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AN ECONOMIC ANALYSIS OF 5G WIRELESS DEPLOYMENT: IMPACT ON THE U.S. AND LOCAL ECONOMIES

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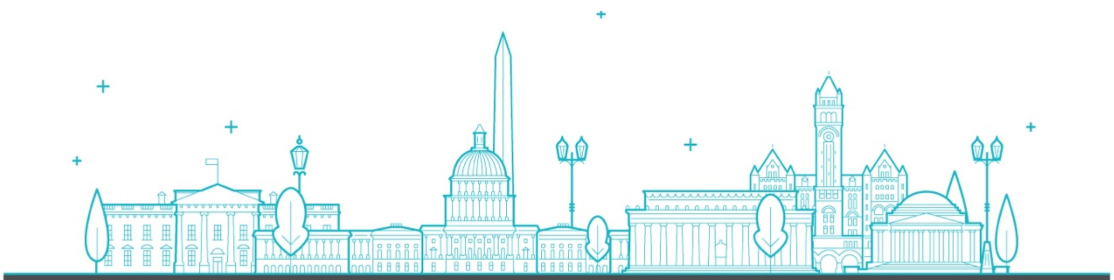

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About this report

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An economic analysis of 5G wireless deployment: Impact on the U.S. and local economies

I. Executive summary

The U.S. has never been a more connected nation, and 5G is the next generation of wireless network technology.[1] 5G offers higher transmission rates, more reliable connectivity, and lower latency, allowing businesses and consumers to perform existing and entirely new tasks better and cheaper. This report examines the potential of 5G as a general-purpose technology to unleash improvements in economic productivity, employment, and consumer value. 5G will be an important driver of economic growth in the nation. Investment to create 5G networks contributes directly to GDP, and $225 billion in capital expenditure will be needed over the next seven years or so to fully deploy 5G. However, this direct effect on GDP is only a small part of the total economic effects of broadband in general and 5G in particular.

5G will affect the labor market through direct and indirect means. The broadest impact on the labor market comes from new employment opportunities through the way 5G will enable new applications, services, ways of doing business, and general growth of businesses. The additional labor required to build out the network to deploy 5G will create the most immediate demand for new jobs. The analysis here finds that 8.5 million jobs will be created over 2019-2025 compared to a counterfactual 4G-only world, with an average of 1.2 million jobs each year. These workers will earn more than $560 billion during that time, create $1.7 trillion in additional output, and add over $900 billion to U.S. GDP.

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Businesses and consumers will also benefit from 5G networks. The Internet of Things (IoT) and 5G will be a major source of productivity improvements and competitive advantage for businesses. The 5G ecosystem will also create much value for consumers, who can look forward to peak mobile broadband transmission speeds of about 10 to 20 times faster than 4G LTE. The true promise of 5G and IoT for consumers lies in doing completely new things using mobile and fixed wireless and IoT technology devices, such as healthcare devices, autonomous vehicles and traffic management systems, the smart grid for revolutionizing energy management, smart home technology, and wearable devices.

Next-generation wireless networks hold special promise for economic development in rural and economically lagging areas by expanding labor and output markets beyond isolated geographical areas, filling gaps in existing wired and wireless broadband coverage, and granting access to healthcare, educational, and other expertise in urban or more advantaged areas. Case studies on four cities (Los Angeles, New York, Pittsburgh, and Roanoke) show that even the direct economic impacts from deploying the 5G network are large. Employment created by network construction, complementary CAPEX in private industry, and consumer spending on 5G-enabled devices and 5G service are expected to create about 250,000 jobs in Los Angeles, up to about 120,000 jobs in New York City, about 22,000 jobs in Pittsburgh, and about 2,700 jobs in Roanoke. These estimates, along with the forecasted national economic impacts, are supported with careful economic modeling based on established methods for regional economic analysis.

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II. Introduction

In an increasingly mobile and wireless world, 5G is the next generation of wireless network technology. The key advantages of 5G are higher transmission rates, more reliable connectivity, and lower latency (the time it takes for a source to send a packet of data to a receiver). These capabilities allow businesses and consumers to perform existing tasks better and cheaper, but—more importantly—allow entirely new types of productive activity to take place. This report examines the potential of 5G to unleash improvements in economic productivity, employment, and consumer value.

Much of the great promise of 5G for economic growth stems from its role as a general-purpose technology (GPT). A GPT is pervasive, has high potential for technical improvements, is greatly useful to businesses, and can be employed to increase the productivity of R&D in downstream sectors (Bresnahan and Trajtenberg, 1995). Thus, GPT reshapes systems of production and distribution, with wide-ranging effects throughout the economy. Mobile broadband internet access is a GPT (Prieger, 2013), is an increasingly essential part of the information economy, and is a necessary foundation for the "next production revolution" coming with the diffusion of the Internet of Things, robotics, and mobile artificial intelligence (Atkinson, 2018). 5G is thus important to the economic health of a region and the national economy.

5G refers the collection of standards and technologies in the fifth generation of cellular communications technology. In addition to operating frequencies currently used for cellular communications, 5G wireless networks also will use new radio frequencies, such as those above 6 GHz, to maximize improvements in transmission speed, latency, and reliability over previous generations of mobile networks. Such high frequencies do not propagate as far as lower frequencies for a given amount of power to the antenna, and so key to the 5G network architecture in most locations is the "small cell."[2] Small cells are smaller, lower-power base stations used to send and receive wireless traffic. Since each has a smaller effective area of coverage than the macrocells used in previous generations, small cell sites will be deployed 10 to 100 times more densely (Al Amine et al., 2017). The low power requirements of small cell technology means that the radio equipment can be no larger than a mini fridge, and thus can be deployed easily on buildings, poles, and other existing private and municipal infrastructure. Some of the most immediate impacts on the economy will come from the expenditure on construction of the small cell sites necessary to roll out the 5G network.

Much of the excitement about 5G is related to the Internet of Things (IoT). Key to IoT is connectivity. IoT is the system composed of interrelated computing devices, sensors, machines, data centers, objects, people, and even animals with the ability to transfer data among them without requiring direct human intervention. While 5G and IoT are separate concepts, 5G wireless mobile internet is vitally connected to the future of IoT. IoT is growing at a high rate as more devices become connected and additional applications are developed. In 2019, there were 2.7 billion IoT connections in North America alone, and that figure is projected to increase to 5.9 billion by 2025.[3] The increased capacity of the 5G network can accommodate more connected devices, moving more data through the network with lower latency (which degrades local network performance as more devices are added), thus enabling the continued growth of IoT (Lanner, 2017).

While 5G and IoT are separate concepts, 5G wireless mobile internet is vitally connected to the future of IoT.

In the rest of this report, the expected economic impacts of 5G are discussed. The expected importance of 5G for economic development in general, based on the experience with previous generation networks, is covered in the next section. The extent to which 5G can improve the productivity of businesses and the economy, create jobs and raise wages, and create new value for consumers are discussed in turn. The special benefits that 5G can create for rural and economically disadvantaged areas are also presented. In section IV, the specific estimates of the job creation and other economic impacts of 5G for the nation and selected cities are presented.

III. The importance of 5G for economic development

5G, as with other forms of broadband, will be an important driver of continued economic growth in the U.S. This is seen most obviously with the direct contribution to GDP of the investment that will be necessary to deploy next-generation wireless infrastructure. Private investment in broadband appears directly in GDP.[4] Given the huge amount that broadband providers have invested in the United States, the direct contribution of infrastructure investment is sizeable. Since 1996, broadband providers in the U.S. have invested over 1.6 trillion dollars in private capital expenditure on fixed and mobile broadband, and over $720 billion in the last ten years alone.[5] In 2018, American broadband providers invested roughly around $80 billion in total infrastructure.[6] The top providers in the U.S. invested an estimated $30 billion on wireless broadband capex in 2018, with another $33 billion slated for 2019.[7] These investments have been required to expand steadily the availability and speed of fixed and mobile broadband service offered to consumers. Broadband internet access also appears in GDP as personal consumption item. In 2017, Americans spent $76.1 billion on internet access services, increasing GDP by that amount.[8]

However, these direct entries in the national income accounts are only the tip of the iceberg. As a general-purpose technology, 5G will increase the productivity of businesses, create jobs and increase wages in the labor market, and create value for consumers far beyond what they pay for it. This section discusses those advantages of 5G and IoT, and concludes with a special look at the promise of next generation networks for rural and economically disadvantaged areas.

A. Impacts on labor markets and job creation

As with other areas of economic impact, 5G will affect the labor market through direct and indirect means. The broadest impact on the labor market comes from new employment opportunities through the way 5G will enable new applications, services, ways of doing business, and general growth of businesses. And when the productivity of labor rises, wages increase. Economists refer to such network externalities of 5G as positive spillovers. While these broad impacts on employment may take time to develop, as new business plans that rely on 5G are created throughout the economy, other more direct impacts will be felt immediately. The additional labor required to build out the network to deploy 5G will create the most immediate demand for new jobs. In this section, the positive labor market externalities are considered first, then the direct impacts of 5G deployment.

> ***The broadest impact on the labor market comes from new employment opportunities through the way 5G will enable new applications, services, ways of doing business, and general growth of businesses.***

1. Positive externalities on employment

As 5G diffuses through the economy, it will create network externalities far beyond the communications sector. Businesses that use technologies like 5G and IoT to become more productive and efficient will grow, and growing businesses (and the businesses that provide inputs to them) require more workers. Experience from previous generations and other forms of broadband is again instructive. The most relevant broadband externalities for job creation are the new applications and services it enables, the new revenue its adoption produces for businesses, and the growth in certain industries that become heavy users of the new technology. For example, IoT will involve massive amounts of data to be collected, aggregated, and analyzed. While much of the first two steps will be automated, data analysis will often involve skilled workers, and even the necessary support for data collection and aggregation will depend on workers in the field of information and communications technology (ICT). As another example, 5G will allow telemedicine, based in part on remote wearable or home-based health sensors, to expand in rural areas, creating opportunities for local and remote healthcare workers and technicians to assist patients.

5G can also increase employment by drawing new workers into the labor force. The preference for a work environment that allows its employees to dictate when and where they work is growing in popularity, particularly among younger workers, and 5G mobile broadband access will enable ever more creative forms of flexible working arrangements (Hanson, 2019). This greatly expands both the pool of potential hires for any given firm, who can hire the best-fitting workers regardless of where they live, and the potential labor force, as more flexible labor arrangements draw more people into employment. Indeed, empirical studies have found that increases in local employment associated with broadband deployment arise mostly from new workers entering the labor force, not just from the unemployed finding new jobs (Atasoy, 2013).

Broadband in general and 5G in particular can also affect employment in less direct—but no less important—ways. Some rural and minority populations face challenges to employment from poor health and healthcare, educational deficiencies, and lack of access to transportation and government services. IoT has great promise to lower the cost of delivering many of these services, which can potentially solve, or at least lessen, some of these challenges facing isolated communities (Turner Lee, 2019).

Since the externalities from 5G affect most of the economy, the estimates of job creation from this aspect of 5G are large. To support the new revenue streams in the IoT value chain alone, a white paper from the World Economic Forum estimates that more than 400,000 new jobs in the U.S. will be required (WEF, 2017).[9] Including all indirect impacts, Al Amine et al. (2017) estimate that the adoption of 5G technology into the broader economy will create an additional 2.2 million jobs.[10] These estimates depend on the amount of investment and R&D assumed to be required for 5G deployment; when those are assumed to be higher than the job creation figures rise accordingly. For example, IHS Markit (2017) estimates that investment of $1.2 trillion of R&D and $1.1 trillion of capital expenditure will be needed over 16 years to fully deploy 5G worldwide, which by the year 2035 will support 22 million jobs worldwide in the 5G value chain, with 3.4 million of those jobs being in the U.S.[11]

Complementing the estimates above, which are based on value-chain analyses built from input-output analysis, econometric studies have also attempted to measure directly the impact of broadband on employment. For the early years of wired broadband, for example, econometric studies found that each one percent of penetration resulted in 0.2 to 5.3 percent employment growth.[12] The results vary due to the different data, methods, and years studied, but the positive link to job creation is found in many studies. Later studies also found positive links between broadband availability and increased employment, particularly during the recession years around 2008 when there was significant slack in the economy (Katz and Suter, 2009; Holt and Jamison, 2009).[13]

The employment impacts of broadband are not limited to the early generations of wired and wireless technology. 5G will be fast – fast enough to challenge and replace wired broadband in some areas. Econometric studies that specifically examine very high-speed broadband (often defined in the literature as a download transmission rate of at least 1 Gbps) find that its availability is positively related to county-level employment in the U.S. (Bai, 2017; Lobo et al., 2019) and negatively related to the unemployment rate in France (Hasbi, 2017). The latter study is particularly notable for the large effect found[14] and its numerous techniques used to verify the causality of the association.

Scholars have also researched the industry-specific impact of broadband and found that the job creation effect exists mainly in technology-concentrated industries (Kolko, 2012) and high-end service industries such as finance and insurance, education services and health care services (Crandall et al., 2007). These industries, of course, depend on a highly skilled workforce. The important connection between broadband and high-skilled labor is highlighted by the econometric study of Atasoy (2013), who found that broadband availability increases employment and wages more in areas with more skilled workers and in industries and occupations that require highly skilled and educated workers. Similar results along these lines in a study of firm-level data from Norway showed that broadband availability and adoption complements the abilities of high-skill workers, increasing their productivity, wages, and employment (Akerman et al., 2015).

Thus it is important that IoT can improve the learning process in education, for example by facilitating interaction between physical and virtual objects and students in the learning environment in the context of virtual academic communities (Marquez et al., 2016). Such communities will broaden educational opportunities, particularly in rural and otherwise isolated areas, as will the greater accessibility of education and effectiveness of distance learning enabled by 5G. Eventually, future IoT learning models will be virtual interactive environments that are “learner-centric, skill-centric, on-demand and personalized... improving student development in the areas of critical-thinking and collaborative learning” (Mirzamany et al., 2016).[15] Thus the possibility of a virtuous cycle, whereby workers gain education and skills facilitated by 5G and IoT, and then have increased employment due to the impact of broadband in the economy.

In closely related work to the employment studies, Hasbi (2017), Mack (2014), McCoy et al. (2018) show that broadband spurs local business creation, which almost by definition creates new employment (now or in the future). Indeed, Falck (2017) concludes that the “employment effects of broadband introduction likely arise from job creation in newly founded establishments.” Mack and Rey (2014) show that broadband availability is positively linked to the number of knowledge intensive businesses in particular.[16] Importantly, their results imply that broadband can increase the numbers of such businesses not only in areas with concentrations of knowledge intensive firms, but also areas without, making broadband infrastructure particularly important for development.

The positive effects of broadband on the labor market are not limited to reducing unemployment. Economists have drawn attention to the large number of Americans who dropped out of the labor force after the last recession; such former workers do not appear in official unemployment statistics.[17] Broadband at home can draw people into the labor force through telework and saving time in home production. For example, Dettling (2017) found that high-speed internet use in the home leads to a 4.1 percentage point increase in labor force participation for married women. As discussed above, 5G and IoT will greatly enhance the prospects for remote employment and virtual workplaces.

What about the fear that as businesses use ever more ICT such as 5G, jobs are put at risk as “machines replace people”? Changes in the structure of the economy due to technological progress are at least as old as the Industrial Revolution and require careful attention to the education, flexibility, and continued reskilling of the workforce. However, the evidence above shows that in the case of broadband ICT the labor market impacts appear to be positive on net. Furthermore, the available research specific to wireless broadband internet access does not support that worry. In a cross-country econometric study of how short-run labor demand is affected by various forms of ICT used by businesses, Biagi and Falk (2017) found no evidence that mobile broadband usage by employees destroys jobs.

