RAND SOCIAL AND ECONOMIC WELL-BEING

The Potential Economic Value of Unlicensed Spectrum in the 5.9 GHz Frequency Band

Insights for Future Spectrum Allocation Policy

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Preface

In today's digital era, the number of devices and applications reliant on unlicensed spectrum—the frequencies that WiFi operates on—is large and growing. Few people are untouched by the wireless communication enabled by WiFi, and the number of wireless-enabled internet device subscriptions in the United States now exceeds the American population. As our society becomes more interconnected, driven by wireless interactions and wireless technologies, our dependence on the availability of WiFi will increase. Understanding the economic power of WiFi is therefore becoming increasingly important in designing effective policy across virtually every dimension.

This study was motivated by the emergence of WiFi as a key enabler to economic growth and prosperity, and in turn the ongoing debates surrounding unlicensed spectrum allocation. Given the importance of WiFi, having accurate and reliable data on the magnitude of its role is critical. Yet there are few empirically driven estimates on how WiFi contributes to the economy. Both data and methodological limitations related to the fact that spectrum is not a traditional good or service create unique challenges to understanding WiFi's value. We sought to contribute to the ongoing policy discussions by providing a new data point for the potential economic importance of one unlicensed portion of spectrum that is the current subject of debate—the 75 MHz that comprises the 5.9 GHz frequency band.

This study had several core objectives:

- Estimate the potential economic value of an unlicensed frequency band that is currently under discussion for reallocation.
- Understand the trade-offs associated with realizing this potential value, in terms of existing and future trends and policies and in terms of how this spectrum could be allocated.
- Provide a new perspective on the current discourse surrounding unlicensed spectrum allocation policy.

This research was funded by the Comcast Innovation Fund. Our intended audience is broad—any policymaker, regulator, legislator, academic, or consumer interested in having a stronger appreciation for the potential economic importance of unlicensed spectrum as we move into an increasingly digitized and interconnected world.

This study was designed to augment the ongoing work the RAND Corporation is conducting on other emerging technology policy issues, such as artificial intelligence, autonomous vehicles, and cybersecurity. All of these applications either do or could rely on WiFi—and therefore unlicensed spectrum—making a strong understanding of unlicensed spectrum policy important.

RAND Social and Economic Well-Being is a division of the RAND Corporation that seeks to actively improve the health and social and economic well-being of populations and

communities throughout the world. This research was conducted in the Community Health and Environmental Policy Program within RAND Social and Economic Well-Being. The program focuses on such topics as infrastructure, science and technology, community design, community health promotion, migration and population dynamics, transportation, energy, and climate and the environment, as well as other policy concerns that are influenced by the natural and built environment, technology, and community organizations and institutions that affect well-being. For more information, email chep@rand.org.

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WiFi is an important part of the internet ecosystem. It is the conduit for the majority of online data traffic, for consumers and businesses. It also enables the proliferation of technologies such as smart homes, sensor-based transportation networks, smart electric grids, and sustainable smart cities. Yet this emergence also creates new challenges for policymakers and raises questions about what 21st century spectrum management should look like. Policymakers are grappling with regulations and policies that ensure the development of the internet ecosystem in a way that promotes adequate consumer protections.

Many ongoing policy discussions in the technology policy arena relate to the importance of the internet and therefore to the need to meet future WiFi demand. One key area of this consideration is in the corresponding allocation of unlicensed spectrum—the frequency bands that enable WiFi communications. (Unlicensed spectrum is spectrum dedicated explicitly for public and commercial use. In contrast, licensed spectrum is licensed to commercial entities, such as telecommunications firms, that then have exclusive rights to that frequency range.)

One prominent discussion on unlicensed spectrum relates to the 5.9 GHz band, a 75 MHz frequency band that spans 5.850 GHz to 5.925 GHz. It is currently allocated to dedicated short-range communications (DSRC) for vehicle-to-vehicle communications. Allocated by the Federal Communications Commission (FCC) for this use in 1999, it remains little used, with a current market value of $6.2 million in the United States. The allocation of this frequency band is currently being reconsidered by the FCC for open use, which makes it a topical subject worthy of additional study. (In keeping with the original FCC press release establishing the DSRC set-aside, this report will use *5.9 GHz band* to refer to the collective frequency band between 5.850 GHz to 5.925 GHz.)

In this report, we estimate the current economic potential of the 5.9 GHz band, providing a new measure for policymakers to consider going forward. The estimates provided in this report are constructed under the premise that instead of spectrum in the 5.9 GHz band being allocated to DSRC, it is instead fully reallocated to open unlicensed use.

Similar to traditional economic studies of value, we consider three types of contributions: to gross domestic product (GDP), to consumers in the form of economic surplus, and to producers also as surplus. We approach the contribution to GDP in two ways. First, we calculate returns to speed from the increased bandwidth enabled by the 5.9 GHz band using a new estimate of the contribution of internet speed on real GDP (Approach 1). Second, we calculate a more technical value of the 5.9 GHz band by considering the potential data traffic enabled by 75 MHz and monetizing it (Approach 2). We also use available data and literature to estimate values for consumer and producer surplus, with our estimate for consumer surplus presented as a range.

For Approach 1, we estimate that the annual potential contribution to GDP ranges from $59.8 billion to $96.8 billion. For Approach 2, we estimate that the potential annual contribution to GDP ranges from $71.0 billion to $105.8 billion. Across both approaches, the total gains to economic welfare in the form of consumer and producer surplus range from $82.2 billion to $189.9 billion.

We believe that these are the first such estimates for the potential value of the 5.9 GHz frequency band. As such, we present these estimates as preliminary. We acknowledge, as does the literature, the many data challenges and limitations associated with measuring the economic value of unlicensed spectrum. We detail these limitations in the body of this report, which include the unknown impact of advancements in technology. We also provide a sensitivity analysis for both approaches in our measurement of contribution to GDP.

In addition to providing these estimates, we further consider them in the context of current policy discussions that could affect the estimates' accuracy. For example, privacy regulation, trade policy, and fifth-generation (5G) network deployment could all affect the demand for and value of WiFi.

Finally, we explore the possible allocation options of the 5.9 GHz band and associated trade-offs for potential economic value—specifically, the trade-off with the potential value of the emerging DSRC V2V and vehicle-to-infrastructure (V2I) market. This includes consideration of the status quo allocation relative to partial reallocation, shared allocation, and full reallocation. Accurately estimating the potential value of DSRC is complicated given the many uncertainties regarding the widespread adoption of DSRC by auto manufacturers and policymakers. We do, however, note qualitatively that the potential value of V2V and V2I technologies, were they to gain momentum on the DSRC-designated spectrum, could reduce our estimate of the potential economic value of repurposing the 5.9 GHz band.

The goal of these estimates is to help inform the ongoing debate regarding the 5.9 GHz band. We believe that decisions made regarding the allocation of this frequency band could set a precedent for future unlicensed spectrum policymaking, especially in the context of higher millimeter wave frequencies.

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We would like to thank our reviewers, Scott Grossman and Lloyd Dixon of the RAND Corporation and Raul Katz of Columbia University and Telecom Advisory Services. We would also like to thank Tom Whitmore for his invaluable help, contribution, and insights for our research and Chris Nicholson at Akamai Technologies for sharing data used in our estimation. Finally, we would like to thank our sponsor, the Comcast Innovation Fund, for its support for this study.

Abbreviations

4G	fourth-generation
5G	fifth-generation
AIC	Akaike information criterion
BIC	Bayesian information criterion
DFS	dynamic frequency sharing
DSRC	dedicated short-range communications
FCC	Federal Communications Commission
GB	gigabyte
GDP	gross domestic product
GHz	gigahertz
Gbps	gigabit(s) per second
IEEE	Institute of Electrical and Electronics Engineers
ISP	internet service provider
IV	instrumental variables
M2M	machine-to-machine
MB	megabyte
Mbps	megabit(s) per second
MCS	modulation and coding scheme
MHz	megahertz
ns	nanosecond
QAM	quadrature amplitude modulation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

1. Introduction

The rise of the internet ecosystem may well be among the most important economic stories of our time. As the world continues to become more interconnected, wireless communications—particularly those enabled by WiFi—have played and will continue to play an indispensable role in generating economic prosperity and opportunity. Wireless communication networks that rely on a WiFi connection, for example, have the power to bring new ideas and innovations to life at low cost, expand access to information and knowledge, and bridge the digital divide. They enable smart homes, public safety communications, sensor-based transportation networks, smart electric grids, and sustainable smart cities, which all have the potential to boost productivity and wages, increasing quality of life.[1]

Today, WiFi serves as a major connection to the internet for all mobile devices and as the primary connection for WiFi-enabled devices such as tablets and wearable technology. In 2016, according to Cisco's Visual Networking Index, "More traffic was offloaded from cellular networks [on to WiFi] than remained on cellular networks" (Cisco, 2017). Deployment and use of commercial and public hotspots are growing, and use of private or home fixed WiFi networks is growing even faster (Cisco, 2017). The availability of these WiFi networks will have particularly large implications for underserved and rural populations, enabling greater and faster broadband access.

In this context, unlicensed spectrum is foundational in the development and sustainment of the "internet ecosystem."[2] This is true for personal home networks, business private networks, public networks, and WiFi-enabled hotspots. It is also true for the increasing amount of mobile traffic off-loading by carriers balancing congestion on their networks (Bhas, 2016). That makes understanding the economic potential of unlicensed spectrum critical in designing spectrum allocation policies that maximize benefits to consumers and the economy (Benkler, 2012).

If there is inadequate unlicensed spectrum available to carry WiFi traffic, these advances could be constrained. Imagine the unrealized economic potential and gains to consumers if the future availability of unlicensed spectrum were unable to keep up with demand. Concerns have been raised, for example, about sufficient spectrum throughput to access the millions of apps that do everything from online banking to health monitoring, and the resulting effect on consumers if

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[1] For example, see Zaber, Bohlin, and Lindmark (2017).

[2] Unlicensed spectrum is spectrum dedicated explicitly for public and commercial use. In contrast, licensed spectrum is licensed to commercial entities, such as telecommunications firms, that then have exclusive rights to that frequency range.

only fixed wireline connections and cellular networks were available.[3] This is true not just in the United States, but globally. WiFi is also increasing access to public services, and it is making governments more transparent (World Bank Group, 2016).

That makes this an opportunity for quality data and research to inform the public discourse on spectrum policy. To facilitate such discourse, this report focuses on one facet of spectrum policy—unlicensed spectrum allocation in the 5.9 GHz band. A band of 75 MHz between 5.850 GHz and 5.925 GHz, the allocation of this band is currently a subject of policy debate. In 1999, the Federal Communications Commission (FCC) allocated this band to dedicated short-range communications (DSRC) for vehicle-to-vehicle (V2V) communications (Federal Communications Commission, 1999). Since then, it has remained underused, with some automobile manufacturers and suppliers moving V2V onto cellular networks. As a result, the FCC has put it back on the table for possible reallocation to unprioritized unlicensed use (Alleven, 2018a).[4]

The discussion over the 5.9 GHz band demonstrates the need for more literature to help policymakers explore the options for how to best approach spectrum allocation policy going forward (Lofquist and Reed, 2018). In fact, the outcome may well set a precedent for discussions of other frequency bands, having a lasting implication for future policy. The questions raised by the 5.9 GHz band are being considered not just in the United States but across the globe: Alongside the United States, other countries are determining which frequency bands to harmonize and allocate toward fifth-generation (5G) use (Bhattarai et al., 2016). This report seeks to provide a new data point for that conversation.

This study had several core objectives:

- Estimate the potential economic value of an unlicensed frequency band that is currently under discussion for reallocation.
- Understand the trade-offs associated with realizing this potential value, in terms of existing and future trends and policies and in terms of how this spectrum could be allocated.
- Provide a new perspective on the current discourse surrounding unlicensed spectrum allocation policy.

This report is structured as follows. Chapter 2 explains the motivation for and policy relevance of this study. Chapter 3 provides a primer on measuring economic value, along with the challenges inherent in estimating the potential economic value of spectrum, and explains our methodological approach to valuation. Chapter 4 explores the potential net effect on our estimates of the inherent trade-off that comes with repurposing DSRC-allocated spectrum. Chapter 5 describes our first approach to estimating contribution to gross domestic product

[3] See, for example, Lehr (2004).

[4] In keeping consistent with the original FCC press release establishing the DSRC set-aside, this report will use *5.9 GHz band* to refer to the collective frequency band between 5.850 GHz and 5.925 GHz.

(GDP), and Chapter 6 describes our second approach. Chapter 7 provides our estimates of consumer surplus and producer surplus, and comparability with our other estimates. Chapter 8 discusses the potential implications of current policies and regulations on these estimates. Chapter 9 explores the options for allocation of the 5.9 GHz frequency band and the effect on potential economic value, along with associated trade-offs. Chapter 10 concludes.

2. Policy Importance of Unlicensed Spectrum

The issue of how and how much unlicensed spectrum is allocated for public use is of increasing importance because of the tremendous growth in wireless internet-enabled devices and demand for online data. There are currently about 310 million data-enabled mobile devices connected to the internet in the United States—roughly equivalent to 94 percent of the U.S. population (CTIA, 2017b). As broadband connections have become faster and more ubiquitous, ownership of smartphones and tablets has exploded. A 2015 Pew Research survey found that 68 percent of Americans owned a smartphone in 2016, up from just 35 percent in 2011. Ownership of tablets has likewise jumped, from just 4 percent of Americans in 2010 to 45 percent in 2015 (Anderson, 2015).

Alongside the rapid growth in mobile device adoption is a corresponding growth in demand for data. In 2016, smartphones generated an average 3.87 GB of data per month, an increase of 1,400 percent since 2010. Total wireless data traffic reached 13.72 trillion MB in 2016, up 238 percent in just two years (CTIA, 2017a), with Americans now spending an average of 5 hours per day on their mobile devices (Perez, 2017). Over half of American households have formally cut the cord to their landline telephones, relying solely on mobile devices for communication (CTIA, 2017a).

Moreover, this proliferation of mobile devices, and the corresponding increase in online data consumed, is forecast to grow with 5G network deployment. Technology company Ericsson, for example, predicts that smartphones in North America will see average monthly data consumption rise from an estimated 5.1 GB/month at the end of 2016 to a staggering 25 GB/month by 2022 (Ericsson, undated). Cisco's Visual Networking Index predicts that global mobile traffic will increase at a compound annual growth rate of 47 percent though 2021, at which time three-quarters of all mobile data traffic will be high-bandwidth video (Cisco, 2017). Cisco also predicts strong growth in demand for WiFi—which uses unlicensed spectrum—as a vehicle for cellular traffic offload given the rise in data consumption.

The steady growth in wireless data demand and WiFi device interconnectedness has led to growing congestion of WiFi networks, however (Obiodu and Giles, 2017). The 2.4 GHz band, typically used for consumer products such as garage door openers, microwaves, and Bluetooth, has been the dominant band for carrying WiFi traffic across devices. That band is now increasingly saturated; the 5 GHz band, used for home routers, game consoles, and other devices that require high-speed WiFi connections, is able to relieve some of this traffic but remains at risk of becoming similarly overcrowded.[5] The increased demand for WiFi and need for

[5] See, for example, Alderfer (2013) and De Vries et al. (2013) for context.

additional unlicensed spectrum in the future has been quantified in studies from the WiFi Alliance and Qualcomm (WiFi Alliance, 2017; de Vegt et al., 2017). These studies find that, given the saturation of the 2.4 GHz band, and the extensive reliance on the 5 GHz band, the United States will face a spectrum shortfall by 2025.

