A 2017 Assessment *of the* Current & Future Economic Value *of* Unlicensed Spectrum *in the* United States

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Executive Summary

This is the third study assessing the value of Wi-Fi spectrum in the United States, following a study completed by this author in February of 2014,[1] and a subsequent study, completed in August of the same year.[2] This research refines and improves upon the earlier analyses, by assessing the economic contribution of a subset of Wi-Fi and other technologies that depend on unlicensed bands while accounting for more recent developments. It estimates that the current economic surplus of unlicensed spectrum in the United States from a selected set of unlicensed application amounts to, at least, $496.13 billion today, while also contributing $29.06 billion to the nation's GDP (a total of $525.19 billion).[3] It further finds that the economic value of this subset of applications will continue increasing, reaching a total of $834.48 billion by 2020.

It is the assumption that several market and technology conditions have changed since earlier studies on the contribution of unlicensed spectrum were completed. For example:

- Explosive growth in overall traffic driven by video usage;
- Maturity of what were considered to be new technologies at the time, like Wi-Fi tablets;
- Explosive development of Bluetooth-enabled applications; and
- Higher certainty about deployment plans of 5G networks.

These changes have modified some of the modeling assumptions used in the prior studies. It has been, therefore, necessary to conduct a new study that factors in all of these and any other industry, technology, and economic changes, to generate a new study, comprising:

- An estimation of 2017 current economic value that provides a validation (and/or adjustment) of the prior estimates of future economic value; and
- An estimation of future economic value resulting from technological and applications advances that have become more robust since 2014.

Based on these two objectives, the following study tackles three sets of key issues:

- How have the assumptions of prior estimates of economic value changed since 2014 (for example, Internet traffic, Wi-Fi rerouting patterns, usage volumes per device, etc.)? Have the applications considered as "emerging" in the last study matured since, which would allow providing a better estimation of their economic value?
- In light of recent changes, what would the resulting scenario be of a forward-looking extrapolation of current trends?
- Have new applications, technologies, and business models emerged since 2014 that should be added to the estimation of current and future economic surplus?

This study provides evidence of an exponential growth in unlicensed spectrum use since 2013 with vast implications for economic value creation:

1 Katz, R. (2014). *Assessment of the economic value of unlicensed spectrum in the United States.* New York: Telecom Advisory Services. Retrieved from: Wi-Fiforward.org/resources. ("Katz (2014a)").

2 Katz, R. (2014). *Assessment of the future economic value of unlicensed spectrum in the United States.* New York: Telecom Advisory Services. Retrieved from: Wi-Fiforward.org/resources. ("Katz (2014b)").

3 This study's approach to measuring the economic value focuses first on the surplus generated from the adoption of the technologies operating in the unlicensed network bands. The underlying premise is that the unlicensed spectrum resource generates a shift in both the demand and the supply curves resulting from changes in the production function of services as well as the corresponding consumers' willingness to pay. However, beyond the concept of economic surplus, the study also measures any direct contribution of technologies, applications, and computer-mediated transactions that run on unlicensed spectrum bands to the nation's GDP (see Thanki, 2009; Cooper, 2012; Alston & Wohlgenant, 1990;, Mensah & Wohlgenant, 2010).

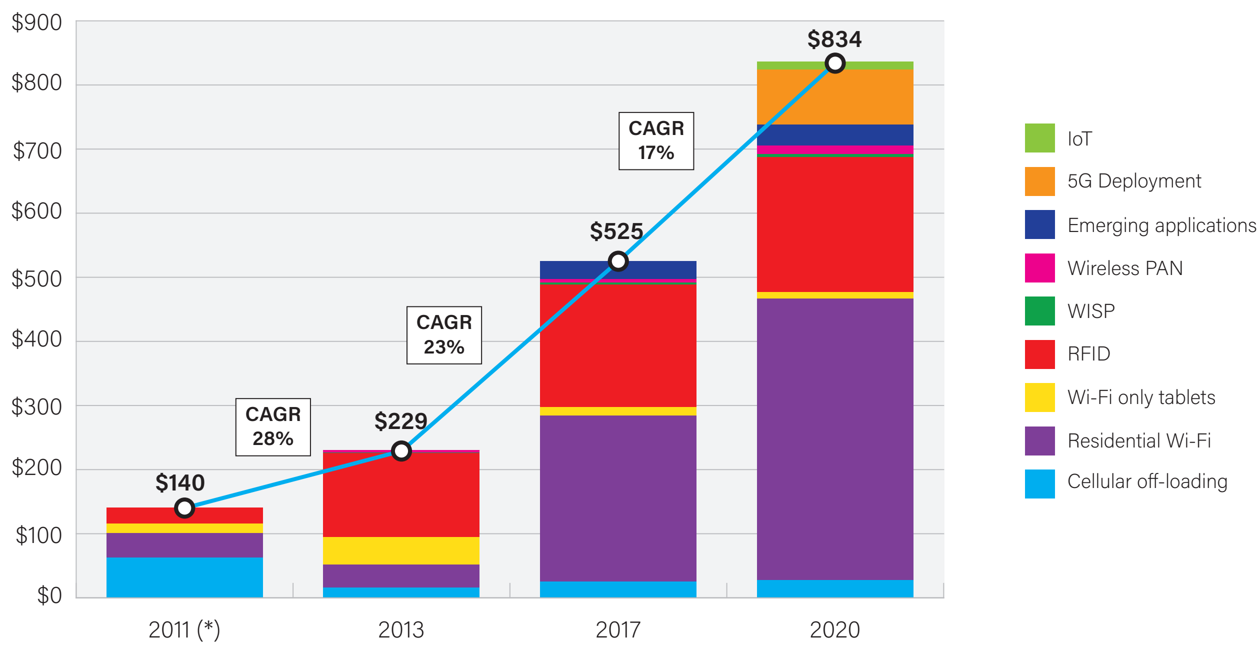
- It estimates that the current economic surplus of unlicensed spectrum in the United States from a selected set of unlicensed application amounts to, at least, $496.13 billion today.
- In addition, these unlicensed applications contribute $29.06 billion to the nation's GDP (a total of $525.19 billion).
- This is slightly lower (-12%) than the $547.22 billion in economic surplus and $49.78 billion in GDP contribution predicted as a 2017 value in the 2014 study due to lower smartphone adoption, differences in Wi-Fi-only tablet sales, and cellular data pricing changes, as discussed below—but does not account for several new and unexpected drivers of Wi-Fi value that are outside of the subset of applications originally studied, as also discussed below.
- The economic contribution of this subset of unlicensed applications will continue increasing, reaching a total of $834.48 billion by 2020.

Importantly, the variability in the values between the 2014 and 2018 studies also demonstrates that the full set of unlicensed applications contributing to economic value is more varied and diverse than expected in the previous research, and that more technologies and applications rely on both licensed and unlicensed spectrum. As a result, the total contribution of unlicensed spectrum is substantially higher than the figures reported for the subset considered specifically herein, and that because of the pace of innovation, capturing the full range of contributions by unlicensed technologies is increasingly difficult—the figures in this report are the readily measurable portion of a larger overall contribution.

In light of this evidence, two key conclusions can be drawn:

- **The economic value of unlicensed spectrum increases over time:** Because of its intrinsic characteristic as an enabling factor of production, unlicensed spectrum is a platform that complements other technologies (such as cellular) and promotes innovation (such as Bluetooth). In 2008, wireless personal area networks and other technologies such as machine-to-machine communications were at an initial diffusion stage and, therefore, did not represent a source of economic surplus. Over time, however, their economic value started to grow. Likewise, in the future, 5G deployment and Internet of Things ("IoT") will become critical growth drivers (see Graph A).

Graph A. Economic value of unlicensed spectrum in the U.S. in Billions (2011-2020)



(*) Composite of previous research by Thanki (2009), Milgrom et al. (2011), and Cooper (2012)
Source: Telecom Advisory Services analysis

- **While economic value continues to grow, the sources of economic value of unlicensed spectrum vary over time:** While the economic value of unlicensed spectrum grows over time, the contribution of some technologies may increase and decrease following their specific product life cycle. That is the case with Wi-Fi tablets, which were a key source of value in the 2013 estimate, but started declining as a result of competitive and product substitution dynamics. But other Wi-Fi-dependent devices, such as video game consoles and intelligent personal assistants, produced far more value than predicted in 2013 (e.g., Amazon Echo, Apple HomePod and Google Home). At the same time, unlicensed spectrum facilitates competition among substitute technologies relying on it. This can result in an increase of economic value of some technologies combined with a simultaneous decrease in value of competing technologies. For example, between 2013 and 2017, the value of Bluetooth-enabled products increased 166%, while the value of Wireless HART-enabled offerings decreased 81%. Yet, in the aggregate, the economic value of Wireless Personal Area Network-enabled products increased 137%.

Table A describes the examined subset of unlicensed technologies and applications, and their estimated roles in 2017 economic value creation.

Table A. Summary of future economic value of applications and technologies relying on unlicensed spectrum in the U.S. (2017) (in $ billions)

Drivers	Technologies and Applications	Economic Surplus: Consumer Surplus	Producer Surplus	Economic Surplus	GDP Contribution
Value of widely deployed technologies and applications	Wi-Fi cellular off-loading	$5.82	$10.70	$16.52	$8.70
	Residential Wi-Fi	$236.95	$21.75	$258.70	N.A.
	Wireless ISPs	N.A.	N.A.	N.A.	$2.87
	Wi-Fi-only tablets	$4.08	$9.48	$13.56	N.A.
	Wireless personal area networks[1]	N.A.	N.A.	N.A.	$5.53
	RFID	$84.94	$106.31	$191.25	N.A.
	SUBTOTAL	**$331.79**	**$148.24**	**$480.03**	**$17.10**
Value of emerging applications and technologies	High-speed wireless[2]	N.A.	N.A.	N.A.	$0.63
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	$3.72
	Machine-to-machine[3]	N.A.	N.A.	N.A.	$6.82
	Smart City deployments	$15.10	N.A.	$15.10	$0.79
	Agriculture automation	N.A.	$1.10	$1.00	N.A.
	SUBTOTAL	**$15.10**	**$1.10**	**$16.2**	**$11.96**
TOTAL		$346.89	$149.34	$496.13	$29.06

N.A. (Not applicable) means that primary value creation effect is either in creating economic surplus or contributing to the GDP.
Source: Telecom Advisory Services analysis

The $496.13 billion economic surplus estimate is a more conservative value of the forecast conducted in 2014 study, resulting in a Figure that is 12% lower for the group of Wi-Fi applications considered. This is due to several factors: smartphone adoption slowed after 2015 as a result of market saturation, tablet traffic was lower as a result of smartphone substitution, and because cellular data prices declined faster, the economic advantage of Wi-Fi substitution was lower. Furthermore, the previous study considered Wi-Fi-only tablets as one of its measures of economic contribution, but did not consider many of the Wi-Fi devices that have emerged since that time. By 2017 producer and consumer surplus derived from Wi-Fi-only tablets significantly diminished as a result of a drop in tablet shipments driven by smartphone substitution coupled with a loss of U.S. manufacturers' global market share, and eroding margins—but shipments of devices that are not part of the group of studied devices, such as Wi-Fi-powered home assistants like the Amazon Echo, Apple HomePod and Google Home, exploded. This has driven an increase in economic value, mitigating the decline in tablet shipments. Finally, the report finds slower than expected growth in high-speed wireless technologies (such as ZigBee and WiGig) as well as revenues of the Wireless Internet Service Provider ("WISP") industry.

On the other hand, part of the value loss was compensated by an exponential growth in smartphone traffic, driven by video usage, a widening speed gap between Wi-Fi and cellular average download speed, emergence of new business models such as in-flight Wi-Fi, and a substantial increase in Bluetooth chipset applications, especially in the automotive market, as well as in video game consoles.

Therefore, despite the slower than forecast growth in some sources of value, the economic surplus of unlicensed spectrum in 2017 increased 23% per year since 2013 from $229.09 billion to $525.19 billion. Looking forward, the economic value of unlicensed spectrum will continue increasing, driven by the growth of widely adopted technologies, combined with new developments such as 5G deployment, reaching a total of $834.48 billion by 2020 (an annual increase of 17%).

The increase in economic value for the next three years is driven, on one side, by the persistent growth in existing applications and technology, but, more importantly, from two key factors: a) the deployment of 5G networks, which will require a significant contribution from Wi-Fi hot-spots and other unlicensed technologies, and b) the efficiency contribution of IoT in vertical markets such as warehouse automation and air transportation. These two new sources of economic surplus will add on their own $98.11 billion in value.

In the context of accelerating adoption of applications operating in unlicensed spectrum, it would be relevant to ask the question whether there is enough spectrum space to accommodate the expected growth. As noted by several analysts, congestion could result either from the density of devices used for a given application or when one set of devices of a given application interferes with a set of devices running another application. When Wi-Fi hot-spot deployment accelerates and transmission bandwidth increases, so does the risk of congestion.

If future assignment of unlicensed spectrum is not fulfilled, it is plausible to consider that economic value creation would be at risk. This case is similar to the transition from 3G to 4G and the allocation of additional licensed spectrum for mobile broadband. Where do we see the effects that would be most at risk? Our quantification of the risk of not assigning additional unlicensed spectrum assumes that, beyond a certain point of network congestion, application or technology demand stops growing.

In the first place, let us address the so-called return to speed. At the current rate of traffic off-loading, the average speed of mobile traffic in the United States in 2017 was 30.20 Mbps.[4] Our analysis showed that if all the off-loaded traffic were to be conveyed through cellular networks, the speed would decline to 13.52 Mbps, with the consequent negative impact of $7.7 billion in GDP. By 2020, the impact would amount to $9.8 billion. However, if we assume that, due to congestion, the average Wi-Fi speed does not increase to 56 Mbps, but stays at current levels (37.93 Mbps), the average speed of all mobile traffic would not change significantly from today, which means that $3.0 billion of the Wi-Fi speed return in 2020 alone would disappear.

Obviously, average speed could decline even further beyond the current level, with the consequent increase in value erosion. According to a study by Williamson et al. (2013), this scenario is highly likely. Once an 80-100 Mbps fiber link is deployed to a customer premise, the last mile is not the bottleneck any more, and residential Wi-Fi becomes the congestion point. This is because there is a difference between the advertised speed in a typical Wi-Fi router (150 Mbps) and the delivered speed, which is below 70 Mbps.[5] Given that Wi-Fi shares available capacity across devices, if a typical Wi-Fi household is running multiple devices, the service will degrade and be substantially less than what could be handled by a fiber link.

4 This is calculated by prorating total mobile traffic by Wi-Fi and cellular speeds according to off-loading factors (see Appendix C).

5 The difference is due in part to the need to assign part of the capacity to the data overheads. In addition, advertised speeds are based on tests that relying on large packets, while the average packet size is much smaller. Finally, range and attenuation are factors to be considered in the reduction of speed. Williamson et al. (2013) estimate that delivered speed is approximately 50% of the advertised.

A second area of negative impact under a scenario of limited unlicensed spectrum assignment is service degradation in public places (airports, convention halls, etc.). Research by Wagstaff (2009) and Van Bloem et al. (2011) indicates that in dense device environments, data overheads that are generated to keep the connection running consume between 80% and 90% of capacity. In the context of increasing traffic volumes, Wi-Fi is becoming the contention point in public access networks. Some of this pressure could be alleviated by the Wi-Fi standard 802.11ac, but without additional unlicensed spectrum designations that accommodate larger 802.11ac channels, we will see far less benefit from this new standard. While it is difficult to quantify the negative impact of this degradation, a large portion has been considered above in the reduction of the so-called Wi-Fi speed return. Furthermore, no additional assignment of unlicensed spectrum could result in the disappearance of the Wi-Fi service provider industry since, with lower service quality level, these operators could not compete with cellular service provider.

A third area of negative impact, if additional unlicensed spectrum is not assigned, could be an erosion of the benefit to carriers generated by cellular traffic off-loading. With high-density device environments being so prone to contention, if Wi-Fi does not benefit from additional spectrum, cellular carriers would experience service degradation when users roam into Wi-Fi. In other words, Wi-Fi's value of complementarity would be greatly diminished, reducing the $10.7 billion estimated producer surplus.

1. Introduction

This is the third study assessing the value of Wi-Fi spectrum in the United States, following a study completed by this author in February of 2014,[6] and a subsequent one, completed in August of the same year.[7] This research refines and improves upon the earlier analyses, by assessing the economic contribution of a subset of Wi-Fi and other technologies that depend on unlicensed bands while accounting for more recent developments. It estimates that the current economic surplus of unlicensed spectrum in the United States from a selected set of unlicensed application amounts to, at least, $452.73 billion today, while also contributing $29.06 billion to the nation's GDP (a total of $481.79 billion). It further finds that the economic contribution of this subset of unlicensed applications will continue increasing, reaching a total of $834.48 billion by 2020.

This assessment refines and improves upon the two earlier studies. A study completed by this author in February of 2014 provided an estimate of the economic value of unlicensed spectrum in the United States.[8] The estimate was based on the adoption of technologies relying on unlicensed bands as of the end of 2013, which, by definition, comprised only widely adopted technologies, such as Wi-Fi and RFID. The study concluded that the technologies operating in unlicensed spectrum bands in the United States at the time generated a total economic value of $222.4 billion in 2013 and contributed $6.7 billion to the nation's GDP. A subsequent study, completed in August of the same year attempted to estimate the future economic value of unlicensed spectrum.[9] The underlying drivers of future economic value were to be expected: the adoption of technologies that relied on unlicensed bands and were already widely diffused, as well as the deployment of emerging innovations, such as what was known at the time as machine-to-machine communications and agricultural automation. The study concluded that by 2017 the economic value of unlicensed spectrum would amount to at least $547.22 billion in economic surplus annually and $49.78 billion in contribution to the annual GDP (see Table 1-1).

Table 1-1. Prior estimates of economic value of unlicensed spectrum in the U.S. (2003-2017) (in $ billions)

		Economic Surplus		GDP Contribution	
Drivers	Technologies and Applications	2013	2017 (E)	2013	2017 (E)
Future value of currently deployed technologies and applications	Wi-Fi cellular off-loading	$12.60	$22.83	$3.102	$7.033
	Residential Wi-Fi	$36.08	$268.74	N.A.	N.A.
	Wireless ISPs	N.A.	N.A.	$1.439	$4.80
	Wi-Fi-only tablets	$42.87	$47.99	N.A.	N.A.
	Wireless personal area networks	N.A.	N.A.	$2.166	$1.652
	RFID	$130.87	$197.46	N.A.	N.A.
	SUBTOTAL	**$222.38**	**$531.02**	**$6.778**	**$13.485**
Value of net yet adopted technologies and applications	High-speed wireless	---	N.A.	---	$4.81
	Machine-to-machine	---	N.A.	---	$31.49
	Smart City deployments	---	$15.1	---	$0.79
	Agriculture automation	---	$1.1	---	N.A.
	SUBTOTAL	**---**	**$16.20**	**---**	**$36.30**
TOTAL		$222.38	$547.22	$6.78	$49.78

Source: Telecom Advisory Services analysis

6 Katz (2014a).
7 Katz (2014b).
8 Katz (2014a).
9 Katz (2014b).

It is the assumption that several market and technology conditions have changed since those studies were completed. For example:

- Explosive growth in overall traffic driven by video usage;
- Maturity of what were considered to be new technologies at the time, like Wi-Fi tablets;
- Explosive development of Bluetooth-enabled applications; and
- Higher certainty about deployment plans of 5G networks.

These changes modified some of the modeling assumptions used in the prior studies. In this context, it was necessary to conduct a new study that factors in all of these and any other industry and technology changes, thereby generating new evidence:

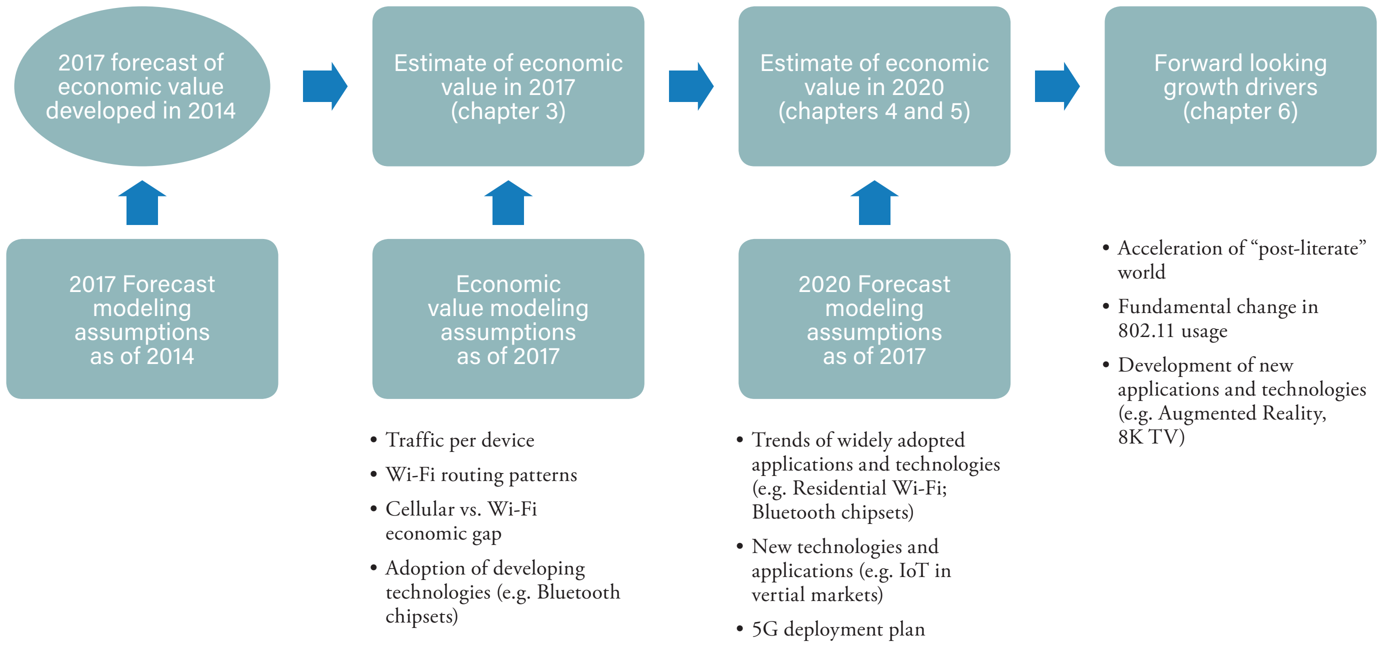
- An estimation of 2017 current economic value that provides a validation (and/or adjustment) of our prior estimates of future economic value; and
- An estimation of 2020 economic value as a result of technological and applications advances that have become more robust since 2014.

Based on these objectives, the following study proceeds along three sequential work streams:

- How have the assumptions of prior estimates of economic value changed since 2014 (for example, traffic, rerouting patterns, usage volumes per device, etc.)? Have the applications considered as "emerging" in our last study matured since, which would allow for providing a better estimation of their economic value (Chapter 3)?
- Having calibrated the original 2017 forecast, what would the resulting scenario be of an extrapolation of current trends to 2020 (Chapter 4)?
- Have new applications, technologies, and business models emerged since 2014 that would add to the current economic surplus (Chapters 5 and 6)?

The approach followed in this study is based on a recalculation of 2017 economic value, in order to develop a forecast for 2020, while still outlining a number of forward-looking value growth drivers that are still difficult to quantify (see Figure 1-1).

Figure 1-1. Study research approach



Before presenting the results of this research, a brief chapter outlining the methodologies used is included.

2. Methodology

2.1. Theoretical Underpinnings of the Value of Unlicensed Spectrum

Unlicensed spectrum has fostered the establishment of standards that have enabled the development of numerous applications and devices (see Table 2-1):

Table 2-1. Standards and enabled complementary technologies

Standards	Frequency Bands	Geographic Range	Data Rate	Devices and Applications
Wi-Fi (802.11b, 802.11g)	• 2.4 GHz • 3.6 GHz • 5 GHz	• Indoor: 38 meters • Outdoor: 125 meters	• Up to 54 Mbps	• Computers • Printers • Mobile phones • Tablets
Bluetooth (802.15.1)	• 2.4 GHz	• Short range indoors	• 1-3 Mbps	• Phone headsets • PC networks • Barcode scanners • Credit card payment machines
ZigBee (802.15.4)	• 915 MHz	• 75 meters	• 250 Kbps	• Wireless light switches • Electrical meters with in-home-displays • Traffic management systems
Wireless HART (802.15.4)	• 2.4 GHz	• Indoor: 60-100 meters • Outdoor: 250 meters	• 250 Kbps	• Equipment and process monitoring • Environmental monitoring, energy management • Asset management, predictive maintenance, advanced diagnostics
WirelessHD	• 60 GHz	• 30 feet	• 28 Gbps	• HD consumer electronic devices
WiGig (802.11ad)	• 60 GHz	• 5 -10 meters	• 6 Gbps	• Smartphones • Tablets • Docking stations • PCs & Peripherals • TV & Peripherals • Digital Cameras • Camcorders
RFID	• 50-500 KHz • 13.56 MHz • 0.9-2.5 GHz	• Up to 29 inches	• Read-only: 8.75 Kbps • Active Read-Write: 3 Kbps	• Asset tracking • Livestock tracking, credit card payments • Highway toll payments • Supply chain management

Source: Compiled by Telecom Advisory Services

In this context, unlicensed spectrum is considered a critical factor of production generating value across four dimensions:

- **Complementing wireline and cellular technologies, thereby enhancing their effectiveness:** A complementary technology is a resource that, due to its intrinsic strengths, compensates for the limitations of another. In the case of spectrum management, unlicensed frequency bands can enhance the effectiveness of devices that use licensed spectrum. For example, Wi-Fi hot-spots operating in unlicensed bands can enhance the value of cellular networks operating in licensed frequencies by allowing wireless devices to switch to carrier grade hot-spots, thereby reducing the cost of broadband access and increasing the access speed rate. Furthermore, consumers accessing the Internet within the reach of a Wi-Fi site can reduce their costs of access by turning off their wideband service. They can also gain additional access speed because the transfer rate of Wi-Fi sites is generally faster than that offered by cellular technology. Similarly, applications and technologies relying on unlicensed spectrum can provide all in-premise connectivity for devices accessing the Internet.

- **Developing alternative technologies, thus expanding consumer choice:** In addition to complementing cellular networks, unlicensed spectrum can provide the environment needed for operating technologies that are substitutes to licensed uses, thereby providing consumers with a larger set of choices. By limiting power and relying on spectrum with low propagation, unlicensed bands avoid interference, rendering the need to assign property rights in unlicensed bands unnecessary (Milgrom et al., 2011). In fact, some of the most important innovations in wireless communications, such as consumer data devices or industrial sensors, are intimately linked to unlicensed spectrum for gaining Internet access.
- **Supporting innovative business models:** By providing consumers with additional service choices, unlicensed spectrum also supports the development of innovative business models. The causality between unlicensed spectrum and innovation occurs at multiple levels. Firms developing new applications in an unlicensed spectrum environment do not need approval from the operators of cellular networks. Along those lines, if a product requires the acceptance and coordination of multiple license holders (say multiple cellular network operators), the innovator must negotiate with every one of them (unless it is willing to face the problem of restricting its market reach). Beyond the impact on time-to-market, small firms face an additional obstacle: spectrum exclusive license holders can impose a financial *hold-up* threat by raising the fraction of the potential revenues they would appropriate. This could reduce the incentive for small firms to launch new products.
- **Expanding access to communications services:** In addition to the applications discussed above, technologies operating in unlicensed spectrum can bridge the broadband coverage digital divide. The Federal Communications Commission ("FCC") estimates that approximately 12.6 million U.S. households lack access to broadband.[10] As expected, the majority of these households are located in rural and isolated areas of the country. While the FCC report does not track broadband over cellular coverage, the National Broadband Map indicates that 3.2 million households (34% of the underserved number mentioned above) can only gain access to broadband services provided by the so-called Wireless Internet Service Providers ("WISPs"), which typically operate on unlicensed or lightly licensed spectrum in the 5 GHz and 3.65 GHz bands. Additionally, further developments in the areas of spectrum sensing, dynamic spectrum access, and geo-location techniques could improve the quality of wireless service based on unlicensed spectrum technologies. For example, as described in this study, a new version of the Wi-Fi standard, 802.11af, sometimes called "Super Wi-Fi," can substantially extend the geographic range of the conventional 802.11 standard and provide cost-efficient access in rural settings.

In this context, as done in previous studies by this author, the approach to measuring economic value focuses first on the surplus generated after the adoption of the technologies operating in the unlicensed network bands. The underlying assumption of this approach is that the unlicensed spectrum resource generates a shift both in the demand and supply curves resulting from changes in the production function of services as well as their corresponding willingness to pay by consumers. On the supply side, the approach measures changes in the value of inputs in the production of wireless communications. The most obvious example is whether Wi-Fi, enabled by unlicensed spectrum, represents a positive contribution to wireless carriers' CAPEX and OPEX insofar as they can control their spending while meeting demand for increased wireless traffic. From an economic theory standpoint, the wireless industry can then increase its output, yielding a marginal benefit exceeding the marginal cost. Additionally, since the demand curve is derived from the utility function, higher benefit to the consumer derived from the reliance on technologies enabled by unlicensed spectrum at a sTable price will yield an increase in the willingness to pay, and consequently a shift in the demand curve.