2. Impact of network construction on employment

Deploying the infrastructure necessary for the 5G network will require much labor. CTIA (2018), the trade association for America’s wireless industry, estimates that in 2018 the U.S. had only 86,000 small cell sites, out of the estimated 800,000 expected to be built by 2026 if regulatory hurdles do not disrupt the necessary investment. Of that total, about 300,000 will need to be built by 2022 (Safer et al., 2018a). Building that many new network sites and the infrastructure needed to serve them will create many jobs. Some studies use methodology akin to the present analysis to estimate the jobs impact of 5G infrastructure deployment. The report by Accenture (Al Amine et al., 2017) estimates that building the 5G network will create 50,000 new construction jobs in the U.S. each year to install new wireless infrastructure over a seven-year period. Including the industries supporting and supplying the construction effort, total direct employment creation rises to 120,000 jobs per year. Including all areas of wireless investment in 5G networks, the report arrives at a total of about 429,000 jobs each year.[18] Accenture’s estimate of construction jobs is similar to the estimates computed here and discussed in section IV.B.1 below.[19] The estimates presented there, however, are larger even than Accenture's total jobs figure because the present estimates include employment from other parts of the 5G ecosystem. Such estimates are in line with econometric estimates of existing forms of broadband; Hasbi (2017) found that when a very high-speed broadband network has been deployed in a municipality, it created (or attracted) new construction firms, and therefore construction jobs. In particular, fiber networks increase the number of construction companies by 4.7% due to the deployment, installation, and maintenance needs of the networks.

B. Improved productivity and competitive advantages for businesses

IoT and 5G will be a major source of productivity improvements and competitive advantage for businesses, first through creating operational efficiencies and next through new business models and other forms of innovation in processes and products (K@W, 2016). Productivity is enhanced by lowering the transaction costs involved in monitoring, measuring, and managing business activities. IoT sensors with remote monitoring capabilities lower such costs of controlling inputs and outputs.[20]

Of course, IoT and 5G are not just about devices; connected devices and the enhanced communications experience offered by 5G will make possible increased engagement of employees. The superior indoor and outdoor mobile broadband experience will make many workers more productive. 5G will further the move toward virtual and remote teamwork with enterprises by enabling streaming of ultra-high definition video and telepresence, augmented and virtual reality (smart glasses), and tactile internet (IHS, 2017).[21] Smart glasses can improve productivity, for example, by providing remote support from centralized specialists to workers in the field. IoT-based improvement in the management of mobile devices, inventory and assets, safety and security, and workers and their time can boost productivity as well (NET, 2017).

Past experience with previous broadband, communications, and mobile technologies shows that we can expect 5G to usher new improvements in the productivity of labor. Some studies have considered the labor productivity impacts of broadband in general, including wired and wireless, fixed and mobile. Some studies use data from individual firms. For example, Akerman et al. (2015) show that broadband availability and adoption at the firm level increases the productivity of highly skilled labor. Their econometric estimations indicate that increasing broadband availability by 10 percent raises a firm's output by 0.4 percent on average (holding other productive inputs constant). The average effects can mask a large amount of heterogeneity across industries and countries, of course. However, a study of 400,000 observations on firms in European countries showed that in a majority of those nations there is a significant positive relationship between employees' access to broadband and the firms' labor productivity in both manufacturing and service industries (Hagsten, 2016).[22]

Other studies on labor productivity look specifically at mobile broadband. In a cross-country econometric study, Gruber and Koutroumpis (2011) find that mobile telephony and broadband usage increases output per worker-hour, contributing 0.19 percentage points to annual productivity growth in the United States.[23] Bertschek and Niebel (2016) examine how 3G and 4G mobile internet access affected the labor productivity of workers in Germany. Their results suggest that the former is causally and positively linked to the latter. A ten point increase in the percentage of employees using the mobile internet is associated with increased labor productivity (sales per employee) in the range of 1.7% to 9.3%, depending on the regression method and control variables employed. Improved labor productivity also results in increased economic productivity overall and faster GDP growth, as will be discussed in section IV below.

C. Creating new value for consumers

Economists typically measure net benefits to consumers with consumer surplus, a quantity reflecting that most people would be willing to pay more for a good or service than the price actually paid in the market. As early as 2005, the annual consumer surplus created by the internet was estimated to be about $3,000 per person (Goolsbee and Klenow, 2006). Greenstein and McDevitt (2011) measure total consumer surplus associated with diffusion of broadband service to be between $4.8 and $6.7 billion in the U.S. between 1999 and 2006. Specific uses of internet access also can create large amounts of value. Brynjolfsson and Oh (2012) estimate the consumer surplus from free online services such as Facebook, Google, Wikipedia and YouTube to be almost $100 billion for users in the U.S. Cohen et al. (2016) estimate $6.8 billion in consumer surplus from the UberX car service in the U.S. in 2015 alone. It is important to note that these welfare gains are completely overlooked by statistics on GDP or anything else in the official national economic accounts, including the economic impacts calculated in the present report.

Much of the value of 5G and IoT will be largely hidden from consumers, as Smart Grids, machine-to-machine wireless communication, and Smart Supply Chains work out of view. Nevertheless, the 5G ecosystem will also create much value for consumers. Many consumers look forward to 5G mobile broadband to get and do more of what they are used to on their devices, but faster. Video will take less time to load, and higher quality video becomes feasible to consume on mobile devices. With peak transmission speeds of about 10 to 20 times faster than 4G LTE, 5G will be fast enough to replace wired broadband networks to access the internet in many homes. In some areas of the country, 5G wireless will extend high-speed internet to place where the wired broadband network is lacking, as previous generations of mobile broadband have done.[24] But in addition to doing the same things faster, the true promise of 5G and IoT for consumers lies in doing completely new things.

Healthcare

Wearable and home medical monitoring devices connected to IoT can link patients directly to healthcare providers. Examples of such devices include heart rate monitors, fall detection equipment for the elderly, microphones to measure air flow in the breathing of patients with lung disease, and ingestible sensors to detect internal bleeding or monitor adherence to medication plans (Pradhan, 2019; Turner Lee, 2019). If 5G is deployed in a timely fashion, the healthcare segment of IoT is forecast to grow to be a $180 billion market in 2022.[25]

Transportation

Autonomous vehicles of the future – 21 million of them in the U.S. by 2030[26] – will rely on 5G networks to make driving smarter and safer. The data generated from the dozens or hundreds of sensors in each vehicle must be transmitted and analyzed nearly instantaneously to allow the vehicle to make complex driving decisions in real time. Such volumes of vehicular data – forecasted to be up to 2 petabits a week per car in the future – require 5G's large bandwidth to turn autonomous vehicles into mobile data centers (Llanasas, 2019). 5G will thus be a key enabler in the creation of a market for self-driving vehicles forecasted to be worth $2.8 trillion by 2030.[27]

Autonomous vehicles can also be convoyed into groups by traffic management systems, whether such platooning is centralized (i.e., coordinated by an authority) or decentralized (coordinated spontaneously by independent vehicle-agents) (Halle et al., 2004). Platooning reduces traffic congestion, thus saving time and money for commuters. Closely spaced vehicles in platoons also save fuel and energy, much like race car drivers or peloton cyclists do when drafting on leaders.

All told, autonomous vehicles are estimated to provide benefits to consumers and society of $2,000 to $4,000 per vehicle, with the higher figure applying after accounting for the comprehensive benefits of crashes avoided (Fagnant and Kockelman, 2015). But the benefits are not limited to those owning self-driving cars. Even for those people without autonomous vehicles, platooning of the trucking industry will lower transportation costs, and this reduces prices of delivered intermediate and final goods (Adler, et al., 2016). Also for people without vehicles, 5G will increase the quality of public transportation and potentially lower its cost. With increased wireless information about where riders are waiting or currently using the system, 5G enables Smart Transportation such as dynamic routing of buses and light rail (Al Amine et al., 2017).

Energy

The addition of currently unconnected, energy-hungry appliances and devices to IoT will allow better management of the electricity energy network. The resulting Smart Grid enabled by 5G connections will better manage electricity demand and balance loads away from peak periods, thereby reducing electricity costs and ultimately prices (Al Amine et al., 2017). 5G can reduce municipal energy costs through smart public lighting, as already deployed in cities such as Sacramento. The millions of dollars saved in municipal electricity costs can result in lower taxes (or at least lower growth in taxes), leading to more disposable income for residents. Annual investment on smart grids in the U.S. is projected to be $13.7 billion 2024,[28] but only if 5G infrastructure has been adequately deployed in a timely fashion.

Other aspects of IoT for consumers

Other aspects of IoT for consumers include the following:

- Smart Homes. From home security to energy usage to control of rooms and entertainment systems, Smart Home applications can make households safer, more comfortable, more enjoyable, and cheaper to maintain. At the same time, energy bills and the carbon footprint of the household can be reduced through increased efficiency in energy usage. The Smart Home sector is forecast to be a $43.7 billion market by 2023.[29]

- Personal asset tracking. From smart phones to pets to any asset fitted with a tracker tag, 5G IoT networks enable tracking of valuable assets.
- Wearable personal technology. From fitness devices to smart glasses, consumer wearables will change how we live and interact with other people, the internet, and our smart homes. Fitness wearables alone will generate an estimated $14.5 billion in revenue in 2019.[30]

Measuring the economic benefits to consumers created by the 5G revolution will be possible only after there is widespread experience with the technology and data becomes available on how much people value the activities that 5G enables. However, studies of existing forms of broadband and internet access have already shown the huge value they created for consumers, and 5G will almost certainly do the same.

D. Special impacts on rural and economically disadvantaged areas

Next-generation wireless networks hold special promise for economic development in rural and economically lagging areas by expanding labor and output markets beyond isolated geographical areas, filling gaps in existing wired and wireless broadband coverage, and granting access to healthcare, educational, and other expertise in urban or more advantaged areas.

The IoT-related benefits of 5G are not limited to urban areas. Smart watering systems, light sensors, soil sensors, livestock sensors, self-driving tractors, and other devices – Smart Farming – will enable precision farming to improve agricultural productivity. For animal husbandry, IoT and 5G-enabled livestock monitoring can help ranchers gather information on the health and location of their animals.[31] Precision farming for crops increases agricultural yields and sustainability through close monitoring of moisture, nutrients, and weather for optimal planting and harvesting with fewer chemical inputs (Liaghat and Balasundram, 2010). While precision farming methods predate IoT, the evolution to Smart Farming allows farm management tasks to be enhanced by context and situational awareness created by data on real-time events (Sundmaeker et al., 2016). Furthermore, cloud-based agriculture for unified data, farm, and decision management requires integrated IoT and fast mobile internet (Xin & Zazueta, 2016). By 2024, the market value of precision farming in the U.S. is forecast to be $2.5 billion.[32]

Mobile broadband helps to fill gaps in fixed broadband coverage in rural areas and can create economic benefits there (Prieger, 2013, 2017). By providing expanded access to very high-speed broadband, 5G deployment in rural areas can ensure that the many consumer benefits discussed in section B above accrue to rural residents as well. For example, lack of adequate bandwidth is holding back telemedicine and remote healthcare monitoring in rural areas, as came up in a recent Congressional hearing (Arndt, 2017). Without high-quality access to the internet, rural students can fail to gain technical competencies and social development in the online context, falling behind their urban peers (Freeman et al., 2016).

An econometric study by Whitacre et al. (2014a) examined the impacts of broadband on rural areas over the period 2001 to 2010. This study is notable for its credible econometric approach to identify the causal effect of broadband on employment.[33] They find that non-metropolitan counties with high levels of broadband adoption had significantly greater reductions in the unemployment rate than otherwise similar counties with lower adoption rates. This finding is in accord with other research concluding that broadband's positive impact on the labor market is higher in rural areas (Atasoy, 2013). Whitacre et al. (2014a) also find that broadband adoption in rural areas leads to greater increases in household income and greater growth in the number of businesses. Furthermore, the availability of higher broadband speeds in non-metropolitan counties is associated with reductions in the poverty level, "suggesting that broadband speed can potentially contribute to general community well-being" (p.1020). In another study, the same authors also found that broadband adoption contributed to household income in rural areas (Whitacre et al., 2014b).

Studies from elsewhere in the developed world confirm that broadband can play an important role in the development of rural economies. In research on broadband expansion in Germany between 2005 and 2009, Fabritz (2013) found that the positive effects on employment seem to be larger in rural municipalities, perhaps because the internet enlarges the market for service firms in rural areas by granting access to customers elsewhere. Ivus and Boland (2015) find that the deployment of broadband in 1997–2011 promoted aggregate employment and average wages in service industries in rural regions of Canada, with overall employment effects 1.2 percentage points per year of employment growth in service industries in rural regions.

Next-generation wireless networks can also play an important role for residents in disadvantaged urban areas. Some research suggests that minority users in general and African-Americans in particular rely more heavily than others do on mobile devices for their broadband internet access.[34] Mobile phone ownership is much more common among minorities than computer ownership, which helps overcome the hardware barrier to broadband usage. Thus improving the quality of mobile access to the internet is particularly important to these communities. Broadband can help minorities to improve their personal lives. For example, many disadvantaged urban communities face issues similar to rural areas lacking access to high-quality healthcare. Thus, whether through enhancing prospects for participation in online health communities or through providing the necessary bandwidth to enable mobile health applications and devices, as well as the more advanced forms of telemedicine allowed by 5G discussed above, mobile broadband can facilitate access to better health information and care (Prieger, 2015).

IV. Quantifying the economic impacts of 5G

Putting together all the ways 5G wireless can improve economic performance discussed above, this section discusses evidence on how mobile broadband has affected GDP growth in the past and presents projections of how 5G may be expected to boost the economy going forward.

A. Overall economic impacts of mobile broadband

Several econometric studies have investigated how past generations of mobile broadband have increased national economic growth. Such studies can account for the many ways broadband affects the economy without the necessity of assuming exactly which paths lead from investment to ultimate economic outcomes. In one of the first studies looking at the economic impact of mobility, Gruber and Koutroumpis (2011) find a sizable positive impact of mobile infrastructure on GDP across many years and countries. The authors calculate that mobile telecommunications contributed 0.4 percentage points to GDP growth in high-income countries like the United States.[35] Thompson and Garbacz (2011) also found econometric evidence that mobile broadband has an important effect on GDP, and that it is even more important than the effect from fixed broadband. Their estimates imply that in high income countries like the U.S., an additional mobile broadband line per household increases GDP per household directly by relatively large 4.7%. Furthermore (when indirect impacts are accounted for) mobile broadband decreases the distance between the country's actual and potential GDP.[36] Similarly, Forero (2013) also found that mobile services are significantly and positively associated to decreases in such inefficiency in a country's production.

Other research has examined broadband penetration more broadly to verify that it stimulates economic growth. Czernich, Falck, Kretschmer, and Woessmann (2011) estimate a sophisticated econometric model using data for 25 developed countries during 1996–2007. The authors find that a 10 percentage point increase in broadband penetration raised annual per capita growth by 0.9–1.5 percentage points. These results are in accord with earlier results from Qiang and Rossotto (2009), who addressed the same question, although the methodology was quite different. Gruber et al. (2014) use data from European Union countries from 2005 to 2011 to evaluate the benefits of broadband deployment and usage. The estimates suggest that broadband adoption rates, as measured by broadband lines (including wireless) had a significant positive effect on GDP in the observed period, with an estimated average annual contribution to GDP of 1.36% for the countries in the sample.

With all such country-level econometric studies associating broadband with increased GDP growth, one must worry about reverse or simultaneous causality. For example, a simple correlation between broadband and GDP growth might reveal only that faster growing economies demand more and better broadband. Nearly all of the studies cited herein address this potential problem with econometric methodology of various types. In a study that specifically address simultaneous causality, Arvin and Pradhan (2014) show that for developed countries such as the U.S., broadband penetration indeed has a causal link to growth in real per capita GDP.[37] And in later work for European countries, Pradhan et al. (2019) confirm that causality runs from ICT (including various mobile, internet, and broadband measures) to long-run economic growth.

Research shows that when it comes to the impact on GDP growth from broadband, the faster the better. Kongaut and Bohlin (2014) show that a 10% increase in the average download transmission speed of broadband internet in the country has a statistically significant 0.8% impact on GDP in developed (OECD) countries. It is interesting to consider how much 5G could improve average download speeds. In the U.S., combined fixed and mobile download speed was about 69 Mbps on average in 2018.[38] If the proportion of mobile traffic remained the same, then at a conservative estimate of 5G download speed, the overall average broadband download speed would rise to 165 Mbps – a huge increase.[39] Since a 140% increase is average speed like this is far outside the range of the data considered in Kongaut and Bohlin's (2014) study, their results cannot be extrapolated to this scenario. Nevertheless, their results and the large speed increases that 5G will make possible suggest that there will be potentially very large improvements in GDP growth.