The ongoing policy discussion surrounding the best use of the 5.9 GHz band exemplifies how regulators continue to grapple with the conventional top-down allocation framework (Lowy, 2017). Although it was intended for DSRC for V2V operations, few automobile manufacturers are using it. Instead, several major automakers are publicly pushing for 5G networks as the primary mode of V2V communication (Bliss, 2018). This is playing out in federal policy circles as well: While the National Highway Traffic Safety Administration is in the process of finalizing informal guidelines for DSRC (National Highway Traffic Safety Administration, 2017), the FCC is considering a possible reallocation to public unlicensed use (Alleven, 2018a). Moreover, recent literature questions the efficacy of the current allocation, finding that partitioning the frequency band to permit more WiFi is significantly more efficient than keeping WiFi devices off the band entirely (Bhattarai et al., 2016; Peha and Ligo, 2017).

As technology developments continue to enable new uses for the 5.9 GHz band, and as these conversations are ongoing, understanding the economic and social trade-offs to the current allocation structure is critical to making informed policy decisions. Current spectrum allocation policy struggles to keep pace with the prolific innovation in wireless network technology[6] and the corresponding growth in consumer demand for WiFi-enabled communications.[7] We hope that this study helps advance the question of how to allocate spectrum going forward, given the pace of wireless communications innovation and the projected proliferation in wireless data demand.

[6] A great discussion of the current debates can be found in Bhattarai et al. (2016).

[7] See, for example, Cisco (2016).

3. Measuring the Economic Value of the 5.9 GHz Band

In this chapter, we discuss our approach to measuring the potential economic value of unlicensed spectrum in the 5.9 GHz band. We begin by going over the types of economic measures. We next discuss the challenges in applying these measures to unlicensed spectrum, reviewing the literature on this subject. We then explain how we will approach our estimation, given these challenges.

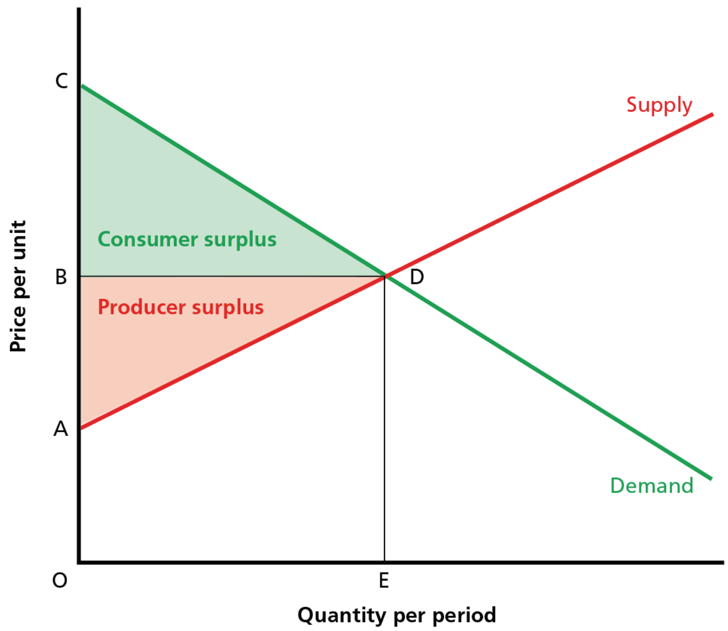
Measures of Economic Value

In measuring economic value, there are several types of possible gains that should be considered. First are the direct gains to GDP. These are gains resulting from direct spending related to the consumption of goods and services in the U.S. economy. For example, the purchase of WiFi-enabled devices such as smartphones and tablets, associated applications, a cellular data plan, and a residential internet package all contribute directly to GDP.

Second are gains to consumers, in the form of consumer surplus. This is a direct benefit to consumers, in that they value a particular good or service at an amount that is greater than what they pay for it. Mathematically, it is the difference between the most consumers would be willing to pay and what they actually pay. If the price is greater than their “willingness to pay,” consumers will not purchase the good or service. This extra value of paying a price less than their willingness to pay is money they could use for additional consumption, saving, or investment that they would not have otherwise had.

A third gain is to producers—market firms that are selling a good or service at a value greater than what it costs to make or provide. These gains go directly to producers. A traditional supply and demand curve, along with associated gains to producers and consumers at the market equilibrium price, is shown in Figure 3.1.

Figure 3.1. Market Equilibrium



Challenges in Measuring the Economic Value of Unlicensed Spectrum

Conducting a traditional economic valuation generally provides its share of challenges, but these challenges are amplified when measuring the potential value of spectrum. To start, spectrum is neither a typical industry nor commodity. It cannot be considered a good or service, it does not have a market in the traditional sense, and it does not represent a single industry's output.

Moreover, along the electromagnetic spectrum, it is arguable whether a given portion of spectrum is a homogenous good (i.e., if the marginal value is constant), which adds to measurement challenges. The actual value of a given MHz of frequency will depend on the modulation scheme that runs on it and the type of device or application that is sending or receiving data. Marginal value is also likely dependent on where in the frequency band it is, if the FCC has imposed restrictions on it. For example, much of the 5 GHz band has dynamic frequency sharing (DFS) requirements that the 2.4 GHz band does not. At the same time, traffic on the 2.4 GHz band has a larger likelihood for interference.

The value of spectrum ultimately lies in its utilization—the ability for it to transmit data and information. That is, the real value of spectrum is in the available data rate and data capacity for a given bandwidth. Higher frequencies will have potentially less interference because the signal does not travel as far, allowing for better data rates (Levi, 2014).

The larger bandwidths and number of channels afforded by the 5 GHz band are what adds to the value of spectrum in that range. Not only can larger-bandwidth channels handle more throughput to, for example, meet the demand of high-definition video with low latency, but more

channels can also accommodate more traffic. Sufficient unlicensed spectrum is essential to meet ever-rising data needs, arising from more video streaming, gaming, cellular off-loading, and the fact that Americans are increasingly spending more time online. There is ample literature on the need for more unlicensed spectrum to meet the demands of a digitally connected world. A study by Ofcom in 2013 explains:

> This [5 GHz] band will become the main high speed WiFi band. In addition to strong general growth there are potentially specific doublings of resource requirements in this band. Firstly this will occur indoors due to concurrent Internet streaming/screencasting; and secondly outdoors due to in-band backhaul of hotspots. . . . There is a need for more contiguous spectrum to support a larger number of wider channels . . . since fragmented spectrum might not allow wider channels to be created efficiently or indeed at all. (Methley and Salsas, 2013, pp. 80, 83)

On top of the complexity associated with understanding the source of value of spectrum, there are also data limitations. There simply are not good data on the use of spectrum in the 5 GHz band versus the 2.4 GHz band, especially in residences, where what happens after the signal enters the house is not publicly available. We know only that the share of traffic on the 5 GHz band is increasing, especially since the introduction in 2013 of the Institute of Electrical and Electronics Engineers (IEEE) 802.11ac standards, which provide high-throughput wireless local area networks on the 5 GHz band.

With this appreciation, the literature on measuring gains specific to unlicensed spectrum and broadband engage in a measurement approach that uses proxies and rough approximation for demand, such as through number of internet-enabled devices and wireless data consumption. This includes studies by Katz (2018), GSMA Intelligence (Lewin, Phillipa, and Nicoletti, 2013), the International Telecommunication Union (Katz, 2012), Thanki (2009), Cooper (2011), and Milgrom, Levin, and Eilat (2011).

These studies offer different approaches to measuring economic value for a market good or service. Typical studies begin by estimating a demand curve for a product and how changes in supply affect equilibrium quantity and price. A robust body of empirical literature exists on measuring an economic benefit to consumers through demand identification and estimation (Berry and Haile, 2016). Economic literature typically is focused on specific industries or products, using microdata on market demand and modeling consumer preferences from consumer surveys or other proprietary sources. This literature also highlights the challenges and limitations associated with demand curve estimation.

The few empirical studies that do employ traditional economic measurement techniques relevant to unlicensed spectrum focus on residential broadband. This is because consumers are explicitly paying for internet access, and therefore it can be treated as a market good with the right data. Goolsbee and Klenow (2006) instead modeled the consumer value obtained from residential internet using time spent online as a key input of consumption, in addition to physical monthly cost. Nevo (2016) used microlevel data on one internet service provider's (ISP's)

consumers to model preferences and willingness to pay for increased monthly data caps and residential internet speeds, estimating an elasticity that we will employ in measuring consumer surplus.

Finally, there is a complementary body of literature analyzing the impact of various facets of the internet—the Internet of Things, the app economy, the gig economy, etc. These studies take a very high-level approach, estimating economic and societal gains from the entire "internet ecosystem"—the interconnection of ISPs and over-the-top service operators, device manufacturers, app developers, and online content creators and distributors. They consider the impact of the internet ecosystem on indicators such as economic growth, trade, wages and productivity, employment, and human capital accumulation. Some studies estimate an aggregate level of revenue or output, or use a multiplier to estimate spillover effects in creating additional indirect revenue or jobs.[8]

Measuring the Economic Potential of the 5.9 GHz Band

In this report, we measure the potential contribution to GDP, consumer surplus, and producer surplus of the 5.9 GHz band were it to be fully reallocated to unlicensed use. To measure this, we must first understand what makes this 75 MHz valuable. We see two ways in which this frequency could generate potential economic gains: (1) It supplies an additional 75 MHz of spectrum for unlicensed use, and (2) it enables the creation of larger-bandwidth channels—80 MHz and 160 MHz channels—because of the proximate unlicensed spectrum in the lower 5 GHz band. This enables both more traffic—from consumer use and from mobile off-loading from cellular networks—and faster data rates (speed) from the larger-bandwidth channels. Aggregating channels would allow for use of 80 MHz and 160 MHz channels in the 5 GHz band through channel bonding (Hintersteiner, 2016). As of mid-2018, one 160 MHz channel is possible in the lower 5 GHz band, but it is not used because of existing DFS requirements.

Of course, we acknowledge that, in addition to the core trade-off of DSRC-allocated use, operating in the 5 GHz band comes with another potential trade-off: At a higher frequency, the 5 GHz band is not able to carry the signal as far at the same radiated power, being more susceptible to drop-off and attenuation. The quality of service depends on how close the device is to the router or wireless mesh connection (Radio-Electronics.com, 2018). Moreover, as wireless devices expand the channel sizes in use, larger channels compete against the smaller channels they subsume when used in areas of heavy digital congestion.

In measuring the contribution to GDP, we exploit the two ways in which the 5.9 GHz band creates potential value: Approach 1 measures the contribution to GDP resulting from higher speeds enabled by increased channel bandwidth, and Approach 2 measures the direct potential

[8] For example, see Adler (2018), Entner (2016), Bazelon and McHenry (2015), and GSMA (2016).

value of the 75 MHz as a stand-alone frequency band. Approach 1 emphasizes the fact that the value of the 5.9 GHz band is to create an additional 80 MHz channel and the first 160 MHz channel not subject to DFS and is therefore more reliable. Having this extra bandwidth will increase the data rate at which consumers can access and consume online content. Approach 2 considers the theoretical data traffic and associated device count by device type that can be carried over 75 MHz. It then monetizes this in terms of data revenue to ISPs and revenues from device sales using average prices. We employ both approaches because of the difficulties associated with estimating the value of unlicensed spectrum.

We next provide estimates of potential consumer and producer surplus. We estimate potential consumer surplus in two ways, one that is provided in Chapter 7 and one that is presented in Appendix C. For the approach we use in the main report, we base our willingness to pay for an additional megabit per second (Mbps) of broadband speed on previous empirical research. We use a similar methodology as employed in Approach 1 for our estimate for contribution to GDP, this time looking at the gains to consumers from having faster speeds enabled by higher-bandwidth channels. Implicit in this estimate is an assumption that the price that consumers pay for WiFi is unchanged, so that they paying the same price but enjoying all of the gains in speed that their willingness to pay suggests they would have paid more for. The estimate presented in Appendix C corrects for this by using a more traditional economic measurement approach. It assumes an isoelastic demand function that allows the price that consumers pay for WiFi data to decrease as the data rate enabled by larger-bandwidth channels increases. Our estimate for producer surplus treats producers as consumers in an input market (for spectrum) instead of as producers in an output market (provision of wireless broadband services). We use the 2016 FCC Incentive Auction as a way to measure what producers are willing to pay for a MHz of spectrum and, therefore, their potential valuation of what additional spectrum is worth given their business models.

Our estimates are preliminary and should be regarded as such. In particular, our estimate of producer surplus should be viewed as only a start. The potential gains to producers from reduced operating expenditures is an area ripe for future research.

Focus on Residential WiFi Usage

For Approach 2 in our estimate of contribution to GDP and for our estimates of consumer surplus, we focus on residential WiFi consumption. Generally, wireless access happens across four domains:

- residential (including hotspots accessed through a residential account)
- business
- cellular off-loading
- public.

There is little publicly available data that disaggregate WiFi traffic. However, Table 3.1 lists Katz's (2018) estimates of the share of wireless data traffic by location, for personal devices that rely on a wireless connection.

Table 3.1. Daily Share of Traffic and Time Spent on Wireless Internet, 2017

Location	Hours	Share (%)
Home	2.60	43.12
At work	0.80	13.27
On the go	0.60	9.95
Public location (parks, schools)	0.45	7.46
Travel locations	0.45	7.45
At work remote location	0.40	6.63
Retail location (stores, restaurants)	0.38	6.30
Friend's home	0.35	5.80
Total	6.03	100.00

SOURCE: Katz, 2018.
NOTE: Includes smartphones, tablets, and game consoles.

These data show that, between one's own home and a friend's home, about half of WiFi access occurs through a residence. This could be larger if some of the "on the go," retail, or public locations include access through a residential hotspot, the availability of which are growing rapidly.

Katz (2018) further estimates that the economic contribution from public WiFi (e.g., "free" WiFi) is relatively small, while the potential gains to consumers and the economy from residential use are large. Economic benefits stemming from residential use of WiFi represent the largest segment of current value according to Katz: about 50 percent of the total estimated value in 2017, and forecast to increase to 60 percent of total value by 2020. Moreover, from a practical measurement perspective, residential access is also reflective of the true value that consumers get from WiFi, since it is the access they most directly pay for (via their monthly internet plan). Therefore, because of the prominence of residential WiFi in terms of access points generating the most economic value, we focus on residential WiFi when appropriate and apply a 0.43 conversion share when appropriate. We note that this is arguably a more conservative approach, since enterprise WiFi is not included.

4. Trade-Off of DSRC-Allocated Spectrum

The economic estimates provided in this report come from raising the question: What if spectrum in the 5.9 GHz band were fully reallocated to open unlicensed use? That said, any potential value to the economy, consumers, and producers derived from this assumption comes with a trade-off. That is, the true potential value would be at the expense of the potential value of the DSRC V2V and vehicle-to-infrastructure (V2I) market.

