foreign competition. Most U.S. mobile chip designs are manufactured at a few large foundries in Taiwan (accounting for 66 percent) or South Korea (another 16 percent). Foreign companies dominate other precursor markets, such as the high-end lithography equipment to make leading-edge chipsets and instruction coding.[24] Foreign firms also lead in patent filing—although the number of patents by itself is an imperfect indicator of technical value (which we discuss in the security section that follows). As we discussed above, U.S. firms have completely exited the mobile RAN base station business, and foreign firms (principally Huawei, ZTE, Nokia, and Ericsson) are now the only competitors in this market.

Although we discuss potential supply chain disruption in the security section that follows, we note here that the mobile chips produced in Taiwan and South Korea have the smallest feature size and hence the best performance.[25] Supply limitations could also have near-term effects on the technical competitiveness of products made in the United States.

Foreign companies are leaders in smartphones (Samsung and Huawei) and have strong positions in core switches and servers (Huawei and ZTE). Finally, Chinese companies, such as Baidu, Alibaba, and Tencent, are growing rapidly, with some applications, such as TikTok, gaining users outside of China (Bellman, 2019).

Despite the urgency that surrounds much of the public discussion, 5G technology is still very much under development, both in terms of technical standards and in terms of user applications. There is still huge uncertainty as to eventual 5G uses, how much value they will generate, who will capture that value, and who will spectacularly fail.

Products launched in each generation of cellular networks have faced uncertainty as to their success. As a historical example, in 2006, the Walt Disney Company started ESPN Mobile and Disney Mobile as 3G mobile virtual networks. Despite exclusive content and deep corporate pockets, both had shut down by 2007 (Reardon, 2007). That same year, Netflix began to transition from a small movies-by-mail company to a video-on-demand streaming company (Watson, 2020)—reaching 117 million subscribers in 2018, with 25 percent of its streaming over wireless networks (Solsman, 2018). In 2006, outside observers might have predicted that ESPN and Disney would account for more of 4G's eventual use than then-fledgling Netflix would—but they disappeared and Netflix skyrocketed.

Similarly, it is difficult to assess how well U.S.-based companies will compete in 5G because no one knows at this point which use cases will ultimately drive 5G. The rollout of every previous wireless generation took well over a decade, and major parts of the 5G technical ecosystem (such as the 5G core) have not yet even been fully standardized, let alone built out. Inevitably, unexpected applications will emerge, while some early favorites will fizzle. With such great uncertainty about eventual uses and market leaders, it is vital that the United States maintain a thriving technical base and continue to be a major source of ideas and invention, with entrepreneurs able to quickly seize opportunities as they emerge. Investment in research and development, access to venture capital, and a skilled workforce are high on the list of resources needed to enable a thriving 5G ecosystem.

Another vital resource is the radio-frequency spectrum available to support new applications. The United States is significantly behind many other countries on spectrum licensing, particularly in the midband.[26] This spectrum will be needed to enable deployment of 5G with all of its features—especially where mmWave is not practical given its range limitations. Although the Federal Communications Commission (FCC) has begun the process of setting up auctions, it has not yet licensed any meaningful amount of midband spectrum, while other countries are moving ahead much faster.

While markets around the world are developing 5G applications, industry and government leaders in the United States should work to ensure that the United States maintains leadership in the technologies that will be foundational for 5G—as well as for 6G and future cellular generations as they are conceived (see Zhao, Moritz, and Seal, 2021). Novel approaches to sharing radio-frequency spectrum are an important example.[27] More generally, the United States needs to establish and maintain leadership in a wide variety of technologies—including rapidly emerging technologies, such as artificial intelligence (AI).[28] Some experts, notably Eric Schmidt, former CEO of Google, have expressed concern that the United States depends too much on the private sector to maintain its technical edge and that the federal government should directly support more research and development.

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What Is the Security Competition? What Are Its Implications?

There is a third dimension of competition: the competition to determine how future 5G networks, systems, and applications will be secured and who will control how third parties, including law enforcement and intelligence agencies, might access them. Reliable networks that properly safeguard the data they transmit are fundamentally important to privacy, corporate competitiveness, and national security. Therefore, although policymakers might have a limited role in the wireless economic and technical competitions, it is imperative that they pay close attention to how wireless networks are secured.