B. New estimates of the economic impacts of 5G network deployment

To assess the impact of deploying a national 5G broadband network in the United States, a medium-term analysis covering 2019–2025 was performed.[40] The following four economic activities were considered:

1. Capital expenditure in the mobile broadband provision industry to deploy 5G networks.
2. Additional spending in other industries as firms benefit from the 5G broadband deployment and incorporate it into their businesses.
3. Additional spending by mobile broadband subscribers on 5G service, net of what they would have spent on 4G service. This category includes additional spending by enterprises on 5G IoT connectivity. (Enterprise spending on IoT hardware, software, and professional services such as IoT management consulting services and computer systems design services is included in item number 2 above.)
4. Additional spending by consumers on mobile broadband devices – smartphones, computers, and tablets – net of a "4G only" counterfactual. (Enterprise spending on connected devices is included in item number 2 above.)

For each category of spending, standard methods of determining national or regional economic impacts based on input-output analysis were followed. The essential idea is that the total economic effects resulting from investment or other spending in the 5G ecosystem are greater than the direct expenditure because any dollar injected into an economy is partially spent again, creating additional economic activity. This additional economic activity is quantified with multipliers showing the relationship between initial spending and final total activity. Impacts are of three types: direct, indirect, and induced. Direct impacts are straightforward: if an extra dollar of output is required from the wireless communications service industry, for example, then a dollar of extra output is created. The direct impact includes all the inputs purchased by the wireless service industry to deploy 5G: communications equipment, construction, network design services, etc. The indirect effects, on the other hand, reflect that the direct inputs themselves came from supporting upstream industries, and creating the inputs required additional purchases by those industries. Thus the expenditure on capital, connectivity, or services in the ultimate industry results in further rounds of new spending[41] as the inputs used by the industries are linked to the outputs of the supplying industries. The final type of economic effect, the induced impact, arises from the additional household spending of workers whose earnings are affected by the investment and who spend that additional income in turn. The modeling software used, IMPLAN, relies mainly on data from the U.S. Bureau of Economic Analysis (BEA) to calculate economic activity multipliers for regions, industries, and commodities based on regional input-output tables of the flow of goods and services in the economy. The figures presented here are the sum of direct, indirect, and induced effects (which are known as impacts based on Type II multipliers).

The multipliers available to convert expenditure in the 5G ecosystem to total economic outcomes include those for employment, output (sales), value added (GDP), and labor earnings. The total employment change throughout the economy resulting from deployment of wireless broadband is greater than the labor directly employed to design, construct, and operate the network and to create and sell the devices. The employment multiplier estimates how investment spending translates into additional employment.[42] In keeping with BEA convention, created jobs are counted as job-years, so that one job for two years or two jobs in the same year are equivalent. The output multiplier is the ratio of the total change in sales to the change in local output purchased by final users. Whereas the output multiplier is for gross sales, the value-added multiplier measures the total change in value added per dollar of investment.[43] Hence, the value-added multiplier is comparable to increases in GDP. Since sales inevitably involve double-counting as commodities are passed up and down the supply chain, the GDP multiplier is smaller than the output multiplier. The earnings multiplier measures the increase in labor earnings per dollar of local output purchased through investment.[44]

Similar analyses using multipliers from input-output analysis to estimate the economic impacts of current and past broadband investment in the United States have been conducted by many researchers.[45] Analyses specific to 5G deployment include those of Singer et al. (2017) and Sosa and Rafert (2019). While the methods employed here are standard to input-output analysis, it is important to note potential limitations in the results. The calculations assume there are no changes in commodity or labor prices resulting from the increase in investment. When the economy is at or close to full employment, some of the demand for additional labor may come from reskilling previously employed workers or result in higher wages instead of the full number of jobs predicted here (as businesses seek to attract needed workers). Of course, higher wages benefits workers as well as new job opportunities.

The analysis here also does not include jobs created by the innovation resulting from the investment across private industry as businesses incorporate 5G technology and services into their products, services, and business methods. That is, the economic impacts from spending in categories 1 and 2 are from the capital expenditure, not the innovation following from it. While a few researchers have attempted to estimate such additional economic impacts from broadband technology (e.g., Katz and Suter, 2009), such results are highly speculative. The uncertainty in the estimates results in part because the dynamic links between a new generation of broadband technology and innovation in the wider economy, and between innovation and new jobs, cannot be estimated precisely. Also contributing to the difficulty of such estimation are the potentially competing effects. While innovation that creates new products and sales supports jobs, the relationship between productivity enhancements and employment is unsettled in the literature (Vivarelli, 2014). For the latter, however, note that productivity enhancements raise wages even if the amount of employment is unchanged.

Detailed assumptions for the analysis are in the appendix, but the broad outlines of the methodology and assumptions are presented here. For capital expenditure by wireless network service providers, investment is required into communications equipment, network design services, and construction. Relying both on extant top-down and bottom-up estimates of the cost of deploying 5G in the U.S., it was estimated that $225B of capital expenditure would be required over the study period (2019–2025). The CAPEX is assumed to be spent on wired and wireless network equipment, fiber optic cable, engineering, programming, and systems design services, and construction.

Investment in other industries reflects that 5G is a GPT that creates spillover effects throughout the economy. The importance of broadband and wireless technology for businesses and consumers across the economy has been discussed above. To gain value from 5G and increase productivity, businesses across all private industry will need to invest in 5G-related equipment and services, such as those related to IoT. However, 5G will also create additional investment as firms develop new products, services, and ways of doing business enabled by 5G. For purposes of the calculations, in part due to data limitations, it is assumed that only private industry so benefits from 5G as a GPT.[46] The analysis assumes that the past linkages between CAPEX in the broadband industry and CAPEX in other industries, formed in the context of previous generations of broadband services, will continue to hold in the 5G era. A statistical analysis finds that for every 1% additional investment in the Broadcast and Telecommunications industry (the most specific industry group that contains the broadband service provision industry for which investment data are available), the following year there is an additional 0.18% investment in other private industries, followed by a 0.12% reduction the year after that (perhaps due to fixed or constrained CAPEX budgets being shifted earlier in time to take advantage of new opportunities created by new broadband capabilities).[47] Thus, over the succeeding two years, a 1% additional investment in telecom leads to a net 0.06% increase in investment in another industry. While this percentage looks small, the rest of the private economy is so large that for every job created directly from investment by the wireless industry about 1.9 jobs are created elsewhere from these spillover effects. This result is in accord with previous studies of broadband and employment.[48]

To estimate additional expenditure on the provision of 5G mobile wireless service, forecasts of the number of 5G subscribers and the premium paid over 4G were made. While 5G is not expected to result in large price increases, the new service offerings will help preserve the revenue of wireless providers that otherwise is eroding in the late-stage era of 4G LTE. This category of expenditure includes IoT connectivity. However, while growing rapidly during the study period, most IoT expenditure during the limited forecast period analyzed here will be on 3G, 4G, wifi, and other IoT technology apart from 5G. (Analysts expect 5G IoT to take off in a large way during the second half of the next decade.) Thus, the contribution of 5G IoT spending on connectivity to the economic impacts is relatively small through 2025. Any economic impacts due to spending on devices, software, or consulting services for 5G IoT are subsumed into category 2 expenditure.

The forecasted additional expenditure on 5G smartphones, computer, and tablets assumes that if 5G were not available, an otherwise equivalent 4G device would have been purchased. Thus only the difference in expenditure between the two types of devices is counted. Economic activity in this area is apportioned to device manufacturers (much of which leaks to foreign makers) as well as to other participants in the supply chain: retailers, wholesalers, and transportation providers.

In the following sections, the economic impacts of 5G deployment are estimated for the entire nation first and then for selected specific localities.

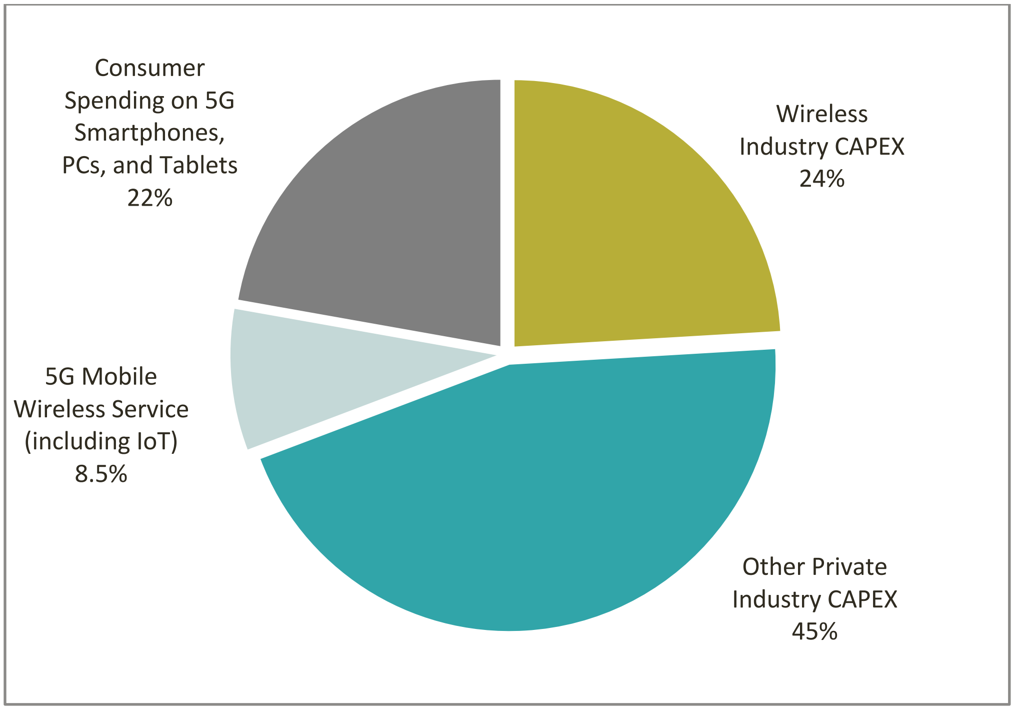
1. The national economic impact of 5G deployment

Deployment of the nationwide 5G network will have large impacts on employment, output, sales, and labor earnings (Table 1). About 8.5 million jobs are created over the study period compared to the 4G-only world, with an average of 1.2 million jobs each year. Workers in those jobs will earn $564 billion total. As shown in the figure, the largest source of jobs is investment throughout the wireless industry (24% of all jobs created) and other private industry (45%). Incremental spending on 5G consumer devices is the next largest category, creating 22% of all jobs. Provision of 5G wireless service (incremental beyond 4G) is the smallest job creator. The 5G-related investment and spending will also create a yearly average of $237 billion in additional sales of output, adding an average of $130 billion each year to GDP in the U.S. economy during 2019–2025. Overall, 5G will add over $900 billion to GDP during the forecast period. This amount is expected to be about 0.6% of total GDP during that time.[49]

Table 1: Economic Impacts of National 5G Network Deployment

	Jobs	Labor Earnings	Output	Value Added (GDP)
	000s	$B	$B	$B
Total (2019-2025)	8,452.30	563.95	1,660.72	907.29
Average per year	1,207.47	80.56	237.25	129.61

Figure 1: Composition of Jobs Created



It is important to note that these estimates are above and beyond a counterfactual scenario in which only current 4G technology continues to exist. As such, these figures are best understood as the gains from 5G deployment and adoption (or, alternatively, an indication of the costs to the U.S. economy if 5G does not fully develop due to regulatory barriers).

However, 5G will help support many more jobs than just these new ones, since wireless broadband affects so much economic activity. For example, the wireless ecosystem (including infrastructure and service providers, device makers, retailers and wholesalers, and content, app, and service creators) directly or indirectly supports between 2.4 to 4.7 million jobs in the U.S., depending on which economic activity is included in the calculations.[50] These figures include jobs directly within the wireless industry, as well as indirect jobs in adjacent and supporting industries and induced effects from the household spending based on income received from the jobs.

2. Regional economic analyses

For the regional economic analyses, three types of economic impacts from 5G deployment are estimated.[51] The first is the economic impact from network construction and deployment in the local area. The direct impact is closest to the analysis conducted for the nation; the chief differences are that spending is smaller at the local level and that the leakages outside the local economy are larger. The fraction of national spending on wireless CAPEX apportioned to the local area was computed using estimates of how 5G deployment cost varies with population density.[52] Leakage of economic activity occurs not only because some manufactured goods are imported, but because much of the total economic impact created by local spending accrues to businesses and workers outside the area. For example, spending on fiber optic cable in New York City benefits no local manufacturers, since there are none in the five boroughs.[53] This portion of the direct economic impact benefits others in the nation but is an externality from the region's point of view.

The second type of local economic impact is the positive spillover from economic activity elsewhere in the nation as 5G networks are deployed. For example, when a network is deployed outside the local area, local suppliers may make sales or receive contracts for consulting services. These positive externalities generated by outside network deployment are estimated using the local market fractions of the national market for the individual relevant manufactured goods and services. For example, about 2.6% of spending on telephone apparatus (such as network switchgear) in the U.S. benefits manufacturers in the Los Angeles area. Such economic activity flowing into the area from investment outside the area is much smaller than the direct impact.

As a third way to estimate the importance of 5G for local areas, employment in the national wireless telecommunications ecosystem can be apportioned to the regions. Beginning with the estimates cited above of jobs supported directly and indirectly by the various parts of the wireless industry, a fraction of the whole is computed for each region based on the local fraction of national employment and economic activity in the telecommunications industry, mobile device manufacturing, distribution and retail, and industries and occupations related to content, applications, and services for online devices. Depending on the local importance of such economic activity, the fraction of total wireless industry-related jobs estimated to be in the local area may be greater or less than the population share of the region. In contrast to the first two types of economic impacts, this estimate of jobs supported is meant to encompass the whole wireless industry ecosystem, not just the incremental impact of 5G.

Los Angeles, California

The impacts of the 5G network on the economy in Los Angeles are shown in Table 2. The area of economic activity is the Los Angeles metropolitan area.[54] Investment of $8.4 billion by the wireless broadband industry will be required to deploy 5G services, which will spur other local industries to invest another $17.8 billion during 2019–2025. Subscribers in Los Angeles will spend about $3.6 billion more on 5G mobile services than they would have on 4G service, given the higher value they will place on the service.[55] Consumer spending on 5G devices will total $4.9 billion.

While not all of that spending stays in the local economy, about a quarter of a million jobs are created over the study period compared to the 4G-only world, with an average of 35,500 jobs each year. About 95% of the jobs are created by local network investment, investment by other local industries, and local spending on 5G devices and wireless service. The remaining 5% of jobs are created by 5G-related demand for local goods and services coming from outside the region. Workers in these jobs will earn $17 billion total. The 5G-related investment and spending will also create $47 billion in additional sales of output over seven years, adding an average of $4.0 billion of value[56] each year to the Los Angeles economy during 2019–2025. Overall, 5G will add $28 billion of value during the forecast period.

Table 2: Economic Impacts of 5G Network Deployment in Los Angeles

	Jobs	Jobs from Local 5G Deployment	Labor Earnings	Output	Value Added
	000s		$B	$B	$B
Total (2019–2025)	248.3	94.8%	17.4	47.2	27.9
Average per year	35.5		2.5	6.7	4.0

Results are for the Los Angeles metropolitan statistical area. Jobs from Local 5G Deployment are those that would be lost if the local area did not deploy 5G; the rest of the jobs come from 5G deployment elsewhere in the nation.

The estimates in Table 2 are above and beyond a counterfactual scenario in which 5G is not deployed in the nation, and 19 in 20 jobs specifically depend on deployment in the Los Angeles area. If regulatory barriers delay local implementation, these potential benefits will be pushed further into the future or lost.