To quantify incremental surplus derived from the adoption of technologies operating in the unlicensed spectrum

10 Corasanti, N. (2017, March 20). In New York, bringing broadband to everyone by 2018. *The New York Times*. Retrieved from: https://www.nytimes.com/2017/03/20/nyregion/new-york-broadband-cuomo-internet.html?_r=0.

bands, we itemize the number of technologies and applications intricately linked to this environment. In addition, we complement the concept of economic surplus with an assessment of the direct contribution of some technologies and applications to the nation's GDP. By including the GDP contribution measurement, we follow Greenstein et al. (2010) and prior literature measuring the economic gains of new goods. In measuring the GDP direct contribution, we strictly consider the revenues added "above and beyond" what would have occurred had the unassigned spectrum been licensed. Along those lines, if unit costs of the new technology or application are available, we do not add them to the GDP contribution, but rather include them as a metric of producer surplus.

The assignment of each effect and underlying rationale is included in Table 2-2.

Table 2-2. Approaches to measure economic value of unlicensed spectrum in prior studies

Technologies and Applications	Economic Effect	Quantification	Rationale
Wi-Fi cellular offloading	Value of free Wi-Fi traffic offered in public sites	Consumer surplus	Price to be paid if transported through the cellular network equals the willingness to pay
	Total cost of ownership (cumulative CAPEX and OPEX) necessary to accommodate future capacity requirement with Wi-Fi complementing cellular networks	Producer Surplus	Since mobile broadband prices do not decline when traffic is off-loaded to Wi-Fi, the gain triggered by cost reduction becomes producer surplus
	Contribution to GDP from the increase in average mobile speed resulting from Wi-Fi off-loading	GDP contribution	While speed increase could be considered consumer surplus, recent research asserts a spill-over in terms of economic efficiency
	Sum of revenues of service providers offering paid Wi-Fi access in public places	GDP contribution	These revenues would not exist without the availability of unlicensed spectrum
Residential Wi-Fi	Internet access for devices that lack a wired port (e.g., tablets, smartphones, game consoles)	Consumer surplus	Price to be paid if transported through the cellular network; this equals the willingness to pay
	Avoidance of investment in in-house wiring	Consumer surplus	Price to be paid for in-house Ethernet wiring equals willingness to pay
Wireless ISPs	Aggregated revenues of 1,800 WISPs	GDP contribution	These revenues would not exist without the availability of unlicensed spectrum
Wi-Fi-only tablets	Difference between retail price and manufacturing costs for a weighted average of tablet suppliers	Producer surplus	Availability of manufacturing and retail costs as well as sales volume
	Difference between willingness to pay for entry level tablet and prices of iPad and Android products	Consumer surplus	Availability of willingness to pay data, retail pricing, and sales volume
Home device eco-systems (e.g., Google Home, Amazon Echo)	Revenues derived from product sales	GDP contribution	These revenues would not exist without the availability of unlicensed spectrum
Industrial applications (e.g., warehouse automation, airline gate coordination)	Reduction in operating costs resulting from adoption of Wi-Fi enabled platforms	Producer surplus	Efficiency benefits to firms resulting from adoption of technologies
Wireless personal area networks	Sum of revenues of Bluetooth-enabled products	GDP contribution	These revenues would not exist without the availability of unlicensed spectrum
	Sum of revenues of other WPAN standards (ZigBee, Wireless HART)	GDP contribution	
RFID	RFID value in retailing	Consumer and producer surplus	Benefits to consumers and savings to producers
	RFID value in health care		
Machine-to-machine (e.g., wearables, Demand Side Management, Telehealth)	Revenues to be generated by device sales	GDP contribution	These revenues would not exist without the availability of unlicensed spectrum

Source: Telecom Advisory Services analysis

Replicating the analyses conducted in the 2014 studies, we first proceed to validate the 2017 forecast modeling assumptions to determine whether they are consistent or not with the industry trends since then. For example, what has happened in terms of device adoption and usage of wireless broadband since then and what are the implications for the current assessment of unlicensed spectrum of economic value?

Once a new 2017 estimate of economic value is produced, we then generate a new forecast for the next three years predicated on an evolution of the current conditions. According to this, for example, we would explore the value of unlicensed spectrum resulting from a forecast of future wireless Internet traffic.

Beyond assessing current and future value of unlicensed spectrum resulting from the economic effects depicted in Table 2-2, we identify other emerging sources of economic surplus (see Table 2-3).

Table 2-3. New sources of economic value of unlicensed spectrum

Driver	Economic Effect	Quantification	Rationale
An expansion of the wireless device ecosystem	Difference between retail price and manufacturing costs of a new range of Bluetooth enabled devices	GDP contribution	These revenues would not exist without the availability of unlicensed spectrum
New industrial applications benefitting from unlicensed spectrum	Streamlining manufacturing operations	Producer surplus	Savings in operational efficiencies
	Productivity in distribution fulfillment operations		
	Efficiency in airline operations		
5G deployment	Total cost of ownership (cumulative CAPEX and OPEX) necessary to accommodate future capacity requirement with Wi-Fi complementing cellular networks	Producer surplus	When 5G broadband traffic is off-loaded to Wi-Fi micro-cells, the gain triggered by cost reduction becomes producer surplus

Source: Telecom Advisory Services analysis

In sum, this approach would yield a new assessment of the 2017 actual economic value of unlicensed spectrum and a forecast of future value resulting from the adoption and usage trends of existing applications combined with new emerging use cases.

2.2. Why Does the Economic Value of Unlicensed Spectrum Increase Over Time?

As explained above, the need to conduct a new study assessing the economic value of unlicensed spectrum is predicated on the notion that changing environmental and industry conditions could yield additional effects not included in the original estimates. In other words, the four sources of economic value discussed above—complementarity with cellular networks, development of alternative technologies, supporting innovative business models, and expansion of access—are not static. For example, the larger the portion of wireless traffic routed through free Wi-Fi sites, the higher its Wi-Fi economic surplus would be. Similarly, if new business models or alternative technologies were developed relying on unlicensed bands, this would cause an increase in the economic value of the spectrum.

Three studies measuring the economic value of unlicensed spectrum conducted at different points in time, and reviewed in the first paper by this author (Katz, 2014a) indicated increasing estimates (see Table 2-4).

Table 2-4. Prior research on economic value of unlicensed spectrum in the U.S. (in $ billions)

Technologies and Applications	Effect	Thanki (2009)	Milgrom et al. (2011)	Cooper (2012)
Wi-Fi cellular off-loading	Consumer surplus	N.A.	$25.0	$20.0
	Producer surplus	N.A.	N.A.	$26.0
	Return to speed	N.A.	$12.0	(*)
	New business revenue	N.A.	N.A.	N.A.
	SUBTOTAL	**N.A.**	**$37.0**	**$46.0**
Residential Wi-Fi		$4.3-$12.6	>$12.6	$38 0
	SUBTOTAL	**$4.3-$12.6**	**>$12.6**	**$38 0**
Wi-Fi-only tablets	Producer surplus	N.A.	$7.5	N.A.
	Consumer surplus	N.A.	$7.5	N.A.
	SUBTOTAL	**N.A.**	**$15.0**	**N.A.**
Hospital Wi-Fi		$9.6-$16.1	N.A.	(*)
	SUBTOTAL	**$9.6-$16.1**	**N.A.**	**(*)**
Clothing RFID		$2.0-$8.1	N.A.	(*)
	SUBTOTAL	**$2.0-$8.1**	**N.A.**	**(*)**
Wireless ISPs		N.A.	N.A.	N.A.
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**
TOTAL		$16.0-$36.8	$64.6	$84.0

(*) Referenced but not quantified

N.A. Not addressed

Source: Telecom Advisory Services analysis

As indicated in Table 2-4, Thanki (2009), based mostly on 2008 and earlier data, concluded that the economic value of unlicensed spectrum could be estimated within a $16.0 to $36.8 billion range (primarily depending on RFID adoption). Milgrom et al. (2011), based on 2010 data, estimated economic value at $64.6 billion, even without estimating value of important sources such as RFID. Finally, Cooper (2012), based on 2011 data, estimated economic value at $84.0 billion, again without addressing RFID. A comparison over time for residential Wi-Fi value indicates a continuing growth in economic value.

Along those lines, the study completed by this author in 2014 (relying on 2013 data) yielded a higher estimate than the prior research (see Table 2-5).

Table 2-5. Prior research on economic value of unlicensed spectrum in the U.S. vs. Katz (2014) (in $ billions)

Technologies and Applications	Effect	Thanki (2009)	Milgrom et al. (2011)	Cooper (2012)	Katz (2013)
Wi-Fi cellular offloading	Consumer surplus	N.A.	$25.0	$20.0	$1.90
	Producer surplus	N.A.	N.A.	$26.0	$10.70
	Return to speed	N.A.	$12.0	(*)	$2.83
	New business revenue	N.A.	N.A.	N.A.	$0.27
	SUBTOTAL	**N.A.**	**$37.0**	**$46.0**	**$15.70**
Residential Wi-Fi		$4.3-$12.6	>$12.6	$38 0	$36.08
	SUBTOTAL	**$4.3-$12.6**	**>$12.6**	**$38 0**	**$36.08**
Wi-Fi-only tablets	Producer surplus	N.A.	$7.5	N.A.	$34.88
	Consumer surplus	N.A.	$7.5	N.A.	$7.99
	SUBTOTAL	**N.A.**	**$15.0**	**N.A.**	**$42.87**
Hospital Wi-Fi		$9.6-$16.1	N.A.	(*)	$35.99 (***)
	SUBTOTAL	**$9.6-$16.1**	**N.A.**	**(*)**	**$35.99 (***)**
Clothing RFID		$2.0-$8.1	N.A.	(*)	$94.84 (**)
	SUBTOTAL	**$2.0-$8.1**	**N.A.**	**(*)**	**$94.84 (**)**
Wireless ISPs		N.A.	N.A.	N.A.	$1.44
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$1.44**
Wireless personal area networks	Bluetooth products	N.A.	N.A.	N.A.	$1.74
	ZigBee products	N.A.	N.A.	N.A.	$0.27
	Wireless HART products	N.A.	N.A.	N.A.	$0.16
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$2.17**
TOTAL		$16.0-$36.8	$64.6	$84.0	$229.09

(*) Referenced but not quantified

(**) Calculated for total retail sector

(***) Calculated for total health care including pharmaceutical supply chain.

N.A. Not addressed

Source: Telecom Advisory Services analysis

While it is difficult to compare studies that have partly relied on different methodologies, the data in Table 2-5 allows us to draw several conclusions:

- First and foremost, the economic value of unlicensed spectrum increases with each study, starting within a range of $16.0 to $36.0 billion by Thanki (2009) and ending with $229.09 billion by Katz (2014a). Part of this increase is naturally resulting from the fact that the last study tends to rely on a larger number of sources of value. However, some of these were not addressed in prior studies simply because they were at an embryonic stage of diffusion (e.g., Bluetooth-enabled products).
- Secondly, over time, research was able to make more precise the value quantification methodology. For example, Katz (2014a) benefitted from econometric research on the "return to broadband speed" conducted by Bohlin and Rohman in 2012, which allowed a more precise estimation of the impact of faster Wi-Fi connections.
- Similarly, Katz (2014a) benefitted from more detailed information, such as manufacturing and willingness to pay data on Wi-Fi tablets.

- That said, the data in Table 2-5 also indicate that, despite the increase in total economic value of unlicensed spectrum over time, the growth is not a mere extrapolation of trends: some sources of value tend to increase (Wi-Fi tablets in Milgrom et al., 2011 vs. Katz, 2014), while others decrease (Wi-Fi cellular off-loading in Milgrom et al., 2011 and Cooper, 2012 vs. Katz, 2014), and others remain fairly similar (e.g., residential Wi-Fi in Cooper, 2012 vs. Katz, 2014). This points to an extremely important finding in assessing the sources of economic value of unlicensed spectrum: **sources of economic value are not constant, but tend to change over time following technology innovation cycles.** As mentioned by Milgrom et al. (2011),

> "unlicensed spectrum is an enabling resource. It provides a platform for innovation upon which innovators may face lower barriers to bringing wireless products to market."[11]

Along those lines, the sources of value could change over time.

As mentioned in the introduction, later in 2014, this author prepared a new study, attempting to forecast the value of unlicensed spectrum bands by 2017. This last study relied on a number of assumptions of the evolution of key drivers and resulted in the following values (restated from Table 1-1 for comparison purposes).

11 Milgrom, P., Levin, J., & Eilat, A. (2011, Oct. 12). *The case for unlicensed spectrum*. Stanford Institute for Economic Policy Research Discussion, Paper No. 10-036, p. 2. Retrieved from: https://web.stanford.edu/~jdlevin/Papers/UnlicensedSpectrum.pdf. ("Milgrom et al. (2011)").

Table 2-6. Prior research on economic value of unlicensed spectrum in the U.S. vs. Katz (2014) (in $ billions)

Technologies and Applications	Effect	Thanki (2009)	Milgrom et al. (2011)	Cooper (2012)	Katz (2013)	Katz 2017 Forecast (2014)
Wi-Fi cellular offloading	Consumer surplus	N.A.	$25.0	$20.0	$1.90	$12.13
	Producer surplus	N.A.	N.A.	$26.0	$10.70	$10.70
	Return to speed	N.A.	$12.0	(*)	$2.83	$6.56
	New business revenue	N.A.	N.A.	N.A.	$0.27	$0.47
	SUBTOTAL	**N.A.**	**$37.0**	**$46.0**	**$15.70**	**$29.86**
Residential Wi-Fi		$4.3-$12.6	>$12.6	$38 0	$36.08	$268.74
	SUBTOTAL	**$4.3-$12.6**	**>$12.6**	**$38 0**	**$36.08**	**$268.74**
Wi-Fi-only tablets	Producer surplus	N.A.	$7.5	N.A.	$34.88	$22.11
	Consumer surplus	N.A.	$7.5	N.A.	$7.99	$25.88
	SUBTOTAL	**N.A.**	**$15.0**	**N.A.**	**$42.87**	**$47.99**
Hospital Wi-Fi		$9.6-$16.1	N.A.	(*)	$35.99 (***)	$52.60 (***)
	SUBTOTAL	**$9.6-$16.1**	**N.A.**	**(*)**	**$35.99 (***)**	**$52.60 (***)**
Clothing RFID		$2.0-$8.1	N.A.	(*)	$94.84 (**)	$138.85 (***)
	SUBTOTAL	**$2.0-$8.1**	**N.A.**	**(*)**	**$94.84 (**)**	**$138.85 (***)**
Wireless ISPs		N.A.	N.A.	N.A.	$1.44	$4.8
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$1.44**	**$4.8**
Wireless personal area networks	Bluetooth products	N.A.	N.A.	N.A.	$1.74	$0.77
	ZigBee products	N.A.	N.A.	N.A.	$0.27	$0.83
	Wireless HART products	N.A.	N.A.	N.A.	$0.16	$0.05
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$2.17**	**$1.65**
Emerging technologies and applications	High-speed wireless	N.A.	N.A.	N.A.	N.A.	$4.81
	Machine-to-machine	N.A.	N.A.	N.A.	N.A.	$31.49
	Smart City deployments	N.A.	N.A.	N.A.	N.A.	$15.89
	Agriculture automation	N.A.	N.A.	N.A.	N.A.	$2.20
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**$54.39**
TOTAL		$16.0-$36.8	$64.6	$84.0	$229.09	$598.88

(*) Referenced but not quantified

(**) Calculated for total retail sector

(***) Calculated for total health care including pharmaceutical supply chain.

N.A. Not addressed

The more than doubling of economic value estimated for 2017 was based, first, on the emergence of new sources of value, such as high-speed wireless technologies for home automation, Smart City deployments leveraging Wi-Fi and Bluetooth sensors, and, in general, machine-to-machine networking. In addition, the increase in value was driven by an exponential growth in wireless traffic propelled by video usage and growing importance of tablets as an access device. In light of the evidence generated in comparing prior studies, it is relevant to examine the 2017 forecast along the following key questions:

- How have the assumptions of prior estimates of economic value changed since 2014 (for example, traffic, rerouting patterns, usage volumes per device, etc.)
- Have the applications considered as "emerging" in the 2017 forecast matured since, which would allow for providing a better estimation of their economic value?
- Have new applications, technologies, and business models emerged since 2014 that would add to the current economic surplus?

This will be the focus on the following chapter.

3. The Value of Unlicensed Spectrum in 2017 has Increased 129% Since 2013

The 2017 economic value of unlicensed spectrum has been assessed in this research across four dimensions: (1) complementing wireline and cellular technologies, thereby enhancing their effectiveness; (2) developing alternative technologies, thus expanding consumer choice; (3) supporting innovative business models, and (4) expanding access to communications services. The analysis was based first on a number of assumptions regarding growth of widely diffused applications and technologies (see Table 3-1).

Table 3-1. Key questions regarding future economic value of unlicensed spectrum

Technologies and Applications	Key Questions
Free public Wi-Fi	• What is the expected growth in Wi-Fi traffic in public sites? • What is the future price of cellular GB?
Residential Wi-Fi	• What is the growth in annual home traffic of devices with no wireline connectivity? • Is there surplus to be quantified in the adoption of Wi-Fi enabled residential equipment?
Network off-loading	• Are there any changes in carriers' cumulative Wi-Fi CAPEX and OPEX to accommodate future traffic?
Revenues of Wi-Fi provision	• What is the expected growth of retail Wi-Fi service providers?
Faster wireless	• What is the increase of average cellular and Wi-Fi speeds?
Wi-Fi-only tablets	• What is the expected growth of Wi-Fi-only tablet shipments? • What is the projected Apple market share?
RFID technology	• What is the future adoption of RFID technology in retail and health care?
Bluetooth products	• What is the growth of Bluetooth enabled devices? • What is the future cost of Bluetooth chipset?
ZigBee and Wireless HART products	• What is the expected growth of ZigBee market? • What is the expected growth of Wireless HART market?
WISPs	• What is the expected growth of WISPs subscribers and ARPU?

Additionally, the estimation of economic value was based on an assessment of emerging technologies (see Table 3-2).

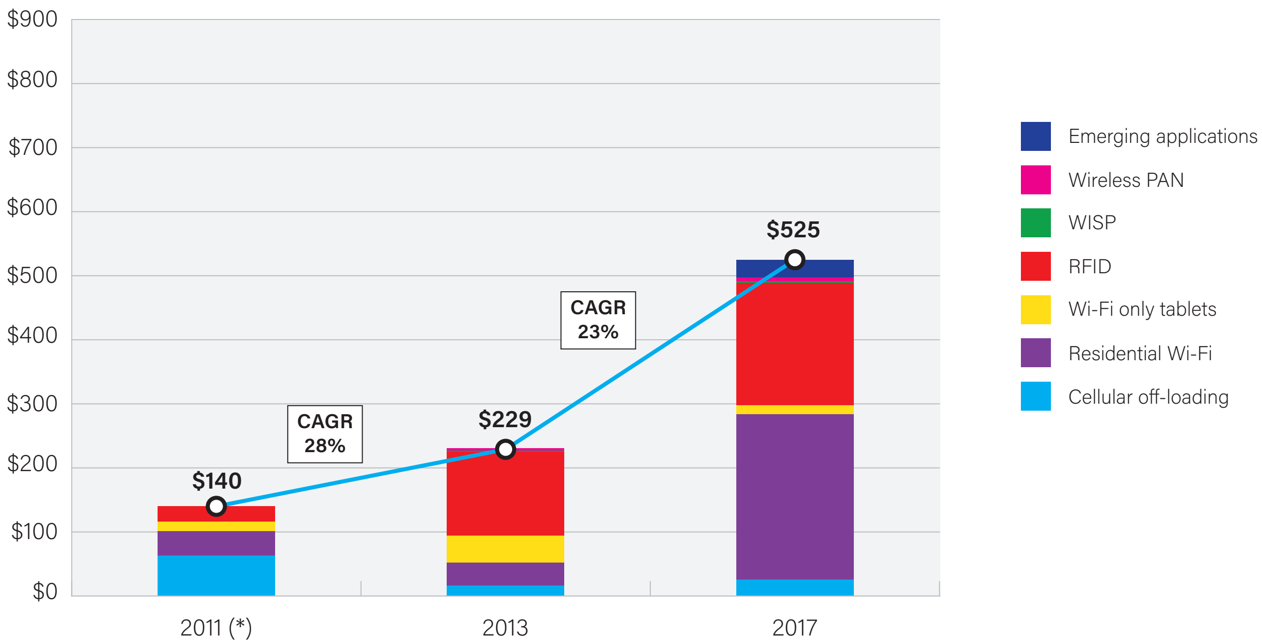
Table 3-2. Economic value of emerging technologies

Emerging Technology	Subset	Examples of Impact
High-speed wireless	• WirelessHD • WiGig	• Ease of deployment of in-house devices • Complement residential Wi-Fi networks
Low-frequency Wi-Fi	• Broadband provision in wide areas	• Rural broadband coverage
Machine-to-machine	• M2M applications relying on unlicensed spectrum • Wearable devices	• Improved energy consumption • Security • Health monitoring
Smart City deployments	• Distributed networks of wireless intelligent sensors	• Reduce pollution concentration • Optimization of energy consumption and traffic flows
Agricultural automation	• Network of wireless sensors • RFID tags for field data collection	• Increase in Total Factor Productivity

Source: Telecom Advisory Services analysis

On the basis of these analyses, the economic surplus value of unlicensed spectrum in 2017 in the United States is estimated at $496.13 billion, while the contribution to the nation's GDP of this set of technologies is at least $29.06 billion (for a total of $525.19 billion). Thus, total economic value has increased 129% since our estimate for 2013 at a compound annual rate of 23% (see Graph 3-1).

Graph 3-1. Economic value of unlicensed spectrum in the U.S. (2011-2017)



(*) Composite of previous research by Thanki (2009), Milgrom et al. (2011), and Cooper (2012)
Source: Telecom Advisory Services analysis

It is important to note that, as discussed below, the study also found that the full set of unlicensed applications contributing to economic value is more varied and diverse than expected in previous studies, and that more technologies and applications rely on both licensed and unlicensed spectrum (see Table 3-3).

Table 3-3. Summary of future economic value of unlicensed spectrum in the U.S. (2017) (in $ billions)

Technologies and Applications	Effect	Economic Value Consumer Surplus	Producer Surplus	Total Surplus	GDP
Wi-Fi cellular off-loading	Value of free Wi-Fi traffic offered in public sites	$5.82	N.A.	$5.82	N.A.
	Benefit of total cost of ownership required to support future capacity requirement with Wi-Fi complementing cellular networks	N.A.	$10.70	$10.70	N.A.
	Contribution to GDP of increase of average mobile speed resulting from Wi-Fi off-loading	N.A.	N.A.	N.A.	$7.7
	Sum of revenues of service providers offering paid Wi-Fi access in public places	N.A.	N.A.	N.A.	$1.0
	SUBTOTAL	**$5.82**	**$10.7**	**$16.52**	**$8.70**
Residential Wi-Fi	Internet access for devices that lack a wired port	$156.0	N.A.	$156.0	N.A.
	Avoidance of investment in in-house wiring	$59.20	N.A.	$59.20	N.A.
	Economic value of Wi-Fi enabled residential equipment	$21.75	$21.75	$43.50	N.A.
	SUBTOTAL	**$236.95**	**$21.75**	**$258.70**	**N.A.**
Wireless ISPs	Aggregated revenues of WISPs	N.A.	N.A.	N.A.	$2.87
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$2.87**
Wi-Fi-only tablets	Difference between retail price and manufacturing costs for a weighted average of tablet suppliers	N.A.	$9.48	$9.48	N.A.
	Difference between willingness to pay for entry level tablet and prices of iPad and Android products	$4.08	N.A.	$4.08	N.A.
	SUBTOTAL	**$4.08**	**$9.48**	**$13.57**	**N.A.**
Wireless personal area networks	Sum of revenues of Bluetooth-enabled products	N.A.	N.A.	N.A.	$5.00
	Sum of revenues of ZigBee-enabled products	N.A.	N.A.	N.A.	$0.50
	Sum of revenues of Wireless HART-enabled products	N.A.	N.A.	N.A.	$0.03
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$5.53**
RFID	RFID value in retailing	$38.14	$100.41	$138.55	N.A.
	RFID value in health care	$46.80	$5.90	$52.70	N.A.
	SUBTOTAL	**$84.94**	**$106.31**	**$191.25**	**N.A.**
High-speed wireless	WirelessHD	N.A.	N.A.	N.A.	$0.52
	WiGig	N.A.	N.A.	N.A.	$0.11
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$0.63**
Low-frequency Wi-Fi	**SUBTOTAL**	**N.A.**	**N.A.**	**N.A.**	**$3.72**
Machine-to-machine	M2M applications relying on unlicensed spectrum	N.A.	N.A.	N.A.	$2.43
	Wearable devices	N.A.	N.A.	N.A.	$4.39
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$6.82**
Smart City deployments	Reduce pollution concentration, optimization of park irrigation or lighting, traffic optimization	$15.1	N.A.	$15.1	$0.79
	SUBTOTAL	**$15.1**	**N.A.**	**$15.1**	**$0.79**
Agriculture automation	Increase in Total Factor Productivity resulting from improved fertilizer management, and a reduction of overlap of spraying	N.A.	$1.0	$1.0	N.A.
	SUBTOTAL	**N.A.**	**$1.0**	**$1.0**	**N.A.**
TOTAL		$346.89	$194.24	$496.13	$29.06

(1) Already captured in 2013 estimates; therefore, should be the same.

Source: Telecom Advisory Services analysis

The 2017 actual estimates are 12% under the forecast developed in 2014, as a result of a number of factors ranging from slower smartphone adoption due to market saturation, to faster drop in cellular data pricing eroding part of the Wi-Fi advantage, a drop of tablet shipments due to smartphone substitution, and lower revenues from Wireless ISPs. On the other hand, these effects were partially compensated by an explosive growth in Bluetooth-enabled devices and an increase in Wi-Fi speed advantage vis-à-vis cellular networks. The following chapter will present first the analyses leading to the estimation of value in 2017 and compare them at the end with the forecast for the same year developed in 2014.

3.1. The 2017 Economic Value of Cellular Off-Loading

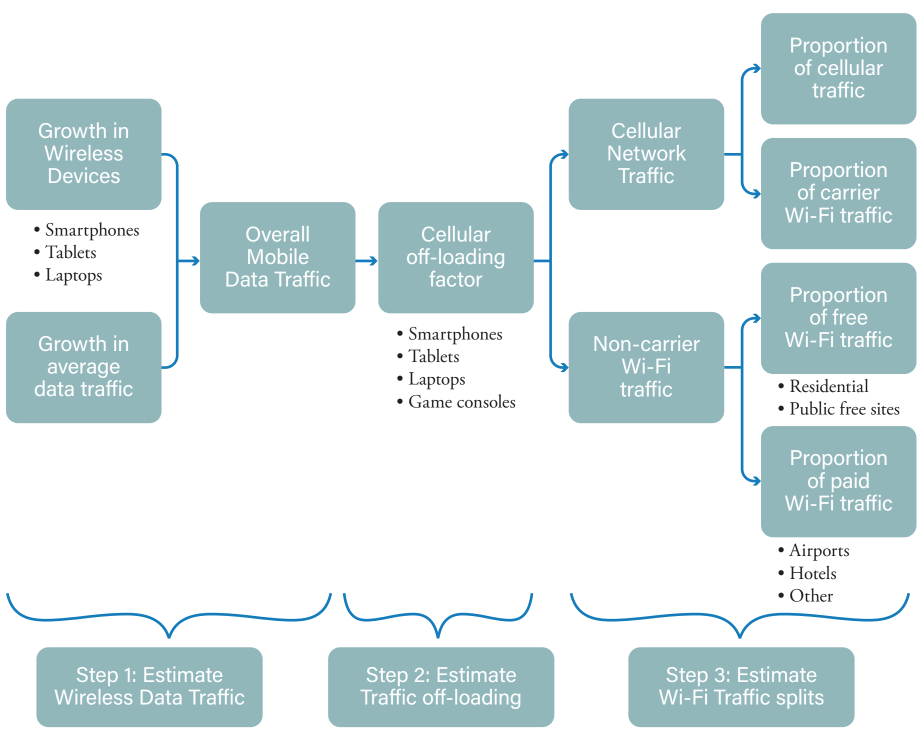
The economic value of Wi-Fi for cellular off-loading for 2017 is estimated in four areas:

- **Consumer surplus:** Consumer surplus is calculated as the difference between the consumer's willingness to pay and the price paid for the service; along these lines, if a consumer accesses the Internet in a public hot-spot for free, surplus would equate to the monetary value he/she would pay to a cellular operator for gaining similar connectivity;
- **Producer surplus:** In light of the explosive growth in data traffic, wireless carriers operating in licensed bands deploy Wi-Fi facilities to reduce both capital and operating expenses while dealing with congestion challenges; since they monetize the Wi-Fi access they provide, surplus measures the difference in capital and operating expenses for the off-loaded traffic;
- **Return to speed:** Since Wi-Fi accessibility allows, in general, faster access to the Internet than cellular networks do, higher speeds have a positive contribution on the economy in terms of increased efficiency and innovation; and
- **New business models:** Wi-Fi allows for the entry of service providers of paid Internet access in public places (such as Boingo Wireless and Gogo Inflight Internet); they generate new revenue.