Chinese equipment makers have a documented history of inserting "back doors" into networks to steal data. In 2012, China gifted the African Union a headquarters building complete with its own information technology system; in 2018, that system was caught downloading large amounts of data each night to Chinese servers in Shanghai (see Maasho, 2018; Tilouine and Kadiri, 2018; and Vaswani, 2019). In 2019, Vodafone in the United Kingdom found hidden back doors in its Chinese-made network equipment (Lepido, 2019).

The U.S. government has also been caught unaware by recent security breaches. These include buying Android devices to be given to low-income households, only to find that they had backdoor malware preinstalled on them by Chinese company Adups (Brewster, 2020). Perhaps more startling is that the FCC and other U.S. agencies have allowed three Chinese network service providers to operate in the United States since 2001 with almost no oversight (Brodkin, 2020). Finally, in April 2020, cognizant federal agencies recommended revoking those providers' licenses to operate in the United States because of "'substantial and unacceptable' national security risks" (Brodkin, 2020, quoting Office of Public Affairs, 2020).

More recently, U.S. officials accused Chinese equipment maker Huawei of building similar back doors into the equipment it sells and maintains around the world. They charged that Huawei had accessed these back doors in the past decade independently from the network operators or government authorities in the countries buying these systems.

Huawei also has a history of corporate espionage. In 2003, Huawei admitted to stealing software code from Cisco Systems (Thurm, 2003) and is reported to provide cash bonuses to employees who steal intellectual property from competitors (Clancy, 2019; Clark, 2020). In January 2019, the U.S. Department of Justice indicted Huawei for the theft of trade secrets, wire fraud, and obstruction of justice (Office of Public Affairs, 2019; Thurm, 2003). And Huawei might have some help from the Chinese government—hackers believed to be part of Advanced Persistent Threat 10, a Chinese cyberespionage group, have infiltrated the cellular networks of at least ten global carriers since 2012 (Nichols, 2019; Martin and Dou, 2019).

In the 5G era, Chinese companies present a new risk: They might succeed in having their hardware or software—with back doors—built into the 5G network standards themselves.[29] 3GPP (3GPP, 2020), which consists of representatives from the organizations that set technical standards in each region of the world, is currently developing 5G standards.[30] Chinese companies have cultivated a leading role in the cognizant committees—for example, chairing two of the six RAN working groups and having three of the vice chair positions (see 3GPP, 2020). 5G technical standards developed by 3GPP will be global in nature and will enable vendors to develop products that can then be integrated into any country's 5G networks. (And, as mentioned previously, development of 6G standards is beginning now and must also be addressed.)

If a specific algorithm or technology, and the patents associated with it, is deemed to be essential to a 5G technical standard, 3GPP might declare it to be a SEP. Once something is declared a SEP, all 5G participants can then be compelled to use chipsets and algorithms produced by the SEP holders to ensure compatibility with the 3GPP global standards.

The problem is that dominance of standards by one actor provides a pathway for that actor to insert a back door to exploit later or to ensure that privacy can be compromised. To date, Huawei and fellow Chinese firm ZTE have filed for nearly 24,000 SEPs—as compared with fewer than 3,000 SEPs filed by U.S. companies Intel and Qualcomm combined (Tanaka, 2019). If Huawei and ZTE are granted SEPs, companies building devices, networks, or applications could be compelled to use chipsets or algorithms implanted with back doors that enable espionage or injecting malicious code.[31]

To the extent that U.S. counterintelligence officials have evidence that Huawei, ZTE, and other Chinese equipment producers are inserting back doors into hardware and software they produce, it would be prudent for the United States to continue—and even expand—the current ban on compromised equipment in U.S. networks and encourage allies to do the same. Furthermore, we warn against the use of federal regulatory rulings, such as the recent Federal Trade Commission rulings on antitrust, to force U.S. companies to share their intellectual property with Huawei or other companies found to be security threats (L. Thompson, 2020). U.S. federal authorities should improve interagency coordination to avoid this present threat and should promote active participation of U.S. companies in the 3GPP and other standard-setting bodies.[32]

Dominance of standards by one actor provides a pathway for that actor to insert a back door to exploit later or to ensure that privacy can be compromised.