Estimating the potential value of DSRC is complicated. To date, one automobile manufacturer, General Motors, has incorporated technology into its Cadillac model that uses the DSRC-designated frequency. Two additional manufacturers, Toyota and Lexus, have also announced plans to incorporate the DSRC band into their V2V communications in the coming years. At the same time, other automobile manufacturers are using cellular networks for their V2V communications and embedded technologies.

Still, proponents of the current DSRC allocation argue that DSRC is essential for saving lives by preventing traffic fatalities. Advocates argue that, because spectrum is increasingly hard to come by, the industry should harness the fact that there is spectrum already dedicated explicitly for this purpose (Winfree and Head, 2018).

Given the uncertainty in the direction of the market, industry players are hedging their bets. Qualcomm, for example, is developing both approaches to V2V technologies (DSRC and cellular networks) in parallel (Alleven, 2018b). States such as Colorado are also planning their modern transportation infrastructure to be compatible with both approaches. Meanwhile, the National Highway Traffic Safety Administration had been in the process of establishing V2V guidelines that codify the use of the DSRC band for autonomous vehicles, but a recently issued report suggests that the agency is advocating for V2V communications that are technology-neutral (National Highway Traffic Safety Administration, 2018). The implication is that the agency instead seeks to provide informal guidance for manufacturers using DSRC.

The relatively limited launch of V2V technology using the DSRC band in the United States means the current economic market value of such technology is likely small.[9] One recent report found that the U.S. DSRC market was forecast to reach a value of $12.2 million by 2023, at a compound annual growth rate of 11.92 percent (EIN Presswire, 2018). This suggests that the 2017 U.S. market value of V2V technologies was approximately $6.2 million.

Of course, there are also social aspects that could increase the value of V2V communications—and therefore the potential value of DSRC spectrum that must be acknowledged. Reducing injuries and fatalities from traffic accidents provides important value to

[9] The use of a DSRC frequency band in some other countries, including China, is higher.

society, which will likely increase with greater adoption of V2V and V2I technologies. For example, the U.S. Department of Transportation released several studies and congressional testimony (e.g., Beuse, 2015) looking at the potential reduction in accidents and automobile-related fatalities that V2V could enable. A 2014 U.S. Department of Transportation study (Harding et al., 2014) that accompanied its initial DSRC rule establishing a V2V standard estimated that V2V technologies could reduce crashes by up to 412,000–592,000 annually, assuming 100 percent vehicle adoption and after 36 years of implementation. A separate study (Kockelman and Li, 2016) considered the potential benefits of connected and automated vehicle technologies and estimated that Americans could save $76 billion per year in reduced costs associated with collisions, along with almost 740,000 functional-life-years saved per year.

However, these estimates, although important, are also subject to measurement issues for the purposes of inclusion in this study, for three reasons. First, there is the large range of estimates that make up the literature, which is suggestive that there are still uncertainties around a single estimate appropriate for use. One study by researchers at Carnegie Mellon University and University of Pennsylvania, for example, estimate the range of potential net benefits of connected and automated vehicle technologies to be between $4 billion and $216 billion (Hendrickson and Harper, undated). Second, there is the potential for sizable measurement range and error when considering the value of a statistical life, which could be rather subjective.[10] Third, and perhaps most pressing for this study, it is difficult to attribute these values entirely to DSRC spectrum, because V2V and V2I communications can, and sometimes do, run over cellular networks.

One way to incorporate the trade-off of the V2V and V2I market value would be to subtract it from our estimates of contribution to GDP from reallocation to reduce the additional potential value. However, because of the wide range in forecasted value of the V2V and V2I technologies market, over long time horizons, along with uncertainty in the estimates of social value, we do not pursue that calculation here. Given the limited data on consumption of these technologies, and their limited production, we also do not pursue measures of consumer and producer surplus. We instead note qualitatively that the potential value of V2V and V2I technologies, were they to gain momentum using the DSRC-designated spectrum, could reduce any estimates of the net potential economic value of repurposing the 5.9 GHz band. This is also qualitatively true for other regulatory and policy issues we consider in this study that could affect our findings.

[10] Other literature also points out difficulties associated with this type of measurement. For example, see Bazelon and Figurelli (2016).

5. Contribution to GDP—Approach 1

Approach 1: Aggregate Contribution from Larger-Bandwidth Channels

This approach considers the current potential contribution to GDP of all possible value from applications and devices, across all types of WiFi access points. The estimation of the potential value comes from looking at returns to speed obtained through the larger bandwidth availability afforded by aggregating unlicensed spectrum in the proximate band, enabling additional 80 MHz and 160 MHz channels.

Effect of Internet Speed on GDP

To estimate the contribution of GDP from increased bandwidth channels, and the resulting increase in data rate (speed), we first need to understand the impact of speed on GDP. In other words, we need to measure the elasticity of demand for internet speed. This report provides a new measure for the United States. This estimate is at the state level, which we extrapolate to the national level.

The current widely cited measure of the impact of speed on economic growth is from a 2012 paper by Rohman and Bohlin, which estimates elasticity from speed to be about 0.3 percent. That is, a 100 percent increase (or doubling) of speed corresponds to a 0.3 percent increase in GDP. Rohman and Bohlin arrived at this estimate using data over two years on average speeds across 38 Organisation for Economic Co-operation and Development (OECD) countries (about 72 observations). They employ a fixed effects regression design with two-stage least squares, using penetration rate as an instrument for speed in the first stage to resolve issues related to endogeneity (Rohman and Bohlin, 2012).

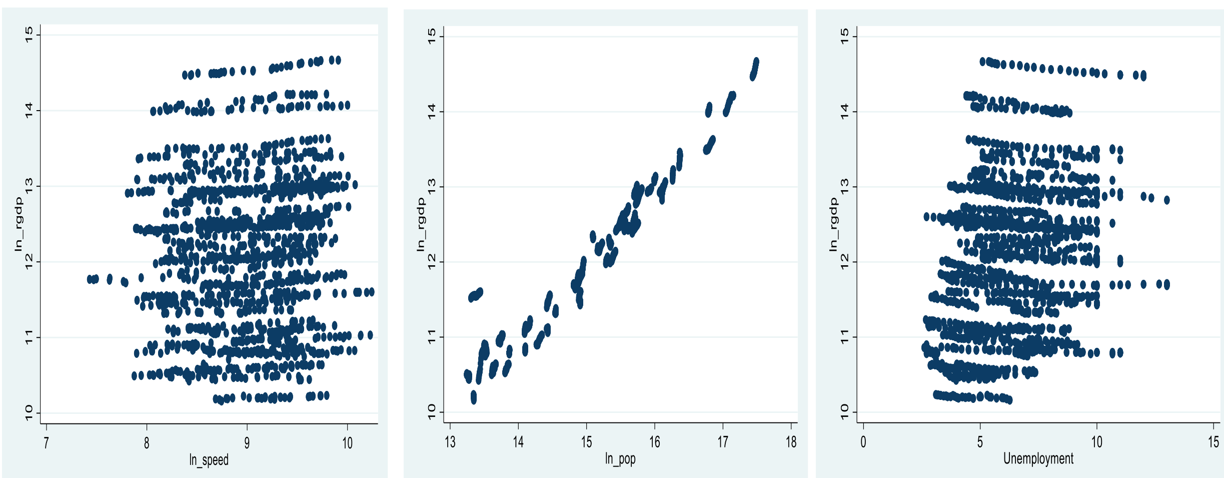
Rohman and Bohlin's analysis demonstrates that this is not an easy measure to compute. There are several ways in which their estimate—in addition to using older data and not being specific to the United States—is problematic. For example, there is not enough power for a fixed effects design in the number of available observations, which could lead to bias in the estimates. The instrument used for speed is also not valid, as an analysis of U.S. data shows that the residential internet penetration rate is highly correlated with GDP. Moreover, the justification for using the coefficient on the independent variable of the square of speed for the elasticity seems arbitrary, which is then multiplied by 2 before being multiplied by 100 to reflect the doubling of speed.

Similar to Rohman and Bohlin, we employ a panel data fixed effects regression design. Panel data consist of multiple observations over multiple periods of time. A fixed effects regression design assists in controlling for unobserved, omitted variables that are constant over time. We also include non-fixed controls to reduce bias in our estimates. Several foundational papers

discuss this regression approach, and its role in causal inference.[11] Our model includes 1,450 observations, spanning all 50 states plus the District of Columbia for 29 quarters covering 2010 through the first quarter of 2017 (2017Q1). Data on average bandwidth (speed) by state was provided by Akamai Research, a content delivery network and cloud service provider, as published in its "State of the Internet" quarterly reports (Akamai Research, undated). We obtained state-level data on real GDP and population from the U.S. Bureau of Economic Analysis, and unemployment rate data are from the U.S. Bureau of Labor Statistics.

An initial exploratory analysis revealed the correlation graph in Figure 5.1. Interestingly, average speed and real GDP have a correlation of 0.0634, which is relatively low. Correlations among our variables of interest are graphed in Figure 5.1, where "ln_rgdp" is the natural log of real GDP, "ln_speed" is the natural log of average speed, "ln_pop" is the natural log of the population, and "Unemployment" is the unemployment rate.

Figure 5.1 Correlation Among Variables of Interest



Having sufficient variation in average speed is essential for this type of statistical analysis. From our exploration, we believe the variation in average speed from the mean across states over the 2010–2017Q1 period is sufficient.

However, once we control for linear variation through fixed, time, and interaction effects, which is standard for this type of analysis, the predictive power of average speed on real GDP must then come from nonlinear trends. To explore this, we take a deeper look at the variation within average speed. Figure 5.2 shows the variation of average speed by states over time relative to the mean of average speed across all states.

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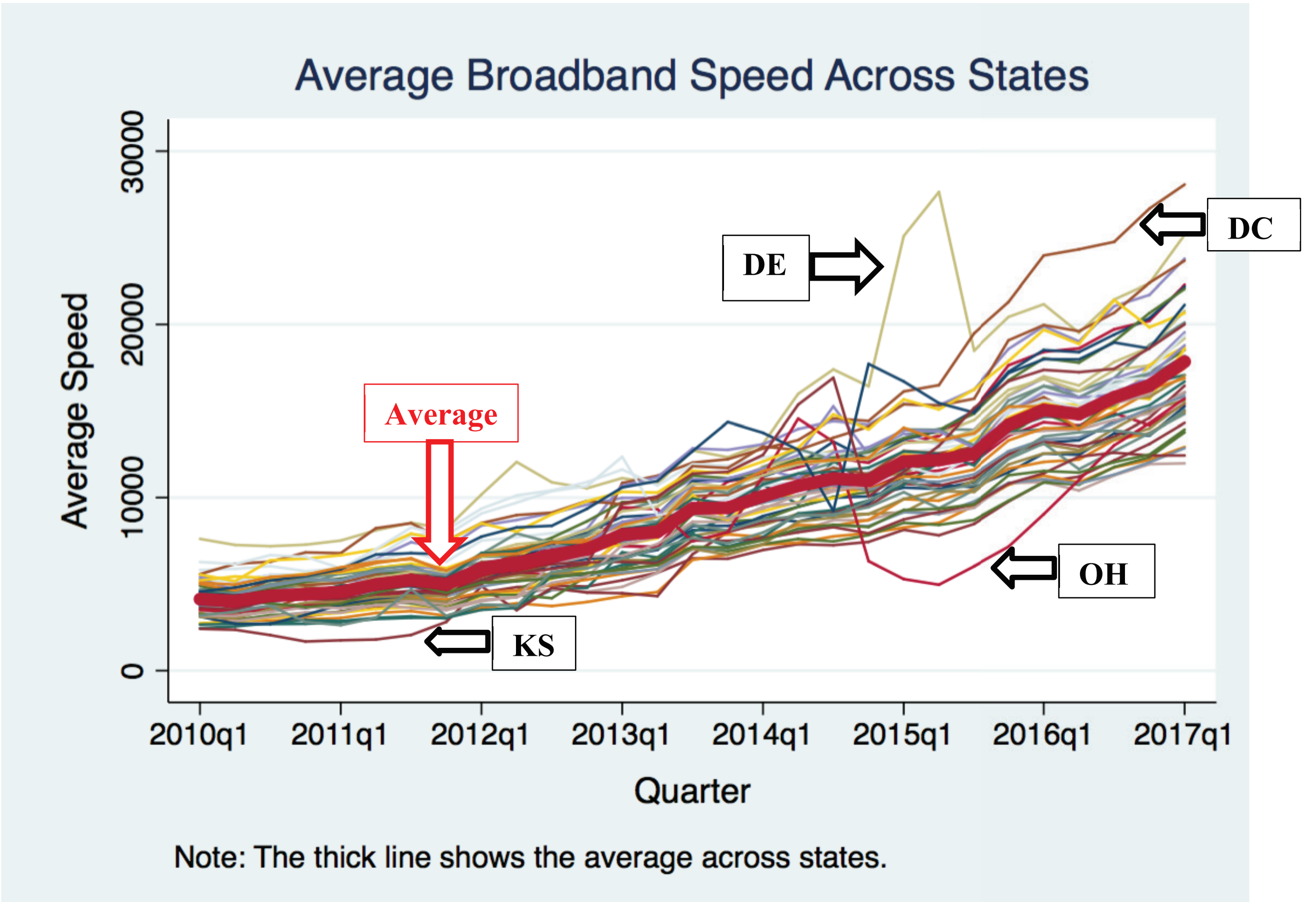
[11] For more information on panel data fixed effects regressions, and on causal inference regression design, see Wooldridge (2002) and Allison (2005).

Figure 5.2. Variation in Speed Relative to Average Speed Across All States over Time



Using this graph, we identified four states that could be potential outliers in terms of variation. Three states—Delaware, Ohio, and Kansas—demonstrate large deviations from the mean relative to other states at various points in time (e.g., variation outliers). The fourth "state" is the District of Columbia, which demonstrated a much faster growth in average speed than any of the 50 states (e.g., temporal trend outlier).

With this enhanced understanding of our predictor, average speed (avgbw), we run multiple model specifications to check for the robustness of our estimate of speed elasticity. This includes model specifications using per capita measures, excluding the above identified outliers, using a quarter lag for speed, and an instrumental variables (IV) approach using lags of speed as instruments for speed.[12]

[12] See Angrist and Pischke (2009) for a detailed discussion of instrumental variables regression design and its importance in addressing selection bias for making causal inference.