3.1.1. 2017 Consumer Surplus of Wi-Fi for Cellular Off-Loading

The estimate of consumer surplus for 2017 of Wi-Fi off-loading follows three steps.

Figure 3-1. Methodology for estimating off-loading traffic



The analysis begins by estimating total Wi-Fi traffic and factoring in the portion of it that is conveyed through public free and "guest" sites. Based on the evolution of off-loading coefficients and consumer behavior, the 2017 estimated free Wi-Fi traffic reached 2,186 million Gigabytes (see Table 3-4).

Table 3-4. Free Wi-Fi traffic in the U.S. (2017)

Variable	Value
Smartphone installed base	282,027,102 (*)
Smartphone penetration	86.07 %
Tablets installed base	126,222,535 (**)
Tablets penetration	38.52 %
Laptops installed base	229,680,000 (***)
Laptops penetration	70.10 %
Average traffic per smartphone (GB per month)	14.076 (**)
Average traffic per tablet (GB per month)	14.791 (**)
Average traffic per laptop (GB per month)	4.034 (**)
Smartphones percent Wi-Fi off-loading (%)	62% (**)
Tablets percent Wi-Fi off-loading (%)	72% (**)
Laptops percent Wi-Fi off-loading (%)	66%
Percent of off-loading traffic to free Wi-Fi sites	4.32%
Total free Wi-Fi traffic (GB per year)	**2,186.57**

Sources: (*) GSMA; (**) Cisco; (***) Statista; Telecom Advisory Services analysis

Consumer surplus from off-loading traffic to free sites was calculated, in turn, by multiplying the total free traffic by the difference between what the consumer would have to pay if he/she were to utilize a wireless carrier and the cost of offering free Wi-Fi (incurred by the retailer or public site). The key variable in this case is the average price per cellular GB, which reached $5.16 in 2017 (see Table 3-5).

Table 3-5. Cellular pricing in the U.S. (in 2017) (per GB)

Carrier	Pricing
AT&T	$6.70 (Mobile share data: $335/50 GB cap)
Verizon	$7.10 (Data only, 100 Gb: $710/100 GB cap)
Sprint	$2.50 (Unlimited data: $25/10 GB cap 4G)
T-Mobile	$4.32 (Mobile Internet, 22 Gb: $95/22 GB cap)
Average	**$5.16**

Note: Price per cellular gigabyte calculated by averaging the most economic "dollar per GB" plan of four major U.S. wireless carriers in 2017
Source: Telecom Advisory Services analysis

The consumer surplus per GB is calculated by subtracting the cost of Wi-Fi provisioning (estimated at $2.50) from the average price per cellular GB. Therefore, the Wi-Fi economic advantage dropped is $2.66. As a result, the consumer surplus derived from cellular off-loading to free Wi-Fi sites in 2017 was $5.8 billion (see Table 3-6).

Table 3-6. Consumer surplus of free Wi-Fi traffic in the U.S. (2017)

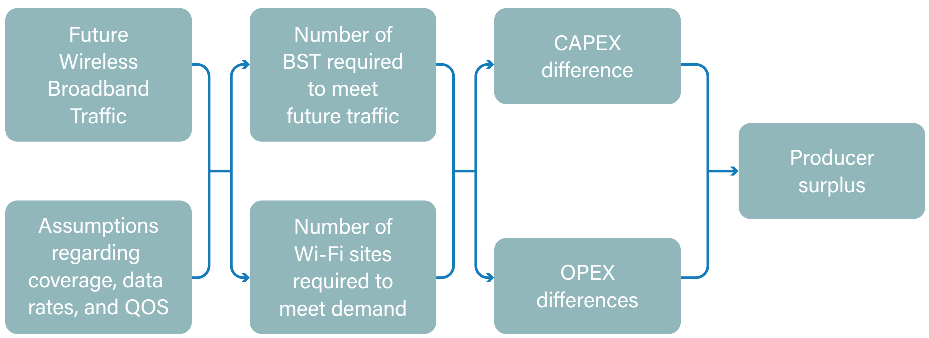
Variable	Value
Total free traffic (million GB per year)	2,186.57
Price per cellular gigabyte ($)	$5.16
Cost per Wi-Fi provisioning ($)	$2.50
Consumer surplus per GB ($)	$2.66
Total consumer surplus ($ million)	**$5,816.27**

Source: Telecom Advisory Services analysis

3.1.2. 2017 Producer Surplus of Wi-Fi for Cellular Off-Loading

The estimate of producer surplus in 2017 was based on the portion of capital investments spent in base stations and spectrum (and potential incremental network operations and maintenance operating expenses) that service providers could avoid when they shifted routing from the cellular network to carrier-grade Wi-Fi (see Figure 3-2).

Figure 3-2. Model structure for calculating cellular off-loading producer surplus



By 2017, LTE networks had been fully deployed in the United States.[12] Therefore, the estimation of savings has to be done by quantifying how much of the current cellular networks are complemented by Wi-Fi base stations. For example, in North America as of 2017, the cellular carriers operate 1,800,000 carrier grade Wi-Fi hot-spots.[13] The importance of Wi-Fi is clearly depicted in data traffic flows by U.S. cellular carriers (see Table 3-7).

Table 3-7. Wireless data traffic across cellular and Wi-Fi networks in the U.S. (2017)

	Average Number of Daily Sessions per User				Average Daily Traffic per User (GB)				Average Daily Usage Time per User			
	Cellular		Wi-Fi		Cellular		Wi-Fi		Cellular		Wi-Fi	
Carrier	N	%	N	%		%		%	Min	%	Min	%
AT&T	102.32	53.1%	90.48	46.9%	74.18	24.7%	225.98	75.3%	137.54	46.2%	160.04	53.8%
Sprint	84.97	50.0%	85.14	50.0%	88.64	34.5%	168.34	65.5%	129.19	41.3%	183.35	58.7%
T-Mobile	141.37	58.5%	100.48	41.5%	139.19	34.2%	268.24	65.8%	174.66	52.2%	159.69	47.8%
Verizon	71.77	46.9%	81.15	53.1%	69.06	32.0%	146.99	68.0%	107.56	41.1%	154.32	58.9%

Sources: P3; Telecom Advisory Services analysis

12 By 2015, 100% of the US population was already covered by LTE networks. See ITU (2017). *Measuring the information society.* Geneva: International Telecommunications Union.

13 Gabriel, C. (2015, May 20). *Towards 2020: Emerging opportunities for Wi-Fi services.* Maravedis-Rethink, p.15. Retrieved from: https://cdn.shopify.com/s/files/1/0313/2473/files/wba-interim-report.pdf?12935325085178333557.

As data in Table 3-7 indicates, Wi-Fi and cellular sites convey fairly equal number of data sessions, although Wi-Fi captures a larger share of data traffic. This is the result of Wi-Fi deployment complementing the LTE roll-out. Along those lines, the estimate calculated for the 2017 forecast was maintained in the actual calculations, thereby conservatively assuming a constant producer surplus of $10.7 billion.

That being said, the evolution toward IoT and 5G will drive increasing deployment of Wi-Fi access points. While some of the trends that will result in 5G deployment are already starting to be implemented in Wi-Fi (such as densification, virtualization, ultra-low latency and expansions of MIMO smart antennas), we believe that for estimation purposes, the incremental value to be derived from 5G and IoT should be included in the value estimation for 2020 of Section 5.1.

3.1.3. Estimating the Economic Return to Speed of Wi-Fi Off-Loading

To measure the economic value of Wi-Fi speed, this analysis focuses on measuring the speed of wireless networks by 2017 if they did not have faster Wi-Fi technology as a complement. In this case, it considers the total traffic without differentiating between points of access (residences or public places). The analysis was based on quantifying the speed differential between average cellular and Wi-Fi access. By factoring off-loading effects in relation to cellular we can then calculate speed increases and apply the Bohlin & Rohman (2012) model to estimate the impact of increased speed on GDP (see Table 3-8).[14]

Table 3-8. Economic return to speed from Wi-Fi off-loading in the U.S. (2017)

Variable	Value
Average speed of cellular networks (Mbps)	13.52
Average Wi-Fi speed (Mbps)	37.93
Average speed of weighted average of cellular and Wi-Fi traffic	30.20
Speed decrease (average speed of cellular/average weighted average speed)	-55.22%
Model coefficient	0.30%
Decrease in GDP per capita	-0.17%
GDP per capita (current prices)	61,690
Wi-Fi traffic (% total traffic)	23.01%
GDP reduction ($ million) (current prices)	-7,703

Sources: Cisco; Telecom Advisory Services analysis

As a result, the Wi-Fi speed advantage resulted in a GDP contribution of $7.703 billion.

14 For a full description of methodology, see Katz (2014a).

3.1.4. New Business Models

To estimate the business revenues generated by service providers offering Wi-Fi services in public places (airports, hotels) for a fee in 2017, we added up the revenues of all firms operating in this space in the United States, which have reached $1,011.77 million (see Table 3-9).

Table 3-9. Compilation of retail revenues of Wi-Fi service providers in the U.S. (2017) (in $ millions)

Company	Business Focus	Value
Boingo Wireless	Retail access; wholesale access (to AT&T, Verizon); military bases; advertising	$192.00 (*)
iPass	Enterprise Wi-Fi services; wholesale access	$54.0 (*)
SONIFI Solutions, Inc.	Hotels and health care (cable and Wi-Fi)	$95.77
Gogo Inflight Internet	In-flight Internet access	$670.00 (*)
TOTAL		**$1,011.77**

(*) Company outlook 2017 revenue based on 1H2017 performance.

(**) LTM 9/30/17

Sources: Company Annual reports and 10-K reports; Informa; Telecom Advisory Services analysis

3.2. The 2017 Value of Residential Wi-Fi

The economic value of residential Wi-Fi results from three benefits:

- Providing Internet access for devices that lack a wired port (e.g. tablets, smartphones, game consoles);
- Avoidance of investment in in-home wiring; and
- Revenues derived from sales of consumer residential equipment (wireless speakers, security systems, etc.).

3.2.1. Internet Access for Devices that Lack a Wired Port

The underlying premise of this analysis is that, in the absence of Wi-Fi, users would have to depend on the cellular network to gain Internet access. It assumes that those devices that have the capacity to connect through a wired port (e.g., personal computers) would, in the absence of Wi-Fi, rely on wired Ethernet connections. We are left, however, with those devices that do not have the capability of a wired connection (tablets, smartphones, and game consoles). For this reason, estimating economic value would first measure the traffic generated by these devices at home and then multiply it by the average price charged by cellular carriers, as presented above (see Table 3-10).

Table 3-10. Annual costs to be incurred by home traffic generated by devices with no wireline connectivity (2017)

Variable		Value
Annual traffic generated by devices with no wireline connectivity	Smartphones (billion GB)	47.64
	Tablets (billion GB)	22.40
	Game consoles (billion GB)	0.93
	Total (billion GB)	70.13
Percent home traffic generated by devices with no wireline connectivity (*)		43.1%
Total annual home traffic generated by devices with no wireline connectivity		30.24
Average price per GB		$5.16
Total cost of home traffic generated by devices with no wireline connectivity ($ billion)		**$156.04**

(*) 43% of use time of these devices takes place at home

Sources: Cisco; Park Associates; Telecom Advisory Services analysis

As indicated in Table 3-10, the value to be derived by Wi-Fi access at home in the United States reaches $156 billion.

3.2.2. Avoidance of Investment in In-House Wiring

In addition, the residential Wi-Fi benefit considers that the technology allows consumers to avoid paying for wiring to connect all home devices (printers, laptops, storage units, etc.). Household Wi-Fi penetration in 2017 has reached 71%, while the cost of deploying a Cat 6 network in a residence ranges from $320 for one room with an 8-port router to $2,200 for 4 rooms in difficult to access areas. The assumed cost was for a 2-room residence in a low cost area, which yields a total cost avoidance benefit of $59.15 billion (see Table 3-11).

Table 3-11. Cost avoidance of inside wiring (2017)

Variable	Value
Number of households	126,224,000
Percentage of Wi-Fi households	71%
Number of Wi-Fi households	89,619,040
Unit cost of inside wiring	$660 (*)
Total cost avoidance ($ billion)	**$59.15**

(*) National average for wiring a 2-room residence with CAT 6.

Sources: U.S. Census; Rural Telephone Company; Strategy Analytics; Park Associates; Telecom Advisory Services analysis

3.2.3. Economic Surplus Derived from Wi-Fi-Enabled Consumer Residential Equipment

In addition to the surplus to consumers derived from cost avoidance of cellular traffic and inside wiring, residential Wi-Fi has benefits that can be quantified both in terms of the producer surplus to manufacturers and consumer surplus of Wi-Fi enabled residential equipment. For purposes of this analysis, we focus on wireless speakers, security systems, and home networking systems. The market for these three categories in the U.S. amounts to $48,978 million.

Table 3-12. Revenues of residential Wi-Fi enabled consumer electronics in the U.S. (2017) (in $ millions)

System	Revenues
Wireless speakers	$41,120 (1)
Security systems	$4,506
Home networking systems	$3,352
TOTAL	**$48,978**

(1) Includes only Wi-Fi enabled wireless speakers, excluding Bluetooth to avoid double counting.

Source: Consumer Technology Association (2018). U.S. Consumer Technology Sales and Forecasts, January.

Our assessment of economic value of Wi-Fi-enabled residential equipment assumes that the producer surplus is equivalent to the average of the consumer electronics gross margin, and the consumer surplus is the difference between revenues and costs. It is important to mention that this assumption equates consumer surplus to price, therefore without considering a willingness to pay beyond the retail price (Katz, 2014a; 2014b).

Considering that the consumer electronics industry gross margin for 2017 is 55.59%,[15] producer surplus would equate to $21,751 million, and consumer surplus would be the same value.

* * * * *

15 Source: CSI Market Inc. retrieved in: https://csimarket.com/Industry/industry_Profitability_Ratios.php?ind=1012

In sum, the surplus associated with residential Wi-Fi would amount to $258.69 billion (see Table 3-12).

Table 3-12. Summary of economic value of Wi-Fi enabled residential equipment (2017) (in $ billions)

Effect	Underlying Premise	Value
Internet access for devices that lack a wired port	Cost required for those devices to access the Internet via cellular networks	$156.04
Avoidance of investment in in-house wiring	Cost to wire the residence	$59.15
Surplus of Wi-Fi enabled consumer residential equipment	Sales of wireless speakers, alarm systems, headphones, and home networking equipment	$43.50
TOTAL		**$258.69**

Source: Telecom Advisory Services analysis

3.3 The 2017 Economic Value Generated by the WISP Industry

To estimate the revenues for 2017, WISPA estimated a subscriber count of 4.6 million in that year and an ARPU of $52.00 month.[16] This would yield a total revenue generation of $2.87 billion (see Table 3-13).[17]

Table 3-13. Wireless internet service providers in the U.S. (2017) ($ billion)

Category	Value
Subscribers	4,600,000
ARPU	$52.00
Revenues	$2.87

Sources: WISPA (2017).

3.4 The 2017 Economic Value of Wi-Fi-Only Tablets

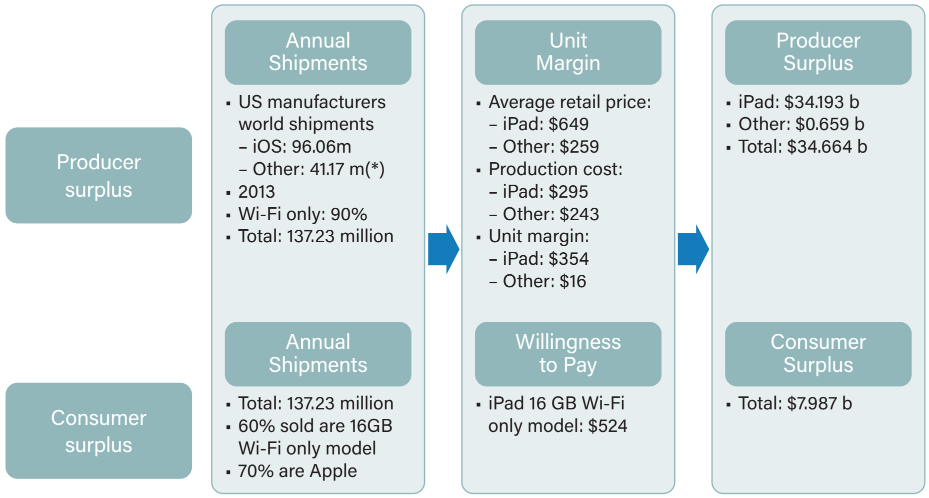
As discussed in the 2014 study, Wi-Fi-only tablets also represent a source of growth in economic value of unlicensed spectrum. In the section above, consumer surplus was estimated in terms of the savings incurred by U.S. consumers that do not need to rely on cellular networks to connect their devices (smartphones and tablets) to the Internet because they use Wi-Fi access. Beyond this, additional economic value is being originated by the margin generated by U.S. tablet manufacturers selling their products worldwide as well as the consumer surplus calculated by the difference between consumers' willingness to pay and actual prices of tablets (see Figure 3-3).[18]

16 Number provided by the Wireless Internet Service Providers Association ("WISPA") based on an informal poll among its members.

17 WISPA (2017, Sept. 25). *Ready for take-off: Broadband Wireless Access providers prepare to soar with fixed wireless.* Retrieved from: http://www.wispa.org/News/wispa_news_09-25-17_Fixed_Wireless_Broadband_Industry_Projected_to_Nearly_Double_in_Five_Years.

18 A similar methodology used by Milgrom et al. (2011).

Figure 3-3. Framework for estimating economic value of Wi-Fi-only tablets



This methodology was applied to forecast the economic value of these devices to be generated in 2017, concluding that total economic value attached to this device reached nearly $13.57 billion (see Table 3-14).

Table 3-14. Economic value of Wi-Fi-only tablets (2017)

Key Driver	Value	Source
Global tablet shipments (millions)	166.1	IDC
Share of U.S. manufacturers (%)	34.6%	IDC
Global tablet shipments of U.S. manufacturers (million)	57.47	Calculated
Portion of Wi-Fi-only (%)	95.0%	Moffett
Wi-Fi-only global shipments by U.S. manufacturers (million)	54.60	Calculated
Producer surplus estimates		
Apple shipments (million)	42.34	IDC
Non-Apple shipments (million)	12.26	IDC: Amazon
Apple margin (in $)	$224	IHS
Non-Apple margin (in $)	$0	Amazon
Apple producer surplus ($ million)	$9,483.35	Calculated
Non-Apple producer surplus ($ million)	$0	Calculated
Total producer surplus (million)	$9,483.35	Calculated
Consumer surplus estimates		
Apple shipments (million)	42.34	IDC
Non-Apple shipments (million)	12.26	IDC: Amazon
Apple average retail price ($)	$429	iPad 128 GB
Non-Apple average retail price ($)	$199	Amazon
Apple average willingness to pay	$524	IMMR
Non-Apple average willingness to pay	$204	IMMR
Apple consumer surplus ($ million)	$4,022	Calculated
Non-Apple consumer surplus ($ million)	$61.30	Calculated
Total consumer surplus ($ million)	$4,083.30	Calculated
TOTAL	**$13,566.65**	**Calculated**

Sources: IDC; iSuppli; Institute for Mobile Market Research; Telecom Advisory Services analysis

Each key driver in this model will be reviewed in turn.

First, tablet global sales have stabilized at 166 million in 2017, having declined from 220 million in 2014.[19] This trend is driven by multiple factors: (a) PC to tablet substitution has not materialized as much due to reduced feature set of the latter in relation to the former; (b) users have not assimilated the tablet upgrade rate to the smartphone one; (c) tablets have undergone a slower innovation cycle; and (d) laptop sales have declined as well partly driven by smartphone substitution in late adopters.[20] Second, U.S. manufacturers have been losing global market share since 2011 (when it peaked at 66%). In the first three quarters of 2017, Apple and Amazon controlled 34.60% of tablet shipments.[21] Third, going forward, while LTE tablets will greatly enhance the usage based on use cases such as video streaming, 802.11ac will partially overcome this substitution threat. Therefore, we estimate that total Wi-Fi-only tablets in 2017 would be 95%.

To calculate producer and consumer surplus, it is necessary to project total market share of Apple versus the rest, because the company's margins are much higher than those of Amazon and HP, among others. Apple's market share for the first three quarters of 2017 is 26.83%,[22] which results in global shipments from this manufacturer of 42.3 million units.

The calculation of producer surplus is driven by the difference between manufacturing costs and selling price. According to HIS, the base model of the iPad Air 2, the 16 gigabyte Wi-Fi version, which sells for $499, costs $275 to build, exactly one dollar higher than the previous base model.[23] This yields a surplus of $224. On the other hand, no changes took place in Amazon's $0 margins. The net result in terms of producer surplus is $9,483 million. When it comes to consumer surplus, the current price of iPad 128 GB ($429) was subtracted from the original willingness to pay ($524). Thus, consumer surplus reaches $4 billion.

In total, the resulting actual 2017 economic surplus of Wi-Fi-enabled tablets sold by U.S. manufacturers amounts to $13.566 billion in 2017.

3.5 The 2017 Economic Value of Wireless Personal Area Networks

The economic value of wireless personal area networks in 2017 is created from three technologies: Bluetooth, ZigBee and Wireless HART, which support automotive applications, home automation, and industrial device monitoring. The value contribution of each technology will be assessed in turn.

3.5.1. Bluetooth Market

The estimation of Bluetooth economic value, driven by sales of devices, needs to account for two opposing trends: increased number of applications and scale-driven declining unit price per chipset.

Bluetooth automotive applications
Between 2013 and 2017, the use of Bluetooth technology rapidly increased in the automotive industry, resulting in a significant growth in chipset demand. This growth was driven by factors such as the increasing demand for smartphone features in cars and the ability to carry out vehicle diagnostics. As a result, the global market for Bluetooth automotive devices in 2017 amounts to $18,581 million and is forecast to grow by a CAGR of 34.65%.[24]

19 Statista (2017, Nov.). Worldwide tablet shipments from 2nd quarter 2010 to 4th quarter 2017 (in million units). Retrieved from: https://www.statista.com/statistics/272070/global-tablet-shipments-by-quarter/.
20 Gartner (2016, Apr. 11). Gartner says worldwide PC shipments declined 9.6 percent in first quarter of 2016. Retrieved from: https://www.gartner.com/newsroom/id/3280626.
21 Jones, C. (2013, Dec. 4). IDC predicts that tablet unit sales will slow to single-digits by 2017. Forbes. Retrieved from: https://www.forbes.com/sites/chuckjones/2013/12/04/idc-predicts-that-tablet-unit-sales-will-slow-to-single-digits-by-2017/#674059fc19a5.
22 *Id.*
23 Hesseldahl, A. (2014, Oct. 28). Apple's latest iPad costs about the same as the first but with slightly lower profits. *RECODE*. Retrieved from: https://www.recode.net/2014/10/28/11632352/apples-latest-ipad-costs-about-the-same-as-the-first-but-with.
24 WiseGuyReports (2017, Nov. 29). Bluetooth in automotive 2017 global market to reach USD 1,09,979.0 million and growing at CAGR of 34.65% by 2023. ABNewswire. Retrieved from: http://www.abnewswire.com/pressreleases/bluetooth-in-automotive-2017-global-market-to-reach-usd-1-099790-million-and-growing-at-cagr-of-3465-by-2023_165039.html.

Two approaches can be taken to estimate the U.S. economic value of the Bluetooth automotive technology market. From a demand standpoint (the approach used in the 2014 forecast), the U.S. represents approximately 22.5% of the total market, resulting in $4.2 billion. From a supply standpoint (an approach similar to the quantification of the tablet market presented above), the United States companies control approximately 68% of the market: Qualcomm (28.1%), Broadcom (11.5%), MediaTek (9.4%), Texas Instruments (9.0%), and Marvell Technology Group (10%). This would result in $12.63 billion. For purposes of consistency with the prior 2017 forecast prepared in 2014, we will rely on the demand estimate: an economic value of $4.2 billion.

Bluetooth mobile telephony

The U.S. economic value of the mobile telephony Bluetooth chipset market is driven by: (a) the number of devices shipped worldwide, and (b) the U.S. suppliers' market share of shipments.[25] The 2017 shipments of smartphones that carry a Bluetooth chipset originated in the United States amount to 537.40 million (see 3-15).

Table 3-15. 2017 Smartphones shipments (in millions)

Manufacturer	4Q16	1Q17	2Q17	3Q17	Total
Samsung	77.5	79.2	79.8	83.3	319.8
Apple	78.3	51.6	41	46.7	217.6
Total U.S. Bluetooth chipsets	**155.8**	**130.8**	**120.8**	**130**	**537.4**
Huawei	45.4	34.2	38.5	39.1	157.2
OPPO	31.1	25.6	27.8	30.7	115.2
Xiaomi	24.7	16.1	21.2	27.6	89.6
Others	171.4	138.7	133.4	145.7	589.2
Total non-U.S. Bluetooth chipsets	**272.6**	**214.6**	**220.9**	**243.1**	**951.2**

Sources: IDC; China Internet Watch; Telecom Advisory Services analysis

Assuming that the 2017 chipset unit value is $0.90[26] yields an actual economic value for Bluetooth mobile telephony of $483.66 million.

Bluetooth peripherals market

In a similar vein, the economic value of Bluetooth chipsets in the PC and peripherals market in 2017 is driven by the worldwide shipment of devices that carry a U.S. manufactured semiconductor. The 2017 shipments of PCs, tablets and printers that carry a Bluetooth chipset originated in the United States are estimated at 296.34 million (see 3-16).

25 For example, Apple Inc.'s iPad Mini and iPhone 5 employ Broadcom's BCM4334 single-chip, dual-band device, as revealed by a dissection of the products conducted by the IHS iSuppli Teardown Analysis Service. Similarly, based on a virtual teardown, IHS iSuppli believes that Samsung's new Galaxy S4 smartphone includes the Broadcom BCM4335. On the other hand, Samsung's Galaxy A5 and A7 rely on the company's proprietary Exynos 7885. Due to the lack of precise information it was assumed that Samsung and Apple carry U.S.-based Bluetooth chipsets.

26 The Digikey reports that the unit price of Bluetooth RF Transceiver ICs ranges from $0.91 to $1.729 at volumes ranging between 500 and 3,000. Assuming that Digikey is on the upper side of IC wholesalers and that manufacturers order much higher quantities, it is reasonable to assume a unit price for 100,000 units of approximately $0.90.

Table 3-16. 2017 Bluetooth chipsets shipments (in thousands)

Device	Manufacturer	4Q16	1Q17	2Q17	3Q17	Total	Chipsets
Laptops	HP Inc.	15,268	13,143	13,782	15,295	57,488	Intel, Atheros, Broadcom
	Lenovo	15,693	12,322	12,434	14,506	54,955	Intel, RealTek
	Dell	11,000	9,573	10,328	10,836	41,737	Intel
	Apple	5,263	4,201	4,331	4,901	18,696	Broadcom, Apple
	ASUS	5,167	4,121	4,112	4,189	17,589	Intel
	Total U.S. Bluetooth chipsets	52,391	43,360	44,987	49,727	190,465	
	Others	17,812	16,967	15,555	17,457	67,791	
	Total non-U.S. Bluetooth chipsets	17,812	16,967	15,555	17,457	67,791	
Tablets	Apple	13,100	8,900	11,400	10,300	43,700	Broadcom, Apple
	Amazon	5,200	2,200	2,400	4,400	14,200	
	Lenovo	3,700	2,100	2,200	3,000	11,000	Intel, RealTek
	Total U.S. Bluetooth chipsets	22,000	13,200	16,000	17,700	68,900	
	Samsung	8,000	6,000	6,000	6,000	26,000	Samsung
	Huawei	3,200	2,700	3,000	3,000	11,900	
	Others	19,800	14,400	12,900	13,300	60,400	
	Total non-U.S. Bluetooth chipsets	31,000	23,100	21,900	22,300	98,300	
Printers	HP Inc.	10,021	8,633	8,588	9,786	37,028	
	Total U.S. Bluetooth chipsets	10,021	8,633	8,588	9,786	37,028	
	Canon Group	6,402	4,545	4,896	4,940	20,783	
	Epson	4,938	4,224	3,958	4,531	17,651	
	Brother	2,011	1,787	1,778	1,841	7,417	
	Samsung	767	973	859	879	3,478	Samsung
	Others	3,620	3,244	3,231	3,286	13,381	
	Total non-U.S. Bluetooth chipsets	17,738	14,773	14,722	15,477	62,710	
Total U.S. Bluetooth chipsets		**84,412**	**65,193**	**69,575**	**77,213**	**296,393**	

Sources: IDC; Telecom Advisory Services analysis

At $0.90 chipset unit price, the total economic value associated with Bluetooth-enabled devices amounts to $266.75 million.

3.5.2. ZigBee Market

ZigBee is a wireless language that enables machine-to-machine networking and IoT, with applications in home automation, smart lightning, telemetry and the like.[27] Therefore, it is important to avoid double counting when assessing the unlicensed spectrum value derived from the IoT domain.