The United States also needs to develop a clearer strategy to secure the supply chain in those market segments that U.S.-based companies have exited. It will be important for this strategy to address threats against potential points of failure, such as the chip foundries in Taiwan and South Korea that supply most of the market. For example, both U.S. companies and friendly foreign suppliers could be incentivized to build leading-edge mobile chip foundries in the United States. In addition, policymakers might consider options for encouraging RAN equipment makers that offer alternatives to Chinese manufacturers. Approaches being considered under a proposed “techno-democracy” alliance might represent a step in this direction (Ignatius, 2021). A new initiative among RAN hardware and software providers to develop open standards for the next genera-

Trading data for free services and applications has become embedded in the basic societal structure of the United States—including interacting on social media, buying goods and services, and informing and entertaining.

tion of RAN systems could also be helpful.[33] An open RAN architecture could lower the entry barriers for new participants to enter selected portions of the RAN hardware and software markets rather than having to develop complete stand-alone systems.

The Competition Between the Business of Big Data and Securing Individual Privacy and Well-Being

A fourth competition exists between the business (whether performed by government or by the private sector) of gathering and using big data and safeguarding the privacy, well-being, and—in some striking cases—the security of individuals. Today, trading data for free services and applications has become embedded in the basic societal structure of the United States—including interacting on social media, buying goods and services, and informing and entertaining.

The 5G era will feed that data trade with an astounding number of tracking devices, cameras and other sensors, and networked AI algorithms built to make sense of it all. More than 13 billion mobile wireless devices—with built-in cameras, microphones (with Siri, Alexa, or equivalent), and location trackers—are projected to be in service worldwide (Cisco, 2020). By 2021, 1 billion public surveillance cameras and, by 2023, 29 billion networked devices are projected to be in service—half of them machines talking to machines (Lin and Purnell, 2019; Cisco, 2020). A leading example is in China—which owns nearly half of the surveillance cameras mentioned above, including some installed to watch household doorways (Gan, 2020). In every square kilometer, 5G protocols can support up to 1 million such devices—this is one in every square meter—which would make surveillance at an individual level truly ubiquitous.

Data from these systems and services are used today by government agencies and commercial industry around the world. The ability to track people commuting from their homes to the Pentagon or soldiers jogging in overseas locations has already been demonstrated (see S. Thompson and Warzel, 2019, and Sly, 2018). Chinese authorities use smartphone tracking and facial recognition to identify people suspected of coming into contact with COVID-19 (Cadell, 2020) and then use algorithms to assign each person a green, yellow, or red code to designate their infection status

(Mozur, Zhong, and Krolik, 2020). Some Chinese citizens complained that the algorithms are opaque and that their codes suddenly changed from green to red without explanation—which can cause the miscoded individuals to be barred from workplaces and highways (Yang et al., 2020). Chinese party officials are developing new uses for these algorithms and systems for after the pandemic has ended—including linking the algorithms (which have not been disclosed to the public) with personal health and Communist Party records to assign each person a "health code" and linking each with party records to assign an "honesty" code grading each person's "uprightness and diligence" (Zhong, 2020).

Although it is less pervasive or centrally organized, the use of public surveillance and personal data is increasing in the United States as well. Law enforcement authorities in the United States use automated devices to detect traffic violations, identify vehicle owners, and prepare citations (Eccles et al., 2012). More recently, police have used home doorbell videos in their investigations (Harwell, 2019) and have used fitness-tracking data to match the movements of individuals with the location of crimes (Schuppe, 2020). Law enforcement agencies in Utah have partnered with an AI company to monitor traffic cameras, 911 emergency systems, social media posts, and other data streams to "reduce time and resources typically required to generate leads" ("Utah Police Look to Artificial Intelligence for Assistance," 2020).

In the commercial world, credit card companies have long used intelligent algorithms to monitor card use at every keyboard and payment device and cross-reference transaction type, location, and frequency with the home address and typical travel patterns of the card owner (Nelsen, undated). Google is now mining millions of patient records with the goal of improving patient care and is developing an AI-based algorithm to improve cancer diagnoses (Abbott, 2020). Google, Amazon, and Apple have each deployed AI-based digital assistants that can answer questions and perform tasks—and have also recorded some of these (and unrelated ambient) conversations. Google, Amazon, and Apple have said that these recordings were made to improve system performance and have since stated that they have stopped using outside contractors to review them (Haselton, 2019b; Crist, 2019).