In additional to the new jobs created, 5G services will help sustain existing local jobs related to wireless service in the area. The local wireless ecosystem, including service and infrastructure providers, device manufacturers and sellers, and creators of content, apps, and services for wireless devices, is estimated to directly or indirectly support 95,600 to 200,700 jobs in Los Angeles.[57]

New York City

The impacts of the 5G network on the economy in New York City are shown in Table 3. The area of economic activity is the five boroughs. Investment of $2.4-5.1 billion by the wireless broadband industry will be required to deploy 5G services, which will spur other local industries to invest another $15.5 billion during 2019–2025. Subscribers in New York will spend about $2.2 billion more on 5G mobile services than they would have on 4G service, given the higher value they will place on the service.[58] Consumer spending on 5G devices will total $3.0 billion.

While not all of that spending stays in the local economy, between 109,700 and 119,500 jobs are created over the study period compared to the 4G-only counterfactual case, with an average of 15,700 to 17,100 jobs per year. Most of the jobs are created by local network investment, investment by other local industries, and local spending on 5G devices and wireless service. However, given the size of New York's economy, about 4% of the jobs are created by 5G-related demand for local goods and services coming from outside the region. Workers in these jobs will earn $9-10 billion total. The 5G-related investment and spending will also create $23-24 billion in additional sales of output over seven years, adding an average of $2.0 billion of value[59] each year to the economy in New York City during 2019–2025. Overall, 5G will add $14-16 billion of value during the forecast period.

Table 3: Economic Impacts of 5G Network Deployment in New York City

	Jobs	Jobs from Local 5G Deployment	Labor Earnings	Output	Value Added
	000s		$B	$B	$B
Total (2019–2025)	109.7–119.5	96.0%–96.2%	9.4–10.2	22.6–24.4	14.3–15.5
Average per year	15.7–17.1		1.3–1.5	3.2–3.5	2.0–2.2

Results are for New York City. The range of the estimates reflects uncertainty about the cost of deploying 5G in such a dense urban area. Jobs from Local 5G Deployment are those that would be lost if the local area did not deploy 5G; the rest of the jobs come from 5G deployment elsewhere in the nation.

The estimates in Table 3 are above and beyond a counterfactual scenario in which 5G is not deployed in the nation, and 24 out of every 25 jobs depend on deployment in New York City. If regulatory barriers delay local implementation, these potential benefits will be pushed further into the future or lost.

In additional to the new jobs created, 5G services will help sustain existing local jobs related to wireless service in the area. The local wireless ecosystem, including service and infrastructure providers, device manufacturers and sellers, and creators of content, apps, and services for wireless devices, is estimated to directly or indirectly support 69,000 to 144,900 jobs in New York City.[60]

Pittsburgh, Pennsylvania

The impacts of the 5G network on the economy in Pittsburgh are shown in Table 4. The area of economic activity is Allegheny County, which contains the city and its immediate suburbs.[61] Investment of $1.2 billion by the wireless broadband industry will be required to deploy 5G services, which will spur other local industries to invest another $1.8 billion during 2019–2025. Subscribers in Pittsburgh will spend about $330 million more on 5G mobile services than they would have on 4G service, given the higher value they will place on the service.[62] Consumer spending on 5G devices will total $453 million.

While not all of that spending stays in the local economy, about 21,600 local jobs are created over the study period compared to the 4G-only counterfactual case, with an average of 3,100 jobs each year. Nearly all of the jobs are created by local network investment, investment by other local industries, and local spending on 5G devices and wireless service; only 0.4% of the jobs are created by 5G-related demand for local goods and services coming from outside the region. Workers in these jobs will earn $1.4 billion total. The 5G-related investment and spending will also create about $4 billion in additional sales of output over seven years, adding an average of $333 million of value[63] each year to the Pittsburgh economy during 2019–2025. Overall, 5G will add $2.3 billion of value during the forecast period.

Table 4: Economic Impacts of 5G Network Deployment in Pittsburgh

	Jobs	Jobs from Local 5G Deployment	Labor Earnings	Output	Value Added
	000s		$B	$B	$B
Total (2019–2025)	21.64	99.6%	1.44	3.80	2.33
Average per year	3.09		0.21	0.54	0.333

Results are for Allegheny. Jobs from Local 5G Deployment are those that would be lost if the local area did not deploy 5G; the rest of the jobs come from 5G deployment elsewhere in the nation.

The estimates in Table 4 are above and beyond a counterfactual scenario in which 5G is not deployed in the nation, and all but 1 out of every 250 jobs created specifically depend on deployment in the Pittsburgh area. If regulatory barriers delay local implementation, these potential benefits will be pushed further into the future or lost.

In additional to the new jobs created, 5G services will help sustain existing local jobs related to wireless service in the area. The local wireless ecosystem, including service and infrastructure providers, device manufacturers and sellers, and creators of content, apps, and services for wireless devices, is estimated to directly or indirectly support 12,200 to 25,700 jobs in the Pittsburgh area.[64]

Roanoke, Virginia

The impacts of the 5G network on the economy in Roanoke are shown in Table 5. The area of economic activity is Roanoke City and County, which contains the city and its immediate suburbs. Investment of $205 million by the wireless broadband industry will be required to deploy 5G services, which will spur other local industries to invest another $184 million during 2019–2025. Subscribers in Roanoke will spend about $55 million more on 5G mobile services than they would have on 4G service, given the higher value they will place on the service.[65] Consumer spending on 5G devices will total $75 million.

While not all of that spending stays in the local economy, an estimated 2,700 local jobs are created over the study period compared to the 4G-only counterfactual case, with an average of 386 jobs each year. Since Roanoke is a small fraction of the national 5G-related economy, virtually all of the jobs are created by local network investment, investment by other local industries, and local spending on 5G devices. Workers in these jobs will earn $136 million total. The 5G-related investment and spending will also create $433 million in additional sales of output over seven years, adding an average of $32 million of value[66] each year to the Roanoke economy during 2019–2025. Overall, 5G will add $223 million of value during the forecast period.

Table 5: Economic Impacts of 5G Network Deployment in Roanoke

	Jobs	Jobs from Local 5G Deployment	Labor Earnings	Output	Value Added
			$M	$M	$M
Total (2019–2025)	2,705	100.0%	0.136	0.440	0.225
Average per year	386		0.019	0.063	0.032

Results are for Roanoke City and County. Jobs from Local 5G Deployment are those that would be lost if the local area did not deploy 5G.

The estimates in Table 5 are above and beyond a counterfactual scenario in which 5G is not deployed in Roanoke. If regulatory barriers delay local implementation, these potential benefits will be pushed further into the future or lost.

In additional to the new jobs created, 5G services will help sustain existing local jobs related to wireless service in the area. The local wireless ecosystem, including service and infrastructure providers, device manufacturers and sellers, and creators of content, apps, and services for wireless devices, is estimated to directly or indirectly support 1,400 to 3,000 jobs in Roanoke.[67]

V. Summary and Conclusions

5G wireless broadband will be an important part of the workplace of the near future and other parts of the economy. The estimates computed here suggest that during the next seven years, an average of about 1.2 million workers will owe their jobs each year to economic activity spurred by the deployment of 5G networks. Many more will benefit from increased flexibility in labor arrangements, better education, improved productivity, and higher wages. As consumers, those same workers will enjoy the improvements in healthcare technology, transportation, energy, and other aspects of IoT that 5G will usher in. Those improvements will be especially welcome in rural and disadvantaged urban areas, where higher speed wireless broadband will contribute to the well-being of communities by extending and improving broadband access, enhancing healthcare through telemedicine and IoT medical technology, and encouraging general economic development.

The most direct impacts on the economy from 5G – the more than $900 billion of GDP expected to be created during the study period – are only the first rising of the 5G wave, not its crest. The figures computed here do not include the broader impacts of how the new technology will create value for local businesses and the nation's economy through improving productivity, allowing the creation of entirely new goods and services, and improving the welfare of consumers. Also missing from the economic impacts are the undoubtedly huge amounts of consumer surplus (i.e., benefits enjoyed by consumers beyond what they pay for 5G-related goods and services) that will be generated. Three decades ago, few people anticipated how the internet would fundamentally transform so many areas of economic and personal life. In the coming decades, 5G and succeeding generations of wireless broadband and the IoT will likely revolutionize the worlds of employment, production, consumption, and quality of life at least as much.

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Note: all internet sources were accessible as of July 20, 2019.

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Notes

[1] The assistance of Michael Shires and Christina Syriani, both of Pepperdine University School of Public Policy, in the preparation of this report is gratefully acknowledged.
[2] Lower frequency and hence larger cell 5G is also possible and may be particularly useful for rural networks, which must cover greater distances (Segan, 2019).
[3] Statista, "Internet of Things (IoT) in the U.S." (Study ID 61733), accessed May 17, 2019.
[4] Investment is one of the main components of GDP. Gross private domestic investment in the national economic accounts includes both investment in new fixed assets as well as investment to replace depreciated assets (BEA, 2015).
[5] The data on total capex are from USTelecom and are current through 2017. Figures for the last ten years are also from USTelecom and include investment from 2009 through 2018, although only the top six providers are included in the preliminary figures for 2018.
[6] The total figure is based on data from USTelecom, which reports figures for the top six providers with a note stating that these companies typically account for 80 to 85 percent of annual broadband provider capital spending. The approximate figure in the text marks up the reported totals in line with those percentages.
[7] The estimates are for wireless capex spending by AT&T, Verizon, Sprint, T-Mobile, Dish, Charter, Comcast, and Altice USA; the latter four cable operators invest in wireless because they have launched or are developing mobile services that rely on MVNO (mobile virtual network operator) agreements. The figures are from MoffettNathanson LLC, as cited in Baumgartner (2019).
[8] Datum is from Table 2.5.5. (Personal Consumption Expenditures by Function) of the National Income and Product Accounts from the US Bureau of Economic Analysis and is in current (nominal) dollars.
[9] These are gross job gains. The report states that net job creation would be lower because some jobs will be filled by reskilling existing workers, but that the new economic activity "will nonetheless create thousands of new jobs across the industry" (WEF 2017, p.20)
[10] This estimate comes from applying the results of Shapiro and Hassett (2012), who looked at 2G to 3G mobile transition, to the 4G to 5G transition, and thus perhaps should be seen as suggestive at best.
[11] These figures appear to include all jobs needed to support the new investment effort, not all of which will be newly created positions. The employment figure in IHS Markit (2017) for the US is higher than the estimates computed in this report because of the difference in the years considered and because the former estimate includes certain economic activity (such as additional sales following from capex in industries outside the communications industry) not considered in the present report.
[12] See the summary of early studies in Katz (2012).
[13] Other studies fail to find uniformly positive effects on employment from broadband availability in some settings. For example, Stockinger (2019) studied the German experience with broadband during 2005–2010 and found that robustly positive effect on employment in Eastern Germany and in Western service establishments, but a small negative effect on Western manufacturing establishments. However, the latter result "turns out to be less robust to changes of the estimated specification" and the author concludes that "[o]verall, the findings suggest that broadband expansion has helped create jobs in firms which use broadband intensely."
[14] The presence of fiber broadband decreases unemployment in an employment zone (a French administrative division larger than a municipality) by an average of 7 percentage points.
[15] Mirzamany et al. (2016) point specifically to the potential roles of IoT applications such as virtual and augmented reality and tactile internet (see note 21) to redefine tele-teaching, tele-mentoring, and virtual classrooms and universities.
[16] The authors account for the possibility that the broadband variable is endogenous in the regression equation (for example, due to reverse causality between broadband and where knowledge intensive firms choose to locate, which would destroy the causal interpretation of the results), using econometric methodology designed to address the issue where the data indicate that it arises (Mack and Rey, 2014).
[17] See Sherman (2018) for a simple description of this phenomenon and Krueger (2017) for formal empirical investigation.

[18] The report states that 3 million jobs (a figure which is presumably heavily rounded) will be created over seven years (Al Amine et al., 2017). Assuming that these are job-years as usual in regional economic analysis, the figure implies about 428,600 jobs each year on average.
[19] The estimates computed below imply the creation of 144,059 total direct and indirect jobs each year (on average during the forecast period) from expenditure on construction. However, construction jobs are only 46% of all jobs created from CAPEX spending in the wireless telecommunications industry, and CAPEX spending in that industry accounts for only 25% of all jobs created incrementally by 5G deployment. Thus, the total job figures presented in section IV.B.1 below are many times larger.
[20] See Green Econometrics (2015) for further discussion of this point.
[21] The tactile internet allows users to interact with a remote or virtual environment in real time, even while on the move. It requires an internet network that combines ultra-low latency with extremely high availability, reliability and security. The haptic interaction with visual feedback can be used to interact with others from afar (the next step beyond mere telepresence), control robots, or even make use of robotic exoskeletons for those with disabilities (Kavanagh, 2018).
[22] Given the challenging methodological and data issues involved with measuring productivity at the level of individual firms, it is perhaps unsurprising that some other studies fail to find significant changes in firm performance from broadband. Most such studies focus on areas outside the US, however (e.g., De Stefano et al. (2014), who examined firms in Kingston-upon-Hull, UK in unpublished work, and Haller & Lyons (2015), who investigated the performance of manufacturing firms in Ireland).
[23] Their data are for the penetration rate of mobile telecommunications of any sort, not exclusively mobile broadband. However, by the end of their sample period (2007) this measure includes mobile-broadband enabled devices.
[24] Prieger (2013) shows that mobile broadband partially fills in geographical gaps in fixed-line broadband coverage in the US.
[25] Statista, "Size of the Internet of Things (IoT) market by application in North America from 2012 to 2022 (in billion U.S. dollars)," accessed May 17, 2019.
[26] See PWC (2017), p.9.
[27] The forecast is from a May 2018 UBS Q-Series report, "Who will win the race to autonomous cars?" cited in Shah (2018).
[28] US Department of Energy, "Annual investment on smart grids in the United States from 2014 to 2024, by technology (in billion U.S. dollars)," accessed May 17, 2019.
[29] Statista, "Smart Home revenue forecast for selected countries in the segment Energy Management 2023 (in million U.S. dollars)," accessed May 17, 2019.
[30] Statista, "Wearables", accessed May 17, 2019.
[31] For example, cattle can be fitted with a wireless bolus in the stomach for the life of the animal, which can communicate via Bluetooth to an ear tag. See LinkLabs, "An In-Depth Look At IoT In Agriculture & Smart Farming Solutions," Nov. 30, 2017.
[32] Of this revenue, about 67% is from hardware, 29% is from software, and the small remainder is from precision farming services. Statista, "Estimated market value of the precision farming in the United States in 2016 and 2024, by application)," accessed May 17, 2019.
[33] The study carefully matches counties with a high level of broadband adoption to observably otherwise-similar counties with lower adoption. This allows causal estimation of the effect of broadband adoption on changes in employment between 2001 and 2010.
[34] See Prieger (2015) and the studies cited therein.
[35] In their study of the impact of mobile telephony and broadband usage on labor productivity, Gruber and Koutroumpis (2011) show that there are increasing returns in the impact of mobile infrastructure deployment and usage of mobile broadband. Thus, investment in mobile broadband infrastructure would yield more than proportional increases in income and employment growth, possibly due to the multiplier effects discussed in this section.
[36] The latter results are from a separate model of the stochastic frontier production function, an econometric model for ideal "frontier" GDP and the actual gap from it. The specific finding is that a 10% increase in mobile broadband lines per household results in a decrease in the average productive inefficiency by 0.02 points in

high income countries. This magnitude can be compared to the average total efficiency gap of 0.026 for the US (Thompson and Garbasz, 2011).

[37] The study also found that GDP growth further causes additional broadband penetration, leading to a virtuous cycle of growth.

[38] Per Ookla, in Q2-Q3 the average fixed broadband download speed in the US was 96 Mbps, the same for mobile broadband was 27 Mbps. Mobile traffic accounted for about 40% of the whole, per Statista, "Percentage of mobile device website traffic in the United States from 1st quarter 2015 to 1st quarter 2019," accessed May 20, 2019.