An approach to estimating the 2017 economic value of the ZigBee market is based on quantifying the annual shipments for IEEE 802.15.4 low-power wireless chipsets (of which ZigBee standards amount to 80%). It is estimated that in 2017, total ZigBee enabled device shipments reached 120 million[28] (of which 60% are set top boxes, 12% are smart meters,

27 Zigbee is used by a variety of cable and telecommunication companies including Comcast, Time Warner Cable, EchoStar, DirecTV, Charter, Rogers, Deutsche Telekom, and Videocon. These companies are using Zigbee in their set-top boxes, satellite transceivers and home gateways to deliver home monitoring and energy management solutions to their customers. Additionally, Zigbee allows consumers easy-to-use control over all their LED fixtures, light bulbs, remotes and switches. Products based on Zigbee let consumers change lighting remotely to reflect ambiance, task or season, all while managing energy use and making their homes greener. Finally, Zigbee Smart Energy is the world's leading standard for interoperable products that monitor, control, inform, and automate the delivery and use of energy and water. It is used to deliver innovative solutions for smart meters and the home area network (HAN) that allow consumers to know and control their energy use by connecting them to the smart grid and helps create greener homes by giving consumers the information and automation needed to easily reduce their consumption and save money.

28 Technavio (2016, Jan.). Global ZigBee enabled devices market 2016-2020. Retrieved from: https://www.technavio.com/report/global-computing-devices-zigbee-enabled-devices-market.

and the remainder is shared across connected light bulbs, remote controls, and smart thermostats). The average value of a ZigBee chipset approximates $6.00,[29] which results in a total market of $720 million (this number could be larger since the ZigBee market includes also modules, devices, multi-market platforms, and service providers).

In order to estimate the U.S. economic value, total value should be calculated only for U.S. manufacturers of ZigBee chipsets. Out of the top nine Zigbee chipset manufacturers, six are U.S.-based (Atmel, Digi International, Freescale Semiconductor, Qorvo-acquirer of Greenpeak Technologies, Silicon Laboratories, and Texas Instruments), controlling approximately 70% of the worldwide demand. This results in total U.S. economic value of $504 million. Four accelerating growth drivers were identified in this market:

- Smart home applications, representing 2/3 of the growth;
- Smart lighting adoption increasing by 2900% between 2012 and 2014;
- Thread, an IP-based wireless mesh specification; and
- Development of ZigBee 3.0 that unified all ZigBee standards.

3.5.3. Wireless HART Market

Wireless HART is a wireless sensor networking technology based on the Highway Addressable Remote Transducer Protocol (“HART”). Developed as a multi-vendor, interoperable wireless standard, Wireless HART was defined for the requirements of process field device networks. While the standard competes with other substitutes such as ZigBee and Bluetooth, approximately 70% of process control automation devices rely on Wireless HART.

Three out of the top seven world companies in this domain are U.S. based: Linear Technology, AVID Technologies, Inc., and Emerson Electric Company.[30] With a global market estimated at $100 million, the US-based share represents $27 million.

3.5.4. Total 2017 Economic Value of Wireless Personal Area Networks

To sum up, the 2017 economic value of unlicensed spectrum-enabled personal area networks amounts to $4,997.62 million. The three-time increase vis-à-vis the original forecast is driven by the explosive demand in automotive applications, an expansion of smartphone demand, both of which amply compensated for the decline in PC and peripherals. Finally, a supply approach used for estimating the ZigBee and Wireless HART value yielded a lower estimate than a demand assessment utilized in our prior study (see Table 3-17).

29 The Digikey reports the unit price of Zigbee RF Transceiver ICs ranging from $1.31 to $11.14 at volumes ranging between 500 and 5,000. Assuming that Digikey is on the upper side of IC wholesalers, it is reasonable to assume a unit price of approximately $6.00.

30 Markets and Markets (2017, June). Wireless sensor network market by offering (hardware, software, services), sensor type, connectivity type, end-user industry (building automation, wearable devices, healthcare, automotive & transportation, industrial), and region - global forecast to 2023. Retrieved from: https://www.marketsandmarkets.com/Market-Reports/wireless-sensor-networks-market-445.html.

Table 3-17. Economic value of wireless personal area networks in the U.S. (in $ millions) (2017)

Standard	Applications	Growth Drivers	Value
Bluetooth	Automotive	• Size of Bluetooth market	$4,250.00
	Mobile telephony	• Smartphone unit sales: 537.4 million • Cost of Bluetooth chipset: $0.90	$483.66
	PC & peripherals	• PC unit sales: 190.5 million • Tablet unit sales: 68.9 million • Printer unit sales: 37.0 million • Cost of Bluetooth chipset: $0.90	$266.76
Zigbee		• ZigBee device shipments: 120 million • Cost of ZigBee chipset: $6.00 • U.S. manufacturers share: 70%	$504.00
Wireless HART		• U.S. share (27%) of global Wireless HART market: $100 million	$27.00
TOTAL			**$4,997.62**

(1) 2017 value excludes health and wellness because this category will be covered under wearable technologies in Section 3.3.

Sources: IDC; Technavio; IDTech; Telecom Advisory Services analysis.

3.6. The 2017 Economic Value of RFID

The value of Radio Frequency Identification ("RFID") technology is dependent on its level of adoption among enterprises. In the 2014 study, the penetration of RFID technology was estimated for only two major sectors in 2017: retailing and health care. At the time, it was reported that more than 50% of U.S. retailers had already adopted RFID. Similarly, adoption of RFID in health care was estimated between 23% (pharmaceutical distributors), 40% (hospitals), and 50% (pharmaceutical manufacturers). Assuming that cost savings and consumer benefits remain constant, a key driver of growth in consumer value would be an increase in enterprise adoption. We will now examine its evolution in the two verticals: retail and health care.

3.6.1. 2017 RFID Value in Retailing

The methodology utilized for assessing the economic value of RFID in retailing relied on quantifying the operational efficiencies and enhancement of consumer value derived from adopting the technology (see Table 3-18).

Table 3-18. Estimates of RFID benefits in U.S. retailing (in $ billions)

Benefit	Total Cost/Losses	Cost Reduction at 45% Adoption	Cost Reduction at 100% Adoption
Reduction in labor costs	$260.63	$46. 33	$102.95
Reduction in shrinkage losses	$60.22	$11.67	$19.06
Enhanced inventory turns	$105.65	$7.35	$16.33
Reduction in inventory write-offs	$26.41	$2.11	$10.56
Reduced stock-outs	$51.00	$0.294 (*)	$0.652 (*)
Reduced shipment errors	$5.61	$0.089 (*)	$0.197 (*)
Faster time to market	$39.15	$0.63 (*)	$3.132 (*)
Ubiquitous access across multiple channels	$2.28	$0.112 (*)	$0.559 (*)
Customization	Not Applicable	$20.45	$102.24
Enhanced customer experience	$29.05 (**)	$5.81	$29.05

(*) Quantified as EBITDA impact

(**) Measured as willingness-to-pay.

Source: Barua et al. (2006)

In the 2013 study, based on a variety of market assessments, it was stipulated that RFID retailing benefits would be driven by a 45% technology adoption rate, thereby reaching a total surplus of $94.84 billion. The 2017 forecast assumed, based on adoption trends, that surplus would increase at 10% annually. Actual data indicates that RFID adoption in retail is increasing rapidly: 50% of top retailers have already deployed the technology, while 15% are at a pilot stage.[31] We believe, therefore, that the original forecast of economic value for 2017 retail RFID remains valid (see Table 3-19).

Table 3-19. RFID economic value in U.S. retailing (2017) (in $ billions)

Benefit	Producer Surplus	Consumer Surplus
Reduction in labor costs	$67.83	N.A.
Reduction in shrinkage losses	$17.09	N.A.
Enhanced inventory turns	$10.76	N.A.
Reduction in inventory write-offs	$3.09	N.A.
Reduced stock-outs	$0.42	N.A.
Reduced shipment errors	$0.13	N.A.
Faster time to market	$0.92	N.A.
Ubiquitous access across multiple channels	$0.16	N.A.
Customization	N.A.	$29.63
Enhanced experience	N.A.	$8.51
TOTAL	**$100.41**	**$38.14**

Source: Telecom Advisory Services analysis based on Barua et al. (2006)

3.6.2. 2017 RFID Value in Health Care

Similar to the assessment of the economic value linked to RFID adoption in retailing, the assessment of benefits in the health care sector addressed producer and consumer surplus, although differentiating value chain players for the former (see Table 3-20).

Table 3-20. Estimates of RFID benefits in U.S. health care (in $ billions)

Product and Service Providers	Benefit	Total Cost/ Losses	Cost Reduction at 50% Adoption	Cost Reduction at 100% Adoption
Pharmaceutical manufacturers	Reduction in counterfeit, shrinkage and parallel trade	$4.307	$1.000	$1.852
	Efficient sample management	N.A.	$6.500	$12.73
	Enhanced inventory turns	N.A.	$4.505 (**)	$15.54
	Shorter clinical trials and faster time-to-market	N.A.	$0.100	$0.159 (*)
Healthcare distributors	Enhanced inventory turns	$5.984	$0.410 (***)	$1.784
	Reduction in labor costs	$1.878	$0.130 (***)	$0.563
Hospitals	Better equipment tracking	$7.253	$1.451 (****)	$3.627
	Enhanced inventory turns	$544.02	$17.952 (****)	$44.881
	Wider access to health care at reduced costs	N.A.	N.A.	$2.503
Consumers	Faster access to better health care	N.A.	$1.500	$3.417
	Improved quality of patient care – fewer medical errors and improved compliance	$148.30	(*****)	(*****)

(*) Quantified as EBITDA impact. (**) At 29% adoption levels. (***) At 23% adoption levels
(****) At 40% adoption levels. (*****) Excluded because difficult to replicate calculations
Source: Barua et al. (2006)

31 Roberti, M. (2017, Oct. 2). Is retail approaching the tipping point for RFID? *RFID Journal.* Retrieved from: http://www.rfidjournal.com/articles/view?16668.

Based on the 50% adoption estimates of the study, the total economic value of RFID in the health care sector in 2013 was estimated at $36.07 billion. The 2017 forecast assumed a 10% annual increase in economic surplus. While lacking 2017 adoption statistics, surveyed trends confirmed the increase:

- The use of RFID in the pharmaceutical industry has grown in recent years. The technology has matured from its specialized tracking and retail uses to a systemic part of supply chain management in international pharmaceutical production and distribution.[32]
- Utilization of health information technology ("HIT") to improve patient safety and quality of care has become an area of high priority for the U.S. government and healthcare organizations. The Health Information Technology for Clinical Health ("HITECH") Act mandates the implementation of new healthcare technologies and promotes the development and use of new HIT to further improve healthcare in the US.[33]

Consequently, we believe that the originally forecast economic value for 2017 health care RFID is still valid (see Table 3-21).

Table 3-21. RFID economic value in U.S. health care (2017) (in $ billions)

Product and Service Providers	Benefit	Producer Surplus	Consumer Surplus
Pharmaceutical manufacturers	Reduction in counterfeit, shrinkage and parallel trade	$1.35	N.A.
	Efficient sample management	$9.52	N.A.
	Enhanced inventory turns	$6.59	N.A.
	Shorter clinical trials and faster time-to-market	$0.15	N.A.
Healthcare distributors	Enhanced inventory turns	$0.60	N.A.
	Reduction in labor costs	$0.19	N.A.
Hospitals	Better equipment tracking	$2.12	N.A.
	Enhanced inventory turns	$26.28	N.A.
	Wider access to health care at reduced costs	N.A.	$3.70
Consumers	Faster access to better health care	N.A.	$2.20
	Improved quality of patient care – fewer medical errors and improved compliance	N.A.	$0.00
TOTAL		**$46.80**	**$5.90**

Source: Telecom Advisory Services analysis based on Barua et al. (2006)

3.7. The 2017 Economic Value of High-Speed Wireless Data Transfer Technologies

High-speed wireless data transfer technologies rely on the 60 GHz unlicensed spectrum band to deliver a data transfer rate between 6 Gbps and 28 Gbps over a range between 5 and 30 meters. WirelessHD is primarily used for high definition consumer electronic devices, while WiGig supports smartphones, PCs, tablets, and related peripherals.[34]

3.7.1. WirelessHD Market

In the 2017 forecast study, the economic value of high-speed wireless data transfer devices operating in WirelessHD estimated the revenues (and consequently GDP contribution) derived from unit shipments. At the time, it was considered that, as more consumer electronics products took advantage of rapid wireless transfer opportunities, annual shipment of high-speed wireless data chipsets was expected to increase significantly. The market research firm HIS projected that by 2018, shipment of high-speed wireless integrated circuits IC would reach 1.7 billion units, including chipsets

32 Taylor, D. (2014). RFID in the pharmaceutical industry: addressing counterfeits with technology. *Journal of Medical Systems,* 38(141). Retrieved from: https://doi.org/10.1007/s10916-014-0141-y.

33 Paaske, S., Bauer, A., Moser, T., & Seckman, C. (2017). The benefits and barriers to RFID technology in healthcare. *Online Journal of Nursing Informatics,* 21(2). Retrieved from: http://www.himss.org/library/benefits-and-barriers-rfid-technology-healthcare.

34 WirelessHD Consortium (2018). Specification summary. Retrieved from: http://www.wirelesshd.org/about/specification-summary/.

for smartphones, TVs, and mobile PCs. On the other hand, the total wireless/video display market (which includes WirelessHD, WiDi, and Wi-Fi display) was estimated to represent over $1 billion in 2012, growing at 28.03% through 2017.[35] Considering that WirelessHD represents 20% of the total wireless/video display market,[36] we projected 2017 revenues to reach $690 million.

An updated version of the global wireless display market completed in 2017[37] estimates the 2016 market at $2.34 billion, growing at 11.1% through 2023. This results in a total 2017 market of $2.59 billion, of which WirelessHD represents $519 million.

3.7.2. WiGig Market

The 2017 forecast study reported that the WiGig market currently represented $269.9 million, and was expected to reach $4.58 billion in 2019, growing at a CAGR of 111.2%. In 2017, unit shipments would exceed 1 billion, generating $4.12 billion in revenues. An updated assessment of the global WiGig market estimates the 2017 size at $310 million, growing at a CAGR of 105.42% by the end of 2021.[38] Assuming a 35% U.S. share, that would amount to $109 million.

3.8. The 2017 Economic Value of Low-Frequency Wi-Fi

Low-frequency Wi-Fi operates in the frequency bands between 512 MHz and 698 MHz to deliver broadband over distances of up to 10 miles with high penetration at 20 Mbps download and 6 Mbps upload speeds.[39] The technology can provide broadband in rural areas and extend the range of Wi-Fi everywhere. Additionally, low-frequency Wi-Fi will enable a variety of new power-efficient use cases in the Smart Home, connected cars, and digital health care, as well as industrial, retail, agriculture, and Smart City environments. Low-frequency Wi-Fi relies on empty channels of broadcast television spectrum (known as White Spaces) and uses dynamic spectrum sharing that optimizes access to available unused bands.

In the 2014 forecast for 2017, it was considered that given the emerging adoption of this technology, it remained difficult to estimate its economic value. Since then, changes in spectrum management resulting from auctions closed in 2017 have provided more certainty to the adoption of super Wi-Fi primarily in rural areas but also potentially in urban settings as well. From that standpoint, the economic value of this technology could include both consumer surplus derived from reducing the rural digital divide and consequent GDP impact from rural WISPs, like Q-Wireless in Evansville, Indiana and Cal.Net in Shingle Springs, California.[40]

On the consumer side, there are 24.9 million people residing in rural areas of the United States with no broadband access.[41] Low-frequency Wi-Fi could be a technology capable of filling up this gap. On the service provider side, considering that the digital divide at the individual end translates into 6.2 million households and that each household

35 Markets and Markets (2017, June).
36 Silicon Image, Inc. a leader in WirelessHD appears to generate approximately $132 million in manufacturing and licensing revenues of High Definition wireless chipsets.
37 Markets and Markets (2017, Oct.). Wireless display market by offering (hardware, software & services), application (consumer, commercial - corporate, education, healthcare, signage, government), technology protocols (Miracast, WiDi), and geography - global forecast to 2023. Retrieved from: https://www.marketsandmarkets.com/Market-Reports/wireless-display-market-41146860.html.
38 Mordor Intelligence (2017, Oct.). WiGig market - by devices (network infrastructure devices, communication or display devices), applications (point to point IP applications, HDMI data streaming, cordless computing, Internet support), usage models (instant wireless sync, wire). Retrieved from: https://www.mordorintelligence.com/industry-reports/global-wigig-market-industry.
39 Low-frequency Wi-Fi operates in the frequency bands between 512 MHz and 698 MHz. Some have estimated that low-frequency Wi-Fi will enable fixed, higher-power access points to deliver broadband over distances of up to 10 miles with high penetration of up to 20 Mbps download and 6 Mbps upload speeds, (Vaughan-Nichols, S. (2013, Feb. 5). What is "Super Wi-Fi? ZDNet.com. Retrieved from: http://www.zdnet.com/article/what-is-super-wi-fi/), although further testing will be required to fully explore the throughput rates possible in this band.
40 Wolverton, T. (2017, Mar. 30). 'Super' Wi-Fi may finally be coming your way. *The Mercury News*. Retrieved from: https://www.mercurynews.com/2017/03/30/super-Wi-Fi-may-finally-be-coming-your-way/.
41 Kang, C. (2017, July 11). To close the digital divide, Microsoft to harness unused television channels. *The New York Times*. Retrieved from: https://www.nytimes.com/2017/07/11/technology/to-close-digital-divide-microsoft-to-harness-unused-television-channels.html.

could generate monthly revenues of $50.00 (as is the experience of the WISP industry), this could translate into a revenue potential of $3.72 billion.

3.9. The 2017 Economic Value of Machine-to-Machine Communications

Unlicensed spectrum bands are critical to the communication of devices equipped with microcontrollers in order to deliver applications in areas as diverse as environmental management (pollution/air quality monitors, weather stations, water level monitors), urban landscape (street lighting control systems, parking meters), and health care (dialysis machines, defibrillators, ventilators, pacemakers). Enhanced connectivity of devices via unlicensed spectrum could increase their ability to process information and interact with other terminals. The 2017 forecast prepared in the 2014 study estimated that the economic value of machine-to-machine ("M2M") communications relying on unlicensed spectrum amounted to $2.8 billion. The methodology for developing such an estimate focused only on four applications known to utilize unlicensed spectrum: Advanced Meter Infrastructure, Security, Energy Demand Side Management devices, and Telehealth. For this purpose, it calculated the percent of total M2M connections that were used for the four applications and applied that proportion to the total M2M market. The following Table presents the actual values for 2017.

Table 3-22. M2M Economic Value in the U.S. (2017)

Variable		Value
Total connections (million)		1,464.7
Connections relying on unlicensed spectrum (million)	AMI	27.83
	Security	18.87
	Demand Side Management	10.02
	Telehealth	10.55
Total share of connections relying on unlicensed spectrum (%)		4.6 %
Total machine-to-machine market ($ billion)		$5.95 (1)
Share of machine-to-machine market relying on unlicensed spectrum ($ billion)		**$2.43**

U.S. machine-to-machine (M2M) connections market worth $7,262.76 Million by 2020

Sources: Cisco VNI; Markets and Markets; ABI Research; IDATE; Telecom Advisory Services analysis

In addition to the M2M applications discussed above, wearable technologies represent an emerging set of uses of unlicensed spectrum. These are devices that can be worn on a person, which have the capability to connect and communicate to the network either directly through embedded cellular connectivity or, primarily, through another device (such as a smartphone) using Wi-Fi, Bluetooth or another technology. These devices include smart watches, smart glasses, heads-up displays ("HUD"), health and fitness trackers, health monitors, wearable scanners, and navigation devices and smart clothing. The growth in these devices has been fueled by enhancements in technology that have supported compression of computing and other electronics (making the devices light enough to be worn).

The methodology used to generate a forecast of economic value associated with the wearable devices market calculated the prorated amount of the global market based on the proportion of devices adopted in the United States (see Table 3-23).

Table 3-23. Wearables economic value in the U.S. (2017)

Variable		Actuals
Global devices sold (million)		310.37
Global market ($ billion)		$30.5
U.S. devices (million)		44.4
Wearable devices (million)	Smart Glasses	4.75
	Smart Watches	27.08
	Fitness and activity monitors	8.88
	Heart rate monitors	3.64
Total U.S. wearables market ($ billion)		**$4.36**

Note: to avoid double counting with ZigBee applications addressed in Table 11, we subtracted $835.4 million from the total machine-to-machine market.

U.S. Machine-to-Machine (M2M) Connections Market worth $7,262.76 Million by 2020

Sources: Cisco VNI; ABI Research; Gartner; eMarketer; Telecom Advisory Services analysis

According to the 2017 forecast, the GDP contribution associated to the diffusion of wearable devices was expected to reach $3.69 million. The actual estimated annual sales are somewhat higher than the original forecast ($4.36 billion).[42]

3.10. Smart City Deployments for Managing Public Infrastructure

Cities rely on wireless sensor networks to improve municipal management. When these networks are deployed, intelligent sensors can measure many parameters for a more efficient management of a city. Relevant data is delivered wirelessly and in real time to citizens or the appropriate authorities. Smart City applications using wireless sensor networks include the following:

- Citizens can monitor the pollution concentration in each street of the city or they can get automatic alarms when the radiation rises to a certain level;
- Municipal authorities can optimize the irrigation of parks or the lighting of the city;
- Water leaks can be easily detected or noise maps can be generated;
- Vehicle traffic can be monitored in order to modify the city lights in a dynamic way;
- Traffic can be reduced with systems that detect the nearest available parking space; and
- Motorists can get timely information so they can locate a free parking space quickly, saving time and fuel. This information can reduce traffic jams and pollution, while improving the quality of life.

Beyond these effects, Smart Cities can deliver a number of indirect benefits effects in terms of economic growth, competitiveness, and a better quality of life for its citizens. In order to provide an estimate of the economic value derived from the deployment of Smart City infrastructure, the 2017 forecast broke down its multiple benefits:

Beyond the consumer surplus, the 2017 forecast isolated the value of Smart City sensor technology on the basis of the contribution to GDP of the revenues generated by infrastructure sales. Based on an estimate of the global wireless sensor network market reaching $2 billion in 2021, of which the United States represents 72%, the forecast estimated a 2017 GDP contribution of approximately $793 million. Given the still embryonic stage of development of this space, it is difficult to generate a more refined estimate from the forecast produced in 2014.

42 Statista reports the 2017 U.S. wearables market to be $1,551, but this Figure excludes smart watches, fitness and nutrition apps, the most important categories.

3.11. Agricultural Automation

Precision agriculture represents a systems-based approach for site-specific management of crop production systems. Efficiency of agricultural machinery is linked to deployment of sensors (grain yield, optical sensors for weed detection, and control systems for fertilizer spreading) linked to standardized bus systems to transmit data streams. In fact, most of the benefit of precision farming systems will come from whole farm management uses, which would include the use of sensors, remote sensing, and telemetry.[43] Sensor networks are dependent on deploying point-to-point and point-to-multipoint network technologies. Point-to-point communications rely on wireless meteorological stations and RFID tags for field information collection. On the other hand, point-to-multipoint communication for data collection relies on 802.15.4 and 61oWPAN, as well as Wi-Fi and ZigBee, which both operate in the 2.4 GHz band.

The impact of agricultural automation, and therefore the economic value of technologies operating in unlicensed spectrum bands, can be estimated based on their contribution to the increase in Total Factor Productivity through more efficient use of labor, timeliness of operations (optimization of agronomic windows, reduction of spoilage and harvest losses), and efficient use of inputs (water, seeds, fertilizers). The United States had a total of 310 million crop acres in 2016, within which the adoption of precision agriculture was likely to reach 40% in 2017. Based on producer benefits of $20 per hectare measured in field research, the producer surplus of agricultural automation could reach $1.003 billion (see Table 3-24).

Table 3-24. Agricultural automation economic value in the U.S. (2017)

Variable	Value
Total harvested crop acres (million)	310
Total crop hectares (million) (acres to hectares conversion rate: 0.4047)	125,457,000.00
2017 Adoption of agriculture automation (%)	40 %
Hectares adopting agriculture automation by 2017	50,182,800
Producer benefits per hectare ($)	$20.00
Economic value of precision agriculture ($ billion)	**$1,003.66**

Sources: USDA Census; Robertson et al. (2007); Norton and Swinton (2000); Wang et al. (2009); Schimmelpfennig and Ebel (2011); Telecom Advisory Services analysis

3.12. Economic Value and Substitute IoT Technologies Operating in Unlicensed Spectrum

The sections above assessed the economic value of technologies operating in unlicensed spectrum fulfilling IoT demand in the following segments:

- Advanced meter infrastructure;
- Demand Side Management;
- Security;
- Telehealth;
- Smart City applications; and
- Precision agriculture.

43 Lowenberg-DeBoer, J. (2000). Economic analysis of precision farming. In: Borem, A. et al. (eds.), *Agricultura de Precisao.* Vicosa, Brazil: Federal University of Vicosa, pp. 147-80.
Retrieved from: http://www.ufrrj.br/institutos/it/deng/varella/Downloads/IT190_principios_em_agricultura_de_precisao/livros/Capitulo_7.pdf.

All of these assessments of IoT were made by measuring the primary demand or the economic benefit that could be generated by different substitute technologies. These technologies include, among others, Bluetooth, Wi-Fi, Zigbee, RFID, and Low Power Wide Area Networks ("LPWAN").[44] For example, in the case of Smart Cities we looked at the total wireless sensor demand for this market or we quantified the value generated by precision agriculture by measuring its aggregated productivity impact. Along these lines, each technology would capture a portion of the primary demand based on their suitability: for example, while Wi-Fi would be suited, at least for the time being, for in-building communications, LPWAN would be ideal for low-power consumption/low-cost applications (e.g. industrial asset tracking, some Smart City applications such as smart parking, lighting detection or waste management). Alternatively, these technologies could complement each other to offer specific services.[45]

It goes without saying that these technologies could also compete among themselves for capturing a larger share of primary demand. For example, areas of contention for market share among competitive substitutes could include precision agriculture, smart metering, and security. That said, we believe this competitive dynamic to be highly beneficial for consumers. Unlicensed spectrum functions as a platform to stimulate innovation among alternative technologies aiming to better serve demand.

3.13. Total 2017 Economic Value of Unlicensed Spectrum

To sum up, the economic value derived in 2017 from the above-described set of already widely adopted technologies operating in unlicensed spectrum in the United States is estimated at $496.13 billion. The contribution to the nation's GDP of this set of technologies is at least $29.06 billion. It is important to note that, as discussed above, the study has also found that the full set of unlicensed applications contributing to economic value is more varied and diverse than expected in previous studies, and that more technologies and applications rely on both licensed and unlicensed spectrum. As a result, the total contribution of unlicensed spectrum is substantially higher than the figures reported for the subset considered specifically herein, and that because of the pace of innovation, capturing the full range of contributions by unlicensed technologies is increasingly difficult—the figures in this report are the readily measurable portion of a larger overall contribution. These estimates should now be compared against other assessments of economic value as well as the 2017 forecast developed by this author in 2014 (see Table 3-25).

44 Forrester estimates that in 2017 there are more than 20 wireless connectivity choices and protocols to support an organization IoT devices. See Gillett, Frank E. et al. (2016, Nov. 2). Predictions 2017: Security and skills will temper growth of IoT. *Forrester*. R
etrieved from: https://www.forrester.com/report/Predictions+2017+Security+And+Skills+Will+Temper+Growth+Of+IoT/-/E-RES136255.

45 See Cisco (2017). Cisco solution for *LoRaWAN*.
Retrieved from: https://www.cisco.com/c/dam/en/us/products/collateral/se/internet-of-things/at-a-glance-c45-737308.pdf.

Table 3-25. Prior research on economic value of unlicensed spectrum in the U.S. vs. Katz 2013, Katz 2017 Forecast (2014) and Katz 2017 Actual (in $ billions)

Technologies and Applications	Effect	Thanki 2008(2009)	Milgrom et al. 2010 (2011)	Cooper 2011 (2012)	Katz 2013 (2014)	Katz 2017 Forecast (2014)	Katz 2017 Actual
Wi-Fi cellular off-loading	Consumer surplus	N.A.	$25.0	$20.0	$1.90	$12.13	$5.82
	Producer surplus	N.A.	N.A.	$26.0	$10.70	$10.70	$10.70
	Return to speed	N.A.	$12.0	(*)	$2.83	$6.56	$7.70
	New business revenue	N.A.	N.A.	N.A.	$0.27	$0.47	$1.01
	SUBTOTAL	**N.A.**	**$37.0**	**$46.0**	**$15.70**	**$29.86**	**$25.23**
Residential Wi-Fi		$4.3-$12.6	>$12.6	$38 0	$36.08	$268.74	$258.69
	SUBTOTAL	**$4.3-$12.6**	**>$12.6**	**$38 0**	**$36.08**	**$268.74**	**$258.69**
Wi-Fi-only tablets	Producer surplus	N.A.	$7.5	N.A.	$34.88	$22.11	$9.48
	Consumer surplus	N.A.	$7.5	N.A.	$7.99	$25.88	$4.08
	SUBTOTAL	**N.A.**	**$15.0**	**N.A.**	**$42.87**	**$47.99**	**$13.56**
Hospital RFID		$9.6-$16.1	N.A.	(*)	$35.99 (***)	$52.70 (***)	$52.70 (***)
	SUBTOTAL	**$9.6-$16.1**	**N.A.**	**(*)**	**$35.99 (***)**	**$52.70 (***)**	**$52.70 (***)**
Clothing RFID		$2.0-$8.1	N.A.	(*)	$94.84 (**)	$138.55 (***)	$138.55 (***)
	SUBTOTAL	**$2.0-$8.1**	**N.A.**	**(*)**	**$94.84 (**)**	**$138.55 (***)**	**$138.55 (***)**
Wireless ISPs		N.A.	N.A.	N.A.	$1.44	$4.8	$2.87
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$1.44**	**$4.8**	**$2.87**
Wireless personal area networks	Bluetooth products	N.A.	N.A.	N.A.	$1.74	$0.77	$5.00
	ZigBee products	N.A.	N.A.	N.A.	$0.27	$0.83	$0.50
	Wireless HART products	N.A.	N.A.	N.A.	$0.16	$0.05	$0.03
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$2.17**	**$1.65**	**$5.53**
Emerging applications and technologies	High-speed wireless	N.A.	N.A.	N.A.	N.A.	$4.81	$0.63
	Machine-to-machine	N.A.	N.A.	N.A.	N.A.	$31.49	$6.82
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	N.A.	N.A.	$3.72
	Smart City deployments	N.A.	N.A.	N.A.	N.A.	$15.89	$15.89
	Agriculture automation	N.A.	N.A.	N.A.	N.A.	$1.10	$1.00
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**$53.29**	**$28.06**
TOTAL		**$16.0-$36.8**	**$64.6**	**$84.0**	**$229.09**	**$597.58**	**$525.19**

(*) Referenced but not quantified

(**) Calculated for total retail sector

(***) Calculated for total health care including pharmaceutical supply chain.