Several issues relate to these data uses for government, businesses, and individuals. First, big data presents a business issue for policymakers. A tension exists among disparate interests in promoting goods and services produced by U.S.-based companies on the one hand and protecting privacy and data rights on the other. At best, failure to properly address this issue might result in leaving it to the European Union (EU)—which enacted individual data protections in 2016—or other governmental entities to set rules that large companies might tend to follow worldwide.[34] Worse would be if lack of clarity in U.S. policy both damaged desirable economic activity and failed to protect individuals. In the case of personal data, the United States would likely prefer that these data remain in the possession of U.S.-based corporations to the maximum extent possible in order to maintain some ability to regulate its collection, protection, and use.

Second and more ominously, feeding more data and inferences to a wider variety of humans and AI algorithms, to help them make quicker decisions, could cause unanticipated effects and negative feedback loops. The potential dangers grow worse if individuals and public officials

The decisions made during the pandemic will have long-lasting effects, so policymakers and members of the public should be careful about the norms they are willing to accept.

become used to uncritically relying on suggestions quickly made by such algorithms or people on social networks. Frustrating examples include the traffic jams caused on usually quiet residential streets by algorithms routing commuters around freeway congestion.[35] More-sinister problems can result from misidentifying individuals as the culprits in misbehaviors or crimes captured on social media (Nuzzi, 2020). People subsequently "doxed" in these episodes have become the targets of widespread abuse by cybermobs and have even been threatened with physical harm.[36] Unfortunately, subsequent efforts to retract accusations and correct the misidentification sometimes achieve a much smaller dissemination and slower response.

The tension between disparate interests, cutting across society, suggests another role for policymakers in establishing a balance between beneficial uses of information about individuals with legitimate concerns for their privacy and well-being. Identifying, defining, and agreeing on potential uses of data before the data are collected and analyzed could facilitate achieving that balance. The United States had begun to grapple with some of these issues in the Fair Information Practice Principles, which applied to government uses of data.[37] The challenge in the current environment is that data are a stand-alone commodity that is bought and sold in a market of its own. Even if one knows how data are being bought and sold, privacy can be compromised by the collector and analyzer of a particular collection of data and by someone buying data from multiple sources and joining the data sets to deanonymize them. Without an updated protocol coordinated across government and industry, the competing risks and benefits of the 5G era could cause dissension and indecision, resulting in losses of the benefits while still permitting some harms.

As a salient example, coping with the COVID-19 pandemic has presented both new, societally beneficial uses for this kind of information and new dangers of long-term misuse. The powerful combination of cameras, microphones, location tracking, and AI algorithms on public and private buildings, automobiles, and the personal devices most people carry can help health authorities conduct contact tracing to minimize disease spreading. But they can also be used by governments and mobs to track, bully, and harm individuals. Governments might be tempted to suspend democratic norms in emergencies—and some short-term emergency measures might later become permanent.[38] The decisions made during this crisis will have long-lasting effects, so policymakers and members of the public should be careful about the norms they are willing to accept. The implications of 5G technologies will last much longer than the current crisis and are different enough in kind and degree to justify rethinking current policies. In rethinking policies, it will also be important to consider how the regulations themselves might be a basis for economic, technical, and security competition.[39]

Some Closing Thoughts on Competition in America's 5G Era

The 5G era will bring a tremendous increase in the numbers and power of wireless devices and services. Many applications of 5G technology will be beneficial and widely welcomed, while some applications have the potential to be extremely detrimental in a democracy, such as the United States. Our purpose here was to characterize key dimensions of the 5G-era competition, assess how well the U.S. wireless-related ecosystem is competing in each dimension, and highlight potential and emerging opportunities and risks in the 5G ecosystem that could suggest a role for policy.

Economic Competition

As measured by market value of wireless ecosystem participants, U.S.-based companies are faring well in the 5G era. In particular, U.S.-based companies providing applications and services appear to be particularly dominant (Figure 4). Still, developments in international and domestic markets could threaten the future economic dominance of U.S.-based companies:

- Stronger competition from Chinese or other countries' applications and services could threaten the United States' leadership, although, at present, competitors, such as TikTok, remain few and specialized.
- Tech companies (among U.S. or foreign market participants) could exercise their established market positions to stifle competition or buy out new startups. 5G involves industries that benefit from network effects and scale economies; the challenge for the U.S. government will be to support economic efficiencies while continuing to monitor markets and regulate companies that misbehave.