Ultimately, our model of choice is an ordinary least squares model specification represented by

$$\ln\_GDP_{it} = \beta_0 + \beta_1 \times \ln\_speed_{it} + \beta_2 \times \ln\_population_{it} + \beta_3 \times unemployment\_rate_{it} + \delta \times State_i + \varphi \times Time_t + \Psi \times (State \times Time)_{it} + u_{it}.$$

In this model (the first of seven), the dependent variable is the natural log of real GDP ($\ln\_GDP_{it}$). Independent variables are the natural log of speed (ln_speed), natural log of population (ln_pop), unemployment rate (unemployment_rate), state fixed effect (State), time effect (Time), and an interaction fixed effect (State × Time).[13] β_1 is the coefficient of interest, representing the elasticity of speed, and the remaining independent variables are included for controls. Effects are represented as δ, φ, and Ψ, which are the variables for fixed, time, and interaction effects, respectively. We use heteroskedastic-robust errors for the residual, u_{it}, clustered by state. We ran a Hausmann test to confirm the use of fixed effects over random effects, and F-tests confirmed the significance of including all three fixed and time effects in the model. This model also has the lowest Akaike information criterion (AIC) and Bayesian information criterion (BIC), which indicates a superior goodness-of-fit.[14]

The specifications for our seven models are as follows:

1. Model specification detailed above.
2. Same specification as Model 1, except the dependent variable is the natural log of per capita real GDP, so that population is not included.
3. Same model specification as Model 1, except adding another predictor for the natural log of the number of unique IP address counts (ln_ipcount).
4. Same specification as Model 1, except using the natural log of a one quarter lag of average speed (ln_speed1) instead of the natural log of average speed.
5. Same specification as Model 1, except variation outlier states (Delaware, Ohio, Kansas) removed.
6. Same specification as Model 1, except temporal trend outlier state (Washington, D.C.) removed.
7. A two-stage least squares IV approach using one quarter, two quarter, and one year lags of speed as instruments for average speed (ln_speed_IV).

The results of each of our seven models are presented in Table 5.1. In the table, coefficients are presented in the first row of each independent variable, and their respective standard errors are provided in parentheses below.

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[13] There will be 50 fixed effects for states, one for each state (51) minus one for the base case to avoid multicollinearity in the variable. Similarly, there will be 28 time effects, one for each quarter (29) minus one for the base case.

[14] AIC and BIC are two measures of regression goodness-of-fit commonly used to determine the best model specification. The lower the values are relative to the other model specifications, the better the relative fit.

Table 5.1. Model Specifications for Elasticity of Speed: Coefficients and Standard Errors

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln_speed	**0.0197****	**0.0193****	**0.0171***		**0.023***	**0.0207****	
	(0.0092)	(0.0095)	(0.0087)		(.0134)	(.0095)	
ln_speed1				**0.0198****			
				(0.0084)			
ln_speed_IV							**0.0222****
							–0.0102
ln_population	3.027**		3.035**	3.129**	3.041**	3.164**	3.362**
	(1.065)		(1.077)	(1.161)	(1.073)	(1.085)	(1.192)
unemployment_rate	–0.0084*	–0.0084*	–0.0085*	–0.0079*	–0.0079	–0.0081*	–0.0068*
	(0.0044)	(0.0044)	(0.0044)	(0.0044)	(.0048)	(.0043)	(0.0039)
ln_ipcount			–0.0039				
			(0.0077)				
N	1,450	1,450	1,450	1,400	1,363	1,421	1,250
R^2	0.9998	0.9961	0.9998	0.9998	0.9998	0.9998	0.9998
AIC	–7980.63	–7841.27	–7980.19	–7787.75	–7471.17	–7812.53	
BIC	–7822.25	–7688.17	–7816.53	–7635.66	–7314.65	–7654.76	

NOTE: Bolded values are the values on the coefficient of interest (β_1) for each model specification. For simplicity, Fixed, Time, and Interaction Fixed × Time Effect coefficients are not reported here.
**Denotes statistical significance at the 0.05 significance level; *Denotes statistical significance at the 0.10 significance level.

For Model 7, our IV model, the first-stage least squares regression has the following specification: $\text{ln\_speed}_{it} = \beta_0 + \beta_1 \times \text{ln\_speed}_{it-1} + \beta_2 \times \text{ln\_speed}_{it-2} + \beta_3 \times \text{ln\_speed}_{it-4} + \varepsilon_{it}$, where independent variables are the first, second, and fourth lag of speed and ε_{it} is the residual. The joint coefficient F-statistic is 82.66, implying the instruments are statistically significant predictors for the natural log of average speed at the 0.05 significance level.

Our primary estimate for the elasticity of speed suggests a 1 percent increase in internet speed results in a 0.0197 percent increase in real GDP. However, given the log-log functional form, this is not a linear estimate and holds only for small changes in speed. To estimate the impact of a larger change in speed, such as a doubling of speed, it is appropriate to solve for the resulting change in real GDP, say *a*, by

$\ln(a \times \text{RGDP}) = 0.0197 \times \ln(2 \times \text{Speed}) \Rightarrow a = e^{\ln(2)*0.0197} = 1.0137$.[15] Therefore, a doubling of speed (100 percent increase) results in a 1.37 percent increase in real GDP.

There are many assumptions and possible confounders associated with making causal inference, and this model is no exception. The discussion of this model should therefore be stated as conditional on national-level shocks, permanent differences across states, linear trends in states, and other covariates, as well as differences in broadband speed across states that cause differences in real GDP.

This estimate is much higher than Rohman and Bohlin's estimate, although, as noted, that estimate may not be an appropriate comparison. The fact that Americans and American businesses rely heavily on the internet for daily activities and functions likely is behind this sizable impact. Many jobs involve internet use, as do such leisure activities as social media communication, video streaming, web browsing, and gaming. The continuing digitization of industry also likely enhances the importance of the contribution of speed to GDP, as more processes move online and into the cloud.

Two main confounders must be addressed as they relate to establishing casual inference. The first is issues related to variable selection. Appropriate selection and inclusion of variables is essential in isolating the true effect of average speed. Otherwise, our estimate may be biased. For example, internet speed and real GDP both exhibit a positive trend, but that association does not imply causality. There may be other variables related to both speed and real GDP that explain the relationship. To address this, we include two controls—population and unemployment—as well as our fixed, time, and interaction effect variables to account for common linear trends.[16]

Here the IV specification also provides important validation for our elasticity estimate, because it instruments the relationship of average speed with GDP instead of measuring it directly. These requirements ensure that there is no endogeneity in the model that could bias the elasticity estimate. The requirement for an adequate instrument is that it is correlated with the predictor (speed) but not correlated with the dependent variable (real GDP). As reported, the F-statistic in the first-stage regression indicates that our instruments for average speed are strong. Moreover, having instruments that are uncorrelated with real GDP (known as the "exclusion" restriction) means that the lags of broadband speed affect current GDP only through current average internet speed. This isolates the true effect.[17]

The second main confounder is reverse causality. It is possible that higher GDP could create more income, and therefore a stronger business case for private investment in broadband infrastructure that would then result in higher average internet speed. This could be seen as an

[15] See Benoit (2011) for more.

[16] We acknowledge that if a nonlinear issue in a separate variable is causing this association, and therefore introducing a selection bias, we may not be accounting for that here.

[17] For more discussion on the role of lagging variables in causal inference, see Reed (2015).

issue, since we are using concurrent speed and GDP measures. Our IV specification helps to account for this. We also ran a separate alternate specification where we include average speed lagged by one-quarter instead of current speed. The results are also reported in Table 5.1. Still, we do note a final test we ran that did affect these findings. We split the data into two time periods (2010–2013 and 2014–2017Q1) and reran our model. To ensure the validity of the truncated samples, we ran the models using the IV specification and instrumented speed with its first lag (a one-quarter lag). We found that the coefficients were within the similar range as our primary and other model specifications. However, while the coefficient on speed over 2014–2017Q1 was statistically significant at the 0.05 significance level, the coefficient on speed for the 2010–2013 period was not statistically significant. We attribute this to the limited variation in speed in the beginning years of the sample, while sufficient variation is necessary in this regression design. This can be seen in Figure 5.2. For this reason, we present our findings as the average effect over the 2010–2017Q1 period (as opposed to the effect at a given speed).

Certainly, there are still other confounders that could impact the strength and accuracy of this estimate that are not easy to measure. For example, business migration to "tech hubs" or areas with economic, tax, or other incentives could result in an increase in internet speed through investment and in an increase in real GDP. This estimate would then be overstating the true impact of internet speed alone on real GDP. We acknowledge that such confounding factors could potentially be an issue, but they are beyond the scope of this study.

Contribution to GDP

With this elasticity, we can estimate what the potential contribution is to GDP from the 5.9 GHz band using a methodology developed in Katz (2018).[18] We do this by considering four scenarios. For each scenario, we assume a set allocation of smartphones, laptops, and tablets in use, using the allocation provided by Katz (2018), which estimates the value of unlicensed spectrum in the United States. However, given the available information on these devices, we assume that each of them has the same product specification in terms of WiFi capability and, therefore, potential data rate.[19]

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[18] While Katz (2018) used this methodology for estimating the contribution to GDP from the speed differential of cellular networks versus WiFi networks, we use this method here to measure the contribution of faster speeds enabled by larger-bandwidth channels enabled by the 5.9 GHz band.

[19] Specifically, we assume for scenarios A and B: 2.4 GHz = 20 MHz channel and 5 GHz = 40 MHz channel; two spatial streams (antennas per device); 256 quadrature amplitude modulation (QAM) (modulation scheme); 3/4 bit coding rate; and 400 ns guard interval; for scenario C: Assume 2.4 GHz = 20 MHz channel and 5 GHz = 80 MHz channel; two spatial streams; 256 QAM; 3/4 coding rate; and 400 ns guard interval; for D: Assume 2.4 GHz = 20 MHz channel and 5 GHz = 160 MHz channel; two spatial streams; 256 QAM; 3/4 coding rate; and 400 ns guard interval. For more information on defining these technical specifications, see Appendix A.

Scenario A is the current estimated benefit of 5 GHz, using a standard 40 MHz bandwidth channel and assuming that the majority of traffic still runs on 2.4 GHz. This scenario assumes 80 percent of WiFi traffic from these devices operate on the 2.4 GHz band.[20]

Scenario B is the estimated benefit given an increase in share of traffic moving to the 5 GHz band, adding the assumption that more traffic will move to 5 GHz as the 2.4 GHz band becomes saturated. Scenario B continues to assume the status quo continued in terms of channel availability. The difference between scenarios A and B is approximately the expected future contribution to GDP, given current trends to move traffic to the 5 GHz band but without increasing capacity from what is currently available.

Scenarios C and D demonstrate the potential value of adding in the 5.9 GHz band above what is currently available in the 5 GHz band, through the availability of an additional 80 MHz channel in Scenario C, and through the first 160 MHz channel not subject to DFS in Scenario D. Scenarios C and D also assume that more traffic will move to the 5 GHz band, as in scenario B, for an even split.

Table 5.2 provides the derivation of our estimates using the relevant inputs, and Table 5.3 provides the summary estimates given our findings in Table 5.2. For example, we arrive at $106.3 billion for scenario D through several calculations. First, we find the weighted average speed of WiFi, using the speeds and relative weights associated with our assumptions. We next find the decrease in speed of 2.4 GHz WiFi over the weighted average speed, here 80 percent, and multiply that by our measure for returns to speed for a 100 percent increase, 1.37, to get 1.10 percent. We next multiply this by per capita GDP along with our share of WiFi consumption that is on the 2.4 GHz network, 50 percent, to arrive at our estimate for the per capita value loss from slower speeds (or gain from faster speeds) of $326. We finally multiply this by the population to get total potential contribution to GDP. However, we must subtract the GDP contribution from the 2.4 GHz network to estimate the value from higher speeds.

The difference between scenarios B and D, $59.8 billion, and the difference between scenarios A and D, $96.8 billion, reflect the range of the potential contribution in GDP from adding the ability to create and utilize a 160 MHz channel. Both 80 MHz and 160 MHz channels could be possible through the availability of the 5.9 GHz band for public use, but since the 160 MHz channel provides the greatest potential value, that is the most accurate estimate.

[20] Actual traffic breakdowns by frequency band are not available. The shares considered here are proxied, given that the migration to the 5 GHz band is relatively recent but is expected to continue as more 802.11ac devices come online.

Table 5.2. Estimation of Speed Differential for Total U.S. Traffic (in Mbps)

Scenario Description Relative to A		Increase 5 GHz Weight; Channel Bandwidth Stays 40 MHz	Increase 5 GHz Weight and Channel Bandwidth to 80 MHz	Increase 5 GHz Weight and Channel Bandwidth to 160 MHz
	Scenario A	**Scenario B**	**Scenario C**	**Scenario D**
Average speed of 2.4 GHz	173	173	173	173
Average speed 5.0 GHz	360	360	780	1560
Average speed of weighted average	211	267	477	867
2.4 WiFi weight	0.8	0.5	0.5	0.5
Speed decrease (average speed of 2.4 GHz/average weighted average speed)	–17.73%	–35.01%	–63.64%	–80.00%
Model coefficient	1.37%	1.37%	1.37%	1.37%
Decrease in real GDP per capita	–0.24%	–0.48%	–0.87%	–1.10%
GDP per capita (current prices)	59,483	59,483	59,483	59,483
5 GHz traffic (% Total WiFi Traffic)	20.00%	50.00%	50.00%	50.00%
Per capita GDP reduction (current prices)	–29	–143	–259	–326
Population	325,983,000	325,983,000	325,983,000	325,983,000
Total contribution	**$9.4 billion**	**$46.5 billion**	**$84.5 billion**	**$106.3 billion**

Table 5.3. Range of Total Additional Contribution to GDP from 5.9 GHz

	2017 C	**2017 D**
Difference from B	$38.0 billion	$59.8 billion
Difference from A	$75.1 billion	$96.8 billion

There are several points worth mentioning related to these estimates. First, adding other devices that require higher bandwidth for wireless functionality, such as gaming consoles and virtual reality/augmented reality equipment (should wireless capabilities become mainstream), would increase the weighted average speed possible in larger-bandwidth channels. Therefore, the contribution to GDP would be potentially larger. Second, as population increases over time, the potential value over time will also increase. This can be demonstrated by extending these estimates out using projections of real GDP per capita and population.

Finally, there is still more to this potential value not being considered here. This focus on returns to speed does not consider the increased revenue from device sales and internet service plans. This is because it is difficult to say with certainty the magnitude by which increased capacity will result in increased device production and sales. (We do attempt to estimate a

hypothetical amount of devices the additional capacity would enable in our second approach, however.) We also do not consider the intangible value of information accessed through WiFi, which could be significant depending on the individual, information source, and intended use. We note correspondingly that this could result in our estimates understating the true value.

Analysis not presented here also shows the influence of speed on number of connected devices. There is a strong correlation between internet speed, number of connections, and data consumption. This suggests a potential multiplier effect on the value of increased bandwidth capability, which translates into more gains for consumers in terms of economic growth and welfare. There are important economic contributions from investment from ISPs and mobile operators investing in capital expenditures related to deploying that frequency. This investment further benefits device hardware manufacturers and software developers, along with edge providers operating their own content development networks, such as Amazon and Netflix. It also benefits commercial enterprises that benefit from WiFi, such as online retailers.

Sensitivity Analysis

Sensitivity analysis considers the impact of changing the underlying assumptions on the estimated potential economic value. That is, how advancements in technology (modulation and coding scheme [MCS] factors identified in Appendix A) and changes in other economic or demographic factors affect the above estimations. For example, we can change any or multiple factors affecting data rate: the modulation scheme, number of spatial streams (antennas) per device, bit coding rate, or length of guard interval between data transmissions.

Given that each of the above technologies affects the theoretical data rate, applying the same technologies across all scenarios will not affect the estimated contribution to GDP. For example, given the technical specifications of mobile devices defined in Appendix A, moving from a 3/4 coding rate to a 5/6 coding rate will not change the estimated contribution to GDP, as long as it is applied across all bandwidth estimates. Similarly, changing from one spatial stream to two spatial streams will not change the estimated contribution to GDP as long as it is consistently applied across scenarios.