N.A. Not addressed

Source: Telecom Advisory Services analysis

The data on Table 3-25 provides several important highlights. We will first focus on the analysis of results of the 2013 and 2017 studies to understand the fundamental trends in increasing value (see Table 3-26).

Table 3-26. Comparison of Katz studies

Technologies and Applications	Effect	Katz 2013 (2014)	Katz 2017 Actual	Katz 2013 vs. 2017 Actual Delta	Reasons
Wi-Fi cellular off-loading	Consumer surplus	$1.90	$5.82	206.31 %	• Increase in smartphone adoption • Exponential growth in smartphone traffic propelled by video usage
	Producer surplus	$10.70	$10.70	---	• Completion of LTE roll-out
	Return to speed	$2.83	$7.70	172.08 %	• Wi-Fi average speed faster than cellular speeds (2013: 11.07 Mbps, 2017: 24.41 Mbps)
	New business revenue	$0.27	$1.01	274.07 %	• Growth of paid Wi-Fi industry
	SUBTOTAL	**$15.70**	**$25.23**	**60.70 %**	
Residential Wi-Fi		$36.08	$258.69	616.99 %	• Exponential growth in Wi-Fi traffic • High cost inside Ethernet wiring • Inclusion of Wi-Fi enabled home equipment
	SUBTOTAL	**$36.08**	**$258.69**	**616.99 %**	
Wi-Fi-only tablets	Producer surplus	$34.88	$9.48	(72.82) %	• Drop in tablet shipments after 2013 driven by smartphone substitution • Loss of U.S. manufacturers' global market share • Apple's eroding tablet margins
	Consumer surplus	$7.99	$4.08	(48.93) %	• Drop in tablet shipments after 2013 driven by smartphone substitution • Loss of U.S. manufacturers' global market share • Declining Apple prices reduced consumer surplus
	SUBTOTAL	**42.87**	**$13.56**	**(68.35) %**	
Health care RFID		$35.99	$52.70	46.42 %	• 10% CAGR in RFID adoption
	SUBTOTAL	**$35.99**	**$52.70**	**46.42 %**	
Retail RFID		$94.84	$138.55	46.08 %	• 10% CAGR in RFID adoption
	SUBTOTAL	**$94.84**	**$138.55**	**46.08 %**	
Wireless ISPs		$1.44	$2.87	99.31 %	• Growth in WISP subscribers and ARPU
	SUBTOTAL	**$1.44**	**$2.87**	**99.31 %**	
Wireless personal area networks	Bluetooth products	$1.74	$5.00	187.35 %	• Growth in Bluetooth automotive applications • Decline in peripherals shipments • Slower than forecast decline in Bluetooth chipsets unit price
	ZigBee products	$0.27	$0.50	85.18 %	• Accelerating growth in smart home applications, smart lightning • Emergence of ZigBee 3.0
	Wireless HART products	$0.16	$0.03	(81.25) %	• Competition from substitute platforms such as Wi-Fi and ZigBee
	SUBTOTAL	**$2.17**	**$5.53**	**154.83%**	
Emerging applications and technologies	High-speed wireless	N.A.	$0.63	---	
	Machine-to-machine	N.A.	$6.82	---	
	Low-frequency Wi-Fi	N.A.	$3.72	---	
	Smart City deployments	N.A.	$15.89	---	
	Agriculture automation	N.A.	$1.00	---	
	SUBTOTAL	**N.A.**	**$27.43**	**---**	
TOTAL		**$229.09**	**$525.19**	**129.25 %**	

Source: Telecom Advisory Services analysis

As indicated in Table 3-26, the 2017 economic value of unlicensed spectrum has increased 129% since 2013, fostered by the complementarity with cellular and development of new applications. Despite the fact that each study, with the exception of those produced by this author, rely on different methodologies and data sources, the comparison of results yield the following conclusions:

- **The economic value of unlicensed spectrum increases over time:** Because of its intrinsic characteristic as an enabling factor of production, unlicensed spectrum is a platform that complements other technologies (such as cellular) and promotes innovation (such as Bluetooth). In 2008, wireless personal area networks and other technologies such as machine-to-machine communications were at an initial diffusion stage and, therefore, did not represent a source of economic surplus. Over time, however, their economic value started to grow from $140 billion in 2010-11 to $525.19 billion in 2017.
- **While economic value continues to grow, the sources of economic value of unlicensed spectrum may vary over time:** While the economic value of unlicensed spectrum grows over time, as explained at the end of Chapter 2, the contribution of some technologies may increase and decrease following their specific product life cycle. That is the case with Wi-Fi tablets, which were a key source of value in the 2013 estimate, but started declining as a result of competitive and product substitution dynamics. At the same, unlicensed spectrum facilitates competition among substitute technologies relying on it. This can result in an increase of economic value of some technologies coupled with a decrease in value of competing technologies. For example, between 2013 and 2017, the value of Bluetooth-enabled products increased 166%, while the value of Wireless Hart-enabled products decreased 81%. Yet, in the aggregate, the economic value of wireless personal area network-enabled products increased 137%.

On the other hand, the 2017 actual estimates are 12% off from the original forecast. The following Table presents the comparison between the 2017 forecast developed in 2014 and the actual estimates presented in this study.

Table 3-27. Comparison of Katz 2017 Forecast and Actual studies

Technologies and Applications	Effect	Katz 2017 Forecast	Katz 2017 Actual	Katz 2013 vs. 2017 actual Delta	Reasons
Wi-Fi cellular off-loading	Consumer surplus	$12.13	$5.82	(52.02)%	• Smartphone adoption slowed down after 2015 due to saturation • Reduction in tablet traffic as a result of smartphone substitution • Faster drop in cellular data prices reduced the Wi-Fi advantage
	Producer surplus	$10.70	$10.70	---	• Completion of LTE roll-out
	Return to speed	$6.56	$7.70	17.37%	• Wi-Fi speed advantage vs. cellular larger than forecast (forecast: 9.95 Mbps vs. actual: 24.41 Mbps)
	New business revenue	$0.47	$1.01	114.89%	• Expansion of in-flight Wi-Fi
	SUBTOTAL	**$29.86**	**$25.23**	**(3.37)%**	
Residential Wi-Fi		$268.74	$258.69	(15.75)%	• Lower than estimated total tablet traffic • Faster drop in cellular data prices reduced the Wi-Fi advantage • Cost of inside wiring was higher than forecast • Diffusion of Wi-Fi-enabled residential equipment
	SUBTOTAL	**$268.74**	**$258.69**	**(15.75)%**	
Wi-Fi-only tablets	Producer surplus	$22.11	$9.48	(57.12)%	• Drop in tablet shipments after 2013 driven by smartphone substitution • Loss of U.S. manufacturers' global market share • Apple's eroding tablet margins
	Consumer surplus	$25.88	$4.08	(84.23)%	• Drop in tablet shipments after 2013 driven by smartphone substitution • Loss of U.S. manufacturers' global market share • Declining Apple prices reduced consumer surplus
	SUBTOTAL	**$47.99**	**$13.56**	**(71.72)%**	
Health care RFID		$52.70	$52.70	---	• Forecast growth in RFID adoption validated
	SUBTOTAL	**$52.70**	**$52.70**	**---**	
Retail RFID		$138.55	$138.55	---	• Forecast growth in RFID adoption validated
	SUBTOTAL	**$138.55**	**$138.55**	**---**	
Wireless ISPs		$4.80	$2.87	(40.20)%	• WISP subscribers lower than forecast (4.6 million vs. 8 million) • ARPU slightly higher ($52 vs. $50 forecast)
	SUBTOTAL	**$4.80**	**$2.87**	**(40.20)%**	
Wireless personal area networks	Bluetooth products	$0.77	$5.00	549.35%	• Growth in Bluetooth automotive applications • Increase in smartphone shipments • Drop in peripherals shipments • Slower than forecast decline in Bluetooth chipsets unit price
	ZigBee products	$0.83	$0.50	(39.75)%	• Reduction of share of U.S. chipset manufacturers
	Wireless HART products	$0.05	$0.03	(40)%	• Competition from substitute platforms such as Wi-Fi and ZigBee
	SUBTOTAL	**$1.65**	**$5.53**	**235.15%**	
Emerging applications and technologies	High-speed wireless	$4.81	$0.63	(86.90)%	• Slower than forecast growth in WirelessHD and WGig shipments
	Machine-to-machine	$31.49	$6.82	(78.34)%	• Slower ramp up in machine-to-machine growth
	Low-frequency Wi-Fi	N.A.	$3.72	---	
	Smart City deployments	$15.89	$15.89	---	• Forecast validated
	Agriculture automation	$1.10	$1.00	(68.18)%	• Lower harvested crop surface • 10 pp. lower adoption of precision agriculture
	SUBTOTAL	**$53.29**	**$28.06**	**(47.24)%**	
TOTAL		**$597.58**	**$525.190**	**(12.11) %**	

Source: Telecom Advisory Services analysis

4. Forecasting the 2020 Economic Surplus of Unlicensed Spectrum Based on Current Sources of Value

Chapter 3 provided an estimate of the economic value of unlicensed spectrum in the United States as of 2017. The economic estimate was based on the adoption of technologies as of the end of 2017 and, by definition, encompassed only a limited set of widely adopted technologies and applications (Wi-Fi cellular off-loading, residential Wi-Fi, wireless Internet service providers, Wi-Fi-only tablets, Bluetooth, ZigBee, Wireless HART, and RFID applications in retailing and health care industries). The study concluded that in 2017 the technologies currently operating in unlicensed spectrum bands in the United States generated a total economic value of $496.13 billion and contributed $29.06 billion to the nation's GDP.

However, a question that still needs to be addressed, particularly in assessing whether to preserve or expand unlicensed spectrum designations, is how much value we can expect unlicensed technologies to contribute to the economy in the future. Such quantification is based on two factors: 1) future adoption of technologies already widely diffused (for example, smartphone U.S. installed base, currently at 282 million, is estimated to reach 330 million by 2020), and 2) deployment of emerging platforms, such as 5G will reach full commercial deployment by the same year.

Forecasting future value derived from current uses is relatively straightforward. It entails primarily projecting adoption curves, while estimating pricing trends and scale and/or learning effects on the cost side. On the other hand, estimating value derived from future innovations is not that easy. In the words of Milgrom et al. (2011), **"[t]he primary benefits of unlicensed spectrum may well come from innovations that cannot yet be foreseen."**[46]

As stated by several researchers, one of the fundamental dimensions of value of unlicensed spectrum is that of providing an environment conducive to the development of innovative technologies and business models.[47] The following chapter will tackle the first factor driving future value. It begins by estimating the value to be derived by currently adopted innovations using the year 2020 as the anchoring point in time in the future. We chose this year as the prediction point because technology predictions that are more than three years out have limited value given the range of uncertainties regarding innovation and adoption pace. Chapter 5 will then focus on future sources of value.

4.1. The 2020 Economic Value of Wi-Fi for Cellular Off-Loading

As reviewed in Chapter 3, the economic value of Wi-Fi for cellular off-loading for 2013 was estimated in four areas:

- **Consumer surplus:** The difference between the consumer's price of cellular data and usage in a public hot-spot for free, meaning that surplus would equate to the monetary value he/she would pay to a cellular operator for gaining equal access;
- **Producer surplus:** The reduction in capital and operating expenses of cellular carriers derived from off-loading data traffic to carrier grade Wi-Fi hot-spots;
- **Return to speed:** The economic impact of higher speeds resulting from off-loading data traffic from cellular networks to Wi-Fi sites; and
- **New business models:** The development of Wi-Fi service providers that would not exist if unlicensed spectrum bands were not available.

As done in Chapter 3 for 2017, the estimate of consumer surplus in 2020 is based on projecting total Wi-Fi traffic and factoring in the portion of it that is conveyed through public free and "guest" sites (see Table 4-1).

46 Milgrom et al. (2011) p. 2.
47 *Id*., Thanki (2012), Carter (2006), among others.

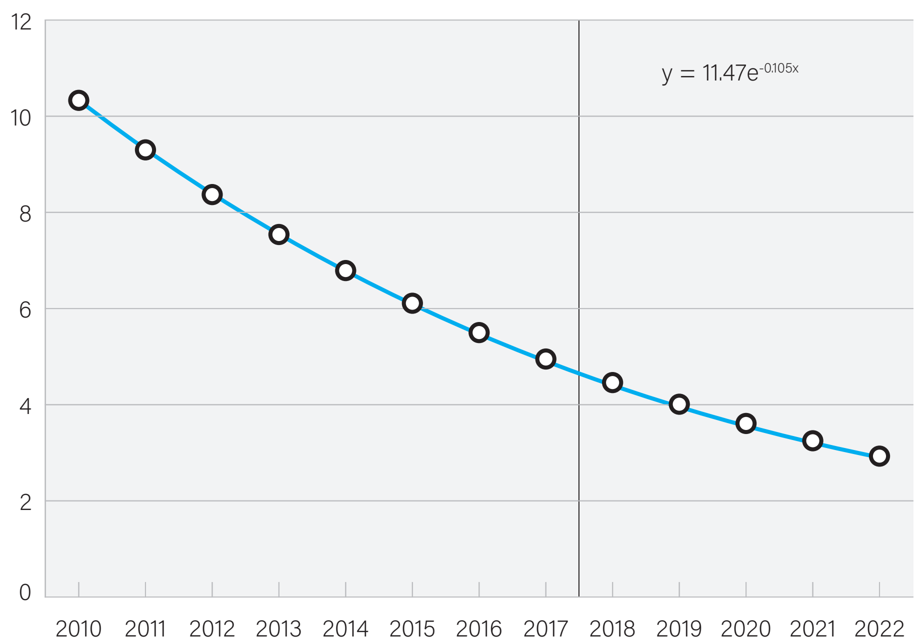
Table 4-1. Total free Wi-Fi traffic in the U.S. (2013-2020)

Variable		2013	2017	2020
Total Wi-Fi traffic (EB per month)	Smartphones	0.08	3.70	8.91
	Tablets	0.28	1.74	3.30
	Laptops	0.30	0.86	1.08
	Total	0.67	6.30	13.29
Total free traffic (EB per month)		0.03	0.17	0.36
Total free traffic (EB per year)		0.35	2.04	4.31
Total free traffic (GB per year)		**372.12**	**2,186.57**	**4,624.68**

Sources: Cisco; GSMA; Telecom Advisory Services analysis

Consumer surplus is calculated, in turn, by multiplying the total free traffic by the difference between what the consumer would have to pay if he/she were to utilize a wireless carrier and the cost of offering free Wi-Fi (incurred by the retailer or public site). However, in this case, a logarithmic model was specified to project what the expected cellular price per GB will be by 2020 given current trends. Accordingly, we expect pricing evolution to start flattening out over time, and reach $3.77 by 2020 (see Graph 4-1).

Graph 4-1. Average price per cellular GB (2010-17 historical/2018-22 forecast)



Average Price per GB (2017)

Carrier	Plan	Price/Gb
ATT	Mobile Share Data: $335/50 Gigabytes cap	$6.70
Verizon	Data Only, 100 Gb: $710/100 Gigabytes cap	$7.10
Sprint	Unlimited data: $25/10 Gigabytes cap 4G	$2.50
T-Mobile	Mobile Internet 22 Gb: $95/22 Gigabytes cap	$4.32
Average		$5.16

Source: Telecom Advisory Services analysis

Assuming $3.77 as the price per GB in 2020, the consumer surplus linked to free Wi-Fi is expected to reach $5,873 million by 2020 (see Table 4-2).

Table 4-2. Consumer surplus of free Wi-Fi traffic in the U.S. (2013-2020)

Variable	2013	2017	2020
Total free traffic (million GB per year)	372.12	2,186.57	4,624.68
Price per cellular GB ($)	$7.61	$5.16	$3.77
Cost per Wi-Fi provisioning ($)	$2.50	$2.50	$2.50
Consumer surplus per GB ($)	$5.11	$2.66	$1.27
Total consumer surplus ($ million)	**$1,902**	**$5,816**	**$5,873.34**

Note: Price per cellular gigabyte calculated by averaging the most economic "dollar per GB" plan of four major U.S. wireless carriers between 2010 and 2017 and extrapolating price decline curves

Source: Telecom Advisory Services analysis

To measure the economic value of Wi-Fi speed, our analysis focused on measuring the speed of wireless networks by 2020 if they did not have faster Wi-Fi technology as a complement. In this case, we considered the total traffic without differentiating between points of access (residences or public places). Our analysis began by quantifying the speed differential between average cellular and Wi-Fi access. By factoring off-loading effects in relation to cellular we could then understand speed increases and apply the Bohlin & Rohman (2012) model to estimate the impact of increased speed on GDP (see Table 4-3).[48]

Table 4-3. Estimate of speed differential for total U.S. traffic (2013-2017)

Variable	2013	2017	2020
Average speed of cellular networks (Mbps)	3.43	13.52	18.59
Average Wi-Fi speed (Mbps)	13.32	37.93	56.00
Average speed of weighted average of cellular and Wi-Fi traffic	10.15	30.20	40.93
Speed decrease (average speed of cellular/average weighted average speed)	-66.21%	-55.22%	-54.59%
Model coefficient	0.30%	0.30%	0.30%
Decrease in GDP per capita	-0.20%	-0.17%	-0.16%
GDP per capita (current prices)	51,248	61,690	65,465
Wi-Fi traffic (% total traffic)	8.79%	23.01%	27.20%
GDP reduction ($ million) (current prices)	-2,831	-7,703	9,761

(1) Detailed model and calculations are included in Katz (2014a).

Sources: Cisco; Telecom Advisory Services analysis

Finally, to estimate the new business revenues generated by service providers offering Wi-Fi services in public places (airports, hotels) for a fee in 2020, we added up the revenues of all firms operating in this space in the United States in 2017, and multiplied the sum by the annual growth rate for the four players whose growth was assessed between 2013 and 2017 (Boingo Wireless, iPass, SONIFI, and Gogo Inflight Internet): 3.45% (see Table 4-4).

Table 4-4. Compilation of retail revenues of Wi-Fi service providers in the U.S. (in $ millions)

Company	2013	2017	2020
Boingo	$105.98	$192.00 (*)	---
iPass	$65.5	$54.0 (*)	---
SONIFI (Lodgnet interactive)	$100	$95.77	---
Gogo Inflight Internet	$408 (excluded from calculation)	$670.00 (**)	---

48 For a full description of methodology, see Katz (2014a).

TOTAL	$468.00	$1,011.77	$1,110.17

(*) Company outlook 2017 revenue based on 1H2017 performance. (**) LTM 9/30/17

Sources: Company annual reports and 10-K reports; Informa; Telecom Advisory Services analysis

In summary, cellular traffic off-loading has multiple drivers of economic value. The analyses contained in this section enabled the calculation of annual economic value of Wi-Fi acting as a complement of wireless networks operating in licensed spectrum in 2020 (see Table 4-5).

Table 4-5. Summary of economic value of Wi-Fi cellular off-loading (2013-2020) (in $ billions)

Effect	Underlying Premise	2013	2017	2020
Consumer surplus	Value of free Wi-Fi traffic offered in public sites	$1.902	$5.816	$5.873
Producer surplus	Total cost of ownership required to accommodate future capacity	$10.7	$10.7	$10.7
Return to speed	Increase of average mobile speed from Wi-Fi off-loading	$2.831	$7.703	$9.761
New business revenue	Revenues of providers offering paid Wi-Fi access in public places	$0.271	$1.012	$1.110
TOTAL		**$15.70**	**$25.23**	**$27.44**

Source: Telecom Advisory Services analysis

The estimates point to a substantial, but slowing, increase in the value of free Wi-Fi resulting from a seven-fold increase in Wi-Fi traffic across devices.

4.2. The Economic 2020 Value of Residential Wi-Fi

The assessment of the economic value of residential Wi-Fi in 2017 in Chapter 3 focused on two benefits:

- Providing Internet access for devices that lack a wired port (e.g., tablets, smartphones, game consoles); and
- Avoidance of investment in in-house wiring.

As explained before, the underlying premise of this analysis was that, in the absence of Wi-Fi, users would have to depend on the cellular network to gain Internet access. This analysis assumed that those devices that have the capacity to connect through a wired port (e.g., personal computers) would, in the absence of Wi-Fi, rely on wired connections. We were left, however, with those devices that do not have the capability of a wired connection (tablets, smartphones, home devices such as Amazon Echo, Google Home, Apple HomePod, and game consoles). For this reason, estimating economic value would first measure the traffic generated by these devices at home and then would multiply it by the average price charged by cellular carriers (see Table 4-6).

Table 4-6. Annual costs to be incurred by home traffic generated by devices with no wireline connectivity (2013-2020)

Variable		2013	2017	2020
Annual traffic generated by devices with no wireline connectivity	Smartphones (billion GB)	1.85	47.64	114.76
	Tablets (billion GB)	4.67	22.40	42.50
	Game Consoles (billion GB)	0.34	0.93	0.141
	Total (billion GB)	6.86	70.13	157.40
Percent home traffic generated by devices with no wireline connectivity (*)		43.1%	43.1%	43.1%
Total annual home traffic generated by devices with no wireline connectivity		2.96	30.24	67.87
Average price per GB		$7.61	$5.16	$3.77
Total cost of home traffic generated by devices with no wireline connectivity ($ billion)		**$22.51**	**$156.04**	**$255.86**

(*) 43% of use time of these devices takes place at home

Sources: Cisco; Park Associates; Telecom Advisory Services analysis

By 2020, we expect the average price per GB to be approximately $3.77, resulting in a consumer surplus associated with residential Wi-Fi usage of $255.86 billion.

In addition, as explained in Chapter 3, residential Wi-Fi allows consumers to avoid paying for wiring to connect all home devices (printers, laptops, storage units, etc.). Assuming constant cost of deploying inside wiring in-residence of approximately $660 per household defined for 2017, the avoidance cost of inside wiring is driven by household growth and Wi-Fi household diffusion (see Table 4-7).

Table 4-7. Cost avoidance of inside wiring (2013-2020)

Variable	2013	2017	2020
Number of households	114,761,359	126,224,000	135,800,000
Percentage of Wi-Fi households	61%	71%	85%
Number of Wi-Fi households	70,004,429	89,619,040	115,430,000
Unit cost of inside wiring	$193.80	$660 (*)	$660 (*)
Total cost avoidance ($ billion)	**$13.57**	**$59.15**	**$76.18**

(*) National average for wiring a 2-room residence with CAT 6.

Sources: U.S. Census; McCue, D. and Herbert, S. Updated household projections 2015-2035; Strategy Analytics; Park Associates; Telecom Advisory Services analysis

In addition, demand for Wi-Fi-enabled consumer residential equipment is forecast to grow 147% by 2020, reaching $121,335 million (see Table 4-8).

Table 4-8. Revenues of residential Wi-Fi-enabled consumer electronics in the U.S. (2017-2020) (in $ millions)

Category	2017	2020
Wireless speakers	$41,120 (1)	$109,578
Security systems	$4,506	$4,239
Home networking systems	$3,352	$7,517
TOTAL	**$48,970**	**$121,335**

(1) Includes only Wi-Fi enabled wireless speakers, excluding Bluetooth to avoid double counting.

Note: Source provides revenues for 2018 only. 2020 values were estimated based on 2017-2018 growth rate.

Source: Consumer Technology Association (2018). U.S. Consumer Technology Sales and Forecasts, January; Telecom Advisory Services analysis

Assuming that the consumer electronics industry gross margin remains stable for 2020 at the 2017 level (55.59%), producer surplus would equate to $53,885 million, and consumer surplus would be the same value.

In sum, the value of residential Wi-Fi in 2020 is forecast to reach $439.81 billion, an increase of 70% over 2017 (see Table 4-9).

Table 4-9. Summary of economic value of residential Wi-Fi (2013-2020) (in $ billions)

Effect	Underlying Premise	2013	2017	2020
Internet access for devices that lack a wired port	Cost required for those devices to access the Internet via cellular networks	$22.51	$156.04	$255.86
Avoidance of investment in in-house wiring	Cost to wire the residence	$13.57	$59.15	$76.18
Economic surplus of Wi-Fi-enabled consumer residential equipment	Sales of wireless speakers, security systems, and home networking equipment	N.A.	$43.50	$107.77
TOTAL		**$36.08**	**$258.69**	**$439.81**

Source: Telecom Advisory Services analysis

The primary driver of the increase in economic value in residential Wi-Fi surplus is the growing adoption of devices and the exploding traffic per unit. As discussed before, tablets are, by definition, primarily Wi-Fi devices (90% of units are not connected to the cellular network), and they lack the capability to connect to the Internet through a wired Ethernet port. On the other hand, the cost of wireless data plans naturally pushes smartphone users to access the Internet via Wi-Fi when they are at home. Between 2017 and 2020, the installed base of wireless devices in the United States is projected to grow from 637 million to 646 million, while more importantly, the prorated unit traffic of wireless devices is expected to grow from 10.6 GB per month to 22.08 GB per month.[49] Considering that 43% of the traffic generated by wireless devices originates at home, the total annual traffic in 2020 will amount to 67 billion GB, growing from 30.2 billion in 2017. Even considering a decline in pricing per GB transported by cellular networks ($5.16 in 2017 to $3.77 in 2020), if the exponential traffic growth were to rely on cellular networks, it would represent $255.86 billion. This is the primary driver in the increase in economic value between 2017 and 2020. In addition, residential Wi-Fi continues to yield savings in Ethernet wiring, projected to reach $76.18 billion in 2020. Finally, the combination of consumer and producer surplus derived from the adoption of Wi-Fi-enabled residential equipment reaches $107.77 billion.

4.3. The 2020 Economic Value of Wi-Fi-Only Tablets

As explained in Chapter 3, beyond the consumer surplus associated to the use of tablets for accessing the Internet via Wi-Fi, additional economic value is being originated by the margin generated by tablet manufacturers selling their products worldwide as well as the consumer surplus calculated by the difference between consumers' willingness to pay and actual prices of the product. This section focuses on these two effects.

Our prior assessments of the economic value of Wi-Fi-only tablets comprised both consumer and producer surplus generated by the purchasing of these devices manufactured by U.S. producers in 2013 and 2017. The same methodology was applied to forecast the economic value of these devices to be generated in 2020 (see Table 4-10).

49 Cisco (2017). *Cisco Visual Networking Index: Global mobile data traffic forecast update, 2016-2021.* Retrieved from: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html. ("Cisco Visual Networking Index").

Table 4-10. Economic value of Wi-Fi-only tablets (2013-2020)

Variable		2013	2017	2020
Global tablet shipments	Total global tablet shipments (million)	221.3	166.1	185
	Share of U.S. manufacturers	68.9 %	34.6%	30%
	Global tablet shipments of U.S. manufacturers (million)	152.47	57.47	55.5
	Portion of Wi-Fi-only	90%	95%	95%
	Wi-Fi-only global shipments by U.S. manufacturers (million)	137.23	54.60	52.73
Producer surplus estimates	Apple shipments (million)	96.06	42.34	40.88
	Non-Apple shipments (million)	41.17	12.26	11.84
	Apple margin ($)	$354	$224	$224
	Non-Apple margin ($)	$16	$0	$0
	Apple producer surplus (million)	$34,196	$9,483.35	$9,158.18
	Non-Apple producer surplus ($ million)	$659	$0	$0
Total estimated producer surplus ($ million)		**$34,855**	**$9,483.35**	**$9,158.18**
Consumer surplus estimates		96.06	42.34	40.88
		41.17	12.26	11.84
		$499	$429	$429
		$199	$199	$199
		$524	$524	$450
		$335	$204	$199
		$2,401	$4,022	$859
		$5,599	$61.30	$0
Total estimated consumer surplus ($ million)		**$7,987**	**$4,083.30**	**$859**
Total estimated economic value ($ million)		**$42,872**	**$13,566.65**	**$10,017**

Sources: IDC; Statista; iSuppli; Telecom Advisory Services analysis

The significant reduction in economic surplus generated by Wi-Fi-only tablets in 2017 was driven by multiple factors:

- Worldwide drop in tablets shipments;
- Loss in market share by U.S. manufacturers;
- Margin erosion on the part of Apple, the dominant U.S. tablet manufacturer, which affects its producer surplus; and
- Reduction in price realization which impacts the consumer surplus.