[39] Instead of the current 27 Mbps average download speed for mobile devices, I assume that 5G speed will be ten times as fast (270 Mbps). This appears to be conservative since many sources say that 5G will be "10 to 100 times faster than 4G." Furthermore, this speed is only half of what Qualcomm was able to achieve (442 Mbps) in a real-world 5G simulation in San Francisco in 2018 (Gartenberg, 2018). Finally, this assumption is modest compared to the theoretical maximum in the 5G standards of 20 Gbps.

[40] Michael Shires (Associate Professor of Public Policy, Pepperdine University) assisted with the estimates from IMPLAN.

[41] The spending diminishes as it moves upstream from the originating industry because leakages occur through spending outside the US economy.

[42] The resulting number of jobs created may not all be full-time positions, since the employment data that IMPLAN and BEA uses to analyze the employment requirements of the affected industries rely on full-time/part-time annual averages.

[43] In the income approach to measuring GDP, value added is the value of income generated from production. This income consists of compensation of employees, taxes on production and imports, and returns on investment (gross operating surplus). In the production approach to measuring GDP, value added is (equivalently) total output less intermediate inputs. National GDP can be calculated as the sum of value added across all industries in the country (BEA, 2013).

[44] Earnings include all additional wages, salaries, proprietors' income, and employer contributions for health insurance. Proprietors' income includes the net earnings of sole-proprietors and partnerships.

[45] Similar studies performed for investment in wired broadband networks and previous generations of wireless networks include Katz and Suter (2009), Atkinson et al. (2009), Eisenach, Singer, and West (2009), Crandall and Singer (2010), Sosa and Van Audenrode (2011), and Prieger (2017).

[46] While the public sector will no doubt also benefit from 5G, detailed data on investment outside the private sector is lacking in the national accounts.

[47] Details of the regression are in section B of the appendix.

[48] Singer et al. (2017) discuss three studies (Atkinson et al., 2009; Katz and Suter, 2009; Pearce et al., 2013) that also find the "spillover jobs multiplier" to be greater than one.

[49] This calculation assumes that real GDP will grow 3.2% in 2019 and a conservative 2% per year thereafter.

[50] The low figure is from GSMA (2019), after adjusting their North American figures to reflect the U.S. only. The high figure is from Safer et al. (2018b).

[51] As with the national estimates, the details of the calculations are in the appendix.

[52] The estimates are from ITU (2018); see the appendix for details.

[53] Leakages are estimated using data on input-output activity in the regional economies; see the technical appendix for details.

[54] As defined by the U.S. Census Bureau, the Los Angeles Metropolitan Statistical Area (MSA) includes the counties of Los Angeles and Orange.

[55] This figure includes 5G IoT connectivity, which composes only 0.1% of incremental connectivity spending during this period.

[56] Value added in a regional context is analogous to the regional contribution to national GDP.

[57] See note 50.

[58] This figure includes 5G IoT connectivity, which composes only 0.14% of incremental connectivity spending during this period.

[59] See note 56.

[60] See note 50.

[61] Allegheny County is larger than the city limits of Pittsburgh, but smaller than the Pittsburgh metropolitan statistical area, which also includes several other surrounding counties.
[62] This figure includes 5G IoT connectivity, which composes only 0.11% of incremental connectivity spending during this period.
[63] See note 56.
[64] See note 50.
[65] This figure includes 5G IoT connectivity, which composes only 0.07% of incremental connectivity spending during this period.
[66] See note 56.
[67] See note 50.

Appendix

This appendix contains the details of the calculations of the economic impacts discussed in the text. All dollar-denominated quantities are in current dollars.[68]

A. Wireless industry CAPEX

1. Total amount required

It is assumed that a total of $225 billion will be spent by the wireless industry on CAPEX for 5G over the study period (2019–2025). This amount includes the 5G edge network, improvements to other parts of the network to handle the additional traffic, and improvements to the 4G network that will eventually be used for or in conjunction with 5G.[69] The amount is an estimate that is in accord with or at the low end of several other forecasts:

- The Federal Communications Commission (2018, at 2) states that "it is estimated that wireless providers will invest $275 billion over the next decade in next generation wireless infrastructure deployments…." This estimate is based on calculations by Accenture (Safer et al., 2018a).
- A study by Analysis Group (Sosa and Rafert, 2019) assumed that deployment of 5G would require $298B over 7 years. They mention other estimates ranging in the literature from $225 billion to over $400 billion, with many estimates falling between $250 billion and $300 billion.
- Morgan Stanley estimates that CAPEX for 5G deployment will be $265 billion in the U.S. (Morgan Stanley, 2019).
- GSMA Intelligence estimates that U.S. wireless network operators will spend about $100 billion in three years on upgrading their LTE networks and investing in 5G.[70] By extrapolation, this figure is in line with $233 billion in 7 years.
- Finally, the largest wireless network providers (AT&T, Verizon, and an assumed merged T-Mobile/Sprint) in the U.S. have announced approximately $115 billion in anticipated CAPEX for 5G deployment in the next few years.[71] Total spending by these companies is likely to be much larger because some of these figures appear to pertain to a shorter horizon and do not include mobile 5G, likely do not include upgrades to the wired network complementary to 5G deployment, possibly are understated to avoid alarming their investors, and almost certainly do not include any possible future investment that may be subsidized by state or federal agencies to reach high cost areas.

The various sources make differing assumptions about when the CAPEX will be spent. A seven year period was adopted for the analysis here because it is a commonly cited length given for 5G deployment and also because many of the necessary forecasts needed for various parts of the analysis run only through 2025. Some estimates cited above pertain to spending beginning in 2018 while others are later. The present analysis takes 2019 as the first year of the study period; to the extent that some spending occurred earlier, consequent benefits are not reflected in the results presented here. Alternatively, the results can be seen as pertaining approximately to the first seven years of 5G investment, whenever it began.

To allocate the total spending to particular years, a common assumption is to spread it evenly across years (e.g., Singer et al., 2019). However, other analysts forecast spending to fall after peaking between 2022 and 2024 (Grijpink et al., 2018, Exhibit 4). Thus the analysis here assumes that CAPEX is $36.8 billion in each year 2019 to 2023 before beginning to taper, with $24.6 in 2024 and $16.4 in 2025 (for a total of $225 billion).

Finally, note that because of the employment creation from purchases of 5G service and devices, the total economic impacts calculated in the text are not proportional to the wireless industry CAPEX assumed here. For example, if wireless CAPEX were only $115 billion (the extreme lower bound of from the final bullet point above), which is about half of the assumed $225, the estimated jobs created would fall by only 34%.

2. Recipient industries/commodities of wireless CAPEX

The main assumptions necessary to convert spending to economic impacts are as follows:

1. Following Prieger (2017), 53.7% of wireless industry CAPEX is assumed to go toward wireless and wired network equipment and fiber, 15.5% is assumed to be spent on engineering, computer, and programming services, and 30.8% is allocated for construction.[72]

2. Of the amounts allocated to equipment and fiber, the split between the RAN (radio access network) and the core (fiber and wired network equipment) is 66%/34% in 2019 and evolves to 86%/14% in 2025. The movement toward higher spending on RAN reflects the need for increasing densification of the 5G small-cell portion of the network as traffic grows.[73]

    - Spending on RAN is associated with BEA commodity 334220, broadcast and wireless communications equipment.

    - Spending on the core is split 68%/32% between wired network equipment and fiber optic cable for backhaul and upgrading the wired network to handle additional traffic. The former is associated with BEA industry 334210, telephone apparatus manufacturing, which produces equipment such as routers. The latter is associated with BEA industry 335921, fiber optic cable manufacturing.

3. Spending on engineering, computer, and programming services includes network design work and virtualization of the 5G network. The spending is assumed to be split evenly among BEA industries 541300 (architectural, engineering, and related services), 541511 (custom computer programming services), and 541512 (computer systems design services). The multipliers for these three service industries are relatively similar to each other, and so the exact division of this part of CAPEX among these services is relatively unimportant.

4. CAPEX spent on construction is assumed to go toward BEA industry 233240, construction of new power and communication structures.

3. CAPEX multipliers

The next step toward calculating the multipliers is to determine for spending on manufactured goods (telephone apparatus, wireless equipment, and fiber) how much of each dollar goes toward the manufacturer, how much goes to the wholesaler, and how much for transportation of the manufactured goods. The BEA refers to these as distribution costs; in IMPLAN they are the "margins." These margins for broadcast and wireless communications equipment are: 87% of spending goes to the manufacturer, 12% to the wholesale industry, and the remainder goes to transportation. For fiber optic cable, the breakdown is 77% to the manufacturer and 22% to wholesale and for telephone apparatus it is 62% to the manufacturer and 35% to wholesale; in each case the small remainder goes to transportation.[74]

Next, how much of the spending on each item that stays within the domestic economy is determined, versus leaking abroad through the purchase of imported goods. In IMPLAN, these figures are the "local purchasing percentages." The fraction of domestically produced and delivered goods out of all domestic and imported purchases by industry is found from United States Census Bureau's Manufacturing and International Trade Report: 2016 and 2015. Matching industries as closely as possible to the BEA categories, the following figures are used: 73% of commodity 334210, 16% of commodity 334220, and 76% of commodity 335921 is domestically produced. The remainder of the spending (the part going to imported goods) disappears from the rest of the calculations.

The multipliers for each spending item, after accounting for margins and local purchasing percentages, were obtained from IMPLAN, where the region of analysis for the national estimates was the United States. The multipliers for employment are:

Table 6: Jobs Created Per $1M Expenditure on CAPEX Items

IMPLAN Sector	BEA Code	Industry/Commodity	Direct	Indirect	Induced	Total
304	334210	Telephone apparatus manufacturing	2.6	2.2	4.2	9.0
305	334220	Broadcast and wireless communications equipment	0.7	0.6	1.0	2.3
338	335921	Fiber optic cable manufacturing	1.3	2.9	3.2	7.4
449	541300	Architectural, engineering, and related services	5.9	4.4	7.6	17.9
451	541511	Custom computer programming services	4.8	3.5	6.8	15.0
452	541512	Computer systems design services	7.1	2.6	8.9	18.6
54	233240	Construction of new power and communications structures	6.9	2.2	5.4	14.6

The final multipliers for wireless industry CAPEX are weighted sums of the commodity-specific multipliers and the allocations of CAPEX discussed above. The final multipliers (which vary year to year as the split in spending between RAN and the core changes) and the total jobs created from them are:

Table 7: Jobs created per $1M expenditure on wireless industry CAPEX

Year	Additional CAPEX ($ billion)	Jobs Multipliers per $1 million expenditure				Total Jobs Created
		Direct Jobs	Indirect Jobs	Induced Jobs	Total Jobs	
2019	36.8	3.7	1.9	3.9	9.5	349,770
2020	36.8	3.6	1.8	3.7	9.1	333,427
2021	36.8	3.6	1.7	3.7	9.0	330,896
2022	36.8	3.5	1.7	3.7	8.9	329,090
2023	36.8	3.5	1.7	3.6	8.9	327,812
2024	24.6	3.5	1.7	3.6	8.9	218,484
2025	16.4	3.5	1.7	3.6	8.8	144,624
Total						2,034,102
Average						290,586

Direct jobs are those created by the industries receiving directly from wireless industry the spending $1 million of CAPEX. Indirect jobs are those created by the business-to-business purchases and sales in the upstream industries that supply the direct recipients of the CAPEX. The direct and indirect effects are known in input-output analysis as "Type I" effects. Induced jobs are created by household purchases derived from labor income payments throughout all rounds of the impact.[75] Total jobs created, therefore, are the sum of the Type I and induced effects (collectively, the "Type II" effects). For example, in the first year expenditure of $1 million creates 3.7 jobs in the industries supplying the wireless industry with capital goods (including the transportation and wholesale industries). To provide those capital goods and services, the supplying industries create another 1.9 jobs in the upstream industries providing needed inputs. The additional labor earnings garnered by workers in all affected industries, when some of it is spent on household consumption, creates another 3.9 jobs. Altogether, 9.5 jobs are created per $1 million expenditure on capital goods and services in 2019.

A job in IMPLAN is computed with reference to the earnings multiplier. Given a certain amount of labor earnings created by the economic activity under consideration, as calculated with the earnings multiplier, employment created is computed using the state-level employment-to-earnings ratios that correspond to the relevant industries.[76] The industry employment statistics used for the calculations include full- and part-time jobs, and are based on annual averages of monthly job figures, and therefore the final estimate of jobs created have the same average hours of work attached to them as the industries in which they are created. This also implies that one job created refers to one worker for 12 months, 12 workers for one month, or any other combination adding up to one job-year. For this reason, along with the fact that individuals can hold more than one job, the number of jobs is not the same as the number of workers benefiting from by the economic activity. From the final column of Table 7, the wireless industry CAPEX creates about 290,600 jobs in the average year.

The final multipliers for CAPEX spending for labor earnings, value added, and output are:

Table 8: Multipliers from $1 expenditure on wireless industry CAPEX for labor income, value added, and output

		2019	2020	2021	2022	2023	2024	2025
Labor Income Multipliers	Direct	0.31	0.30	0.30	0.30	0.29	0.29	0.29
	Indirect	0.13	0.12	0.12	0.12	0.12	0.12	0.12
	Induced	0.21	0.20	0.20	0.20	0.20	0.20	0.19
	Total	0.66	0.62	0.62	0.61	0.61	0.61	0.60
Value Added Multipliers	Direct	0.43	0.40	0.40	0.40	0.39	0.39	0.39
	Indirect	0.21	0.19	0.19	0.19	0.19	0.19	0.19
	Induced	0.37	0.35	0.35	0.35	0.35	0.35	0.34
	Total	1.01	0.95	0.94	0.93	0.93	0.93	0.92
Output Effects Multipliers	Direct	0.70	0.67	0.66	0.66	0.65	0.65	0.65
	Indirect	0.39	0.36	0.35	0.35	0.35	0.35	0.34
	Induced	0.66	0.62	0.62	0.61	0.61	0.61	0.61
	Total	1.76	1.65	1.63	1.62	1.61	1.61	1.60

Note that unlike simple input-output analysis, in which the direct output multiplier is always 1.0 (a dollar spent implies that a dollar's worth of output is purchased), the direct output multipliers here are less than one due to leakage from imported goods. Nevertheless, due to the other domestic economic activity spurred by the CAPEX, the total output multipliers are all greater than one.

B. CAPEX in other industries

Many of the jobs created come from CAPEX in private industry outside the wireless broadband industry. Several other studies, recognizing the nature of broadband and wireless technology as general-purpose technologies, include such economic impacts (e.g., Atkinson et al., 2009; Crandall and Singer, 2010; Katz and Suter, 2009; Singer et al., 2017). Instead of ad hoc assumptions about which industries are affected by 5G, the present study measures how investment in all private industry changes in response to investment by the communications industry.

1. The econometric relationship between wireless CAPEX and investment in other industries

The estimated relationship rests on econometric modeling of how private investment in fixed assets in the broadcast and telecommunications industry (the most specific industry group of which the wireless communications industry is a part,[77] denoted y_{COMM} in the equation below) affects investment in other private industries (denoted y_{it} for industry i [other than COMM] in year t) the next two years. The regression equation is:

$$y_{it} = \alpha_i + \beta_1 y_{COMM,t-1} + \beta_2 y_{COMM,t-2} + \gamma_1 y_{OTHER,t-1} + \gamma_2 y_{OTHER,t-2} + \varepsilon_{it}$$

where investment is measured in logarithms,[78] α_i is an industry specific fixed effect to allow the scale of the relationship between the different types of investment to vary across industries (and to account for other industry-specific factors affecting investment otherwise left out of the equation), and ε_{it} is the econometric error term. To control for general trends in investment and the economy, total investment in industries other than industry i and the broadcast and telecommunications industry is also controlled for (y_{OTHER}). The latter variable is included with the same two lags as broadcast and telecommunications investment to ensure that the relationship of interest between one year's investment in wireless CAPEX and the subsequent two years of investment in other private industry, as measured by coefficients β_1 and β_2, is not merely reflecting patterns in investment across all industry driven by (for example) the business cycle.