The same also holds even if we consider a change in technological capability by type of device (e.g., smartphone, tablet, and laptop). While this would affect the theoretical data rate, it affects the estimated GDP contribution only if we do not apply the same underlying technological assumptions across bandwidth calculations. For example, if smartphones had one spatial stream while tablets and laptops each had two, all else equal, the contribution to GDP would not change if this assumption was applied across all bandwidth calculations.

Changing the underlying technological assumptions across bandwidth estimates in a way that is not consistently applied would affect the contribution to GDP. For example, all else equal, if for some reason the guard interval was longer for a 20 MHz channel than for a 40, 80, or 160 MHz channel, that would affect the ratio by which the data rates are higher for the wider

channels relative to smaller bandwidth channels. This difference would increase the speed differential and therefore total contribution to GDP and is presented as Scenario 1 in Table 5.4.

Finally, potential contribution to GDP will also change with population growth and GDP growth over time. To demonstrate this, it is possible to estimate potential contribution to GDP using the same approach as above, using 2023 forecasted population and GDP as provided by Katz (2018) as an example. All else equal to the baseline assumptions, the potential contribution to GDP would be sizably more than what current estimates suggest. The results of these two scenarios are presented as Scenarios 2 and 3, respectively, in Table 5.4.

Table 5.4. Sensitivity Analysis for Approach 1 Under Three Scenarios

	A	B	C	D
Scenario 1: Devices operating in 2.4 GHz band have an 800ns guard interval compared with 400 ns guard interval in 5 GHz band				
Average speed of 2.4 GHz	156	156	156	156
Total contribution	$11 billion	$52.5 billion	$88.5 billion	$108.7 billion
Potential contribution	D – B	$56.2 billion	D – A	$97.7 billion
Scenario 2: Population growth to projected 2023 level				
Population	339,709,530	339,709,530	339,709,530	339,709,530
Total contribution	$9.8 billion	$48.5 billion	$88.1 billion	$110.7 billion
Potential contribution	D – B	$62.3 billion	D – A	$100.9 billion
Scenario 3: Per capita GDP growth to projected 2023 level				
GDP per capita ($)	71,805	71,805	71,805	71,805
Total contribution	$11.4 billion	$56.1 billion	$102.0 billion	$128.3 billion
Potential contribution	D – B	$72.1 billion	D – A	$116.9 billion

6. Contribution to GDP—Approach 2

Approach 2: Valuation of Additional Capacity

This approach focuses directly on the potential economic value created from opening an additional 75 MHz under given assumptions and conditions. This includes technical assumptions related to device specifications, modulation scheme, bit coding rate, and guard interval, which are defined in Appendix A. It also includes assumptions related to device data consumption rates, average price per gigabyte of data, and number of households impacted. The shift to technology-driven capacity evaluation reflects a core belief that technological advances and spectrum availability each contribute toward optimal utilization of frequency.

This approach considers the potential additional capacity and equivalent value for the following device categories:

- fourth-generation (4G) smartphone
- tablet
- smart home devices
- laptop
- gaming console
- virtual reality system
- fifth-generation (5G) smartphone.

Estimates are provided from two perspectives: (1) using the share of total monthly traffic per device type ("load share"), and (2) using the share of total number of devices by device type. We scale these numbers by the number of internet-enabled households in the United States. We note upfront that this approach assumes constant data consumption by using the average monthly data traffic per device—that is, traffic consumption is an average rate over the course of the month, without stating any variation in hourly or daily consumption. This approach also assumes a standard household, not differentiating household size or data consumption rates among residents.

Using these characteristics and the Nyquist theorem (which relates data throughput capacity to bandwidth) we can determine how much bandwidth each device would require per 20 MHz channel it's apportioned to. Design specifications of the seven representative wireless devices in terms of the unique telecommunication engineering features of those devices (e.g., modulation scheme, bandwidth, spatial streams) are provided in Appendix C. From them, we can determine how many new devices could be added without overburdening the new channels. This assessment is representative of the resource allocation taking place electronically when a new device is added to the current wireless infrastructure of the United States previously discussed.

Since there are an infinite number of combinations by which new devices could be added, we used the ratios of existing network traffic by device, as well as the ratios of existing number of devices fielded, to guide our allotments. This assumes that the relative popularity of these devices remains reasonably constant over our analytic time horizon and the additional bandwidth does not create a disproportionate demand for devices. A sample analysis is described in detail, followed by an expansion to the findings for all seven devices. Using 4G smartphones as an example,[21] we observe the following characteristics:

- two spatial streams
- 80 MHz channel bandwidth (4 x 20-MHz channels, bonded)
- 256 quadrature amplitude modulation (QAM), 5/6 coding rate, 400 ns guard interval
- 802.11ac compliant.

Per the MCS Index,[22] this configuration provides a maximum data rate of 866 Mbps. Using Nyquist's theorem to find the total bandwidth requirement for this data capacity:

$$C_t = 2 * B_t * log_2 M$$

$$866 = 2 * B_t * log_2 256.$$

This yields a total bandwidth of 54.125 MHz. Given the 2 spatial streams and 4×20 MHz channel width, the total bandwidth is spread across 8 (2×4) assigned channels. Therefore, 54.125/8 = 6.77 MHz per 20 MHz channel is accounted for by this device.

Repeating this for all devices yields the results in the far-right column of Table 6.1.

[21] We draw on the specifications for the Apple iPhone X, obtained in mid-2018 from http://www.apple.com/iphone-x/specs/.

[22] The MCS Index is a website (http://www.mcsindex.com) that lists a standardized set of modulation and coding schemes (hence, MCS) based on IEEE standards.

Table 6.1. Per-Channel Bandwidth Apportionment (20 MHz Channels)

Device	As-Designed Channel Bandwidth, MHz	As-Designed Data Rate, Mbps	Nyquist Bandwidth Requirement, MHz	Channel Assignments Required	Per-Channel Requirement, MHz
4G smartphone[a]	80	866	54.125	8	6.77
Tablet[b]	80	866	54.125	8	6.77
Smart home devices[c]	40	300	25	4	6.25
Laptop[d]	40	450	37.5	6	6.25
Gaming console[e]	40	300	25	4	6.25
Virtual reality system[f]	*160*	*7200*	360	48	*7.50*
5G smartphone[g]	40	1000	50	6	8.33

SOURCES AND NOTES: We obtained specifications for the following devices in mid-2018:
[a] Modeled after the Apple iPhone X: http://www.apple.com/iphone-x/specs
[b] Modeled after the Apple iPad 9.7: http://ebookfriendly.com/ipad-2017-tablets-tech-specs-comparisons
[c] Modeled after the Amazon Echo: http://www.amazon.com/gp/help/customer/display.html?nodeId=201549640
[d] Approximated by the Killer Wireless-N modem card: http://www.avadirect.com/killer-wireless-n-1103-wireless-card-ieee-802-11a-b-g-n-Internal-PCIe-Half-Mini-Card/Product/5528552
[e] Modeled after the Sony Playstation 4: http://www.playstation.com/en-gb/explore/ps4/tech-specs
[e] VR systems have not achieved the highest data rates through wireless connectivity. For more information on how we approximated this, please see "Virtual Reality Systems" in Appendix B.
[g] Modeled after the Samsung Galaxy S8: http://www.samsung.com/global/galaxy/galaxy-s8/specs

Next, we determine the traffic load share percentage for each device. This is simply the percentage of total wireless residential traffic attributed to each device. Additionally, we determined the percent share of total devices for each device across the seven categories. The shares for 2017 are given in Table 6.2.

Table 6.2. Demand for Devices by Load Share and Device Share, 2017

Device	Load Share, 2017	Share of Devices, 2017
4G smartphone	17.8%	41.7%
Tablet	14.0%	20.9%
Smart home devices	0.1%	1.1%
Laptop	66.5%	29.0%
Gaming console	0.3%	4.5%
Virtual reality system	0.3%	0.4%
5G smartphone	1.0%	2.4%

SOURCE: Derived from data provided in Katz (2018).

Using the Nyquist-derived bandwidth requirement in Table 6.1, we can compute the average number of additional devices, by type, as 75 MHz divided by bandwidth per device. Taking into

account the load share from Table 6.2 and the estimate of 88.87 million households with wireless data access in the United States in 2017, we can next determine the total number of each device that would be added by consumers.

Taking these additional device totals by load share and device share, we next estimate the monetary equivalence. Here, there are two main sources of direct value: the revenue to ISPs for average data consumption per device and sales of the devices themselves. We use input data on average monthly traffic by device, residential traffic, and number of devices from Katz (2018), and the average monthly price for residential internet (to get data revenue) from public filings of the top ISPs.[23] This approach does not differentiate among household sizes, and it assumes an average consumption level per month per device.[24] The values we use are as follows:

- average monthly residential internet price: $48.37
- total residential internet traffic in 2017 (Katz, 2018): 29,061.7 million GB
- number of internet-enabled households: 88.87 million
- share of WiFi traffic that is residential (Katz, 2018): 0.43
- $ per GB per household per month: 48.37/(29,061.7/88.87) = 0.148.

We then estimate the monetary equivalent for added devices by load share as follows, and present the results in Table 6.3:

$$\text{Data Revenue} = \sum \text{Added Devices}_i \times \text{Average traffic/month}_i \times 0.148 \times 0.43$$

$$\text{Device Revenue} = \sum \text{Added Devices}_i \times \text{Average price}_i$$

Total Revenue = (Data Revenue × 12) + Device Revenue

[23] Using corporate 10-K Securities and Exchange Commission filings, we take total annual residential internet revenue and divide it by total residential internet subscribers, and divide by 12 to obtain an "average revenue per subscriber per month." We then average this value across the top ISPs.

[24] Using the figures provided in Katz (2018, p. 89).

Table 6.3. Economic Value of 75 MHz Using 2017 Device Traffic Load Share

Device	Average Price, $[a]	Device Traffic/ Month (GB)[b]	Devices per 75 MHz (Noiseless)	Device Traffic Load Share, 2017	Added Devices (Load Share)	Data Revenue, $ (Load Share)	Device Revenue, $ (Load Share)
4G smartphone	363	8.73	1.4	17.8%	21,905,852	12,159,432	7,951,824,146
Tablet	247	10.31	1.4	14.0%	17,227,322	11,292,067	4,255,148,529
Smart home devices	75	1.70	3.0	0.1%	245,810	26,579	18,435,730
Laptop	750	43.49	2.0	66.5%	118,219,368	326,981,498	88,664,526,168
Gaming console	300	1.17	3.0	0.3%	681,398	50,794	204,419,259
Virtual reality system	405	18.00	0.2	0.3%	61,506	70,417	24,910,086
5G smartphone	363	8.73	1.5	1.0%	1,373,490	762,393	498,576,850
Monthly total						$351.3 million	
Annual total						$4.2 billion	$101.6 billion
Total annual revenue						**$105.8 billion**	

[a] We used publicly available data elicited from a simple web search for average prices, searching for "average price [X device] United States 2018."
[b] We derive these values using Katz (2018). For example, Katz reports that 62 percent of total smartphone traffic (14.06 GB/month) was fixed wireless traffic (WiFi).

Similarly, the estimated value of 75 MHz using total device share uses the same methodological approach, with results presented in Table 6.4.

Table 6.4. Economic Value of 75 MHz Using 2017 Total Device Share

Device	Average Price, $	Device Traffic/ Month (GB)	Devices per 75 MHz (Noiseless)	Share of Total Devices, 2017	Added Devices (Device Share)	Data Revenue, $ (Device Share)	Device Revenue, $ (Device Share)
4G smartphone	363	8.73	1.4	41.7%	51,346,293	28,501,140	18,638,704,178
Tablet	247	10.31	1.4	20.9%	25,737,930	16,870,551	6,357,268,749
Smart home devices	75	1.70	3.0	1.1%	2,957,804	319,817	221,835,316
Laptop	750	43.49	2.0	29.0%	51,619,170	142,772,829	38,714,377,751
Gaming console	300	1.17	3.0	4.5%	11,893,022	886,549	3,567,906,516
Virtual reality system	405	18.00	0.2	0.4%	69,898	80,024	28,308,835
5G smartphone	363	8.73	1.5	2.4%	3,219,396	1,787,012	1,168,640,836
Monthly total						$191.2 million	
Annual total						$2.3 billion	$68.7 billion
Total annual revenue						**$71.0 billion**	

These estimates yield a potential range of $71 billion to $105.8 billion, depending on whether the distribution basis is share of devices by traffic or share of number of devices. These estimates are similar to the estimates derived in Approach 1. We note, similarly to Approach 1, that there are limitations with this estimate, such as the pace of technological advancement, which we explore in the sensitivity analysis.

Sensitivity Analysis

For Approach 2, we considered sensitivity analysis in two ways. First, we considered how overall data throughput rates would change due to changes in the technical characteristics of wireless devices. This provides insight to how system engineering decisions could affect capacity. Second, we considered two scenarios that deviate from the baseline valuation of additional capacity.

Because there are a large (but finite) number of potential MCS configurations possible based on the IEEE standard 802.11ac, an MCS Index system has been established to enable quick and unambiguous reference to a particular hardware configuration. Because the MCS Index table captures diverse configurations with respect to each system characteristic, it is useful for performing technical sensitivity analysis. Tables 6.5 and 6.6 summarize the sensitivity of each technological change. For example, comparing MCS Index 4 and Index 6 for any given column allows an analyst to determine the change in maximum feasible data rate when the modulation technique employed changes from 16-QAM to 64-QAM.

Table 6.5. Data Rate Sensitivity

Technological Change	Effect on Data Rate
Added spatial streams	Increases by the percentage increase in the number of streams
Change modulation scheme	Increase by factor of increase in the number of bits per symbol
Change coding rate	Increases by the percentage change in coding rate
Move to smaller guard interval	11% increase when changed from 800 ns to 400 ns
Increase bandwidth, MHz	Increase by a factor of 2.08–8. See Table 6.6 for details.

Table 6.6. Factor by Which Data Rate Increases When Bandwidth Is Increased

Initial Bandwidth (MHz)	Increase to 40 MHz	Increase to 80 MHz	Increase to160MHz
20	2.08	3.5	8
40	No change	2.17	3.33
80	Not applicable	No change	2

Beyond the basic technical cases developed above, we also considered the effect on GDP from two alternate futures and conditions:

- doubling the traffic share for each device individually
- increasing the technology level of each device by a step-advance in QAM level.

Doubling Data Traffic by Device

The numbers of connected wireless devices are generally known quantities, and therefore estimates of value based on device share are less susceptible to measurement error. However, because even reliable estimates of expected traffic are still just that—estimates—here we consider the case where each category of device traffic is double the value applied to the baseline estimate. We suppose data traffic in a given device is twice the baseline amount and hold all other device traffic estimates constant. We then recalculate the proportional share of traffic against the increased total. For four of the seven device categories, the change in contribution to GDP is negligible even when the devices double their data consumption: less than 1 percent. For 4G smartphones and tablets, the effect on potential contribution to GDP is reduced by approximately 8.6 percent from the baseline. This can be attributed to shifting bandwidth allotments away from higher-revenue-generating devices in favor of 4G smartphones and tablets, if data traffic was actually double the current estimates. In contrast, if the traffic attributed to laptops is double the baseline estimate, there is a corresponding bump in the potential contribution to GDP of 12.6 percent. The interpretation is that the GDP impact is positively more sensitive to the traffic load from laptops than any other category of device, although overall varying traffic load does not sizably impact the baseline estimates. Table 6.7 shows the GDP

increase comparison against the baseline derived above. Scenario 1 values for each device type should be compared with the $105.8 billion baseline.