Some of these trends are expected to continue through 2020:

- Global tablet shipments are expected to stabilize at a value close to 185 million;[50]
- U.S. manufacturers will continue losing market share (from 35% in 2017 to 30% in 2020) as a result of a decrease in Apple iOs share;[51]
- While margin erosion will stabilize as a result of ongoing model upgrades (the "versioning effect"), willingness to pay is expected to decline due to persistent substitution of feature-rich smartphones.

The resulting 2020 economic surplus forecast of Wi-Fi-enabled tablets sold by U.S. manufacturers amounts to $10.01 billion compared to $13.57 billion in 2017, a decline of 26%.

50 Statista (2018). Forecast unit shipments of tablets worldwide from 2010 to 2022. Retrieved from: https://www.statista.com/statistics/269912/worldwide-tablet-shipments-forecast/.

51 Statista (2018). Global tablet operating systems' market share from 2013 to 2020. Retrieved from: https://www.statista.com/statistics/272446/global-market-share-held-by-tablet-operating-systems/.

On the other hand, other sources of economic value are increasing, compensating for the drop in tablets. In the following section we will focus on the growth of machine-to-machine ("M2M") communications, and in the next chapter we will review a whole new range of home devices relying on Wi-Fi spectrum.

4.4. The 2020 Economic Value of M2M Communications

The 2017 economic value of M2M communications relying on unlicensed spectrum was estimated at $2.43 billion. The methodology for developing such an estimate focused only on four applications known to utilize unlicensed spectrum: Advanced metering infrastructure, security, Energy Demand Side Management devices, and Telehealth. For this purpose, it calculated the percent of total M2M connections that were used for the four applications and applied that proportion to the total M2M market. M2M connections are expected to continue growing through 2020. Accordingly, the economic value of the M2M connections relying on unlicensed spectrum in that year would reach $3.45 billion. The following Table presents the values for 2017 and 2020.

Table 4-11. Economic value of U.S. M2M connections (2017-2020)

Variable		2017	2020
Total connections (million)		1,464.7	2,473.5
Connections relying on unlicensed spectrum (million)	AMI	27.83	49.75
	Security	18.87	32.58
	Demand Side Management	10.02	16.44
	Telehealth	10.55	18.85
Total connections relying on unlicensed spectrum (%)		4.6 %	4.75 %
Global machine-to-machine market ($ billion)		$5.95	$7.26 (2)
Share of M2M market relying on unlicensed spectrum ($ billion)		**$2.43**	**$3.45**

(1) To avoid double counting with ZigBee applications addressed in Table 4-10, we subtracted $835.4 million from the total M2M market.

(2) U.S. M2M connections market worth $7,262.76 million by 2020

Sources: Cisco VNI; Markets and Markets; ABI Research; IDATE; Telecom Advisory Services analysis

In addition to the M2M applications discussed above, wearable technologies represent an emerging set of uses of unlicensed spectrum. The methodology used to generate a forecast of economic value associated with the wearable devices market calculated the prorated amount of the global market based on the proportion of devices adopted in the United States (see Table 4-12).

Table 4-12. Economic value of U.S. wearables (2017-2020)

Variable		2017	2020
Global devices sold (million)		310.37	493.30
Global market ($ billion)		$30.5	$48.47
U.S. devices (million)		44.4	70.6
Wearable devices (million)	Smart Glasses	4.75	7.55
	Smart Watches	27.08	43.04
	Fitness and activity monitors	8.88	14.11
	Heart rate monitors	3.64	5.79
Total value of U.S. wearables market ($ billion)		**$4.36**	**$6.93**

Sources: Cisco VNI; ABI Research; Gartner; eMarketer; Telecom Advisory Services analysis

While the 2017 estimate of the GDP contribution associated to the diffusion of wearable devices reached $4.36 billion in 2017, the 2020 forecast is estimated at $6.93 billion. As a result, the decline in economic surplus in Wi-Fi-only tablets between 2017 and 2020 (-$3.55 billion) is compensated by the increase in M2M and wearables ($3.59 billion).

4.5. The 2020 Economic Value of Wireless Personal Area Networks

The assessment of economic value of wireless personal area networks in 2013 and 2017 covered Bluetooth, ZigBee, and Wireless HART, which support applications such as home automation and industrial device monitoring. The economic value of these technologies was estimated by focusing on the size of the market of the technologies relying on each standard. The same approach was followed for a 2020 forecast.

The 2017 economic value of unlicensed spectrum-enabled personal area networks amounts to $5,158 million. The more than double increase vis-à-vis 2013 was driven by the explosive demand in automotive applications and an expansion of smartphone demand, both of which amply compensated for the decline in PC and peripherals. On the other hand, an increase in the economic value generated by ZigBee-enabled products was driven by the growth of primarily Smart Home applications, which represented two-thirds of the growth.

Moving to 2020, the global market for Bluetooth automotive devices in 2020 will reach $45,363 million.[52] The U.S. represents approximately 20% of the total market, resulting in $9.073 billion.

As explained in Chapter 3, the U.S. economic value of the mobile telephony Bluetooth chipset market is driven by: (a) the number of devices shipped worldwide, and (b) the U.S. suppliers' market share of shipments. In that chapter we reviewed the economic value associated to the delivery of Bluetooth chipsets in smartphones, tablets, PCs and peripherals. The applications considered in those sections were related to interconnectivity of devices.

Global smartphone shipments will reach 1,697 million units.[53] Assuming that the percent of units carrying a Bluetooth chipset manufactured by U.S. firms will remain constant from 3Q17 (34.8%), shipments will reach 590 million. Moreover, considering a decline in chipset unit price from $0.90 in 2017 to $0.80 in 2020, the 2020 value for Bluetooth mobile telephony would amount to $472 million.

Yet, in addition to the economic contribution quantified above, Bluetooth chipsets have enabled the development of a completely new device ecosystem targeted to access and use of the technology: witness the development of Bluetooth connected speakers, headphones, earbuds, and headsets. In 2017, global headphones and headsets sales reached 368 million, of which approximately 20% are Bluetooth-enabled.[54] At an average unit price of $50, and assuming U.S. manufacturers control 35% share of global sales,[55] GDP contribution of this Bluetooth-powered item would be $1.29 billion.

Along the same lines, the economic value of Bluetooth chipsets in the PC and peripherals market in 2020 should be driven by the worldwide shipment of devices that carry a U.S.-manufactured semiconductor. The 2020 shipments of PCs, tablets, and printers that carry a Bluetooth chipset originated in the United States is estimated to reach 298 million (see Table 4-13).

52 WiseGuyReports (2017, Nov. 29). Bluetooth in automotive 2017 global market to reach USD 1, 09,979.0 million and growing at CAGR of 34.65% by 2023. *ABNewswire*. Retrieved from: http://www.abnewswire.com/pressreleases/bluetooth-in-automotive-2017-global-market-to-reach-usd-1-099790-million-and-growing-at-cagr-of-3465-by-2023_165039.html.

53 Statista (2018). Global smartphone shipments forecast from 2010 to 2021. Retrieved from: https://www.statista.com/statistics/263441/global-smartphone-shipments-forecast/.

54 NPD (2016, July 28). Bluetooth capable headphone sales surpass non-Bluetooth sales. Retrieved from https://www.npd.com/wps/portal/npd/us/news/press-releases/2016/bluetooth-capable-headphone-sales-surpass-non-bluetooth-sales/.

55 Richter, F. (2017, Feb. 14). The U.S. wireless headphone market. Manufacturing.net. Retrieved from: https://www.manufacturing.net/data-focus/2017/02/us-wireless-headphone-market.

Table 4-13. 2017 Bluetooth chipsets shipments (in millions) (2017-2020)

Device	Manufacturer	2017	2018	2019	2020
PC	Global	258.3	265.5	272.6	249.1
	U.S. Bluetooth chipsets (*)	190.5	195.8	201.0	183.7
	Non-U.S. Bluetooth chipsets	67.8	69.7	71.6	65.4
Tablets	Global	167.2	173.6	180.0	185.0
	U.S. Bluetooth chipsets (*)	68.9	71.5	74.2	76.2
	Non-U.S. Bluetooth chipsets	98.3	102.1	105.8	108.8
Printers	Global (**)	99.7	100.7	101.7	102.7
	U.S. Bluetooth chipsets (*)	37.0	37.4	37.7	38.1
	Non-U.S. Bluetooth chipsets	62.7	63.3	64.0	64.6
Total U.S. Bluetooth chipsets		**296.4**	**304.7**	**313.0**	**298.1**

(*) 2017 market share of equipment with U.S. Bluetooth chipsets assumed to remain constant. (**) Assumed to grow at 1% per annum as per 2016 and 2017

Sources: IDC; Statista; Telecom Advisory Services analysis

At $0.80 unit cost, the total economic value of Bluetooth devices in 2020 is estimated at $238.45 million, a reduction from $266.76 million in 2017: the number of units carrying a U.S.-manufactured Bluetooth chipset remain fairly constant, while its unit cost declines, causing a reduction of total value of 10.61%.

Moving on to explaining the 2020 Zigbee forecast, devices enabled by this technology are expected to grow 6% through 2020,[56] yielding 142 million units. Assuming that the average value of a Zigbee chipset will decline from $6.00 to $5.00,[57] this would result in a total market of $710 million, of which the U.S. manufacturers are expected to retain 70%: $497 million. Finally, based on an estimated global market of $249.4 million and a share of U.S. manufacturers of 26.7%, the 2020 Wireless HART economic contribution is forecast at $66.6 million.

In sum, the economic value generated by personal area networks innovation occurring within unlicensed spectrum bands is estimated to reach $10.35 billion, an increase of 106% over 2017 (see Table 4-14).

Table 4-14. Economic value of wireless personal area networks (2013-2020) (in $ million)

Standard and Applications		2013	2017 Growth Drivers	2017	2020 Growth Drivers	2020
Bluetooth	Automotive	$1,161.60	• Size of Bluetooth market	$3,716.20	• Size of Bluetooth market	$9,072.66
	Mobile Telephony	$192.75	• Smartphone sales: 537.4 million • Cost of Bluetooth chipset: $0.90	$483.66	• Smartphone sales: 590 million • Cost of Bluetooth chipset: $0.80	$472.00
	PC & Peripherals	$385.03	• PC sales: 190.5 million • Tablet sales: 68.9 million • Printer sales: 37.0 million • Cost of Bluetooth chipset: $0.90	$266.76	• PC sales: 183.7 million • Tablet sales: 76.2 million • Printer sales: 38.1 million • Cost of Bluetooth chipset: $0.90	$238.45
Zigbee		$267.00	• ZigBee device shipments: 120 million • Cost of ZigBee chipset: $6.00 • U.S. manufacturers share: 70%	$504.00	• ZigBee device shipments: 142 million • Cost of ZigBee chipset: $5.00 • U.S. manufacturers share: 70%	$497.00
Wireless HART		$160.00	• U.S. share (27%) of global Wireless HART market: $100 million	$27.00	• Growth in sensor adoption	$66.60
TOTAL		**$2,166.38**		**$4,997.62**		**$10,346.71**

(1) 2017 value excludes health and wellness because this category will be covered under wearable technologies in Section 3.3.

Sources: Yole Development; IDC; Wireless Connectivity; Technavio; ONWorld; IDTech; WiseGuyReports; Statista; Telecom Advisory Services analysis.

56 Technavio (2016 Jan.). Global ZigBee enabled devices market 2016-2020. Retrieved from: https://www.technavio.com/report/global-computing-devices-zigbee-enabled-devices-market.

57 The Digikey site in 2017 reports the unit price of Zigbee RF Transceiver ICs ranging from $1.31 to $11.14 at volumes ranging between 500 and 5,000. Assuming that Digikey is on the upper side of IC wholesalers, it is reasonable to assume a unit price of approximately $6.00. It is assumed that, consistent with the decline in Bluetooth chipsets, the Zigbee semiconductor will diminish to $5.00.

4.6. 2020 Economic Value Generated by the WISP Industry

The 2017 economic surplus related to the WISP industry was calculated as a function of the number of subscribers (4,600,000) and ARPU ($52.00 per month), yielding a total GDP contribution of $2.87 million. The WISPA report cited in Chapter 3 also provides a 2020 forecast (see Table 4-15).[58]

Table 4-15. Wireless internet service providers

Variable	2013	2017	2020
Subscribers	3,000,000	4,600,000	6,900,000
ARPU	$39.99	$52.00	$56.00
Revenues ($ billion)	$1.440	$2.870	$4.636

Source: Katz (2014); WISPA (2017)

As per Table 4-14, the WISP industry GDP contribution would reach $4.636 billion.

4.7. The 2020 Economic Value of RFID

As explained in Chapter 2, the future value of RFID technology is dependent on its level of adoption among enterprises. To remain comparable with the 2017 estimate, we estimate the penetration of RFID technology for only two sectors in 2020: retailing and health care. In 2017, it was estimated, consistently with the original forecast, that RFID would be adopted by 45% of U.S. retailers and 50% among enterprises along the health care value chain. Looking at 2020, assuming that cost savings and consumer benefits remain constant, a key driver of growth in consumer value is an increase in enterprise adoption.

Forecasts of RFID adoption by different market research firms consistently point to increasing penetration. For example, as cited in Chapter 3, the global RFID market, estimated at $5.6 billion in 2010, is expected to grow to $24.1 billion in 2021, resulting in a CAGR of 11% (Das & Harrop, 2011). Based on these estimates, but assuming a conservative increase in economic value of 10% by 2020 driven by increased purchasing and usage of RFID devices, incremental surplus was calculated (see Tables 4-16 and 4-17).[59]

Table 4-16. RFID economic value in U.S. retailing (2013-2020) (in $ billions)

	2013		2017		2020	
Benefit	Producer Surplus	Consumer Surplus	Producer Surplus	Consumer Surplus	Producer Surplus	Consumer Surplus
Reduction in labor costs	$46. 33		$67.83		$74.61	
Reduction in shrinkage losses	$11.67		$17.09		$18.80	
Enhanced inventory turns	$7.35		$10.76		$11.84	
Reduction in inventory write-offs	$2.11		$3.09		$3.40	
Reduced stock-outs	$0.29		$0.42		$0.46	
Reduced shipment errors	$0.09		$0.13		$0.14	
Faster time to market	$0.63		$0.92		$1.01	
Ubiquitous access across multiple channels	$0.11		$0.16		$0.18	
Customization		$20.45		$29.63		$32.59
Enhanced experience		$5.81		$8.51		$9.36
TOTAL	**$68.58**	**$26.26**	**$100.41**	**$38.14**	**$110.44**	**$41.95**

Source: Telecom Advisory Services analysis based on Barua et al. (2006)

58 WISPA (2017).
59 While the forecast is 11 %, it refers to the purchasing of RFID goods and services, which should not equate to producer surplus.

Table 4-17. U.S. RFID economic value in health care (2013-2020) (in $ billions)

Product and Service Providers	Benefit	2013		2017		2020	
		Producer Surplus	Consumer Surplus	Producer Surplus	Consumer Surplus	Producer Surplus	Consumer Surplus
Pharmaceutical manufacturers	Reduction in counterfeit, shrinkage and parallel trade	$0.925		$1.35		$1.49	
	Efficient sample management	$6.50		$9.52		$10.47	
	Enhanced inventory turns	$4.50		$6.59		$7.25	
	Shorter clinical trials and faster time-to-market	$0.10		$0.15		$0.17	
Health care distributors	Enhanced inventory turns	$0.41		$0.60		$0.66	
	Reduction in labor costs	$0.13		$0.19		$0.21	
Hospitals	Better equipment tracking	$1.45		$2.12		$2.33	
	Enhanced inventory turns	$17.95		$26.28		$28.91	
	Wider access to health care at reduced costs		$2.53		$3.70		$4.07
Consumers	Faster access to better health care		$1.50		$2.20		$2.42
	Improved quality of patient care – fewer medical errors and improved compliance		---		$0.00		
TOTAL		**$31.96**	**$4.03**	**$46.80**	**$5.90**	**$51.48**	**$6.49**

Source: Telecom Advisory Services analysis based on Barua et al. (2006)

Based on these estimates, the continuing implementation of RFID in the retail and health care industries would generate total economic value of $210.36 billion by 2020.

4.8. The 2020 Economic Value of High-Speed Wireless Data Transfer Technologies

As indicated in Chapter 3, high-speed wireless data transfer technologies rely on the 60 GHz unlicensed spectrum band to deliver a data transfer rate between 6 and 28 Gbps over a range between 5 and 30 meters. WirelessHD is primarily used for high definition consumer electronic devices, while WiGig supports smartphones, PCs, tablets and related peripherals.

The economic value of high-speed wireless data transfer devices operating in WirelessHD estimated the revenues (and consequently GDP contribution) derived from unit shipments. An updated version of the global wireless display market completed in 2017[60] estimates the 2016 market at $2.34 billion, growing at 11.1% through 2023. Considering that WirelessHD represents 20% of the total wireless/video display market,[61] this results in a total 2017 market of $2.59 billion, of which WirelessHD represents $519 million. Relying on the same global wireless display market assessment, which projects the 2020 market at $3.56 billion, and assuming a constant share of WirelessHD of 20% results in an economic contribution for this technology of $713 million.

On the other hand, a 2017 assessment of the WiGig market estimates the 2020 size at $2,687 million.[62] Assuming a constant U.S. share of 35% yields a GDP contribution of $940 million.

60 Markets and Markets (2017, Oct.).
61 Silicon Image, Inc. a leader in WirelessHD appears to generate approximately 132 million in manufacturing and licensing revenues of High Definition wireless chipsets.
62 Mordor Intelligence (2017).

4.9. The 2020 Economic Value of Low-Frequency Wi-Fi

The 2017 estimate of economic value of low-frequency Wi-Fi assumed a GDP contribution driven by the number of unserved households times a monthly ARPU. Thus, considering that the digital divide at the individual end translates into 6.2 million households and that each household could generate monthly revenues of $50.00 (as is the experience of the WISP industry), this could translate into a revenue potential of $3.72 billion. The same estimate was included for 2020 since there is no clear indication of adoption trends.

4.10. Smart City Deployments for Managing Public Infrastructure

Based on an estimate of the global wireless sensor network market reaching $2 billion in 2021, of which the United States represents 72%, the forecast estimated a 2017 GDP contribution of approximately $793 million. Given the still embryonic state of development of this space, it is difficult to generate a further refined estimate from the 2017 value.

4.11. Agricultural Automation

The impact of agricultural automation, and therefore the economic value of technologies operating in unlicensed spectrum bands, was estimated in Chapter 3 based on its contribution to the increase in Total Factor Productivity through more efficient use of labor, timeliness of operations (optimization of agronomic windows, reduction of spoilage and harvest losses), and efficient use of inputs (water, seeds, fertilizers). The United States in 2017 had a total of 310 million crop acres, within which the adoption of precision agriculture was likely to reach 40% in 2017. Based on producer benefits of $20 per hectare measured in field research, the total producer surplus of agricultural automation amounts to $1.003 billion. (see Table 4-18).

Table 4-18. U.S. agricultural automation economic value (2017-2020)

Variable	2017	2020
Total harvested crop acres (million)	310	310
Total crop hectares (millions) (acres to hectares conversion rate: 0.4047)	125,457,000.00	125,457,000.00
2017 Adoption of agriculture automation (%)	40 %	N.A.
2020 Adoption of agriculture automation (%)	N.A.	60 %
Hectares adopting agriculture automation by 2017	50,182,800	75,274,200
Producer benefits per hectare	$20	$28
Total economic value of precision agriculture ($ billion)	**$1.003**	**$2.108**

Sources: USDA Census; Robertson et al. (2007); Norton and Swinton (2000); Wang et al. (2009); Schimmelpfennig and Ebel (2011) Telecom Advisory Services analysis

Considering a constant value in harvested acres, but assuming an incremental adoption of 20% (thus reaching a total of 60%), the 2020 economic value of agriculture automation will reach $2.108 billion.

4.12. The 2020 Economic Value of Low-Power WAN

As indicated in Section 3.12, the economic value of IoT technologies operating in unlicensed spectrum was defined based on primary demand, assuming the eco-system of alternative substitutes is still in a state of flux. We believe that by 2020 some of the uncertainty will diminish in terms of the respective niches to be occupied by some of these technologies. This allows quantifying the value to Low-Power Wide-Area Network ("LPWAN") in the United States. The starting point is the value generated by total primary demand for each of the segments we have been focusing on so far (see Table 4-19).

Table 4-19. Economic value of IoT technologies operating in unlicensed spectrum (in $ billion)

Technologies and Applications	2017	2020
Machine-to-machine (advanced metering, security, Demand Side Management, Telehealth)	$2.43	$3.45
Smart City deployments	$15.89	$15.89
Agriculture automation	$1.00	$2.11
TOTAL	**$19.32**	**$21.45**

Source: Telecom Advisory Services analysis

On a global scale, analysts predict that LPWAN by 2021 will reach 700 million connections[63] (another source forecasts that by 2025 LPWAN will amount to 11% of all IoT connections–this percentage is for 2025).[64] On the other hand, Markets and Markets forecasts that by 2021, the global LPWAN market will reach $24.46 billion, from $1 billion in 2016.

In 2017, principal development of non-cellular LPWAN is focused on Europe, primarily France but including Netherlands, Belgium, Italy, and Germany. This would mean that global share numbers are much larger than what one would expect in the U.S. The use cases in this country focus, so far, on utility metering, environmental monitoring, and asset tracking on the part of cable TV operators, and smart metering by electric utilities. Based on an estimated share of 4% of the applications assessed in the IoT market presented in Table 418, we estimate a 2020 LPWAN economic of value of $858 million.

4.13. Total 2020 Economic Value of Unlicensed Spectrum

To sum up, the economic value derived in 2020 from the set of widely adopted technologies operating in the United States in the unlicensed spectrum bands described above is estimated at $693.97 billion. The contribution to the nation's GDP is at least $42.40 billion (see Table 4-20).

63 Business Insider Intelligence (2016, Nov. 4). Ericsson just took a significant step toward delivering cellular-based IoT. *Business Insider*. Retrieved from: http://www.businessinsider.com/ericsson-just-took-a-significant-step-toward-delivering-cellular-based-iot-2016-11.

64 Machina Research (2016, Aug. 3). Press release: Global Internet of Things market to grow to 27 billion devices, generating US$3 trillion in revenue by 2025. Retrieved from: https://machinaresearch.com/news/press-release-global-internet-of-things-market-to-grow-to-27-billion-devices-generating-usd3-trillion-revenue-in-2025/.

Table 4-20. Summary of future economic value of unlicensed spectrum in the U.S. (2020) (in $ billions)

		Economic Value			
Technologies and Applications	Effect	Consumer Surplus	Producer Surplus	Total Surplus	GDP
Wi-Fi cellular off-loading	Value of free Wi-Fi traffic offered in public sites	$5.87	N.A.	$5.87	N.A.
	Benefit of total cost of ownership of Wi-Fi complementing cellular networks	N.A.	$10.7	$10.7	N.A.
	Return to speed of Wi-Fi	N.A.	N.A.	N.A.	$9.76
	Sum of revenues of service providers offering paid Wi-Fi access in public places	N.A.	N.A.	N.A.	$1.11
	SUBTOTAL	**$5.87**	**$10.7 (1)**	**$16.6**	**$10.87**
Residential Wi-Fi	Internet access for devices that lack a wired port	$255.86	N.A.	$255.86	N.A.
	Avoidance of investment in in-house wiring	$76.18	N.A.	$76.18	N.A.
	Economic value of Wi-Fi enabled residential equipment	$53.88	$53.88	$107.77	N.A.
	SUBTOTAL (*)	**$385.92**	**$53.88**	**$439.81**	**N.A.**
Wireless ISPs	Aggregated revenues of 1,800 WISPs	N.A.	N.A.	N.A.	$4.64
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$4.64**
Wi-Fi-only tablets	Difference between retail price and manufacturing costs for a weighted average of tablet suppliers	N.A.	$9.16	$9.16	N.A.
	Difference between willingness to pay for entry level tablet and prices of iPad and Android products	$0.86	N.A.	$0.86	N.A.
	SUBTOTAL	**$0.86**	**$9.16**	**$10.02**	**N.A.**
Wireless personal area networks	Sum of revenues of Bluetooth-enabled products	N.A.	N.A.	N.A.	$9.78
	Sum of revenues of ZigBee-enabled products	N.A.	N.A.	N.A.	$0.50
	Sum of revenues of Wireless HART-enabled products	N.A.	N.A.	N.A.	$0.07
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$10.35**
RFID	RFID value in retailing	$41.95	$110.44	$152.39	N.A.
	RFID value in health care	$6.49	$51.48	$57.97	N.A.
	SUBTOTAL	**$48.44**	**$161.92**	**$210.36**	**N.A.**
High-speed wireless	WirelessHD	N.A.	N.A.	N.A.	$0.71
	WiGig	N.A.	N.A.	N.A.	$0.94
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$1.65**
Low-frequency Wi-Fi		N.A.	N.A.	N.A.	$3.72
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$3.72**
Machine-to-machine	M2M applications relying on unlicensed spectrum (2)	N.A.	N.A.	N.A.	$3.45
	Wearable devices	N.A.	N.A.	N.A.	$6.93
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$10.38**
Smart City deployments (2)	Reduce pollution concentration, optimization of park irrigation or lighting, traffic optimization	$15.1	N.A.	$15.1	$0.79
	SUBTOTAL	**$15.1**	**N.A.**	**$15.1**	**$0.79**
Agriculture automation (2)	Increase in Total Factor Productivity resulting from improved fertilizer management, and a reduction of overlap of spraying	N.A.	$2.11	$2.11	N.A.
	SUBTOTAL	**N.A.**	**$2.11**	**$2.11**	**N.A.**
TOTAL		**$456.19**	**$237.77**	**$693.97**	**$42.40**

1. Already captured in 2017 estimates; therefore, should be the same.
2. Of total economic value of $21.45 billion, LPWAN amounts to $858 million.

Source: Telecom Advisory Services analysis

These estimates should now be compared against other assessments of economic value developed since 2009 (see Table 4-21).

Table 4-21. Prior research on economic value of unlicensed spectrum in the U.S. (2009-2020) (in $ billions)

Technologies and Applications	Effect	Thanki 2008 (2009)	Milgrom et al. 2010 (2011)	Cooper 2011 (2012)	Katz 2013 (2014)	Katz 2017	Katz 2020 Forecast
Wi-Fi cellular off-loading	Consumer surplus	N.A.	$25.0	$20.0	$1.90	$5.82	$5.87
	Producer surplus	N.A.	N.A.	$26.0	$10.70	$10.70	$10.70
	Return to speed	N.A.	$12.0	(*)	$2.83	$7.70	$9.76
	New business revenue	N.A.	N.A.	N.A.	$0.27	$1.01	$1.11
	SUBTOTAL	**N.A.**	**$37.0**	**$46.0**	**$15.70**	**$25.23**	**$27.44**
Residential Wi-Fi		$4.3-$12.6	>$12.6	$38 0	$36.08	$258.69	$439.81
	SUBTOTAL	**$4.3-$12.6**	**>$12.6**	**$38 0**	**$36.08**	**$258.69**	**$439.81**
Wi-Fi-only tablets	Producer surplus	N.A.	$7.5	N.A.	$34.88	$9.48	$9.16
	Consumer surplus	N.A.	$7.5	N.A.	$7.99	$4.08	$0.86
	SUBTOTAL	**N.A.**	**$15.0**	**N.A.**	**42.87**	**$13.56**	**$10.02**
Hospital RFID		$9.6-$16.1	N.A.	(*)	$35.99 (***)	$52.70	$57.97
	SUBTOTAL	**$9.6-$16.1**	**N.A.**	**(*)**	**$35.99 (***)**	**$52.70**	**$57.97**
Clothing RFID		$2.0-$8.1	N.A.	(*)	$94.84 (**)	$138.55	$152.39
	SUBTOTAL	**$2.0-$8.1**	**N.A.**	**(*)**	**$94.84 (**)**	**$138.55**	**$152.39**
Wireless ISPs		N.A.	N.A.	N.A.	$1.44	$2.87	$4.64
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$1.44**	**$2.87**	**$4.64**
Wireless personal area networks	Bluetooth products	N.A.	N.A.	N.A.	$1.74	$5.00	$9.78
	ZigBee Products	N.A.	N.A.	N.A.	$0.27	$0.50	$0.50
	Wireless HART products	N.A.	N.A.	N.A.	$0.16	$0.03	$0.07
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$2.17**	**$5.53**	**$0.07**
Emerging applications and technologies	High-speed wireless	N.A.	N.A.	N.A.	N.A.	$0.63	$1.65
	Machine-to-machine	N.A.	N.A.	N.A.	N.A.	$6.82	$10.38
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	N.A.	$3.72	$3.72
	Smart city deployments	N.A.	N.A.	N.A.	N.A.	$15.89	$15.89
	Agriculture automation	N.A.	N.A.	N.A.	N.A.	$1.00	$2.11
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**$28.06**	**$33.75**
TOTAL		**$16.0-$36.8**	**$64.6**	**$84.0**	**$229.09**	**$525.19**	**$736.37**

(*) Referenced but not quantified

(**) Calculated for total retail sector

(***) Calculated for total health care including pharmaceutical supply chain.