Data on investment in fixed assets by the broadcast and telecommunications industry and 63 other private industries were collected from the BEA for years 1999 to 2017,[79] yielding 1,197 observations for use in the regression after accounting for the lags in the specification. The estimated regression equation is:[80]

$$E(y_{it}) = \alpha_i + \underset{(0.072)}{0.187}\ y_{COMM,t-1} - \underset{(0.081)}{0.120}\ y_{COMM,t-2} + \underset{(0.122)}{0.981}\ y_{OTHER,t-1} - \underset{(0.829)}{0.143}\ y_{OTHER,t-2}$$

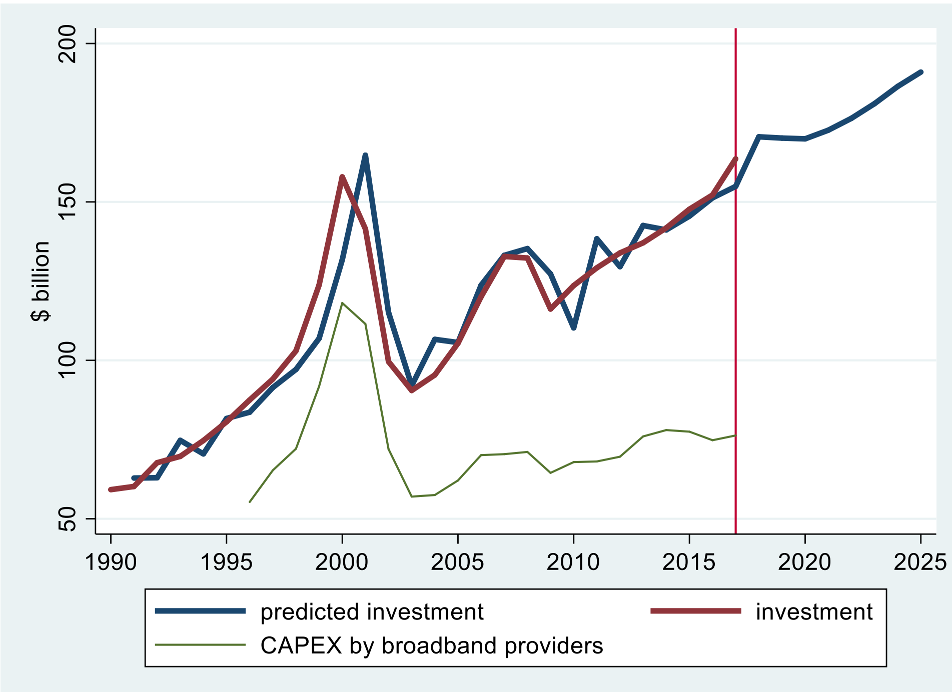
where the figures in parentheses are standard errors computed to be robust to heteroskedasticity and clustering on industry. The results from this log-log specification imply that the coefficients are elasticities: a 1% increase in y_{COMM} leads to an average 0.187% increase in private investment in another industry the next year, followed by an average 0.120% decrease in investment the following year. This pattern of increased investment one year followed by a lesser decrease in two years may be due to managers in industry shifting planned investment budgets forward in time, necessitating reduced expenditure the year after. Regardless, the total impact on investment in the steady state is positive, since the increase is larger than the decrease (0.187 – 0.120 = 0.067% increase overall, if nothing else were to change).[81] With the inclusion of the industry fixed effects and the controls for investment in other industries, these impacts of wireless industry CAPEX can be interpreted as "other things equal," net of overall trends in investment, and untainted by industry-specific unobserved factors.

The coefficients reported above, since they are the same for all industries, represent average responses across industry. Some industries, particularly those with greater use of higher technology, may invest more, and others less. However, using the average relationship between wireless industry CAPEX and investment in other industries is appropriate when the results are applied to total other-industry investment, as is done here.

2. Forecasting the increase in wireless CAPEX

Section A.1 of this appendix presented the assumed wireless industry CAPEX. Since the regression estimates are in the form of elasticities, the CAPEX amounts must be converted to percentage increases beyond what CAPEX would have been absent investment in 5G. This, in turn, requires forecasting what wireless industry CAPEX would be without the additional spending. Given the availability of data, the baseline “no 5G” forecast of CAPEX is computed for private fixed investment in broadcasting and telecommunications. The forecast, shown along with the actual data in Figure 2, is based on an autoregressive integrated time-series regression model.[82] The figure also shows historical CAPEX by broadband services providers,[83] which makes up a sizeable part of the whole.

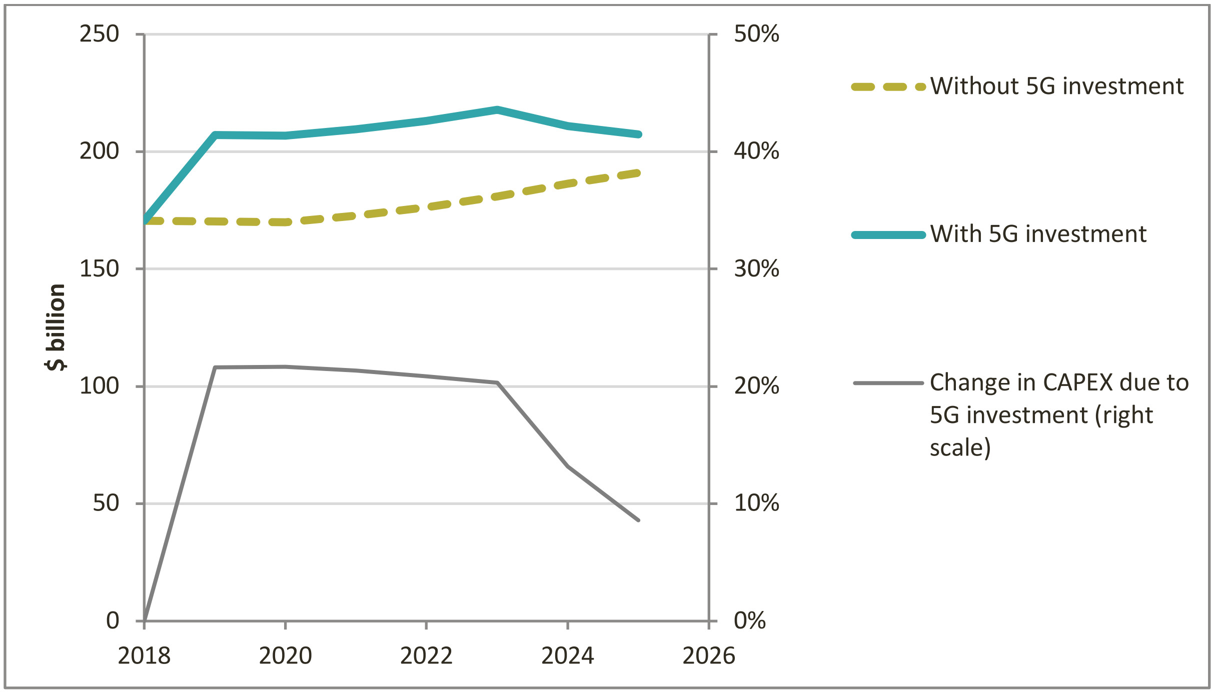
Figure 2: Estimation and Baseline Forecast for Investment in Fixed Assets in the Broadcast and Telecommunications Industry



The amounts of 5G CAPEX from section A.1 above were added to the baseline forecast for investment in broadcasting and telecommunications and the resulting percentage increases were computed. The results are in the following figure. Investment is forecast to be about 20% higher than baseline during 2019 to 2023, when it begins to tail off.

It may be argued that the baseline investment in the forecast thus computed is too large; in the absence of 5G perhaps CAPEX in the wireless industry would be well below its trend. To the extent that is true, then the estimates of jobs computed here are understated, for with a smaller baseline forecast and a fixed CAPEX requirement for 5G ($225 billion) the percentage increases in broadcasting and telecommunications investment would be even larger. The present approach is thus maintained as the more conservative choice.

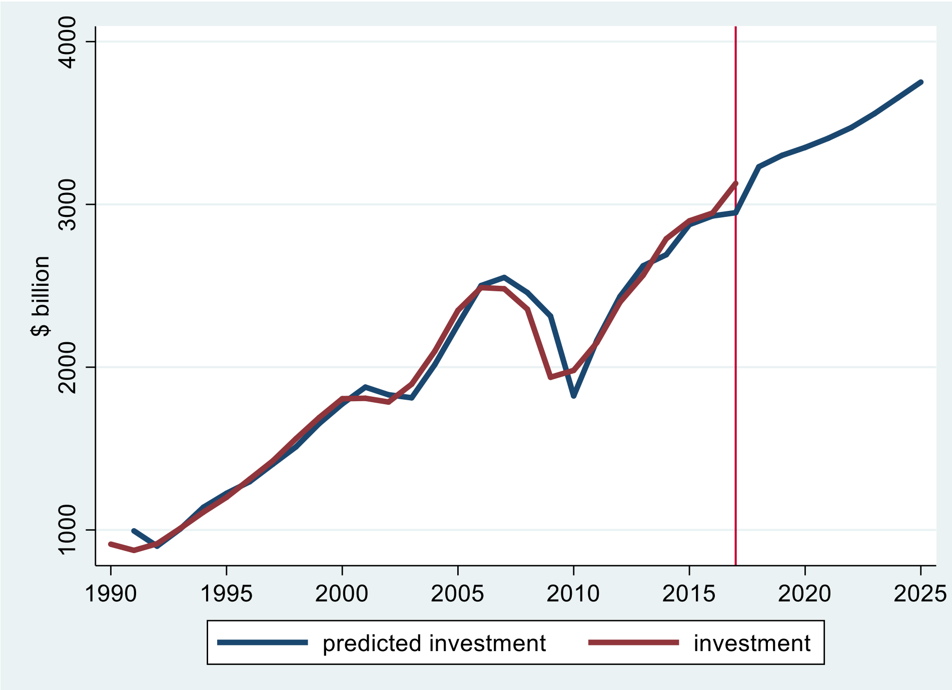
Figure 3: Forecasts for Investment in Fixed Assets in the Broadcast and Telecommunications Industry with and without 5G CAPEX



3. Forecasting the increase in other private industry CAPEX

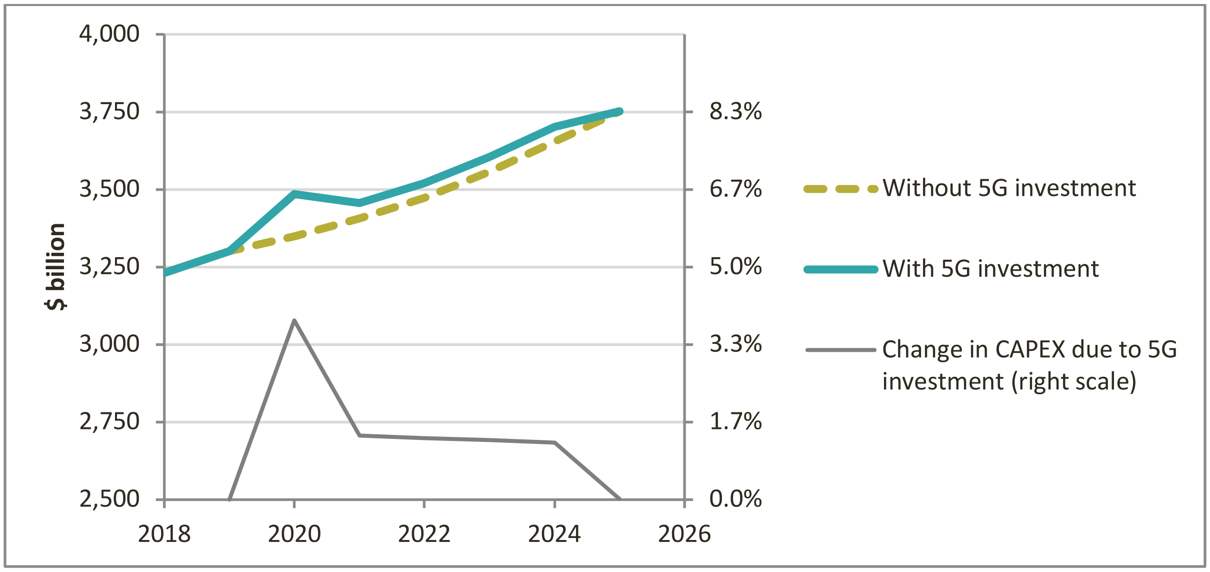
Given the forecasted percentage increase in broadcasting and telecommunications CAPEX, the time series for the percentage increase (ceteris paribus) in each other private industry's CAPEX can be calculated from the estimated regression equation above. These increases must be applied to a baseline forecast for total private industry (except broadcasting and telecommunications) CAPEX. As for the broadcasting and telecommunications forecast, the baseline forecast for the rest of private industry is based on an autoregressive integrated model of private fixed investment; the results are shown in Figure 4.[84]

Figure 4: Estimation and Baseline Forecast for Investment in Fixed Assets in Private Industry Other than Broadcast and Telecommunications



The amount of additional investment in other private industries implied by the econometric model was added to the baseline forecast.[85] The results are in the following figure. Private investment in industry other than broadcasting and telecommunications is forecast to rise about 3.9% in 2020; there is no increase in 2019 because of the lagged nature of the relationship to broadcasting and telecommunications CAPEX. The large initial response is tempered in 2021 and subsequent years, when the coefficient on the second lag of y_{COMM} kicks in. The increase in CAPEX is about 1.2% to 1.4% higher than baseline during 2021 to 2024. In 2025, the decline in additional wireless CAPEX in 2024 (see Figure 3) causes the additional investment in other private industries to be minuscule (about 0.02% above baseline).

Figure 5: Forecasts for Investment in Fixed Assets in Private Industry Other than Broadcast and Telecommunications with and without 5G CAPEX



4. Other-industry CAPEX multipliers

The resulting incremental CAPEX in private industry other than broadcasting and telecommunications is reported in the first data column of Table 9. These are the amounts to which the relevant multipliers will be applied. The multipliers for employment (in the middle columns of Table 9) were computed in IMPLAN for generic private CAPEX (investment not including structures).[86] Compared to the multipliers in Table 6 for wireless CAPEX there are relatively more indirect and induced jobs created, likely because the CAPEX here does not include construction, for which those multipliers are relatively low.

Table 9: Additional CAPEX in Private Industry Other than Broadcast and Telecommunications, Jobs Multipliers, and Jobs Created

Year	Additional CAPEX ($ billion)	Jobs Multipliers per $1 Million Expenditure				Total Jobs Created
		Direct Jobs	Indirect Jobs	Induced Jobs	Total Jobs	
2019	-	3.9	3.2	4.6	11.6	-
2020	135.6	3.9	3.2	4.6	11.6	1,574,051
2021	49.5	3.9	3.2	4.6	11.6	574,327
2022	48.1	3.9	3.2	4.6	11.6	558,320
2023	47.7	3.9	3.2	4.6	11.6	553,966
2024	47.4	3.9	3.2	4.6	11.6	549,548
2025	0.7	3.9	3.2	4.6	11.6	7,907
Total						3,818,119
Average						636,353

The total jobs created per $1M of CAPEX are in the final column of Table 9. The other multipliers for CAPEX spending in other private industry for labor earnings, value added, and output are in Table 10. These are the same for every year of the study period.

Table 10: Multipliers from $1 Expenditure on CAPEX in Other Private Industry for Labor Income, Value Added, and Output

Economic Quantity	Type of Effect	Multiplier
Labor Income	Direct	0.30
	Indirect	0.21
	Induced	0.25
	Total	0.76
Value Added	Direct	0.47
	Indirect	0.34
	Induced	0.43
	Total	1.25
Output	Direct	0.90
	Indirect	0.66
	Induced	0.77
	Total	2.33

C. Spending on 5G connectivity

The next category of economic activity spurred by 5G wireless deployment is incremental spending on mobile connectivity.