Increased Technology Availability

Predicting technological advances is difficult, especially in a field with active research and development, such as telecommunications. But over a five-year timespan, it is unrealistic to not consider the effect of improved electronics and devices. While the MCS Index table can be used to determine data rate sensitivity to the physical configurations of the devices, we also considered a single-step upward improvement in modulation technique for most device categories.[25] More specifically, baseline devices with 64-QAM were reassigned as 256-QAM. Similarly, those with 256-QAM were re-imagined as 1024-QAM devices. The net effect in this scenario is a 32.2 percent increase in the contribution to GDP. This is intuitively consistent, since the improved spectral efficiency due to enhanced modulation is further amplified by the added bandwidth. As with other technological advances, this significant leap forward would likely be adopted in waves and may have other impacts beyond this first-order analysis.[26] Table 6.7 shows the comparison between this scenario (Scenario 2) and the baseline.

Table 6.7. Summary of GDP Effects from Sensitivity Analysis

Scenario	Change	Annual GDP Impact	Comments
Baseline	N/A	$105.8 billion	From traffic load share
		$71.0 billion	From share of devices
1	Traffic load for individual devices doubled	$96.7 billion	4G smartphone
		$96.7 billion	Tablet
		$105.8 billion	Smart home device
		$119.2 billion	Laptop
		$105.8 billion	Gaming console
		$105.5 billion	Virtual reality system
		$105.3 billion	5G smartphone
2	Advanced QAM technology	$139.9 billion	

[25] Since virtual reality systems and 5G smartphones were already modeled with 1024-QAM modulation schemes, these two categories were not increased to, for example, 4096-QAM, since the technology to do so is relatively nascent and unproven for handheld sized devices.

[26] For example, the 4G smartphone with increased modulation scheme would approach in functionality the 5G smartphone, represented separately here.

7. Consumer and Producer Surplus

Consumer Surplus

Consumer surplus—the value to consumers above what they pay—is another source of potential economic value. This report provides two approaches to estimating potential gains in consumer surplus. Importantly, both approaches focus on gains related to residential broadband as noted previously because residential WiFi usage can be seen as a proxy for value to consumers, since they pay for WiFi access privileges (it is included as part of the standard internet package).

The approach presented here aligns with the physics identity presented in Chapter 6 (Approach 2) and takes advantage of a measure of willingness to pay for an additional Mbps data rate from recent literature. It holds prices paid by consumers for monthly residential internet service constant and approximates the gains to consumers from the increase in demand for WiFi from the introduction of a superior product (i.e., faster data rates). In other words, the change in consumer surplus arises from consumers benefiting from faster data rates (Mbps) that they would have been willing to pay for but did not. The increase in demand for WiFi data, at the same service price, is therefore equivalent to a movement along the same demand curve and a lower-per-Mbps price. This increase in demand could be either through more people coming online or by those already online consuming more, although the latter is more likely given the flat trend in residential internet penetration.

This approach assumes constant subscription prices due to data limitations. First, the rapid pace of technological innovation is resulting in a regular evolution in the size and nature of internet packages available on the market. Second, different providers offer different packages, limiting accurate comparability. Third, many data on internet pricing are proprietary outside of the initial offer, which generally lasts for a set period. Finally, because of the many additional features included in residential internet packages, it is difficult to isolate the price of WiFi. This makes any attempt to accurately model a change in equilibrium price challenging and subject to error. At the least, microdata about consumer internet pricing from ISPs would be needed. It is notable that given the available data on ISP residential internet offer pricing, prices are generally consistent across providers by speed and increase with higher data rates. As faster data rate capabilities become available, lower-speed offerings appear to generally decrease in price.

As such, we include in Appendix C a best-available effort to estimate consumer surplus allowing for a decrease in price. This approach works from traditional economic theory regarding demand and supply. It allows both demand to rise and prices paid for internet service to fall correspondingly, increasing the potential gain to consumers over the first approach. This is because, theoretically, the increase in bandwidth afforded by opening the 5.9 GHz band would

enable faster data rates, which would increase the available supply of WiFi data and increase WiFi data consumption, lowering the price paid for residential internet service as discussed in the preceding paragraph.

For this estimate, we employ several known measures:

- Additional amount consumers are willing to pay for an additional Mbps (Nevo, 2016): $1.76.
- U.S. households: 125.1 million.
- U.S. residential internet penetration rate: 0.71.
- residential WiFi share of total WiFi consumption (Katz, 2018): 0.43.

We also assume that devices, in aggregate, operate in 256-QAM for the modulation scheme, as discussed in Approach 1 on estimating contribution to GDP. The change in consumer surplus is then estimated by:

$$\Delta CS_{HH} = \Delta\text{Capacity} \times \text{Willingness to Pay per Mbps} \times \text{Residential WiFi Share}$$

$$\mathbf{\Delta CS_{T} = \Delta CS_{HH} \times \text{Number of Households} \times \text{Penetration Rate}}$$

where ΔCS_{HH} represents the estimated gains to consumers per household, and ΔCS_{T} represents the gains to consumers across all households. Capacity is derived from the Nyquist equation, as discussed in the previous chapter. For example, $960 = 2 \times 60 \times \log_2(256)$ for option 1.

Option 1 refers to the ability of the 5.9 GHz band to create three distinct channels of 20 MHz, and so that value is aggregated.[27] Option 2 allows for the creation of an 80 MHz channel, and similarly, Option 3 allows for the creation of a 160 MHz channel. Our estimates of consumer surplus by channel bandwidth are provided in Table 7.1.

Table 7.1. Estimates of Consumer Surplus from Opening Up the 5.9 GHz Frequency Band (in $)

Option	Bandwidth, MHz	Capacity, Mbps	Willingness to Pay per Mbps	Number of Households	Penetration Rate	Residential WiFi Share	Change in Consumer Surplus per Household per Year	Total Change in Consumer Surplus per Year
1	60	960	1.76	125,170,072	0.71	0.43	726.53	**$64.6 billion**
2	80	1280	1.76	125,170,072	0.71	0.43	968.70	**$86.1 billion**
3	160	2560	1.76	125,170,072	0.71	0.43	1,937.41	**$172.2 billion**

These estimates suggest that the potential annual gains in consumer surplus from opening the 5.9 GHz band range from $64.6 billion to $172.2 billion.

[27] A fourth channel using spectrum from below 5.85 GHz could also be included in this option, but that is included in Option 2.

Of course, there are other applications of WiFi that may not be included in the above estimates, such as machine-to-machine (M2M), transportation, cloud computing, and telemedicine, where consumer surplus would increase from the additional capacity of the 5.9 GHz channel. This may also including freelancing and online work; however, if it is done from home, then it would be included. People have been shown to spend more time daily online, and this alone will potentially drive demand for wireless data and therefore much of the consumer gains (Constine, 2018; Molla, 2018).

Producer Surplus

A final form of economic gains is in producer surplus—returns to suppliers of internet service that are above what it costs to supply it. As noted in Katz (2018), the largest gains to producers are enjoyed by telecommunications providers and come from mobile off-loading. Another potential gain to producers, especially from opening the 5.9 GHz band, is from the increased capacity for backhaul—the middle-mile networks between the consumer's connection point (edge network) and internet connection point (core network)—especially in public hotspots (Methley and Salsas, 2013).

Although this value is challenging to accurately capture, one way to think about the potential gains to producers is in making it equivalent to their willingness to pay for a MHz of spectrum. This is one indicator of how producers value the spectrum. As a combination of licensed and unlicensed spectrum, the FCC's Incentive Auction of 2016 gets at this value. A total of 84 MHz was auctioned off, of which 14 MHz were ultimately allocated for unlicensed, which received $19.6 billion (Shephardson, 2017). That makes a simple estimate of marginal value to producers approximately $235.7 million, and 75 MHz worth roughly $17.7 billion.

This estimate is just one approach and comes with many limitations. We measure changes in producer surplus in the output market by treating producers as consumers in an input market. We also assume we have embedded the potential differences in operating expenditures (OPEX) and capital expenditures (CAPEX) into their bidding decisions and that it is implicitly captured here. Looking explicitly at differences in OPEX and CAPEX could be insightful to this discussion, but doing so was outside of the scope of this study.

Moreover, other factors could result in under or overestimation of our estimate. If the bidding companies would have been willing to pay more in the auction, for example, then our estimate undervalues the producer gains. Charging customers more for broadband access, or off-loading a higher share of data traffic with this additional spectrum, would similarly result in underestimating the true surplus. Should producers have to spend more than implicitly assumed on OPEX and CAPEX to utilize the new spectrum, our estimate would be too high. We therefore put this number forward as a preliminary estimate and hope that it is only the start of the discussion on potential producer surplus.

Comparing Contribution to GDP with Economic Surplus

Chapters 5, 6, and 7 provide our estimates for the potential economic value of the 5.9 GHz band. Although these estimates are all of potential economic value, they are not additive and should not be compared as such. Approaches 1 and 2 for contribution to GDP are separate measures of the same effect. It is appropriate to compare the values to each other but not to add them together. Consumer and producer surplus are measures of economic welfare, and are not explicitly realized monetarily as with direct contribution to GDP. It is appropriate to add them together for total economic surplus, but they should not be added with contribution to GDP.

8. Looking Forward: Implications of Current Trends and Potential Future Policies

In this chapter, we consider how current trends and potential future policies might affect consumers' demand for online data—and therefore unlicensed spectrum. These trends and policies will either increase demand for mobile data (and therefore unlicensed spectrum), decrease potential demand, or be demand-neutral. After a review of the literature, we categorize the potential impact on demand presented in a stoplight chart as Table 8.1.

5G (mmWave Spectrum Auctions in 2019 and 2020)

The development and deployment of 5G is corresponding to the current movement to use and allocate higher frequency bands (above 30 GHz). While some forecasts related to the deployment of 5G networks suggest that this could potentially reduce offloading volume, and therefore demand for unlicensed spectrum, others suggest the opposite (Iacopino et al., 2018).

The Potential Opening Up of the 6 GHz Band for Unlicensed Use[28]

This could potentially free up additional unlicensed spectrum to relieve additional pressure on band saturation, although it may be restricted to small cells.

New Entrants into the Wireless Communications Provider Market

If more competition sparks new or innovative business models, whether mobile operator, mobile virtual network operator, or ISP, the result could be a reduction in price for internet access. The decrease in price could increase demand for online data and therefore unlicensed spectrum.

Trade Policy

Recent developments in U.S. trade policy and retaliatory tariffs could ultimately affect demand for unlicensed spectrum. This also includes disruptions to the supply chain given President Donald Trump's new proposed rules (Brodkin, 2018). In terms of trade policy, making internet-access devices more expensive could lead to fewer sales and therefore lower demand.

[28] According to *Politico* (Lima, 2018), in July 2018 the House Spectrum Caucus "pressed FCC Chairman Ajit Pai to look at ways to open the 6 GHz band of wireless airwaves for unlicensed uses like WiFi."

Internet Regulation

Similarly, the push for internet regulation nationally and internationally could affect the rate at which people are able to connect to the internet and access online content. This involves data localization, net neutrality, antitrust, and other aspects related to regulating the internet. Research suggests that such regulation could reduce demand for online content if latency increases and investment decreases (see, for example, Meltzer and Lovelock, 2018), although the actual effects are not yet known.

Privacy and Cybersecurity Concerns

A facet of internet regulation worthy of separate mention is data privacy and security. It has significant potential to affect the rate at which devices, people, and content come online. Some privacy and security against online threats is likely to make consumers more comfortable relying on the internet, and therefore increase demand. Alternatively, depending on the severity of restrictions, regulation that has unintended consequences could have the opposite effect and reduce demand.

Rise of Digital Natives as Today's Youth Enter Adulthood

As more youth grow up in the digital economy and make up a larger share of the total population, there will be a higher demand for more online data in aggregate.

Rise of Online and Internet-Enabled Work

As more workers rely on the internet for work, especially work done remotely or wirelessly, there will be a higher demand for unlicensed spectrum.

Digitization of Industry (M2M)

A larger number of machines and automated processes moving online will increase the need for unlicensed spectrum. Some of this could be met using dedicated industrial, scientific, and medical (ISM) purpose bands in the 900 MHz frequency range, and through very high frequency spectrum in the 60 GHz frequency range. However, it is possible that the evolution of M2M is synchronous to unlicensed spectrum availability, in that more M2M will occur as more frequency is available.

V2V/V2X Evolution

This evolution gets to the heart of the question raised by this report: whether DSRC or open unlicensed spectrum would be a more efficient use of the 5.9 GHz band. Regardless of which

spectrum is used for V2V or V2X (vehicle-to-everything), increased development and integration of these technologies into vehicles will increase demand for spectrum.

Table 8.1 summarizes the implications of these trends and policies for WiFi demand and value. In the table, red is associated with decreasing potential demand for WiFi, yellow is unclear or demand-neutral, and green is increasing potential WiFi demand.

Table 8.1. Potential Effects of Trends and Policies on WiFi Demand and Value

Trend or Policy	Impact on Demand
5G	Unclear or demand-neutral
Opening of the 6 GHz	Unclear or demand-neutral
New entrants into the wireless communications provider market	Increase
Trade policy	Decrease
Internet regulation	Unclear or demand-neutral
Privacy and cybersecurity concerns	Unclear or demand-neutral
Rise of digital natives as today's youth enter adulthood	Increase
Rise of online and internet-enabled work	Increase
Digitization of industry (M2M)	Increase
V2V/V2X evolution	Increase

9. Allocation Options and Trade-Offs for the 5.9 GHz Band

There are several possible ways in which the 5.9 GHz band of unlicensed spectrum could be allocated. These are the status quo (full DSRC allocation), partial reallocation, shared or prioritized reallocation, and full reallocation for unrestricted unlicensed use. A final option is for this 75 MHz to be auctioned for licensed use, which would not add new WiFi capacity. However, no such discussion for this type of rededication has been noted to date.

Each of these options come with trade-offs that could affect not only the realized economic value of spectrum in the 5 GHz band, but the evolution of the devices and applications that rely on WiFi more broadly. We address each in turn.

Status Quo (No DSRC Reallocation).

Unchanged, this scheme leaves all 75 MHz to DSRC, as is the current allocation. However, given the limited use of this band, the full potential economic value would not be realized.

Partial Unlicensed Reallocation

This option involves an adjacent channel sharing the band with DSRC traffic, so that some portion of the full band would be reallocated to pure unlicensed use. This is the allocation strategy in other parts of the world. For example, in August 2008, the European Telecommunications Standards Institute (ETSI) allocated 30 MHz of spectrum in the 5.9 GHz band for intelligent transportation systems (Antipolis, 2008). Applied to the United States, this could mean allocating the upper 30 MHz to DSRC and the lower 45 MHz to public unlicensed use.