Technical Competition

U.S.-based companies lead in the markets for operating systems for cellular devices and in the development of applications and services that use cellular networks. U.S.-based companies are strong competitors in mobile chipsets, personal devices, and core-network switches and servers. However, they have fallen behind in leading-edge fabrication of mobile chipsets, have abandoned building the lithography machines that make them, and have abandoned manufacturing RAN equipment. Several potential threats could endanger future U.S. technical leadership, including

- potential near-term effects on U.S. technical competitiveness if chip fabrication in Taiwan and, to a lesser extent, South Korea is interrupted
- limited midband (i.e., sub–6 GHz) spectrum availability slowing the growth of 5G networks in the United States and the adoption of new devices, applications, and services
- insufficient research and development investment, especially from federal government sources, to

maintain U.S. technical leadership in the face of strong foreign competition.

To remain competitive, the United States needs to nurture a thriving and dynamic technology base with substantial capacity in new-product development. Leadership in key 5G-ecosystem technologies—notably AI—will require significant federal investment in research and development. The federal government also needs to speed repurposing of midband spectrum for 5G use. Finally, 5G will ultimately be the foundation for 6G and future cellular generations. It will be important for U.S. government policy to keep pace as more industries become part of the wireless communication ecosystem.

Security Competition

The standards by which 5G components and devices will be built are being developed now by 3GPP. Algorithms and chipsets granted SEPs will be baked into these standards, and device and network equipment makers will be compelled to use these components to be compatible with 5G networks around the world. If the components have built-in back doors, they could be used to compromise the security of networks, applications, and services. Huawei and other Chinese entities have recent history installing such back doors in equipment they provide. And Huawei and Chinese equipment maker ZTE account for most of the 5G SEP applications. Given this security imperative, roles for policy in this arena should include

- mitigating threats posed by Chinese equipment producers, which has included establishing bans on their use in partnership with key allies
- supporting U.S. companies participating in 3GPP and its standard-setting committees—including 5G, 6G, and future generations of cellular systems
- reviewing resulting 3GPP standards and SEPs for security and suitability for U.S. networks.

To address the separate risk to the U.S. supply chain in segments that U.S. companies have exited, we suggest considering policies that

- encourage leading-edge chip foundries to be built in the United States
- strengthen the market viability of RAN equipment makers offering alternatives to Huawei and ZTE.

Competition Between the Business of Big Data and Safeguarding Individual Privacy and Well-Being

The 5G era will accelerate the amount and type of personal data that can and will be collected by governments and private industry. Failure to adequately resolve the tension between collecting valuable data and protecting individual privacy and well-being could hurt both corporate and individual interests if the proper balance is not struck.

Much more importantly, uses of these data—both to do good and to cause harm—are still emerging. It is hard for people to protect themselves against harmful outcomes from deeply embedded algorithms using such data—this is a job for governments to do with the help of businesses. To step into their role, policymakers should develop protocols to better balance business and government interests with individual privacy, well-being, and security. Privacy policy within the United States has been fragmented—with some dated policies, such as the Fair

Information Practice Principles, guiding U.S. government departments (DHS, 2020) and the GDPR regulating private corporations that conduct business in Europe. Improved coordination is needed across government and industry for privacy protection—including addressing how interests are balanced.

What Success Will Mean for the United States and Its People

The United States is on the threshold of major changes in its economy and society—many of which will directly result from applications of innovative 5G-era technologies. This can be the greatest of opportunities if the country—both the government and the populace—is prepared to do the hard work outlined in each of the areas above. Success requires coordinating across all levels of government, balancing competing equities among private and public interests, and taking needed actions in a timely manner while also ensuring long-run success.

Notes

[1] President Donald Trump went further, stating, "The race to 5G is on and America must win" (Haselton, 2019a).