1. Connectivity for smartphones, mobile PCs, and tablets

Forecasting expenditure on 5G mobile connectivity requires forecasting what 5G service revenues for wireless service providers may be, and then subtracting what those subscribers would have spent if 4G were the best available technology. The forecast of 5G-subscribing devices is constructed as described in section D below. The number of 5G subscribing devices is multiplied by an estimate of the difference in average revenue per unit (ARPU) between 5G and 4G service. This procedure does not include any additional revenue from 5G fixed wireless broadband service, which, if included, would create even more jobs. The difference in ARPU is set to be equal to that implied by current prices for 2019[87] and declines by 15% per annum thereafter. The decay rate of the 5G premium was determined by examining forecasts of ARPU for 4G and 5G service from Strategy Analytics (Bicheno, 2016).[88]

The resulting incremental 5G wireless service revenue for smartphones, mobile PCs, and tablets is reported in the first data column of Table 11. These are the amounts to which the relevant multipliers are applied. The multipliers for employment are in the middle columns of Table 11.

These were computed for NAICS industry 517312, wireless telecommunications carriers (except satellite).[89]

Table 11: Incremental Revenue for 5G Mobile Wireless Service, Jobs Multipliers, and Jobs Created

Year	Additional service revenue ($ billion)	Jobs Multipliers per $1 Million Expenditure				Total Jobs Created
		Direct Jobs	Indirect Jobs	Induced Jobs	Total Jobs	
2019	0.59	0.4	4.2	3.0	7.6	4,509
2020	2.65	0.4	4.2	3.0	7.6	20,262
2021	8.34	0.4	4.2	3.0	7.6	63,655
2022	14.40	0.4	4.2	3.0	7.6	109,918
2023	19.92	0.4	4.2	3.0	7.6	152,085
2024	22.39	0.4	4.2	3.0	7.6	170,962
2025	26.28	0.4	4.2	3.0	7.6	200,697
Total						722,086
Average						103,155

The total jobs created per $1 million of additional service revenue are in the final column of Table 11. The other multipliers for CAPEX spending in other private industry for labor earnings, value added, and output are in Table 12.

Table 12: Multipliers from $1 Expenditure on 5G Mobile Wireless Service for Labor Income, Value Added, and Output

Economic Quantity	Type of Effect	Multiplier
Labor Income	Direct	0.03
	Indirect	0.31
	Induced	0.16
	Total	0.50
Value Added	Direct	0.36
	Indirect	0.55
	Induced	0.29
	Total	1.20
Output	Direct	1.00
	Indirect	0.98
	Induced	0.51
	Total	2.49

2. Connectivity for 5G IoT

Spending by business enterprises on 5G IoT is divided among IoT hardware, software, professional services, and connectivity. Of these items, the first three are included in the private industry CAPEX forecast (see section B), leaving connectivity to be discussed here. Lacking direct forecasts of connectivity revenue, the following procedure was followed. First, a forecast for expenditure on 5G cellular IoT devices (hardware and software) is taken from Grand View Research,[90] which expects such purchases to begin in 2022. Of expenditure on hardware and software, 65% of the forecasted amount is for IoT hardware,[91] which allows forecasting of software expenditure. Spending on connectivity can then be estimated using data from GSMA (2019) covering the proportions of spending on IoT software, professional services, and connectivity.[92] The resulting enterprise spending on 5G IoT connectivity is reported in Table 13. The multipliers are the same as in the previous section for NAICS industry 517312.

Table 13: Incremental Revenue for 5G IoT Service and Jobs Created

Year	IoT Connectivity Revenue ($ million)	Total Jobs Createc
2019–2021	-	-
2022	6.7	51
2023	11.2	85
2024	18.9	144
2025	33.8	258
Total	70.5	539
Average	10.1	76.9

Note: average is calculated for the seven year period.

D. Spending on 5G electronic consumer goods

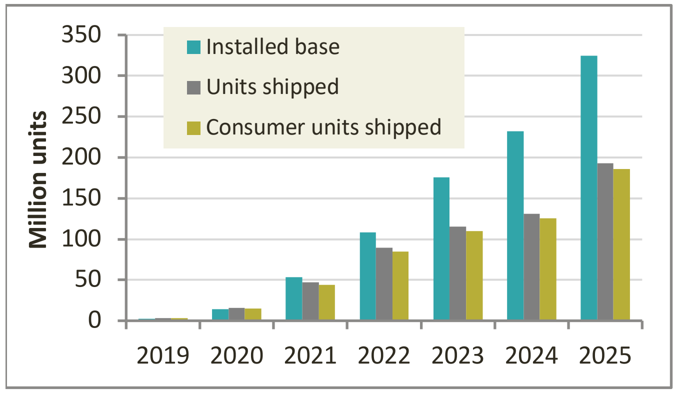
The final category is expenditure by consumers on mobile broadband devices: smartphones, computers, and tablets. While there will be other forms of 5G devices, it is easiest to forecast these major items, which will undoubtedly compose the bulk of near-term 5G device sales. As elsewhere in the analysis, only that part of the expenditure that is expected to be greater than the existing 4G alternatives is counted.

1. 5G smartphones

Forecasts for the installed base of 5G smartphones through 2024 in North America are available from Ericsson.[93] These data were scaled down to include only 5G devices in the U.S.[94] To infer the yearly shipments from the data on the installed base, estimation based on queuing theory was performed. The idea behind the estimation is that with assumptions about the probability distributions of yearly purchases and the elapsed time a device is in service, estimates of yearly sales can be backed out from the data on the installed base. That is, using data on how many devices are in use each year, coupled with assumptions about the random processes giving rise to yearly sales and how long people use a device, the number of new device purchases each year can be estimated.[95] The results are shown in the figure.[96]

Out of all smartphones shipped, the fraction forecast to be purchased by business enterprises is about 8% in 2019, decreasing to about 4% in 2025.[97] Expenditure by businesses is not included separately in the calculations for employment created, since purchases of 5G devices are included in private industry CAPEX as estimated in section B above.

Figure 6: Forecasts of 5G Smartphone Installed Base and Units Shipped



Note: Installed base is from Daniel Research Group (2019); Units shipped are estimated as described in the text.

It is assumed that in the absence of 5G, a 4G smartphone would be purchased instead. The premium for 5G (net of a 4G device) is taken to be $400 per smartphone in the first year,[98] after which the premium is assumed to decline by 10% per annum. The resulting incremental expenditure by consumers on 5G smartphones, net of the 4G counterfactual, is shown in the first data column of Table 14. The employment multipliers, which are for consumer spending on NAICS commodity 334220, broadcast and wireless communications equipment (which includes smartphones), are shown in the middle columns of the table.[99]

Table 14: Incremental Consumer Expenditure on 5G Smartphones, Jobs Multipliers, and Jobs Created

Year	Incremental Expenditure ($ billion)	Jobs Multipliers per $1 Million Expenditure				Total Jobs Created
		Direct Jobs	Indirect Jobs	Induced Jobs	Total Jobs	
2019	1.29	7.4	2.1	5.3	14.7	19,031
2020	5.31	7.4	2.1	5.3	14.7	78,317
2021	14.18	7.4	2.1	5.3	14.7	209,009
2022	23.70	7.4	2.1	5.3	14.7	349,320
2023	26.27	7.4	2.1	5.3	14.7	387,255
2024	25.16	7.4	2.1	5.3	14.7	370,790
2025	29.72	7.4	2.1	5.3	14.7	438,029
Total						1,851,751
Average						264,536

The total jobs created per $1M of spending on smartphones are in the final column of Table 14. The other multipliers for labor earnings, value added, and output for such spending are in Table 15. These are the same for every year of the study period.

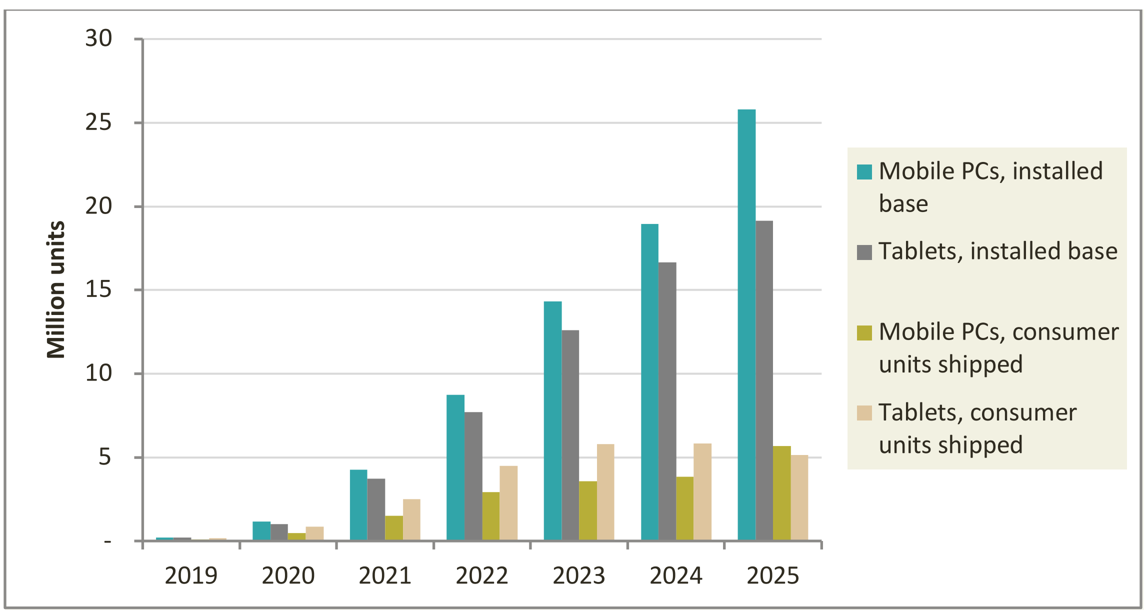
Table 15: Multipliers from $1 Consumer Expenditure on 5G Smartphones

Economic Quantity	Type of Effect	Multiplier
Labor Income	Direct	0.46
	Indirect	0.14
	Induced	0.28
	Total	0.88
Value Added	Direct	0.42
	Indirect	0.23
	Induced	0.50
	Total	1.15
Output	Direct	0.68
	Indirect	0.39
	Induced	0.88
	Total	1.96

2. 5G tablets and mobile PCs

For consumer purchases of 5G tablets and mobile computers, similar methodology was used as for smartphones. The forecast of the installed base for PCs, tablets, and routers with mobile cellular data subscriptions (3G through 5G) in North America is available from Ericsson.[100] These data were scaled down to include only 5G devices[101] and only the U.S.[102] The fractions of the remaining installed base of 5G devices in the U.S. that are tablets and mobile PCs were computed using data from Daniel Research Group (2019).[103] The units of each shipped each year were estimated separately from their installed bases using queuing theory as described above.[104] Enterprise purchases were then removed from the total units shipped to leave consumer devices only (since business purchases are already included in private industry CAPEX; see section B above); enterprise purchases compose 11-16% of tablets shipped and 48-57% of mobile PCs shipped (depending on the year).[105] The results are shown in Figure 7.

Figure 7: Forecasts of 5G Tablets and Mobile PCs, Installed Base and Units Shipped



Note: Installed bases include both consumer and enterprise units; units shipped are for consumer purchases only. See text and footnotes for data sources and methods.

It is assumed that in the absence of 5G, a 4G device would be purchased instead. The premium for 5G (net of a 4G device) is taken to be $150 per mobile PC and $125 per tablet in first year,[106] after which the premium is assumed to decline by 10% per annum. The resulting incremental expenditure by consumers on 5G tablets and mobile PCs, net of the 4G counterfactual, is shown in the first data column of Table 16. The employment multipliers, which are for consumer expenditure on NAICS 334111, electronic computer manufacturing, are shown in the middle columns of the table.[107]

Table 16: Incremental Consumer Expenditure on 5G Tablets and Mobile PCs, Jobs Multipliers, and Jobs Created

Year	Incremental Expenditure ($ million)	Jobs Multipliers per $1 Million Expenditure				Total Jobs Created
		Direct Jobs	Indirect Jobs	Induced Jobs	Total Jobs	
2019	33.3	3.9	1.3	3.9	9.1	305
2020	145.9	3.9	1.3	3.9	9.1	1,334
2021	377.3	3.9	1.3	3.9	9.1	3,448
2022	599.3	3.9	1.3	3.9	9.1	5,476
2023	629.2	3.9	1.3	3.9	9.1	5,750
2024	522.6	3.9	1.3	3.9	9.1	4,775
2025	446.9	3.9	1.3	3.9	9.1	4,083
Total						25,170
Average						3,596

The total jobs created per $1M of spending on mobile PCs and tables are in the final column of Table 16. The other multipliers for labor earnings, value added, and output for such spending are in the following table. These are the same for every year of the study period.

E. Wireless industry OPEX

There is great variation in the literature, the trade press, and the community of analysts as to what the impact of 5G might be on operational expenditure in the wireless service industry. On the one hand, 5G requires some additional OPEX to fund the power and maintenance requirements of the nodes.[108] On the other hand, 5G service is expected to be more energy efficient than 4G LTE, which will reduce that portion of OPEX. Some proponents of 5G claim that there will be massive energy savings from the technology.[109] However, any savings per user will be offset at least in part by the increase in the number of microcell sites.[110] Furthermore, the energy contribution to technology OPEX is no more than 15%, and technology OPEX is less than one quarter of all telco OPEX (Larsen, 2017). For these reasons, the present analysis assumes that there is no change in OPEX, making the jobs-created estimates more conservative than some other analyses (e.g., Singer et al., 2017).

Table 17: Multipliers from $1 Consumer Expenditure on 5G Tablets and Mobile PCs

Economic Quantity	Type of Effect	Multiplier
Labor Income	Direct	0.35
	Indirect	0.09
	Induced	0.21
	Total	0.65
Value Added	Direct	0.53
	Indirect	0.16
	Induced	0.37
	Total	1.05
Output	Direct	0.45
	Indirect	0.27
	Induced	0.65
	Total	1.38

F. Regional calculations

1. Economic impacts from network deployment in the region

For the economic impacts at the regional level, the amount of investment required to deploy 5G was determined using data from the International Telecommunications Union (ITU, 2018). That report presents 5G deployment costs for areas of two small areas within an urban setting with different population densities. Using these figures, estimates of the CAPEX required were computed for each Census tract in the regions considered here. The CAPEX amounts were then aggregated across tracts to arrive at a total for each region.

The exact methodology is as follows. From the two ITU (2018) estimates,[111] a baseline linear relationship between cost per square mile C and population density X is calculated:

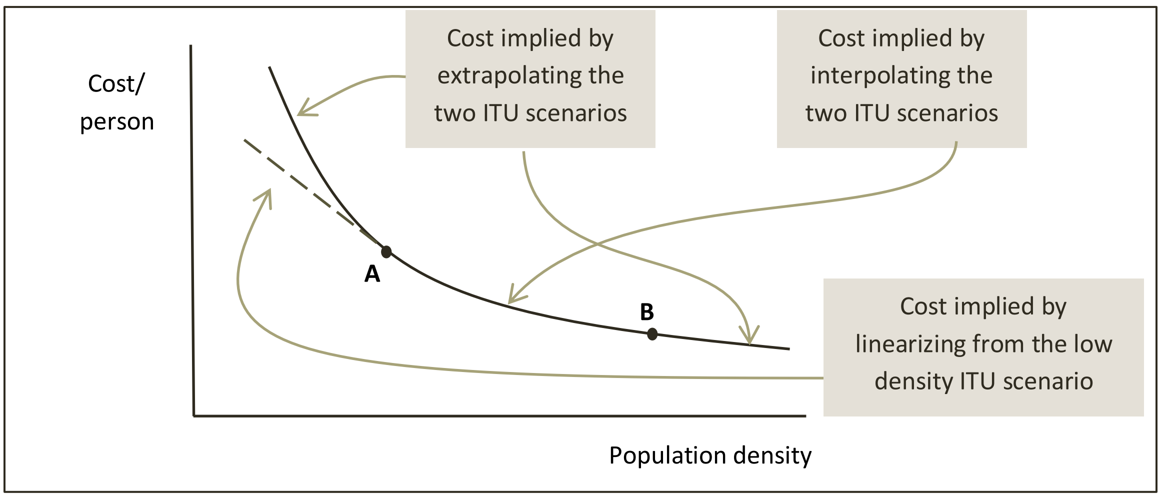
$$\${C}/_{sqmi} = \${a}/_{mi^2} + \left(\${b}/_{person}\right) \times \left({X\ person}/_{mi^2}\right)$$

where C, a = 4.464, b = 1.647×10^{-4}, and X are scalars and the units of each are explicitly stated. From that relationship, cost per person for a Census tract can be computed by dividing both sides by X and its units:

$$\left(\frac{C}{X}\right) \${}/_{person} = \left(\frac{a}{X}\right) \${}/_{person} + \${b}/_{person}$$

While still only an approximation of deployment cost, since it is based on only two scenarios, this relationship between population density and deployment cost per capita does reflect the important feature that the latter declines in more densely populated areas, but at a diminishing rate. The result is then multiplied by the number of people residing in the tract, per the 2010 decennial Census figures to arrive at a cost for the tract. An exception is made when the population density is below the density of the lower-density ITU estimate, because it was found that extrapolation of the inverse relationship shown in the equation in that direction resulted in very large cost estimates. For the sake of arriving at conservative cost estimates, the direct estimates from the equation above were replaced with a linear extrapolation based on the slope of the cost relationship at the point of the lower-cost scenario. This is illustrated in the figure, where the slope of the inverse curve at A is continued linearly to the left of the low-density scenario:

Figure 8: Extrapolating Deployment Cost Per Person Beyond the Low Density Scenario



For New York City only, a range of estimates was computed. The low cost scenario is as described above. The high cost scenario is based on the cost per capita for the entire New York MSA.