As long as the 45 MHz on the lower end of the band is not shared or restricted, at the least an additional 80 MHz channel could be created. This would enable at least some of the estimated value to be realized while preserving the intention of DSRC traffic, although both purposes would have less available spectrum than if it was fully dedicated to one over another.

Shared Unlicensed Reallocation

This option reflects co-channel sharing, or priority signal sharing, with DSRC such that V2V safety traffic gets the right of way even if other traffic is currently occupying the frequency. However, the extent of traffic interference and reassignment will depend on how close the vehicles are to other WiFi applications potentially using the channel. If there is a lot of nearby WiFi traffic that would be regularly relocated, creating a 160 MHz channel could still be difficult, as with the current DFS scheme in the 5 GHz band. It would still potentially drop the

signal and degrade consumer experience. Any sharing allocation would need to minimize the interference with other consumer or residential WiFi traffic—for example, through power limits for signal transmission—to make the public use case feasible.

The findings presented in this report suggest that the true value of the 5.9 GHz band lies in creating wider-bandwidth channels that are not restricted and are reliable. Thus, while sharing the frequency with DSRC may mitigate concerns about DSRC traffic interference by giving it prioritization, the trade-off becomes one that questions the economic value to consumers of having more DFS unlicensed spectrum, and any signal power restrictions that may be associated with that arrangement. Alternatively, another option could be co-channel-sharing without prioritization. One new research study conducted simulations of co-sharing WiFi traffic with DSRC and found little interference when both operated jointly (Pang, Padden, and Alderfer, 2018).

Full Unlicensed Reallocation

This would allow for the maximum additional unlicensed capacity and full realization of the estimated potential economic value. DSRC traffic could either be integrated into standard unlicensed or cellular networks, as some currently is, or DSRC traffic could be relocated to a separate dedicated band that is not a current unlicensed band. The trade-off, should another band not be dedicated to DSRC, is that this traffic will be forced to move on cellular or wireless networks. The investment that has already taken place in the DSRC market would not realize returns. Finally, federal guidelines that reflect DSRC availability would have to be modified.

Summary

Regardless of how spectrum in this band is allocated, these and other unforeseen events could have an impact on the future economic potential and contribution of spectrum. There is a general consensus on the need for more contiguous bandwidth to achieve 1 gigabit per second (Gbps) WiFi speeds and stream more video, for example, as well as to mitigate the approaching saturation of existing unlicensed spectrum bands. There is not yet a corresponding general consensus on the best way to address these challenges.

10. Conclusion

We are in the midst of a rapidly evolving time in wireless technology, communication, and applications. That makes understanding the true potential economic benefit of unlicensed spectrum complex, although it starts with better data. Our estimates provide new insight into the existing policy discussion, at a moment when many important regulatory choices are being made. The pace of 5G deployment, the continued development of mobile devices and apps, and digitization of industry will all depend on these regulatory decisions. And while technological innovation will provide some relief against bandwidth constraints, in the long run, technological capability and spectrum availability must be balanced to ensure that spectrum is utilized optimally.

Our focus on the 5.9 GHz band is a point of discussion in the broader discourse on spectrum. Opening the 5.850–5.925 GHz band currently reserved for DSRC would increase the amount of contiguous bandwidth in the neighboring unlicensed bands, providing greater high-bandwidth throughput at faster speeds. The corresponding increase in data throughput and bandwidth availability could influence consumer demand, resulting available online content, and therefore, potential economic impact.

In particular, we estimate that the total potential contribution of opening the 5.9 GHz band for public use ranges between about $60 billion and $97 billion (Approach 1) or $71 billion and $106 billion (Approach 2) annually, depending on assumptions. We further find a total potential economic surplus that ranges between $82 billion and $190 billion. A summary of our estimates is provided in Table 10.1.

Table 10.1. Summary of Economic Value of 5.9 GHz Band ($ billions)

	Lower Estimate	Upper Estimate
Contribution to GDP		
Approach 1	$59.8	$96.8
Approach 2	$71.0	$105.8
Consumer surplus	$64.6	$172.2
Producer surplus	$17.7	
Total potential economic surplus	$82.3	$189.9

The goal of these estimates is to help shape the broader context of the economic importance of the entire 5 GHz unlicensed band, as it relates to current and future potential WiFi use and

applications. The intention of these estimates is to shed meaningful insight into how policymakers could best approach unlicensed spectrum allocation going forward.[29] Given the growth in consumer demand, and ongoing debate over how to allocate the 5.9 GHz band, new data to inform the discussion could help. We emphasize that these estimates are preliminary and subject to limitations in methodological scope. For example, we do not consider enterprise WiFi, the intangible value of information, or the effect of technological advancements. We also acknowledge that the true value of V2V and V2I technologies is uncertain, although it remains to be seen how much of those communications will go through DSRC-allocated spectrum.

Regardless of how this band is allocated, all options will certainly have trade-offs. Partial reallocation will mean that less bandwidth is available for DSRC communication. Sharing the frequency through a DFS scheme would mitigate the concern for DSRC traffic by giving it prioritization; however, that would make the band less valuable for public use. The greatest potential benefit arrives from having access to the 5.9 GHz in an uninterrupted, reliable way. Completely reallocating the 5.9 GHz band would disrupt the market that does exist for DSRC, along with the investment that has gone into developing DSRC equipment and technology. Finally, the status quo allocation of keeping the 5.9 GHz band for DSRC could potentially limit the value of WiFi to the economy and consumers. Moreover, if companies and states continue to invest in dual technologies to accommodate V2V traffic on both DSRC and cellular networks, this could be, ultimately, an inefficient use of resources. Our estimates suggest a sizable value from having one dedicated 160 MHz channel available, and that advances in technology can only do so much relative to additional bandwidth capability, a point that we hope can help inform the ongoing allocation discussion.

We hope that the policy insights stemming from these estimates, as well as our approaches, can extend to the broader conversation on higher frequency bands and 5G deployment. For example, growing concerns over satellite-based communications creating additional congestion and interference in higher-frequency bands suggests that more research could help policymakers work through these issues (Canis, 2016). This research would also serve to highlight these implications and to demonstrate a new opportunity for the FCC to consider innovation and economic growth in spectrum management as we transition to 5G.

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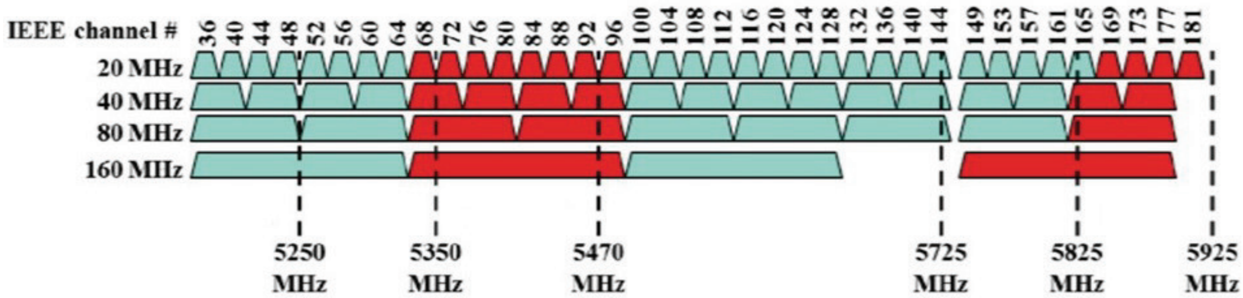
[29] For example, see Brake (2015), De Vries and Westling (2017), and Gomez et al. (2017).

Appendix A. Utilizing Technology in WiFi and the Use of the Nyquist Theorem over the Shannon-Hartley Theorem

WiFi operates over unlicensed spectrum—spectrum dedicated explicitly for public and commercial use. (Licensed spectrum, in contrast, is licensed to commercial entities such as telecommunications firms that then have exclusive rights to that frequency range.) As of mid-2018, two main frequency bands carry the majority of WiFi traffic: 2.4 GHz and 5 GHz. The majority of available spectrum is on the 5 GHz band, but due to restrictions on device standards for accessing WiFi as established by IEEE, the smaller 2.4 GHz band has carried most WiFi traffic. IEEE is responsible for establishing the 802.11 technical standards, which are built into device specifications for smartphones, laptops, tablets, and routers to access the internet wirelessly. The standard designed for operation in the 5 GHz band, 802.11ac, was only introduced in 2013, with previous versions of the standards (such as 802.11n and 802.11g) targeted to the 2.4 GHz band.

In practice, spectrum frequency bands are divided up into 20 MHz channels, each starting 5 MHz apart. However, operationally, channels must be non-overlapping. In the 2.4 GHz band, that equates to three non-overlapping channels of 20 MHz (channels 1, 6, and 11), although a fourth channel (channel 14) is possible. In contrast, the 5 GHz band has 22 non-overlapping channels, although more restrictions are placed on their use. For example, channels in the lower portion of the 5 GHz frequency band had been previously marked for indoor use only, while channels in the middle of the band are subject to DFS, where radar gets priority use. Signals on DFS channels must search for radar traffic and, if such traffic is detected, move to another band. Figure A.1 shows the current channelization plan for the 5 GHz range as established by IEEE standard 802.11ac, wave 2. Channels colored red are currently not available, while the aqua channels are currently available. The channels that would be established by the reallocation of the 5.9 GHz band appear in red at the far right of Figure A.1. When incorporated with existing unallocated bandwidth, it becomes apparent how 75 MHz can be leveraged to make larger channels available.

Figure A.1. 5 GHz Spectrum Channelization Chart



SOURCE: IEEE, 2015.

When determining the economic value of additional unlicensed bandwidth, it is essential to consider the physical limitations of current technical capabilities regarding wireless communications. These attributes are a key factor in understanding how much potential value can be created and realized. This appendix briefly summarizes these technical capabilities, and the important relationships among bandwidth, data rates, and signal modulation. We incorporate these technical attributes and relationships in the subsequent estimation approaches of potential economic value.

Bandwidth availability and wireless technology work in tandem to enable wireless capabilities. In terms of technical capabilities, all WiFi-enabled devices can be characterized by five attributes that fully distinguish the ability of a device to maximize its data throughput:[30]

- spatial streams
- code rate
- guard interval
- modulation technique
- channel size (bandwidth).

Spatial Streams

Spatial streams are independent simultaneous connections between wireless devices, usually some piece of user hardware (i.e., wireless phones, tablets or gaming consoles) and a wireless access point (such as a modem or router). Systems with more than one spatial stream have the capability to handle multiple uplink/downlink connections at once. This allows the full wireless data throughput to increase by a factor up to the capable number of spatial streams.

[30] For more detail on advances in code rate, guard interval, and modulation schemes for wired systems, see, for example, Homeplug Alliance (2015). Historically, technological advances for wireless systems have migrated from wired electronics.

Code Rate

For a given digital stream, the code rate refers to the portion (typically presented as a fraction) that is allotted to usable data. The remaining fraction of the data is used for transmission error identification rates with a ratio closer to one therefore are using more of the bit stream to convey desired digital information, but are susceptible to larger losses once an error is identified because they are not as quickly identified. Most telecommunications systems have a code rate between 1/2 and 5/6,[31] with lower code rates (closer to zero) most likely to be used on systems that require the highest accuracy. The code rate is one component of the Forward Error Correction scheme, which strives to balance data throughput rates with accuracy.

Guard Interval

A guard interval is a temporal spacing used to separate symbols during data transmissions in an effort to avoid overlap, and therefore lost or scrambled data. The spacing may avoid interference caused by transmission delays or signal "echos" caused when receivers must reconcile duplicative messages caused by reflected transmissions. The guard interval is typically a very small unit of time; for example, 400 or 800 ns is the standard described for 802.11ac. As with code rate, guard intervals represent a trade-off between speed and accuracy, as longer guard intervals decrease the amount of usable data received in a given time period.

Modulation Scheme ("QAM")

Modulation techniques are methods by which information in the form of aggregated bits, or symbols, may be added or conveyed through the use of a carrier signal. The two main characteristics of a carrier signal that are changed ("modulated") for information transfer are the amplitude of the signal and the phase of the signal. Each combination of these two changes produces a unique symbol. The dominant modulation scheme in use is the QAM. This conveys ($\log_2$[symbols]) bits of information per symbol. For example, 16-QAM has 16 distinct symbols, described by 16 states in which the carrier wave may be observed. Therefore, each state represents a group of $\log_2 16$ (equal to 4) bits. Said differently, each time the phase or amplitude of the carrier wave is modulated, 4 bits of the digital signal stream are transmitted. To achieve higher numbers of amplitude or phase states requires more precise electronics to measure the modulated signal and/or larger signal-to-noise ratios. As a result, advances in technology become more difficult to adopt for wireless use when trying to reduce the components into handheld devices. Most wireless equipment today maxes out at 256-QAM (8 bits per symbol). Fifth-generation devices just now becoming available are able to take advantage of 1024-QAM (10

[31] As defined in the IEEE 802.11ac standard. See Park (2011).

bits per symbol) technology. By contrast, large fixed communication systems, such as microwave transmitters, are capable of 4096-QAM (12 bits per symbol).

Channel Size (Bandwidth)

IEEE in coordination with the International Telecommunication Union (ITU) has developed standards for wireless communication channel sizes. For current-generation systems, the basic unit of channel bandwidth in the United States is 20 MHz.[32] As noted above, technology can enable channel aggregation to 40, 80, and 160 MHz channels to increase data throughput, but only if additional contiguous channels are available.

Use of Nyquist Theorem Over the Shannon-Hartley Equation

In terms of the relationship between bandwidth and technology, there are two basic governing theorems to determine how much bandwidth is required for a certain data transfer rate. The first is the Nyquist theorem, which identifies the theoretical upper data rate limit possible for a given amount of bandwidth, given a modulation scheme (Nyquist, 1924). This theorem is presented here in equation form:

$$C_c = 2 * B_c * log_2 M$$

where
C_c = Channel capacity in kilobits per second (kbps)
B_c = Bandwidth per channel, in kilohertz (kHz)
M = Signal levels in use, typically 2^n for "n"-bit digital communication systems.

This equation provides the mathematical relationship between bandwidth, data rate, and the signal levels sustainable for the modulation scheme in use. This limit is considered theoretical, because a key underlying assumption is that the channels are "noiseless" and therefore not fully representative of real-world application. Noise impairs data transfer through a given channel and prevents achievement of the Nyquist capacity by diminishing the signal-to-noise ratio in a given bandwidth, ultimately reducing achievable data rate in that bandwidth when needed error correction measures are then implemented. The Shannon-Hartley Theorem overcomes this by accounting for noise; however, limitations restrain use in this analysis (Shannon, Weaver, and Burks, 1948).

While we use the Nyquist theorem's theoretical maximum data rate and capacity for our technical approach to valuing available spectrum, we recognize that actual implementation of bandwidth usage is constrained by the Shannon-Hartley Theorem. Shannon-Hartley sets the

[32] Earlier-generation standards, standards in other countries, and subchannel partitions ranged from 1 to 10 MHz.

upper bound in realistic environments, and the value of M used in the Nyquist theorem must not result in a data rate that exceeds the Shannon-Hartley bound. Specifically, the physical and electromagnetic environment may lower top-end capacities in practice. Additional bandwidth would then need to be leveraged to compensate for this diminished spectral efficiency in achieving desired data rates.