[2] Of course, although 5G standards and protocols support these high densities, network operators still need to deploy a sufficient number of base stations to provide service to these users. As a rough analogy, zoning ordinances and development plans might allow thousands of people to live in a given area, but contractors must put in roads, houses, and utilities to actually house these people. Networks deployed nearly 50,000 base stations in 2019 and might deploy hundreds of thousands of 5G cells to connect users in high-density locations, such as New York City. See Statista, undated b.

[3] This is an average of all of New York City. The borough of Manhattan has a higher density of 27,436 residents per square kilometer, and commuters surge these numbers to nearly 66,000 per square kilometer during weekdays—higher than the 4G standard capability. U.S. city population density figures are from Maciag, 2017. We projected these numbers into 2030 using urban growth rates estimated by the Pew Research Center. See K. Parker et al., 2018.

[4] This is an extrapolation of Cisco's projection. If every New Yorker had one smartphone and one other connected laptop, tablet, or wearable device, the existence of one autonomous door camera, traffic sensor, or other device in every 5 m × 5 m area would exceed 4G capacity limits. Busy city streets, office towers, subways, and other crowded spaces would reach 4G limits even more quickly.

[5] At present, people in Asia, South America, and Africa rely on wireless connections to the internet for 50 percent of their devices, while people in the United States use wireless for 25 percent of internet connections. See Cisco, 2020.

[6] The 4G limit of 60,000 devices per square kilometer pertains to devices that are active, which means that they are engaging in two-way real-time communications over cellular device networks. A cellular network could accommodate more devices if many were in standby mode, others were time-sharing asynchronous transmission of data, and some were connecting through Wi-Fi rather than through cellular networks.

[7] The radio-frequency spectrum as defined by the National Telecommunications and Information Administration (NTIA) runs from 3 kilohertz (kHz) to 300 GHz. It is broken up into discrete radio bands that are then allocated to public agencies and private companies that provide navigation and communication services. These bands tend to become very crowded, as shown in the NTIA frequency allocation charts. Broader frequency bands have been allocated for cell-phone providers at higher frequencies—making them attractive for next-generation wireless services but necessitating significant investments in new technologies and infrastructure. See NTIA, 2016, and Groupe Speciale Mobile Association, 2017.

[8] If not 5G, spectrum that can be shifted to cellular systems from other users. For example, the United States is planning to move satellite communication users out of a 300 MHz–wide portion of the midband so it can be repurposed for 5G cellular users. The FCC held several mmWave auctions in 2019 (24-, 28-, 37-, 39-, and 47-GHz bands) and announced winners of its first tranche of C-band auctions. See FCC, 2019a; FCC, 2019b; FCC, 2020; FCC, 2021; and Reardon, 2020.

[9] Technically, mmWave is from 30 to 300 GHz, although frequencies at 24 GHz are also called mmWave.

[10] The wavelength of wireless signals and, correspondingly, their effective range, decreases at higher frequencies. Water vapor in the air, buildings, vegetation, and people all attenuate high-frequency signals—necessitating a closer spacing of cellular base stations.

[11] In ideal conditions, 4G peak rates can be as high as 100 Mbps, but average 4G data rates are typically 20 Mbps or lower. We derived 4G characteristics from Fenwick and Khatri, 2020, and Frenzel, 2013, and 5G characteristics from Schwechel et al., 2019.

[12] Investment firms trading on the New York Stock Exchange have sought wireless connections that can shave a few milliseconds off the time needed to make trades. These same traders might see an advantage in 5G latency times of 1 ms. See Marek, 2020.

[13] There were 395,562 cell towers in the United States in 2019, according to Statista. With a 2019 U.S. population of 328.2 million, there would be an average of 830 people per cell tower. In Manhattan, with a population of a bit over 1.6 million people, that would suggest nearly 2,000 cell towers for an area of 59 km^2, or more than 33 towers per square kilometer on average. See Statista, undated a, and U.S. Census Bureau, undated a. The number of simultaneous users a cellular base station can support ranges from a few hundred to a few thousand, depending on antenna technology, bandwidth, the density of cells within a given area, and the quality of service offered.

[14] The 5G standard offers three sets of use cases:

- massive machine-type communication, which permits very high device density and likely drives 5G adoption
- enhanced mobile broadband, which offers peak data rates of up to 10 Gbps
- ultrareliable low-latency communication, which offers a decrease in round-trip latency to the base station from a 4G average of 20 ms to as little as 1 ms. For especially time-critical applications, such as automated highways and augmented or virtual reality, 5G networks might locate some computers and databases at the base stations to achieve these low latencies.