Given the amount to be spent locally on CAPEX, the multipliers were constructed as described above for the national analysis. The main differences are the local purchasing percentages (LPPs), which are typically much lower for a city than for the nation; many items will be purchased from suppliers outside the local area. For most commodities, the LPPs were set to reflect typical activity of the relevant kind.[112] Due to their nature, certain items such as wireless service and wholesale trade were assumed to be 100% local.

For the other items of expenditure, various relevant measures of size were chosen to apportion the national spending to the region. Investment by private industry was apportioned by the ratio of regional to national GDP.[113] Mobile connectivity spending and consumer spending on mobile phones, tablets, and computers was apportioned relative to population.[114]

The estimated regional expenditure in these categories are given in the following table.

Table 18: Estimated Regional Expenditure

	Wireless Industry CAPEX ($ billion)	Other Industry CAPEX ($ billion)	Spending on 5G devices ($ billion)	5G Mobile Wireless Service ($ billion)
New York City (low cost scenario)	2.41	15.46	2.96	2.17
New York City (high cost scenario)	5.10	15.46	2.96	2.17
Allegheny County (Pittsburgh)	1.16	1.75	0.45	0.33
Roanoke City and County	0.20	0.18	0.08	0.06
Los Angeles MSA	8.39	17.78	4.87	3.57

2. Positive spillovers from national deployment

Using data from IMPLAN, the spending on investment goods to deploy 5G elsewhere that will leak in to the local area is estimated by the relative size of the local industry. For example, Los Angeles accounts for about 2.6% of the dollar value of output on telephone apparatus (such as network switchgear) manufactured in the U.S. Thus, it was assumed that after accounting for leakage to imports, 2.6% of the remaining spending in other regions on such equipment would go to suppliers in Los Angeles. These figures were adjusted according to the assumptions about LPPs described in the previous section.[115]

3. Employment in the wireless telecommunications ecosystem

To apportion nationwide employment in the wireless telecommunications ecosystem to a region, the jobs were broken down into several categories: infrastructure providers and mobile operators; device manufacturing; distributors and retailers; and content, applications, and services. The national employment in each category is available in the source data. Regional allocations for these were determined as follows:

Infrastructure providers and mobile operators

First, data on the number of establishments, employees, and annual payroll for wired and wireless telecommunications carriers (NAICS 5171 and 5172) were collected from the Census Bureau's County Business Patterns database. Next, the fraction of the whole for the nation was computed for each of these. An evenly weighted average of the local fractions of establishments, employees, and payroll was then computed. This composite allocation factor was applied to the national employment figures for infrastructure providers and mobile operators to arrive at the regional estimate for the initial year of the forecast period. In subsequent years the allocation factor was adjusted in accordance with how local population growth was expected to relate to national population growth.

Device manufacturing

The initial allocation factor for device manufacturing was taken to be the share of regional output in the nation for commodity 334220, broadcast and wireless communications equipment. These data are from IMPLAN, as described in section 2 above. In subsequent years the allocation factor was adjusted in accordance with how local population growth was expected to relate to national population growth.

Distributors and retailers

The same procedure as for infrastructure providers and mobile operators as detailed above was followed, with the exception that the data are for electronics stores (NAICS 443142) and merchant wholesalers of household appliances, electric houseware, and consumer electronics (NAICS 423620).

Content, applications, and services

The initial allocation factor is an evenly weighted average of two local shares of the national economy. The first is a local share for the data processing, hosting, and related services industry (NAICS 518210), constructed as described for infrastructure providers and mobile operators as detailed above. The second is the local share of employment in certain relevant occupations related to developers and content creators: software developers, applications (BLS occupation code 15-1132); software developers, systems software (15-1133); web developers (15-1134); producers and directors (27-2012); musicians and singers (27-2042); audio and video equipment technicians (27-4011); camera operators, television, video, and motion picture (27-4031); and broadcast technicians (27-4012). In subsequent years the allocation factor was adjusted in accordance with how local population growth was expected to relate to national population growth.

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Appendix Notes

[68] While it is typical to perform economic analysis in real terms (accounting for inflation), nominal figures were used in this exercise because all the source forecasts were in nominal terms and future inflation rates are unknown. In any event, inflation is currently low and is generally forecasted to remain so, and so the distinction between real and nominal figures would be small. For example, the International Monetary Fund forecasts an inflation rate of 2.0% in 2019 and 2.7% in 2020, followed by rates around 2.2% through 2024 (see its World Economic Outlook database).
[69] Rossolillo (2019) notes, for example, that even though much of wireless capex in 2019 will go toward the 4G network per se, most of this year's CAPEX can be considered as "go[ing] to 5G" because "5G builds on top of most components of the existing mobile network (like 4G and fiber optic lines). Spending on 5G wireless equipment will likely be a major source of expense, but building 4G assets and other high-speed wireline connections will need to continue to speed up deployment."
[70] While the report itself is not freely available, the figure cited here is reference in Rossolillo (2019).
[71] Overdorff (2018) reports that AT&T announced it will allocate $40 billion of CAPEX for the rollout of 5G wireless network technology. The same source mentions a figure of $35 billion for Verizon, but Arnason (2018) makes it clear that the context for that figure is only for fixed wireless Internet access. In their public interest filing to support their proposed merger, T-Mobile and Sprint committed to "nearly $40 billion" to build a 5G network in the first three years (T-Mobile US, Inc. and Sprint Corporation, 2018).
[72] See Prieger (2017) for justification.
[73] The figures are taken from GSMA Intelligence (2019). The data in the bar graph there were converted to approximate numbers, accurate to the quantizing of the bars to the pixels in the graphic.
[74] These margins are from BEA spreadsheet "Margins_After_Redefinitions_2007_2012_DET.xlsx" and are for 2012 (the latest data available).
[75] See https://implanhelp.zendesk.com/hc/en-us/articles/115009505707-General-Information-About-Multipliers.
[76] The earnings multiplier itself is computed with reference to the output multiplier and the industry-level output-to-earnings ratios. For further explanation of how multipliers in input-output analysis are computed, see BEA (2013).
[77] The BEA investment accounts group the broadcasting and telecommunications industries, which together composed industry 5130 under the older North American Industry Classification System (NAICS). These industries are NAICS 515 and 517 in the 2017 version of the industry codes.
[78] While modeling the relationship between the different types of investment in log-log form complicates the analysis below, it is econometrically appropriate given the skewed distribution of private investment (even after controlling for industry fixed effects).
[79] See BEA Fixed Assets Accounts Table 3.7ESI, Investment in Private Fixed Assets by Industry. The figures include investment in private equipment, intellectual property products, and structures. The industries included in the regression were the most detailed ones available in the data. For some such as wholesale trade, the industry corresponds to a two-digit NAICS code. Other available industries correspond to three-digit NAICS codes.
[80] When estimated by OLS regression with dummy-variable fixed effects, the R^2 is 0.963.
[81] While the estimated coefficient on the second lag of broadcast and telecommunications investment is not statistically significant, this specification was retained because 1) the first and second lags together are jointly significant, 2) the AIC and BIC criteria both indicate that including two lags is preferable to one, 3) the specification reveals an interesting pattern of adjustments in investment over time, and 4) to be conservative in the estimate of jobs created; the impact is even larger if only a single lag is included (the coefficient in that case is 0.096).
[82] The model uses data from 1991–2019 and is an AR(5) specification with integration of order one (and hence is an ARIMA(5,1,0) model).
[83] Data on CAPEX by U.S. broadband service providers is from USTelecom (Brogan, 2018). These data include capital expenditures by wireline and wireless telecommunications and cable broadband providers; satellite providers, resellers, and electric utilities are excluded. This CAPEX is lower than total investment in broadcasting and telecommunications because broadband service providers make up only part of that industry segment.
[84] The same data and econometric model are used as before (see footnote 82).

[85] Given that the regressors for lagged other-industry investment were included only to control for general business and investment trends during the sample period of the data, those variables were held constant in the computation of how much investment would increase in an industry.
[86] The margins and local purchasing percentages for this type of investment were set to the values in IMPLAN's social accounting matrix, and thus should represent averages across the private economy.
[87] At time of writing, AT&T charged a $35/month premium for 5G ($70/month for 15GB of data on its 5G hotspot versus $35/month for 9GB of data on its 4G plan), Verizon charged a $10/month premium for unlimited data, and Sprint and T-Mobile charged no more for 5G than for 4G. Taking the weighted average of these premia, where the weights are the market shares of these carriers (scaled to equal 100%), yields an implied current 5G premium of $15.71/month, or $188.57/year. Data on the market shares of these four carriers (which compose over 98% of subscriptions in the wireless service market) are for Q3 2018 and are from FierceWireless (2018).
[88] The data are presented in Bicheno (2016) in graphical form; the data in the line graph there were converted to approximate numbers (accurate to the quantizing to the pixels in the graphic). The original data extend only to 2022 and were extended by log linear extrapolation. The implied ΔARPU declines by about 33% in 2021 (the first year the figure can be calculated using the source data) and about 15% thereafter. The first-year large decline in ARPU is an artifact of the huge 5G premium for the first year of data for 5G in the source; 5G is shown to be more than three times as expensive as 4G (probably because the figures pertain to the global market, not just the U.S.). Given that the present analysis begin with a much more modest 5G price for the U.S. market (only about 1.2 times that of 4G service), the large first-year decline in the premium was discarded and ΔARPU was assumed to decline at 15% per year.
[89] The margins for services are 100% for the producers' value and the local purchasing percentage is 100%.
[90] Statista, "Cellular IoT market revenue in the United States from 2014 to 2025 (in million U.S. dollars), by type" (from Study ID 780095), accessed July 18, 2019. The forecast is from 2017.
[91] This breakdown is from the summary to the Grand View report.
[92] The latter source provides the proportion of total spending on IoT software (apps, platforms, and services), professional services (consulting and software design), and connectivity for each of those three items, but does not forecast the total spending. However, from the proportions, spending on connectivity as a multiple of spending on software can be computed, which then can be applied to the software spending forecast mentioned earlier in the text.
[93] Data through 2024 are downloaded from the June 2019 version of the Ericsson Mobility Visualizer, and are for 5G smartphones in North America.
[94] The fraction of all mobile subscribers in North American that live in the U.S., 90.8%, is taken from GSMA Intelligence (2019).
[95] The assumed model for the installed base is an $M_t/M/\infty$ queuing system, which means that the distribution of units shipped is modeled as a Poisson stochastic process with time-varying parameters, the length of time a unit remains in use before retirement is exponentially distributed, and units enter the installed base immediately upon shipment. The arrival rate for the Poisson process is modeled as the previous year's rate multiplied by a quadratic function of time; this allows the arrival rate to evolve with a parsimonious specification. The average time in service for a device is taken to be 2.8 years, based on data from Daniel Research Group (2019). With these assumptions, the likelihood function for the four unknown parameters (the three quadratic coefficients and the initial period arrival rate) can be computed and maximized, using the results in section 2.3.1 of Prieger (1999). The MLE estimates are then used to compute the Poisson arrival rate each year and thence the expected units shipped.
[96] Estimates of units shipped for 2025 are computed similarly to other years (i.e., the expected number of shipments based on the Poisson mean for the relevant year as calculated from the estimated coefficients), but note that the source data only extend through 2024. Thus the final year's estimates are both forecasts and extrapolations. The same is true of the estimate for the installed base for 2025, which is calculated as the expected value of the installed base given the estimated queuing system.
[97] Forecasts of the proportions of smartphones shipped to consumers and enterprises through 2023 are from Daniel Research Group (2019). The forecasts were extended to 2025 by extrapolating the decline in the enterprise proportion.
[98] This amount is, e.g., the premium for a Galaxy S10 5G compared to a 4G S10+ in June 2019.

[99] The margins for consumer spending on this commodity are 38% for the producers, 0.4% for transportation, 18% for wholesale, and 43% for retail. The local purchasing percentage is 16.5% for the producers' value (because most of these items are imported); the LPPs for the other margins are taken from IMPLAN's social accounting matrix.
[100] Data through 2024 are downloaded from the June 2019 version of the Ericsson Mobility Visualizer, and are for mobile PCs, tablets, and routers using any 3G/4G/5G technology in North America.
[101] The fraction of all connected devices that are 5G is available only for smartphones in the Ericsson data, and so those fractions were assumed to apply to tablets and mobile PCs as well. The fraction increases from 0.9% in 2019 to 72% in 2024.
[102] See footnote 94.
[103] During the study period, the fraction of tablets and mobile PCs that are the latter is about 53%, and is forecast to change little during that time (Daniel Research Group, 2019). Data on the fraction for routers was not available, and so it was assumed that they composed a de minimis number of connected device units for consumer purchases.
[104] The average lifetime of a tablet or mobile PC is assumed to be 5.6 years, based on data from Daniel Research Group (2019). See footnote 96 on estimates for 2025.
[105] Data on the fraction of mobile PCs and tablets that are purchased by businesses are from Daniel Research Group (2019).
[106] Adding 4G LTE to a mobile PCs adds about $150 to the purchase price (Hunt, 2018). In first generation 5G smartphones, the 5G chipsets cost about twice as much as for LTE. Thus it is assumed that the 5G premium doubles the cost of adding mobile connectivity to the PC. The logic is similar for tablets, except that adding 4G LTE to a tablet "usually carries a $100 to $150 premium" Piltch (2015), and so an initial premium of $125 is assumed.
[107] The margins for consumer spending on this commodity are 63% for the producers, 0.7% for transportation, 18% for wholesale, and 18% for retail. The local purchasing percentage is 13.5% for the producers' value (because most of these items are imported); the LPPs for the other margins are taken from IMPLAN's social accounting matrix.
[108] Singer et al. (2017) assume a figure of $1,300 per year per node for additional OPEX for 5G.
[109] For example, one group of experts early predicted "energy consumption by the whole [5G] network of only half that typically consumed by today's networks" (NGMN Alliance, 2015, at 4.6.2).
[110] One expert, after reviewing data on power savings when using 5G equipment, states: "However, this power efficiency technology and network cellular architecture gain can very easily be destroyed by the massive additional demand of small, smaller and smallest cells combined with highly sophisticated antenna systems consuming additional energy for their compute operations to make such systems work" (Larsen, 2017).
[111] In the higher density scenario, it costs $9.58 per square mile to deploy 5G when the population density is 31,080 people per square mile; in the lower density scenario the cost is $5.87per square mile and the density is 8,542 people per square mile. The constants a and b in the equation are determined from these two points.
[112] That is, the LPP was drawn from IMPLAN's social accounting matrix for the region and commodity.
[113] The initial apportionment was based on latest available GDP figures. Apportionment for future years assumed that future regional GDP ratios would evolve the same as regional population ratios are expected to change, based on Census Bureau projections.
[114] See previous footnote on population projections for future years.
[115] For example, since wireless service is assumed to be an entirely local expenditure, none leaks in from outside the region.