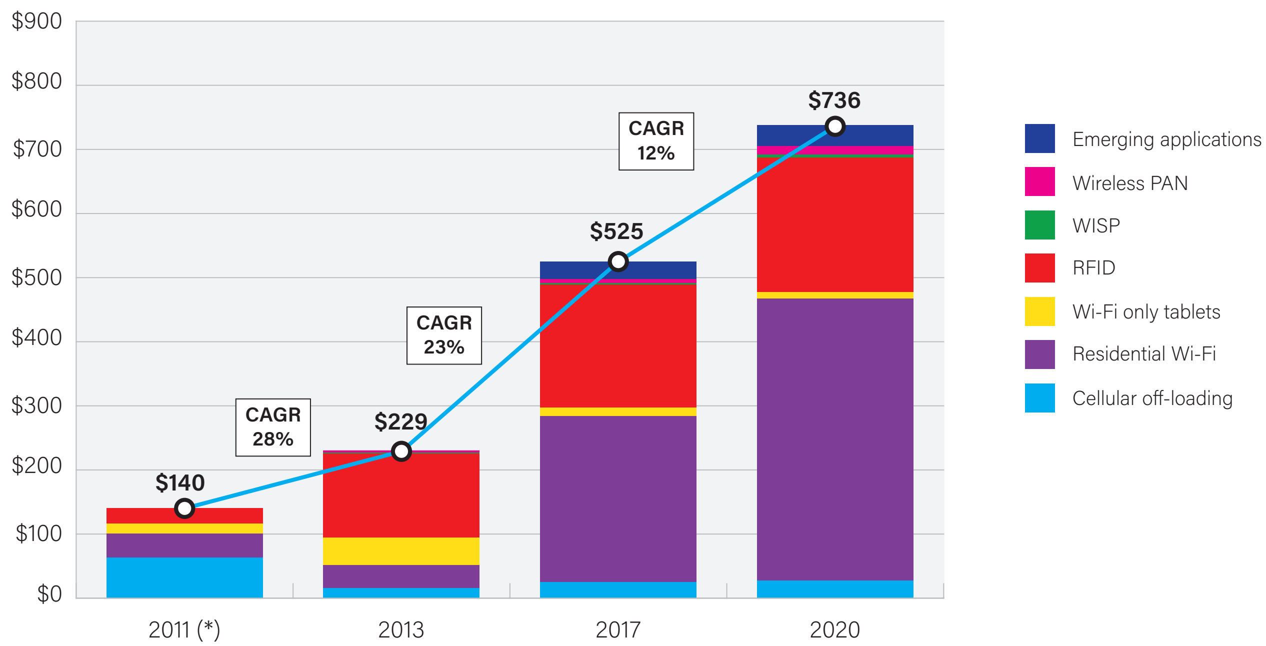
N.A. Not addressed

Source: Telecom Advisory Services analysis

The 2020 forecast based on technologies that are already (or in the course of becoming) widely adopted confirms the trends outlined at the end of Chapter 3:

- The economic value of unlicensed spectrum continues to grow over time driven by increasing complementarity and adoption of innovative technologies: successive estimations conducted since 2011 indicate a continuous growth in the economic surplus associated with the unlicensed spectrum bands (see Graph 4-2).

Graph 4-2. U.S. economic value of unlicensed spectrum (2011-2020)



Source: Telecom Advisory Services analysis

However, as noted above, this growth does not include emerging sources of economic surplus, such as the impact of 5G deployment and wide adoption of IoT. As described below, this should be understood as a portion of the overall value of technologies operating in the unlicensed bands because of the emergence of important technologies that are not represented in the set of technologies considered. The next section will explore the challenge of accounting for emerging innovations.

5. New Sources of Economic Value of Unlicensed Spectrum

The assessment of the economic value of unlicensed spectrum has proceeded so far in refining an estimate based on existing technology trends. Chapter 3 concluded that, as of 2017, the U.S. economic value of a set of technologies that depend on unlicensed bands reached $481.6 billion, derived from multiple sources of complementary and innovation effects. This economic estimate was based on the adoption of technologies as of the end of 2017 and, by definition, encompassed only a limited set of widely adopted technologies and applications (Wi-Fi cellular off-loading, residential Wi-Fi, WISPs, Wi-Fi-only tablets, Bluetooth, ZigBee, Wireless HART, and RFID applications in retailing and health care industries). The study concluded that these technologies currently operating in unlicensed spectrum bands in the United States generated a total economic value of $452.61 billion in 2017 and contributed $28.27 billion to the nation's GDP. Furthermore, a comparison of historical assessments of economic value allowed us to conclude that the sources of economic value might vary over time: current sources leveraging the unlicensed spectrum enabling effects may reduce their importance and new sources could emerge.

The next question focused on how much value we can expect unlicensed technologies to contribute to the economy in the future. As explained before, such quantification is based on two factors: 1) future adoption of technologies already widely diffused (for example, smartphone U.S. installed base, currently at 282 million, is estimated to reach 330 million by 2020), and 2) deployment of emerging platforms, such as 5G, which will begin to deploy after 2020.

Chapter 4 tackled the first factor driving future value. It estimated the value to be derived by currently adopted innovations using the year 2020 as the anchoring point in time in the future. We chose this year as the prediction point because technology predictions that are more than three years out have limited value given the range of uncertainties regarding innovation and adoption pace. It concluded that the economic surplus (consumer and producer) derived in 2020 from technologies widely diffused and operating in unlicensed spectrum bands in the United States is estimated at $585.19 billion. The contribution to the nation's GDP will be at least $43.00 billion, resulting in a total value of $628.19 billion.

This chapter focuses in providing a forward-looking perspective on future sources of economic value of unlicensed spectrum. While the diffusion of these new technologies, applications, and products is still occurring, a consensus exists among industry analysts that they will become a fundamental source of economic surplus in the near future. The economic contribution estimates for 2017 and 2020 described above, however, do not include this value because it remains more difficult to quantify than the value contributed by the limited set of technologies studied. Nonetheless, because these technologies will contribute to economic surplus, we must consider the 2017 and 2020 estimates to represent only part of the larger total contribution of technologies depending on the unlicensed bands.

5.1. Deployment of 5G as a Culmination of Licensed-Unlicensed Convergence

In Section 3.1.2 we assessed the current state of convergence of carrier grade Wi-Fi and cellular networks. Its purpose is to accommodate the continuously growing wireless traffic while allowing carriers to control their CAPEX. Carrier grade hot-spots are considerably less expensive than conventional cellular base stations and facilitate the cell densification required to handle data traffic. However, the process of licensed-unlicensed spectrum convergence is not stopping. In fact, without convergence, IoT, supported by a hyper-dense site network, and, in the long run, 5G will not only be practical or economic.

5G technology is a hybrid licensed-unlicensed deployment that reportedly will provide throughput speeds 10-100 times faster than 4G, which could mean real-world speeds of about 4 Gbps or more. Most of the speed increases are due to how the carriers will be adding more wireless channels, using millimeter wave technology (which means the signal has to travel shorter distances), installing small cells and carrier grade Wi-Fi hot-spots that dramatically increase the coverage map, and increasing capacity in the wired backhaul. The implicit complementarity of licensed and unlicensed spectrum to achieve

5G deployment raises even more the importance of a balanced spectrum policy.

The speed boosts, low latency, and backwards compatibility with existing networks will provide a framework for new network architectures, like Cloud RAN (radio access network) where localized nano-data centers will occur supporting server-based networking functions like Industrial IoT gateways, video caching and transcoding at the edge for Ultra HD video, and newer mesh-like topologies supported with more distributed heterogeneous networks ("HetNets"). In short, 5G will lead to a dramatic increase in cell sites (which due to the higher frequency will result in most of them will have significantly shorter range).

5G wireless technology has been defined according to eight requirements (GSMA, 2014):

1. 1-10 Gbps connections to end points in the field (i.e. not theoretical maximum);[65]
2. 1 millisecond end-to-end round trip delay (latency);
3. 1000x bandwidth per unit area;
4. 10-100x number of connected devices;
5. (Perception of) 99.999% availability;
6. (Perception of) 100% coverage;
7. 90% reduction in network energy usage; and
8. Up to ten-year battery life for low-power, machine-type devices.

Since these requirements are presented from a target perspective as opposed to being formally measured, it is difficult to determine the ultimate network architecture that will emerge in the future. Furthermore, it is conceivable that not all eight requirements would need to be achieved uniformly across a wireless network. However, there is a consensus that requirements 3 (1000x bandwidth per unit area), 4 (10-1000x number of connected devices), 5 (perceived 99.999% availability), and 6 (perceived 100% coverage) will have a significant impact on cell-site and hot-spot density.

5G networks will require frequencies above 6 GHz, potentially reaching as high as 300 GHz. However, as expected, higher frequency bands offer smaller cell radiuses and so achieving widespread coverage will require not only increasing cell sites under current network topology, but also fulfilling the needs of future architectures. For example, the fulfillment of requirement 2 (1 millisecond latency) is estimated to demand an exponential increase in cell sites.[66] The increase in the number of cell sites is dependent on the technology and spectrum bands to be utilized. While all frequencies will trigger a radical increase in sites, some might require a smaller number of outdoor cells due to better signal propagation.

When do we expect 5G deployment to go commercial in the United States? So far, AT&T and Verizon have already launched 5G trials, supported by vendors such as Ericsson, Samsung, and Alcatel Lucent. However, these trials focus only on fixed wireless. Originally, they expected to launch mobile service in 2020 (Follow, 2016; Wheeler, 2016). However, AT&T recently announced plans to launch mobile service in a dozen markets by the end of 2018.[67] This could potentially accelerate a response on the part of competing operators. Yet, so far, Verizon and T-Mobile have indicated they are aiming to begin roll-out by 2019.[68]

65 The maximum theoretical downlink speed for LTE-A is 1 Gbps.

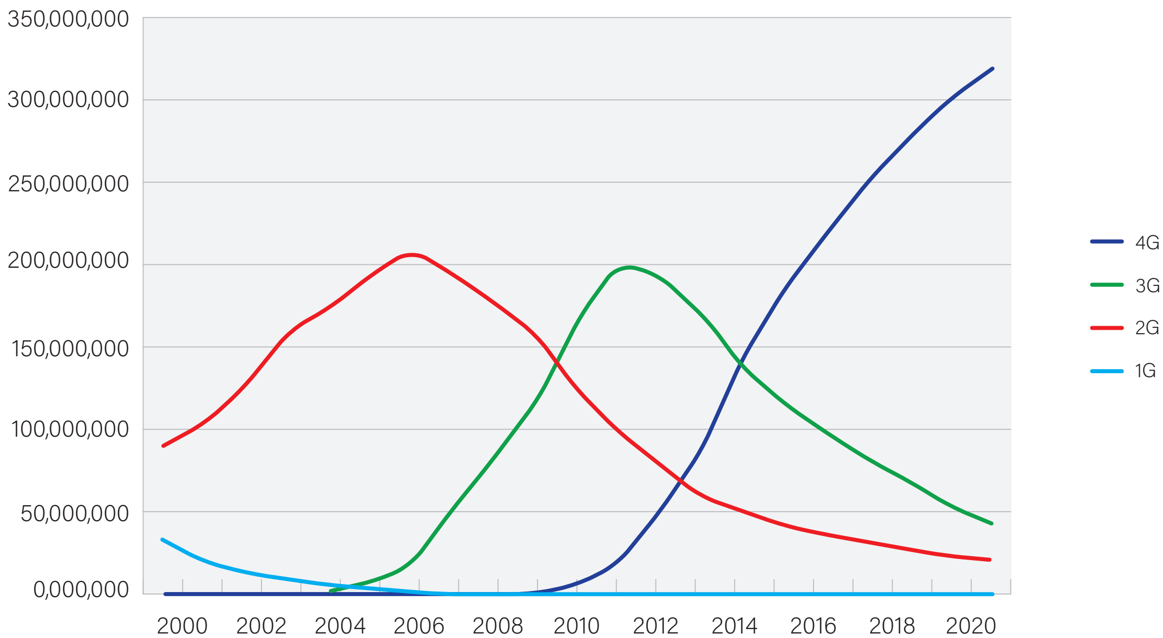
66 While it is difficult at this point to estimate the growth in cell sites, it is relevant to consider that AT&T announced that as part of its new "Project VIP" network upgrade, the carrier is adding 10,000 new large cells and 40,000 small cells in urban areas. Similarly, Verizon has stated that it set aside $500M of capital budget for densification.

67 Majithia, K. (2018, Jan. 4). AT&T trumps rivals with 2018 mobile 5G launch plans. *Mobile World Live.* Retrieved from: https://www.mobileworldlive.com/featured-content/home-banner/att-trumps-rivals-with-2018-mobile-5g-launch-plans/.

68 It is important to mention that 5G is still defined in somewhat imprecise terms. Although there is accelerated progress on the 5G standards front, 5G capable handsets are not expected to be available in the short term. AT&T has defined its initial deployment as based on porTable Wi-Fi hot-spots. On the other hand, Verizon intends to be first with a fixed 5G service providing home broadband service later this year.

A view of the 4G diffusion process provides a benchmark useful for assessing how fast 5G adoption will proceed. The adoption of 4G in the United States has proceeded at a faster rate than the prior generations. By 2020, 84% of U.S. wireless connections will be 4G, which allows us to forecast that, from a generational standpoint, 5G would have already started to deploy (see Graph 5-1).

Graph 5-1. U.S. total cellular connections by technology generation



Sources: GSMA Intelligence; Telecom Advisory Services analysis

Thus, given current announcements and trials, it is conceivable that at least the two ILECs (incumbent local exchange carriers) will launch fixed 5G services to residences in 2019. That said, the migration to 5G has already started from a network topology standpoint. A survey study conducted by Rethink Research among U.S. operators reports that while 8% of service providers are targeting to deploy 5G by 2020, 79% expect to have dense Wi-Fi/cellular HetNets in place in locations of high traffic and 69% will have started to implement virtualization in the access network. As for 5G implementation, 47% of operators would have started between 2020 and 2023 and the remainder in 2024 and later.

In this context, unlicensed spectrum becomes a key enabler of 5G services. The upcoming flexible, radio-neutral 5G environment will be intrinsically supported by the next wave of 802.11 Wi-Fi standards (802.11n/ac, 802.11ax, WiGig), and short range wireless technologies operating in unlicensed bands (Bluetooth, ZigBee, 6LoWPAN, Thread). In fact, the boundary between licensed and unlicensed spectrum will increasingly blur. The traditional dichotomy of licensed-unlicensed will give way to a third category of shared spectrum access, based on centrally coordinated shared access with limited numbers of registered users with "known" technologies sharing with federal and/or other commercial users. While full convergence between spectrum derived from licensing regimes will take time to materialize, carriers are moving beyond the loosely coupled cooperation, exemplified by current off-load techniques (whose economic value was assessed in Chapter 3) and into seamless hand-off. The availability of CBRS (Citizen Broadband Radio Service) in the 3.5 GHz spectrum band will add value to unlicensed spectrum since its use will not be restricted to carriers. Enterprises could use the spectrum to set up their own LTE networks, including to support IoT devices.

From an economic value of unlicensed spectrum standpoint, a potential approach to measure its producer surplus could be calculate the difference between the capital and operating expenses required to roll out a fully cellular-based 5G network (not a feasible option either from a technology[69] or an economic standpoint) and the planned fully convergent licensed-unlicensed architecture. However, in addition to relying on an impractical option, this approach to measuring value is too simplistic.

First, deployment scenarios need to be evaluated within the spatial coverage perspective. As research has indicated for a long time, profiTable deployment of a capital-intensive technology, such as telecommunications, is fundamentally driven by scale and density (Katz and Berry, 2015). Along those lines, as Oughton and Frias (2016) demonstrate in their analysis of 5G cost coverage for the United Kingdom, economic deployment is highly dependent on geospatial considerations: for their baseline case requiring a CAPEX of £42 billion, urban coverage investment amounts only to 700 million, while suburban deployment demands 5.6 billion, and rural coverage 35.6 billion. Along those, lines, the authors conclude that, absent any type of government subsidy, rural deployment is economically impossible. The fact that AT&T has announced 5G roll-out in a dozen U.S. cities by the end of 2018 and that this is being conducted in a context of sTable to declining CAPEX[70] would indicate that deployment is being implemented through the on-going cell-densification and small-cell deployment program. This has already been factored in the 2017 economic value of unlicensed spectrum in Chapter 3. But, considering the cost decomposition of Oughton and Frias (2016), it is reasonable to assume that current CAPEX levels and Wi-Fi utilization will not allow deployment beyond the urban centers. Therefore, one should consider the U.S. 5G suburban deployment as part of the future producer surplus not yet estimated (see Table 5-1).

Table 5-1. Producer surplus of 5G in the United Kingdom v. United States

	United Kingdom			United States	
Geography	Population Breakdown (%)	5G CAPEX (£ billion)	5G CAPEX (%)	Population Breakdown (%)	Producer Surplus ($ million)
Urban (cities>1 million)	29%	£0.7 ($0.948)	1.66%	27%	$10,700
Suburban	54%	£5.6 ($7.592)	13.33%	53%	$85,600
Rural	17%	£35.6 ($48.263)	84.76%	19%	$544,171
TOTAL	**100%**	**£42.0 ($56.939)**	**100%**	**100%**	**$640,471**

Sources: Trading Economics; World Bank; U.S. Census Bureau; Trulia; Telecom Advisory Services analysis

A simple interpolation in Table 5-1 assumes that, if 5G CAPEX in the United Kingdom suburban areas is eight times that of the urban areas, the producer surplus associated with 5G deployment in the United States suburban areas would be eight times that of urban areas: $85.6 billion. We are cognizant that this value is hypothetical because, in the absence of unlicensed spectrum, Wi-Fi hot-spots would not be available and, therefore 5G deployment would be impossible.

The second dimension of 5G economic value is more difficult to estimate. It relates to the consumer surplus derived if 5G were to be deployed in rural areas. Again, recognizing the highly disadvantaged economics of such a roll-out, a number of 5G use cases would be highly beneficial to the population in rural geographies: for example, emergency communication, remote surgery and examination, and tele-protection in Smart Grid networks (Tullberg et al., 2016). This dimension could add to the economic surplus associated to 5G, although given the economic barriers associated with rural deployment, it will not be included in the final estimate.

69 As pointed out in the literature (Ayach et al., 2014; Murdock et al., 2012; Akdeniz et al., 2014), millimeter wave spectrum (28 GHz and 73 GHz), a key component of 5G networks, requires cell-sites with a small radius of 100 to 200 meters, which can only be supported by hot-spots.

70 Celentano, J. (2016, Nov. 16). Trends in U.S. wireless capital expenditures. *AGL Media Group.* Retrieved from: http://www.aglmediagroup.com/u-s-wireless-capital-expenditures-trending/.

5.2. Unlicensed Technologies as an Enabler of IoT

IoT comprises a large number of services ranging from industrial machine connectivity to Smart Cities and consumer wearables. The Federal Trade Commission estimates that there are around 25 billion devices including watches, light switches, speakers, medical devices, and sensors for climate control, which are already connected within the IoT.[71]

Unlicensed spectrum technologies are a key enabler of IoT. As mentioned in Section 3.8, there are a number of specialized technologies supporting low power M2M connectivity (Bluetooth, Zibgee, LPWAN, Thread) to which one could add HaLOW for the wide area. In a study conducted by Rethink Technology Research in 2016, mobile network operators expect by 2020 to deliver IoT services through a mesh of cellular, Low-Power Wideband Personal Area Networks, Wideband Personal Area Networks, and Wi-Fi. IoT pure-play service providers, on the other hand, expect to rely primarily on unlicensed spectrum technologies.

Despite the fact that market potential for some IoT applications still remains uncertain, it is possible to quantify their economic value at the applications level. A more expansive view of enterprise digital transformation enables the identification of industrial applications that could generate additional value for unlicensed spectrum, associated with the producer surplus linked to operational efficiencies.

In an approach similar to the estimation of RFID value in retailing and health care, we estimate the future value of Wi-Fi in streamlining operations in the transportation and logistics industry, looking at examples such as Amazon's facilitation of fulfillment centers, and airlines' coordination of gate operations.

Amazon's fulfillment center robotic technology automates shelf management, stacking, and picking.[72] The robots are controlled by a centralized computer using a secured Wi-Fi network for communications.[73] Adoption of this technology in the warehouse is estimated at 18%, growing at 10% annually.[74] Future diffusion of this technology is predicated upon adoption in warehouses that were not originally designed for its deployment. The operational efficiency of this technology is driven by:

- Productivity increases: reduction of manual effort, including searching for goods in the picking process, which increases overall workforce productivity, and reduction of the training cycle time;
- Faster response times: in high-velocity omni-channel context, warehouse robotics can reduce the pick, pack, and ship times;

71 Federal Trade Commission (2015). *Internet of Things: Privacy and security in a connected world.* Retrieved from: https://www.ftc.gov/system/files/documents/reports/federal-trade-commission-staff-report-november-2013-workshop-entitled-internet-things-privacy/150127iotrpt.pdf.

72 Knight, W. (2015, July 7). Inside Amazon's warehouse, human-robot symbiosis. *MIT Technology Review.* Retrieved from: https://www.technologyreview.com/s/538601/inside-amazons-warehouse-human-robot-symbiosis/.

73 Valerio, P. (2015, Sept. 28). Amazon robotics: IoT in the warehouse. *Information Week.* Retrieved from https://www.informationweek.com/strategic-cio/amazon-robotics-iot-in-the-warehouse/d/d-id/1322366?.

74 Prest, G. & Sopher, S. (2016). *The 2015 MHI annual industry report.* Deloitte. Retrieved from: https://www2.deloitte.com/content/dam/Deloitte/dk/Documents/process-and-operations/2015%20MHI%20Industry%20Report.pdf.

- Improved warehouse efficiency: warehouse robotics helps reduce operating costs, space utilization, and energy efficiency;
- Improved security and inventory accuracy; and
- Improved safety.

Its benefit[75] is estimated at:

- Increase in on-time shipments from 85.6% to 92.10%;
- Increase in order accuracy: 7.50%; and
- Increase in inventory accuracy: 7.50%.

By factoring these three benefits in the case of the retail industry, the producer surplus is estimated at $8.77 billion, where $350 million is associated with the adoption of Low-Power WAN (see Section 4.12).

Table 5-2. Economic value of warehouse automation in U.S. retailing (2020) (in $ billions)

Benefit	Total Losses	Impact rate	Value
Reduction in inventory write-offs	$26.41	7.50 %	$1.98
Reduced stock-outs	$51.00	7.50 %	$3.83
Reduced shipment errors	$5.61	7.50 %	$0.42
Faster time to market	$39.15	6.50 %	$2.54
TOTAL	**$122.17**		**$8.77**

Sources: Barua et al. (2006); Datalogic (2014); Telecom Advisory Services analysis

On the other hand, airlines' coordination of gate operations is based on airline cooperation processes in deployment of common technology. Adoption of platforms underlying Wi-Fi technology helps maximize existing facility utilization, avoid or defer capital costs, maximize facility flexibility, improve quality of service, and decrease the cost of doing business for airports and airlines cost of doing business.[76] Based on 1Q17 data, U.S. airlines register their annual operating expenses estimate at $145.71 billion, of which $70.83 billion is not labor or fuel related.[77] Assuming 5% impact related to the benefits outline above,[78] the producer surplus associated with this initiative could yield a total economic value of $3.74 billion.

We believe the two estimates of producer surplus associated with the use of technologies relying on unlicensed spectrum presented in this section (retail logistics of $8.77 billion and airline gate operations of $3.74 billion) are just the tip of the iceberg. Wi-Fi technology is known to have a much more extended span of applications in manufacturing and service operations.

75 Datalogic (2014). *Benefits from warehouse automation: A comparative report.* Retrieved from: http://www.datalogic.com/upload/marketlit/wp/WP-WAREHOUSEAUTOMATION-ENA4.pdf.

76 Transportation Research Board (2013, Oct.). ACRP impacts on practice—Maximizing airport facility utilization and efficiency with common-use resources. Retrieved from: http://www.trb.org/Publications/Blurbs/169730.aspx.

77 U.S. Bureau of Transportation Statistics (2017, June 19). First quarter 2017 airline financial data. Retrieved from: https://www.bts.gov/newsroom/1st-quarter-2017-airline-financial-data.

78 For reference, airline turnaround time can be improved between 20% and 40%. (See Doig, S. et al. (2003, Nov.). The hidden value in airline operations. *McKinsey Quarterly.* Retrieved from: https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/the-hidden-value-in-airline-operations.)

5.3. Consumer Applications that Will Generate Incremental Value of Unlicensed Spectrum

The products reviewed in the section above do not include a whole new range of uses and applications that leverage any of the unlicensed bands. Specifically, we refer to Smart Home applications aimed at monitoring appliances. The same appliances could be equipped with IoT sensors to send diagnostic data to manufacturers or service providers (e.g. water company or electric utility). These devices could be used to monetize new services such as demand management for electricity. In addition, sensors could be mounted in devices to provide personal consulting services. Beyond widely diffused personal health, they could provide advice regarding sports (e.g. IoT sensors in a golf club providing playing advice).

5.4. Total 2020 Economic Value of Unlicensed Spectrum Derived from New Sources of Value

To sum up, the economic value derived in 2020 from new technologies operating in unlicensed spectrum bands in the United States is estimated at $98.11 billion. The contribution to the nation's GDP is at least $2.69 billion (see Table 5-3).

Table 5-3. Summary of 2020 economic value of unlicensed spectrum in the U.S. derived from new sources (in $ billions)

Technologies and Applications	Effect	Economic Value Consumer Surplus	Economic Value Producer Surplus	Economic Value Total Surplus	GDP
5G Micro-cells	Micro cells in suburban areas	- - -	$85.6	$85.6	N.A.
	SUBTOTAL	**- - -**	**$85.6**	**$85.6**	**N.A.**
IoT	Warehouse automation	N.A.	$8.77	$8.77	N.A.
	Airline gate coordination	N.A.	$3.74	$3.74	N.A.
	SUBTOTAL (*)	**N.A.**	**$12.51**	**$12.51**	**N.A.**
TOTAL		**N.A.**	**$98.11**	**$98.11**	**N.A.**

(*) Referenced but not quantified

Source: Telecom Advisory Services analysis

These estimates should now be added to the values estimated for 2020 for technologies already widely adopted, thus reaching $834.48 billion (see Table 5-4).

Table 5-4. Economic value of unlicensed spectrum in the U.S. (2009-2020) (in $ billions)

Technologies and Applications	Effect	Thanki 2008 (2009)	Milgrom et al. 2010 (2011)	Cooper 2011 (2012)	Katz 2013 (2014)	Katz 2017	Katz 2020 Forecast
Wi-Fi cellular off-loading	Consumer surplus	N.A.	$25.0	$20.0	$1.90	$5.82	$5.87
	Producer surplus	N.A.	N.A.	$26.0	$10.70	$10.70	$10.70
	Return to speed	N.A.	$12.0	(*)	$2.83	$7.70	$9.76
	New business revenue	N.A.	N.A.	N.A.	$0.27	$1.01	$1.11
	SUBTOTAL	**N.A.**	**$37.0**	**$46.0**	**$15.70**	**$25.23**	**$27.44**
Residential Wi-Fi		$4.3-$12.6	>$12.6	$38 0	$36.08	$258.69	$439.81
	SUBTOTAL	**$4.3-$12.6**	**>$12.6**	**$38 0**	**$36.08**	**$258.69**	**$439.81**
Wi-Fi-only tablets	Producer surplus	N.A.	$7.5	N.A.	$34.88	$9.48	$9.16
	Consumer surplus	N.A.	$7.5	N.A.	$7.99	$4.08	$0.86
	SUBTOTAL	**N.A.**	**$15.0**	**N.A.**	**42.87**	**$13.56**	**$10.02**
Hospital RFID		$9-6-$16.1	N.A.	(*)	$35.99 (***)	$52.70	$57.97
	SUBTOTAL	**$9.6-$16.1**	**N.A.**	**(*)**	**$35.99 (***)**	**$52.70**	**$57.97**
Clothing RFID		$2.0-$8.1	N.A.	(*)	$94.84 (**)	$138.55	$152.39
	SUBTOTAL	**$2.0-$8.1**	**N.A.**	**(*)**	**$94.84 (**)**	**$138.55**	**$152.39**
Wireless ISPs		N.A.	N.A.	N.A.	$1.44	$2.87	$4.64
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$1.44**	**$2.87**	**$4.64**
Wireless personal area networks	Bluetooth products	N.A.	N.A.	N.A.	$1.74	$5.00	$9.78
	ZigBee products	N.A.	N.A.	N.A.	$0.27	$0.50	$0.50
	Wireless HART products	N.A.	N.A.	N.A.	$0.16	$0.03	$0.07
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**$2.17**	**$5.53**	**$0.07**
Emerging applications and technologies	High-speed wireless	N.A.	N.A.	N.A.	N.A.	$0.63	$1.65
	Machine-to-machine	N.A.	N.A.	N.A.	N.A.	$6.82	$10.38
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	N.A.	$3.72	$3.72
	Smart City deployments	N.A.	N.A.	N.A.	N.A.	$15.89	$15.89
	Agriculture automation	N.A.	N.A.	N.A.	N.A.	$1.00	$2.11
	SUBTOTAL	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**$28.06**	**$33.75**
5G Micro-cells	Micro cells in suburban areas	N.A.	N.A.	N.A.	N.A.	N.A.	$85.6
	SUBTOTAL (*)	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**$85.6**
IoT	Warehouse automation	N.A.	N.A.	N.A.	N.A.	N.A.	$8.77
	Airline gate coordination	N.A.	N.A.	N.A.	N.A.	N.A.	$3.74
	SUBTOTAL (*)	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**N.A.**	**$12.51**
TOTAL		**$16.0-$36.8**	**$64.6**	**$84.0**	**$229.09**	**$525.19**	**$736.37**

(*) Referenced but not quantified.