[15] 3GPP is the primary standard-setting organization that develops protocols for mobile communication systems, including 5G. See 3GPP, undated.

[16] As described by the Corporate Finance Institute, "The investing community often uses market capitalization value to rank companies and compare their relative sizes in a particular industry or sector" (Corporate Finance Institute, undated).

[17] We included the market capitalization as of May 2019 of those companies among the Forbes Global 2000 that we identified either as driving wireless components (hardware and software), networks, or applications and services or as depending on these segments for their core business operations. Stock values have risen further since that time—with the combined value of Alphabet, Amazon, Apple, Facebook, and Microsoft increasing from $4.2 trillion to $7.5 trillion as of March 8, 2021. Many market watchers think that the latest valuations reflect a tech bubble that will eventually burst. Whether or not a tech bubble now exists, valuations in the 5G ecosystem even two years ago were driven by the five largest tech firms. See Forbes, 2020; YCharts, undated a; YCharts, undated b; YCharts, undated c; YCharts, undated d; YCharts, undated e; and Browne, 2021.

[18] See related corporate annual reports, including Alphabet, 2017; Alphabet, 2018; Alphabet, 2020; Facebook, 2016; Facebook, 2018; Facebook, 2020; Microsoft, 2015; Microsoft, 2016; Microsoft, 2017a; Microsoft, 2017b; Microsoft, 2019; U.S. Securities and Exchange Commission, 2015; U.S. Securities and Exchange Commission, 2016; U.S. Securities and Exchange Commission, 2017a; U.S. Securities and Exchange Commission, 2017b; U.S. Securities and Exchange Commission, 2018; U.S. Securities and Exchange Commission, 2019a; and U.S. Securities and Exchange Commission, 2019b. Also see Levy, 2019; Macrotrends, undated; Microsoft, 2020; and Statista, undated a.

[19] Amazon held its initial public offering (IPO) of common stock on May 15, 1997; Google (now Alphabet) on August 19, 2004; and Facebook on May 18, 2012. See "If You Had Invested Right After Google's IPO," 2015; "If You Invested Right After Amazon's IPO," 2021; and "If You Invested Right After Facebook's IPO," 2020.

[20] Members of the U.S. Senate have urged the U.S. Department of Justice to investigate TikTok and ByteDance out of concern that they share user data with the Chinese government. The Department of Justice has accused ByteDance of being the "mouthpiece" of the Chinese government, and the U.S. Department of Commerce announced a ban on TikTok that was to have taken effect in November 2020. At the time of this writing in March 2021, the U.S. actions against ByteDance and TikTok are the subject of lawsuits that have yet to be resolved. See Strohm, 2020, and Choi, 2020.

[21] It is curious that Apple iOS has a higher operating-system share than the iPhone does. Presumably, this is because iOS operates on other hardware, such as the iPad, that is not counted in the smartphone category. We should note that future U.S. dominance in operating-system software could change if Huawei proceeds in deploying its own operating system.

[22] In this context, a unicorn is a start-up with a valuation of more than $1 billion. See CB Insights, undated.

[23] However, we should note that some components used by U.S. corporations are built overseas. For example, Apple and many other firms contract to have their equipment assembled overseas, and Cisco develops much of the software for its products in India. These relationships also create an exposure to supply-chain issues. See Pham, 2020, and Cisco, undated.

[24] Mobile chipset designs are immensely complex and have rapidly evolved from general-purpose central processing units into multi-core systems on a chip, with various modules exclusively designed for specific functions (such as graphics or AI). These designs are generally reduced–instruction set computers (RISCs) and are almost always based on instruction sets by ARM (a semiconductor-design firm based in the United Kingdom), although the open-source RISC-V instruction set has garnered considerable attention in recent years. See "Open-Source Computing," 2019.

[25] The physical size of the features etched onto the silicon wafers determines chip power. Smaller is better. GLOBALFOUNDRIES, a U.S. company, has halted leading-edge production in favor of more-economical, lower-power designs, and Intel, also a U.S. company, stopped competing in the mobile chipset market after dropping out in mid-2016 to focus on desktop and server chips. See GLOBALFOUNDRIES, 2018, and Savov, 2016.