In practical application, such as system design, we would need to apply both theorems to find what data rate and signal levels are appropriate for each particular channel and for a specified set of conditions. The Shannon-Hartley capacity gives us the upper limit based on environmental factors, while the Nyquist formula could then elicit required characteristics of the modulation construct employed.

However, the factors that determine the signal-to-noise ratio necessary for the Shannon-Hartley equation are highly variable and difficult to estimate. This may include the number and density of users in a given area, hardware placement in a physical space, material properties of the space that contribute to signal attenuation, and, finally, the acceptable error rates for transmitted data. The Shannon-Hartley Theorem accounts for these ambient conditions through a term known as the *signal-to-noise ratio*. This is a generalized term that can be used to account for a variety of environmental conditions surrounding the wireless system, notably the presence of ambient signals that interfere with the signal of interest to a given system. However, this phenomenon is highly localized, affected even by building materials and physical layout of an area. As a result, credible analysis using the Shannon-Hartley noise constraint should not be generalized to large areas. So, *in situ,* we use the Nyquist theorem theoretical limits to broadly assess GDP impacts and therefore to determine the upper limit for spectral efficiency.[33] But device design and manufacturing leads to data rates as close to the Shannon-Hartley limit as possible for the environments and applications where they are intended for use.

[33] Spectral efficiency is a measure of the carrying capacity or data rate (bps) possible per unit of frequency.

Appendix B. Design Specifications of Wireless Devices Used in Approach 2 for GDP Contribution

To analyze the throughput demands of the wireless ecosystem, we considered seven distinct technologies that are available to consumers as of mid-2018 and should remain on the market for the foreseeable future:

- 4G smartphones
- tablets
- smart home devices
- laptop computers
- gaming consoles
- virtual reality systems
- 5G smartphones.

What follows is a short introduction to these systems, including the key technical features that enable the maximum data rate capability of the device.

4G Smartphones

Smartphones in general are the most proliferated consumer wireless device according to Cisco data (Katz, 2018). 4G systems have been available globally for nearly a decade, and even though the 5G technical standard has been released in draft form, 4G devices will be in the majority of fielded systems through 2023 before 5G devices overtake 4G in current sales.

For our analysis, we have used the Apple iPhone X as the representative device for this category. This device is the top end (as of 2018) model of the most popular manufacturer in the United States. Furthermore, we assume that whatever comes next from Apple will be closer in function to a 5G phone with regard to maximum data rates.

Tablets

Since 2013, tablet computers have seemed poised to make a major breakout. However, sales have recently leveled and begun to drop off for some models. These devices have a relatively wide array of sizes and functionality. They are larger than smartphones but smaller than laptops. Functionality and applications range from e-book readers to point-of-sale commercial systems. The diversity in size and utility translates to a wide range of technical specifications, as well. For our standard system, we use the Apple iPad 9.7. Similar to the argument for the iPhone X above, this iPad represents the most current offering of the most popular manufacturer. It acts as a

somewhat stressing case for consumption because of the wide array of applications and functions available that consume data.

Smart Home Devices

This category holds the most uncertainty when trying to predict demand in the next five years. The promise of a "smart home" has endured for decades, but little technical definition exists. As currently imagined, it typically represents an Internet of Things that are connected to some central hub via Bluetooth. This central hub then would require some undetermined amount of bandwidth to network externally. Rather than speculate on this future state of the world, we used as a surrogate the current smart speaker technology as our model. Examples include the Amazon Echo and Google's Home.

Laptop Computers

Laptop computers exceed tablets and smartphones in product diversity, but fortunately there is one key component when it comes to wireless connectivity that is generally standardized: the wireless modem card internal to the device. For this analysis, we selected a commercially available wireless card that is closer to the top end of the state of the industry for the exemplar. This card, the Killer Wireless-N, advances the number of spatial streams available (three, instead of the two found in most other wireless cards) and would likely exceed the demands of most residential WiFi-enabled laptop users today. However, as with most things touched by Moore's Law,[34] the demands on this equipment in the next three to five years will likely grow to a point where the Killer Wireless-N is at the midpoint of performance.

Gaming Consoles

A prolific user of residential WiFi data is the gaming console market. These systems are not new, and upgraded consoles are fielded every few years with more-advanced features for connectivity and graphics resolution. Game play does not always require internet connectivity. Only when one is engaged in online gaming would the data stream be active, at which point throughput speed and data refresh would directly contribute to the operator's overall experience. For analytic purposes, we modeled features similar to the Sony Playstation 4.

[34] Moore's Law, named for Gordon Moore (cofounder of Intel), informally theorizes that processors double in capability every 1.5 to 2 years. This heuristic has generally held true for decades.

Virtual Reality Systems

The newest entrant on our list is not technically a wireless technology, yet. Virtual reality systems have exploded onto the market in the past three years, with headset sales 25.5 percent higher in 2017 than the previous year (Weinschenk, 2017). Virtual reality systems do not operate wirelessly today: The user typically wears a headset that is connected to a central processor system by a tether. This tether necessarily limits the user's range of motion and roaming during game play. This constraint is required since the HDMI or USB wire is the only current mechanism for delivering the speed and quantity of data the headset uses to provide an immersive experience. While these systems are still evolving, and only a handful of systems are available on the market, our research found that a representative data rate for these systems (based on pixel density and screen refresh rates) is approximately 7.2 Gbps. The actual number varies depending on the angular field of view presented to the user and the screen refresh rate. To represent this in a wireless capacity, we used the 802.11ax standard (designed for 5G data throughput rates) and then found the combination of system specifications that came closest to 7.2 Gbps. We arrived at six spatial streams, each capable of 1.2 Gbps when using 1024-QAM modulation, standard 5G coding rate and guard interval, and a full 160 MHz channel bandwidth. Clearly, this system would stretch the capacity of the current state of the art, but as a rapidly growing emergent technology, it must be accounted for.

5G Smartphones

As described above (see 4G smartphones), these devices represent the next evolution in handheld communications. The technical standards defining this category are still somewhat in flux, but cell phone manufacturers have already begun to field devices more advanced than the 4G hardware, in much the same way that LTE-compatible phones bridged the gap between the third and fourth generations. The 5G phone we used as our model is the Samsung Galaxy S8. This phone is designed to use the 5 GHz spectrum, can leverage 80 MHz channels, and also supports 1024-QAM modulation. 4G phones rely almost exclusively on the 256-QAM scheme.

To generalize this category, some assumptions were required to determine the current data demands and device market penetration. Starting with the same Cisco data as 4G, we built on the report that Samsung ended 2017 with 21.9 percent market share for cellphones (Reisenger, 2018). Recognizing that not all of these would be the Galaxy S8 model, we made an assumption that the 5G handset was only 25 percent of the Samsung market. Because we draw down to 5G smartphone data consumption by first conditioning for fixed wireless numbers and then by parsing known market share, our analysis is not unrealistically sensitive to the 25 percent assumption.

Table B.1 summarizes the technical specifications of each of these seven categories of devices.

Table B.1. Wireless Device Technical Specifications

Device	Spatial Streams	IEEE Standard Compliant	Modulation Technique	Coding Rate	Guard Interval	As-Designed Channel Bandwidth, MHz	As-Designed Data Rate, Mbps
4G smartphone	2	802.11ac	256-QAM	5/6	400 ns	80	866
Tablet	2	802.11ac	256-QAM	5/6	400 ns	80	866
Smart home devices	2	802.11n	64-QAM	5/6	400 ns	40	300
Laptop	3	802.11ac	64-QAM	5/6	400 ns	40	450
Gaming console	2	802.11ac/n	64-QAM	5/6	400 ns	40	300
Virtual reality system	*6*	*802.11ax*	*1024-QAM*	*5/6*	*1,600 ns*	*160*	*7,200*
5G smartphone	3	802.11ax	1024-QAM	Unavailable	Unavailable	40	1,000

SOURCES AND NOTES: We obtained these specifications from the following websites in mid-2018:

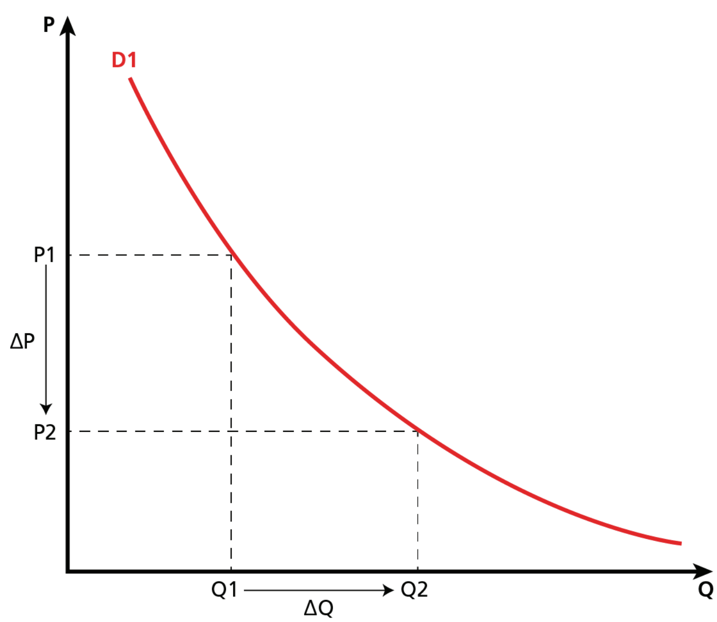
- 4G smartphones: http://www.apple.com/iphone-x/specs
- Tablet: http://ebookfriendly.com/ipad-2017-tablets-tech-specs-comparisons
- Smart home devices: http://www.amazon.com/gp/help/customer/display.html?nodeId=201549640
  (This describes the IEEE compliance, from which standard configuration specification is determined given the minimum data rate used.)
- Laptop: http://www.avadirect.com/killer-wireless-n-1103-wireless-card-ieee-802-11a-b-g-n-Internal-PCIe-Half-Mini-Card/Product/5528552
- Gaming console: http://www.playstation.com/en-gb/explore/ps4/tech-specs
- Virtual reality system: http://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/
  (This site provided only the tethered data rate specification [HDMI, USB 2.0, or USB 3.0.])
- 5G smartphone: http://www.samsung.com/global/galaxy/galaxy-s8/specs.

Appendix C. Alternative Approach to Measuring Potential Consumer Surplus

We considered two approaches to estimating consumer surplus. The first approach, presented in Chapter 7, is based on an estimate of willingness to pay for an increase in Mbps in residential broadband from previous empirical research. It also holds prices constant, for reasons discussed in Chapter 7. Because of the many assumptions that must be made to use the traditional economic theory in this approach, given the limitations in market data and the complex nature of residential broadband as a good and service, we consider the first approach to be the better estimate.

Still, we present the second approach here because it provides additional theoretical context for the potential impact of reallocating the 5.9 GHz band to unlicensed use on consumer surplus. This approach allows for prices to decrease to reflect an increase in quantity of wireless residential data consumption should data capacity be expanded from reallocation of the 5.9 MHz band. We assume an isoelastic demand curve (constant elasticity), as demonstrated in Figure C.1.

Figure C.1. Isoelastic Demand Curve



The functional form of the demand curve is $Q = a \times P^{-r}$, where a is a constant and r is the elasticity of demand. Alternatively, this can be rewritten to $P(Q) = e^{((\ln(a) - \ln(Q))/r)}$. We note that elasticity is the percentage change in demand for a 1 percent change in price, so that $r = \varepsilon_D = (\Delta Q/\Delta P) \times (P/Q)$.

Given this, the change in consumer surplus (ΔCS) is equal to:

$$\Delta CS = \int_{Q1}^{Q2} e^{(\ln(a) - \ln(Q))/r}\, dQ - P2 \times (Q2 - Q1) + Q1 \times (P1 - P2).$$

To solve for ΔCS, we need to first solve for elasticity, *r*. We will then need to solve for *a*, followed by the functional form for the isoelastic demand. Then we can proceed with integrating the demand curve to obtain all three pieces of the change in consumer surplus.

Because of limitations in available data, we solve for *r* twice using the same formula but under two sets of assumptions about wireless residential monthly data consumption. We then carry through these two versions to obtain two values for the change in consumer surplus.

To solve for *r*, we use the formula $r = \varepsilon_D = -(P \times b)/Q$, where $b = ((Q2 - Q1)/(P2 - P1))$. To obtain *b*, we use data provided in Katz (2018) on total U.S. residential internet data consumption in 2013 and 2017 (in billions of GB) for values of Q1 and Q2 respectively. We also use data in Katz (2014) on the 2013 offer price of a middle-tier residential internet package from Comcast for P1 and Comcast's spring 2018 advertised offer price online for an equivalent internet package for P2 (data limitations do not allow for consideration of additional ISPs). This results in b = ((29.06 – 2.73)/(49.99 – 79.99)) = –0.878.

The two values of *r* we estimate are designed to reflect two types of households: one of moderate data consumption and one of heavy data consumption. We choose a monthly residential internet data consumption of 152 GB/month for the moderate household and a value of 294 GB/month for the heavy-consumption household.[35] We then use the same baseline price for both to obtain a value of *r*, which we set as the average advertised offer price for a middle-tier residential internet package (ranging from 100 to 200 Mbps). As of spring 2018, the prices were advertised as shown in Table C.1.

Table C.1. Online Advertised Offer Price for Mid-Tier Residential Internet Packages, Spring 2018

ISP	Offer Price (Spring 2018)
AT&T	$60.00
Verizon	$39.99
Comcast	$49.99
Spectrum	$44.99
CenturyLink	$65.00
Average	$51.99

This results in an *r* of –0.3 for the moderate-consumption household and an *r* of –0.155 for the heavy-consumption household.

[35] Derived using data on total monthly residential internet consumption and share that is WiFi from iGR Research (2014) and Consumer Reports (Wilcox, 2013).

Using the same price and two quantities specified above, we then solve for *a* to obtain the demand function specification for both representative households. Once we have the demand specification, we can integrate over the change in Q to obtain the appropriate term for our change in consumer surplus.[36]

To properly solve for ΔCS, we must make an assumption about how far along the demand curve the equilibrium consumption increases—in other words, the value of Q2. From there, we can use each demand function to resolve for P2. Because we do not have adequate data on the magnitude by which households will increase monthly wireless data consumption, we assume a reasonably small number of 20 GB/month for both types of households. Table C.2 summarizes our input parameters and estimates.

Table C.2. Change in Consumer Surplus per Household with Isoelastic Demand

	Moderate	Heavy
R	–0.3	–0.155
P(Q)	$e^{(\ln(525.6) - \ln(Q))/0.3}$	$e^{(\ln(557.6) - \ln(Q))/0.155}$
Q1	152	294
Q2	172	314
P1	$52	$52
P2	$41.31	$40.65
ΔCS_{HH}	**$3,736.23**	**$8,016.36**

The result of working through the math for the ΔCS is a welfare gain of $3,736 per moderate household and a gain in consumer surplus of $8,386 per heavy consumption household. The implication is that households that consume more wireless data each month will enjoy a greater benefit from the potential increase in data capacity afforded by the opening of the 5.9 GHz band.

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[36] The integral is equal to $e^{\ln(a)/r} * [e^{-1/r} * Q + Q^2/2]$ then estimated over Q2 to Q1.

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