[26] China, South Korea, and other leading nations have already repurposed large portions of the sub–6 GHz band for 5G cellular applications. Although the United States has plans to do so, it has not yet cleared current users, such as satellite communications, from these frequencies. See Medin and Louie, 2019, and Dano, 2020.

[27] Dynamic spectrum sharing might enable mobile operators to dynamically allocate spectrum among users to meet traffic demands. This might allow them to enable sharing between 4G and 5G systems and perhaps even between cellular systems and noncellular users of the same frequency bands. See Weissberger, 2019.

[28] Eric Schmidt, former chief executive officer of Google and chair of the National Security Commission on Artificial Intelligence and the Defense Innovation Board, makes the case that the United States is putting too much faith in the private sector to maintain its technical edge and is in danger of losing its leadership position to China. AI is an especially important case in point—and AI is a technology likely to both enable and be enabled by many 5G-ecosystem technologies. See Schmidt, 2020.

[29] Huawei and ZTE and, through them, the Chinese government, are the only non-U.S. entities making a strong push to develop 5G standards. Although other countries—such as Russia and North Korea—are serious hacking threats, they are not major equipment manufacturers or exporters. China's significant advances in these markets make it a uniquely capable and serious threat.

[30] For example, the regional standard-setting organization for North America is the Alliance for Telecommunications Industry Solutions.

[31] A SEP holder does have the option to license its algorithms or code available to a purchaser. This would allow the purchaser to then inspect the SEP for vulnerabilities or back doors. However, SEP holders might set the price of the algorithms or code too high or license systems with reduced performance—essentially forcing the non–SEP holder to buy chips instead.

[32] In the United States, participation is voluntary, featuring industry-led standard-setting that flows to the international bodies. The National Institute of Standards and Technology and other federal government agencies have a monitoring function that is also important.

[33] The open-RAN initiative seeks a more open architecture that invites new entrants, as well as including current providers. The O-RAN ALLIANCE goes a step further, with a vision to "transform the Radio Access Networks industry towards open, intelligent, virtualized, and fully interoperable RAN" (O-RAN ALLIANCE, undated).

One must note, however, that any hardware and software back doors embedded in participant equipment would still pose a security threat. The U.S. government would still need to carefully vet these participants for potential security issues. See Nokia, 2020, and O-RAN ALLIANCE, undated.

[34] In 2016, the EU implemented the General Data Protection Regulation (GDPR). Among other things, the GDPR requires some personal data to be deleted upon the person's request. See Wolford, undated, and European Data Protection Supervisor, undated.

[35] See Littman, 2019; for a feedback loop, see Barrett, 2020.

[36] The Merriam-Webster dictionary defines *dox* as "to publicly identify or publish private information about (someone) especially as a form of punishment or revenge." See "Dox," undated.

[37] The authors are indebted to colleague Edward Balkovich for suggesting this precedent. See International Association of Privacy Professionals, undated.

[38] According to ABC News, emergency measures remain active in the United States from 31 prior declarations. The oldest of these was enacted November 14, 1979, in response to the Iran hostage crisis. For example, the Federal Register announced the most recent extension of the 9/11 emergency orders. See Heath, 2019, and Trump, 2020b. For additional perspective, see Harari, 2020.

[39] For example,

> The European Commission claims that by having a single supervisor authority for the entire EU, it will make it simpler and cheaper for businesses to operate within the region. Indeed, the Commission claims GDPR will save €2.3 billion per year across Europe. (Palmer, 2019)

The U.S. Attorney General has argued that China is using its economic power to pressure U.S. companies to provide products or place servers in China in a way that could compromise these protections. See Macias and Feiner, 2020.

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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 policy primer for the 5G era and summarizes our observations from the RAND-Initiated Research project titled "America's 5G Era: Securing Its Advantages and Ourselves." As we assessed the 5G wireless ecosystem, we began to see the development of its markets and technologies as an enduring competition rather than a "race." A key observation from that project is that past technical or market leadership does not guarantee a lasting advantage. We also highlight important implications of 5G-era devices, networks, and services for securing data and protecting individual privacy.

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