(**) Calculated for total retail sector.

(***) Calculated for total health care including pharmaceutical supply chain.

N.A. Not addressed

Source: Telecom Advisory Services analysis

6. New Trends: Still Difficult to Assess Their Economic Impact

Even beyond the widely diffused and emerging sources of economic surplus of unlicensed spectrum, a number of new trends are developing, which could result in a substantially higher value of these bands than the one estimated above. These new trends are very difficult to quantify so far in terms of their economic contribution but they need to be examined nevertheless because they could trigger important value shifts in the future. We consider these to include three trends:

- Explosive growth of video, becoming the primary mode of communication;
- An expansion of the role of the 802.11 standard beyond the home and/or enterprise buildings; and
- Development of new applications in the video arena, such as 8K television, which trigger increasing demand for bandwidth.

This chapter provides a first view of these changes and defines some "trigger points" that need to be monitored in order to ascertain the speed at which they will be developing.

6.1. The Acceleration of Video-Based Content and Communication

Ever since the introduction of the Internet, but more importantly, since the technology platforms became capable of delivering and streaming video content, users have been migrating toward consuming a larger portion of non-written content. This does not mean, however, that consumers are reading less; it refers to the fact that, as a proportion of total content received, the share corresponding to video is increasing inexorably. This trend has already been detected by industry analysts, and even measured by platforms such as the Cisco Visual Networking Index. The point is whether this change in data usage will continue extending in the future, resulting in an environment where sharing video information becomes a primary mode of communication. Let's analyze each component and driver of this trend.

First, as indicated in Chapters 3 and 4, the data traffic generated by wireless devices has been increasing constantly, while forecasts point to continuing growth (see Table 6-1).

Table 6-1. U.S. traffic per device (2014-2020) (GB/month)

Device	2014	2015	2016	2017	2018	2019	2020	CAGR 2014-17	CAGR 2017-20
Smartphone	2.04	8.26	10.96	14.076	17.98	22.83	28.93	90.38%	27.14%
Tablet	6.87	8.46	11.33	14.79	18.78	23.51	29.01	29.13%	25.18%
Laptop (*)	27.00	32.93	39.28	47.52	55.76	64.43	73.26	20.74%	15.52%
PC (**)	27.72	30.47	36.41	44.21	51.80	59.63	67.62	16.83%	15.22%

(*) Fixed and mobile

(**) Including desktops

Source: Cisco Visual Networking Index

As Table 6-1 indicates, while the compound annual growth rate of traffic per device is decreasing, the forecast through 2020 indicates a fairly healthy growth (between 15% and 27%).

Second, the portion of video traffic by device has been constantly increasing, indicating that this type of content is the primary traffic growth driver. According to the Cisco Visual Networking Index, in 2016, consumer Internet video represented 79% of all traffic and it is expected to grow to 81% by 2021.

The proliferation of video content beyond the traditional pay-TV networks is prompting growth across all mobile devices, indicating a fundamental shift in viewing habits. Additionally, mobile devices have become a primary way of video consumption, particularly for younger generations. In addition to conventional movie streaming, short and frequent access of videos combined with sharing through social networks is becoming a more frequent communications mode. A U.S.

mobile consumer spends 847 minutes per month on YouTube, watching 230 videos of an average length of 3.7 minutes.[79]

On the other hand, the portion of the total traffic to be routed through Wi-Fi remains constant. As indicated in Chapter 3, the percent of mobile traffic routed through Wi-Fi is expected to remain on average 66% (62% for smartphones, 72% for tablets and 66% for laptops). As reviewed in Chapters 3 and 4, the consumer surplus associated with Wi-Fi rerouting depends on the price of substitute cellular data plans. Based on the past evolution of the cellular price per GB, we expect pricing evolution to start flattening out over time. Under this scenario, the consumer surplus associated with Wi-Fi usage will start to increase. In other words, price decline of cellular will not be able to keep up with the growth of video traffic. This will trigger a new cycle of growth of Wi-Fi-linked consumer surplus.

6.2. A Fundamental Change in 802.11 Usage

The economic value of unlicensed spectrum might accrue with an expansion of the role of Wi-Fi within the wireless ecosystem. Some of these trends, such as the importance of small cells in the 5G network, have been reviewed in Chapter 5. Similarly, low-frequency Wi-Fi has been discussed in Chapter 4 in terms of moving 802.11 out of the home and the enterprise building.

Other technology changes that are taking place might trigger further changes in Wi-Fi's positioning:

- **IEEE 802.11ax:** To be released in 2019, this standard is designed to improve overall spectral efficiency, especially in dense deployment scenarios. While it is still at a very early stage of development, it is predicted to have a top speed of around 10 Gbps, operating in the already existing 2.4 GHz and 5 GHz spectrum bands, and expected to be specified for 5150-7125 MHz. While the nominal data rate is just 37% higher than 802.11ac, the new amendment is expected to achieve a 4 times increase to user throughput—due to more efficient spectrum utilization.
- **Migration of Wi-Fi to multiple access points:** Having addressed the technology power barriers with meshing, one access point is migrating to multiple accesses.
- **Increase in the number of Wi-Fi antennas:** The increase in the number of spatial streams will allow Wi-Fi traffic to be managed in a more efficient manner.

All these upcoming innovations have the potential for increasing the economic value of Wi-Fi beyond the conventional approaches assessed previously in this study.

6.3. Development of New Applications and Technologies Triggering More Traffic

The development of new applications and technologies will have a renewed impact on the need for additional bandwidth. In this context, the economic value of unlicensed spectrum might accrue if it provides the needed infrastructure to handle the new data traffic.

As an example, the development of augmented reality, defined as the "augmentation" of a live, direct or indirect view of a physical environment by computer-generated input, is already having an impact on certain business and educational applications.[80] In addition to representing a market with high potential,[81] augmented reality will trigger the development of a whole new set of consumer services and apps (especially in marketing), which will, in turn, require a large amount

79 Lella, A. (2017, Feb. 23). Unlocking mobile measurement for YouTube. *ComScore*. Retrieved from: https://www.comscore.com/Insights/Data-Mine/Unlocking-Mobile-Measurement-for-YouTube-in-the-US.

80 A simple use case is one where a user captures the image of a real-world object, and the underlying platform detects a marker, which triggers it to add a virtual object on top of the real-world image displaying it on the camera screen.

81 The economic value of augmented reality is forecast to reach $61.39 billion by 2023 (Markets and Markets). Retrieved from: https://www.marketsandmarkets.com/Market-Reports/augmented-reality-market-82758548.html.

of bandwidth to result in an accepTable user experience. It is estimated that augmented reality applications require at least the 100 Mbps needed by the higher quality 360-degree videos. The 360-degree low-resolution videos on augmented reality applications require approximately 25 Mbps of throughput for streaming.[82]

In another example, Ultra-high definition ("UHD") 8K has twice the horizontal and vertical resolution of 4K UHD with four times as many pixels overall (and sixteen times more than the 1080 HDTV format). While it is difficult to predict overall consumer adoption, given the lack of available content, widespread adoption will create the need for additional bandwidth, if and when it occurs. In this case, however, future bandwidth need will have to be assessed in the context of adoption of enhanced video compression standards. It is estimated that, absent better compression, the 8K bit rate requirement could reach between 80 Mbps and 100 Mbps for each channel stream.[83]

Obviously, it is difficult to predict how fast these trends will materialize. However, in the "tug of war" between behavioral changes, device adoption and bandwidth requirements, one should not underestimate future requirements driving still more the economic value of unlicensed spectrum as a key enabling resource. As an example, the Cisco Visual Networking Index forecasts that by 2021 4K TV sets will account for 77% of all flat panel TVs compared to 17.1% in 2016. A 4K stream requires 25 Kbps bit rate. This will trigger an additional push toward video compression and an incentive for adoption of next generation devices.

82 Westphal, C. (2017). *Challenges in networking to support augmented reality and virtual reality.* Santa Cruz, CA: Huawei Technologies & University of California, Santa Cruz. Retrieved from: https://users.soe.ucsc.edu/~cedric/papers/westphal2017challenges.pdf.

83 Kishore, A. (2017, Oct. 17). Worried about bandwidth for 4K? Here comes 8K! *Light Reading.* Retrieved from: http://www.lightreading.com/video/4k-8k-video/worried-about-bandwidth-for-4k-here-comes-8k!/d/d-id/737330.

7. Conclusion

This study has provided evidence of the exponential growth in unlicensed spectrum use and its implications for creation of economic value. Overall, having been able to refine the assessment of economic value for 2017, we estimated that the combined value of future diffusion of the limited set of unlicensed spectrum-powered technologies in the United States, listed in the following table, amounts to at least $496.13 billion in economic value and $29.06 billion in contribution to the GDP (see Table 7-1). Because this set does not include important new technologies in the unlicensed bands it must be seen as representing only a part of the total economic contribution of unlicensed frequencies.

Table 7-1. Summary of future economic value of applications and technologies relying on unlicensed spectrum in the U.S. (2017) (in $ billions)

		Economic Value			
Drivers	**Technologies and Applications**	**Consumer Surplus**	**Producer Surplus**	**Economic Surplus**	**GDP Contribution**
Future value of currently deployed technologies and applications	Wi-Fi cellular off-loading	$5.82	$10.70	$16.52	$8.70
	Residential Wi-Fi	$236.95	421.75	$258.70	N.A.
	Wireless ISPs	N.A.	N.A.	N.A.	$2.87
	Wi-Fi-only tablets	$4.08	$9.48	$13.56	N.A.
	Wireless personal area networks	N.A.	N.A.	N.A.	$5.53
	RFID	$84.94	$106.31	$191.25	N.A.
	SUBTOTAL	**$331.79**	**$148.24**	**$480.03**	**$17.10**
Value of emerging technologies and applications	High-speed wireless	N.A.	N.A.	N.A.	$0.63
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	$3.72
	Machine-to-machine	N.A.	N.A.	N.A.	$6.82
	Smart City deployments	$15.10	N.A.	$15.10	$0.79
	Agriculture automation	N.A.	$1.10	$1.00	N.A.
	SUBTOTAL	**$15.10**	**$1.10**	**$16.1**	**$11.96**
TOTAL		**$346.89**	**$194.34**	**$496.13**	**$29.06**

Source: Telecom Advisory Services analysis

A key lesson of this analysis is that while the economic contribution of Wi-Fi and other unlicensed technologies continues to grow, the particular technologies that underlay that contribution will change rapidly. This is one of the central reasons unlicensed bands are important to the U.S economy, but that rapid change also makes predictions based on measuring the contribution of a limited set of technologies more difficult.

For example, the 2017 total economic value of $525.19 billion established in this paper is 12% under the forecast developed in 2014 because of a slowdown in smartphone adoption, fewer than expected Wi-Fi-only tablet sales, and changes in cellular data prices, among other developments. But part of the value loss was compensated by an exponential growth in smartphone traffic, driven by video usage, a widening speed gap between Wi-Fi and cellular average download speed, emergence of new business models such as in-flight Wi-Fi, and a substantial increase in Bluetooth chipset applications, especially in the automotive market. More fundamentally, this estimate continues to rely on only a limited set of technologies, and does not capture the emergence of new unlicensed innovations which now make important contributions to the economy, such as Wi-Fi-powered digital home assistants, media players, game consoles, speakers, home automation, and Industrial IOT.

Consequently, despite the slower than forecast growth in the previously defined set of unlicensed technologies, the economic surplus of unlicensed spectrum in 2017 increased a minimum of 129% since 2013, from $229.09 billion to $525.19 billion (see Table 7-2), and, in reality, increased substantially more but did so based on a different set of technologies that are not measured in the 2017 figure.

Table 7-2. Summary of future economic value of applications and technologies relying on unlicensed spectrum in the U.S. (2013-2017) (in $ billions)

Drivers	Technologies and Applications	Economic Value: Consumer Surplus 2013	Consumer Surplus 2017	Producer Surplus 2013	Producer Surplus 2017	Economic Surplus 2013	Economic Surplus 2017	GDP Contribution 2013	GDP Contribution 2017
Future value of currently deployed technologies and applications	Wi-Fi cellular off-loading	$1.90	$5.82	$10.70	$10.70	$12,60	$16.52	$3.10	$8.70
	Residential Wi-Fi	$36.08	$236.95	N.A.	$21.75	$36.08	$258.70	N.A.	N.A.
	Wireless ISPs	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$1.44	$2.87
	Wi-Fi-only tablets	$7.99	$4.08	$34.88	$9.48	$42.87	$13.56	N.A.	N.A.
	Wireless personal area networks	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$2.17	$5.53
	RFID	$30.29	$84.94	$100.54	$106.31	$130.83	$191.25	N.A.	N.A.
	SUBTOTAL	**$76.26**	**$331.79**	**$146.13**	**$148.24**	**$222.38**	**$480.03**	**$6.78**	**$17.10**
Value of emerging applications and technologies	High-speed wireless	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$0.63
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$3.72
	Machine-to-machine	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$6.82
	Smart City deployments	N.A.	$15.10	N.A.	N.A.	N.A.	$15.10	N.A.	$0.79
	Agriculture automation	N.A.	N.A.	N.A.	$1.10	N.A.	$1.00	N.A.	N.A.
	SUBTOTAL	**$0**	**$15.10**	**$0**	**$1.10**	**$0**	**$16.1**	**$0**	**$11.96**
TOTAL		**$76.26**	**$346.89**	**$146.13**	**$149.24**	**$222.38**	**$496.13**	**$6.78**	**$29.06**

Source: Telecom Advisory Services analysis

Looking forward, however, we can begin to measure some of these new innovations. The economic value of unlicensed spectrum will continue growing, driven by the original set of widely adopted technologies, but will be bolstered by new developments such as 5G, IOT, digital home assistants, game centers, and other innovations, reaching at least $834.48 billion (see Table 7-3), just from the readily measurable technologies listed below.

Table 7-3. Summary of future economic value of applications and technologies relying on unlicensed spectrum in the U.S. (2013-2020) (in $ billions)

		Economic Value											
		Consumer Surplus			Producer Surplus			Economic Surplus			GDP Contribution		
		2017	2017	2020	2013	2017	2020	2013	2017	2020	2013	2017	2020
Future value of currently deployed technologies and applications	Wi-Fi cellular off-loading	$1.90	$5.82	$5.87	$10.70	$10.70	$10.70	$12,60	$16.52	$16.57	$3.10	$8.70	$10.87
	Residential Wi-Fi	$36.08	$236.95	$385.92	N.A.	$21.75	$53.88	$36.08	$258.70	$439.81	N.A.	N.A.	N.A.
	Wireless ISPs	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$1.44	$2.87	$4.64
	Wi-Fi-only tablets	$7.99	$4.08	$0.86	$34.88	$9.48	$9.16	$42.87	$13.56	$10.02	N.A.	N.A.	N.A.
	Wireless personal area networks	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$2.17	$5.53	$10.35
	RFID	$30.29	$84.94	$48.44	$100.54	$106.31	$161.92	$130.83	$191.25	$210.36	N.A.	N.A.	N.A.
	SUBTOTAL	**$76.26**	**$331.79**	**$441.09**	**$146.13**	**$148.24**	**$241.56**	**$222.38**	**$480.03**	**$676.76**	**$6.78**	**$17.10**	**$25.86**
Value of developing applications and technologies	High-speed wireless	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$0.63	$1.65
	Low-frequency Wi-Fi	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$3.72	$3.72
	Machine-to-machine	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$6.82	$10.38
	Smart City deployments	N.A.	$15.10	$15.10	N.A.	N.A.	$15.10	N.A.	$15.10	$15.10	N.A.	$0.79	$0.79
	Agriculture automation	N.A.	N.A.	N.A.	N.A.	$1.10	$2.11	N.A.	$1.00	$2.11	N.A.	N.A.	N.A.
	SUBTOTAL	**$0**	**$15.10**	**$15.10**	**$0**	**$1.10**	**$17.21**	**$0**	**$16.10**	**$17.21**	**$0**	**$11.96**	**$11.96**
Value of emerging applications and technologies	Microcells in suburban areas	N.A.	N.A.	N.A.	N.A.	N.A.	$85.60	N.A.	N.A.	$85.60	N.A.	N.A.	N.A.
	Warehouse automation	N.A.	N.A.	N.A.	N.A.	N.A.	$8.77	N.A.	N.A.	$8.77	N.A.	N.A.	N.A.
	Airline gate coordination	N.A.	N.A.	N.A.	N.A.	N.A.	$3.74	N.A.	N.A.	$3.74	N.A.	N.A.	42.69
	SUBTOTAL	**$0**	**$0**	**$0**	**$0**	**$0**	**$98.11**	**$0**	**$0**	**$98.11**	**$0**	**$0**	**$2.69**
TOTAL		**$76.26**	**$346.89**	**$456.19**	**$146.13**	**$149.24**	**$356.88**	**$222.38**	**$496.13**	**$792.08**	**$6.78**	**$29.06**	**$45.09**

Source: Telecom Advisory Services analysis

The increase in economic value for the next three years is driven on one side by the persistent growth in existing applications and technology, but, more importantly, the deployment of 5G networks, which depend on unlicensed spectrum, the efficiency contribution of IoT in vertical markets, and an expansion of the Bluetooth-enabled ecosystem. These three effects will add $110.8 billion in economic value.

A final comment related to these estimates has to do with whether the current assignment of unlicensed spectrum bands risks, in light of the explosive growth in usage, becoming a bottleneck of future value creation. Indeed, our estimate of Internet traffic trends indicates that total Wi-Fi traffic in the United States is currently 3.93 EB per month and will reach 8.30 EB by 2020, reflecting a 8.63% annual growth rate. Wi-Fi households in the U.S., currently at 71%, are forecast to reach 85% by 2020.[84]

In the context of accelerating adoption of applications operating in unlicensed spectrum, it would be relevant to ask the question of whether there are enough unlicensed spectrum resources to accommodate the expected growth. As noted

84 Park Associates (2017, Jan. 10). 71% of U.S. broadband households have Wi-Fi or Apple AirPort access. Retrieved from: http://www.parksassociates.com/blog/article/pr-01102017.

by several analysts, congestion could result either from the density of devices used for a given application or when one set of devices of a given application interferes with a set of devices running another application. When Wi-Fi hot-spot deployment accelerates and transmission bandwidth increases, so does the risk of congestion.

If future assignment of unlicensed spectrum is not fulfilled, it is plausible to consider that economic value creation would be at risk. This case is similar to the transition from 3G to 4G and the allocation of additional licensed spectrum for mobile broadband. Where do we see the effects that would be most at risk? Our quantification of the risk of not assigning additional unlicensed spectrum assumes that, beyond a certain point of network congestion, application or technology demand stops growing.

In the first place, let us address the so-called return to speed. At the current rate of traffic off-loading, the average speed of mobile traffic in the United States in 2017 was 30.20 Mbps.[85] Our analysis showed that if all the off-loaded traffic were to be conveyed through cellular networks, the speed would decline to 13.52 Mbps, with the consequent negative impact of $7.7 billion in GDP (see Section 3.3 for detailed calculations). By 2020, the impact would amount to $9.8 billion. The benefit derived from the additional speed resulting from off-loading is what we call the Wi-Fi return to speed. However, if we assume that, due to congestion, the average Wi-Fi speed does not increase to 56 Mbps, as Cisco projects, but stays at current levels (37.93 Mbps), the average speed of all mobile traffic would not change significantly from today, which means that $3.0 billion of the Wi-Fi speed return in 2020 alone would disappear.

Obviously, average speed could decline even further beyond the current level, with the consequent increase in value erosion. According to a study by Williamson et al. (2013), this scenario is highly likely. Once an 80-100 Mbps fiber link is deployed to a customer premise, the last mile is not the bottleneck any more, and residential Wi-Fi becomes the congestion point. This is because there is a difference between the advertised speed in a typical Wi-Fi router (150 Mbps) and the delivered speed, which is below 70 Mbps.[86] Given that Wi-Fi shares available capacity across devices, if a typical Wi-Fi household is running multiple devices, the service will degrade and be substantially less than what could be handled by a fiber link.

A second area of negative impact under a scenario of limited unlicensed spectrum assignment is service degradation in public places (airports, convention halls, etc.). Research by Wagstaff (2009) and Van Bloem et al. (2011) indicates that in dense device environments, data overheads that are generated to keep the connection running consume between 80% and 90% of capacity. In the context of increasing traffic volumes, Wi-Fi is becoming the contention point in public access networks. Some of this pressure could be alleviated by the current Wi-Fi standard 802.11ac and the next-generation 802.11ax, but without additional unlicensed spectrum designations that accommodate larger 802.11ac/ax channels, we will see far less benefit from this new standard. While it is difficult to quantify the negative impact of this degradation, a large portion has been considered above in the reduction of the so-called Wi-Fi return to speed. In addition, no additional assignment of unlicensed spectrum could result in the disappearance of the Wi-Fi service provider industry since, with lower service quality level, these operators could not compete with cellular service providers.

A third area of negative impact if additional unlicensed spectrum is not assigned could be an erosion of the benefit to carriers generated by cellular traffic off-loading. With high-density device environments being so prone to contention, if Wi-Fi does not benefit from additional spectrum, cellular carriers will experience service degradation when users roam into Wi-Fi. In other words, Wi-Fi's value of complementarity would be greatly diminished, reducing the $10.7 billion estimated producer surplus.

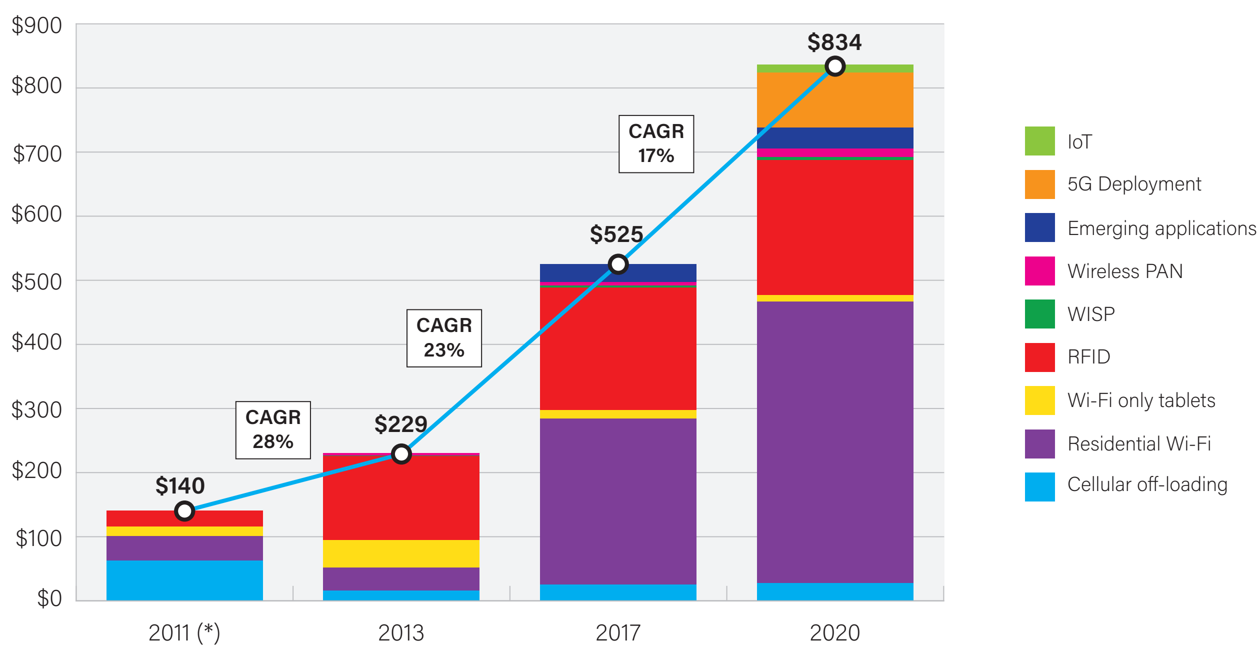
85 This is calculated by prorating total mobile traffic by Wi-Fi and cellular speeds according to off-loading factors (see Appendix C).

86 The difference is due in part to the need to assign part of the capacity to the data overheads. In addition, advertised speeds are based on tests that relying on large packets, while the average packet size is much smaller. Finally, range and attenuation are factors to be considered in the reduction of speed. Williamson et al. (2013) estimate that delivered speed is approximately 50% of the advertised.

In light of this evidence, three key conclusions can be drawn:

- **The economic value of unlicensed spectrum increases over time:** Because of its intrinsic characteristic as an enabling factor of production, unlicensed spectrum is a platform that complements other technologies (such as cellular) and promotes innovation (such as Bluetooth). In 2008, wireless personal area networks and other technologies such as machine-to-machine communications were at an initial diffusion stage and, therefore, did not represent a source of economic surplus. Over time, however, their economic value started to grow. Likewise, in the future, 5G deployment and IoT will become critical growth drivers (see Graph 7-1).

Graph 7-1. Economic value of unlicensed spectrum in the U.S. (2011-2020)



(*) Composite of previous research by Thanki (2009), Milgrom et al. (2011), and Cooper (2012)

Source: Telecom Advisory Services analysis

- **While economic value continues to grow, the sources of economic value of unlicensed spectrum may vary over time:** While the economic value of unlicensed spectrum grows over time, the contribution of some technologies may increase and decrease following their specific product life cycle. That is the case with Wi-Fi tablets, which were a key source of value in the 2013 estimate, but started declining as a result of competitive and product substitution dynamics. At the same, unlicensed spectrum facilitates competition among substitute technologies relying on it. This can result in an increase of economic value of some technologies coupled with a decrease in value of competing technologies. For example, between 2013 and 2017, the value of Bluetooth-enabled products increased 166%, while the value of Wireless Hart-enabled products decreased 81%. Yet, in the aggregate, the economic value of Wireless Personal Area Network-enabled products increased 137%.

- **Without additional unlicensed spectrum resources, the economic value creation of unlicensed technologies is at risk:** As noted by several analysts, congestion could result either from the density of devices used for a given application or when one set of devices of a given application interferes with a set of devices running another application. Moreover, one would expect that, beyond a certain point of network congestion, application or technology demand stops growing. In addition, if we assume that, due to congestion, the average Wi-Fi speed does not increase to 56 Mbps, but stays at current levels (37.93 Mbps), the average speed of all mobile traffic would not change significantly from today, which means that $3.0 billion of the Wi-Fi speed return in 2020 alone would disappear. Obviously, average speed could decline even further beyond the current level, with the consequent increase in value erosion.

A second area of negative impact under a scenario of limited unlicensed spectrum assignment is service degradation in public places (airports, convention halls, etc.). In the context of increasing traffic volumes, Wi-Fi is becoming the contention point in public access networks. Some of this pressure could be alleviated by the Wi-Fi standard 802.11ac, but without additional unlicensed spectrum designations that accommodate larger 802.11ac channels, we will see far less benefit from this new standard.

A third area of negative impact if additional unlicensed spectrum is not assigned could be an erosion of the benefit to carriers generated by cellular traffic off-loading. With high-density device environments being so prone to contention, if Wi-Fi does not benefit from additional spectrum, cellular carriers will experience service degradation when users roam into Wi-Fi. In other words, Wi-Fi's value of complementarity would be greatly diminished, reducing the $10.7 billion estimated producer surplus.

Bibliography

ABI Research (2012). Cellular M2M connectivity services.

Avvott, C. (2016). Corn farmers lead in adoption of precision agriculture.

Akdeniz, M. R., et al. (2014, June). Millimeter wave channel modeling and cellular capacity evaluation. IEEE Journal on *Selected Areas in Communications*, 32(6), pp. 1164–79.

Alston, J.M. & Wohlgenant, M.K. (1990). Measuring research benefits using linear elasticity equilibrium displacement models. In: Alston, J.M. & Mullen, J.D. (eds.), *The Returns to the Australian Wool Industry from Investment in R&D*. Sydney, Australia: New South Wales Department of Agriculture and Fisheries, Division of Rural and Resource Economics.

Ayach, O. E., Rajagopal, S., Abu-Surra, S., Pi, Z., & Heath, R. W. (2014). Spatially sparse precoding in millimeter wave MIMO systems. *IEEE Transactions on Wireless Communications*, 13(3), 1499–1513. Retrieved from: http://dx.doi.org/10.1109/TWC.2014.011714.130846.

Barua, A., Mani, D., & Whinston, A. (2006). *Assessing the financial impacts of RFID technologies on the retail and healthcare sectors*. Austin, TX: The University of Texas at Austin, Center for Research in Electronic Commerce.

Bohlin, E. & Rohman, I. (2012). *Does broadband speed really matter for driving economic growth? Investigating OECD countries?* Available at SSRN: http://ssrn.com/abstract=2034284 or http://dx.doi.org/10.2139/ssrn.2034284.

Business Insider Intelligence (2016, Nov. 4). Ericsson just took a significant step toward delivering cellular-based IoT. *Business Insider*. Retrieved from: http://www.businessinsider.com/ericsson-just-took-a-significant-step-toward-delivering-cellular-based-iot-2016-11.

Celentano, J. (2016, Nov. 16). Trends in U.S. wireless capital expenditures. *AGL Media Group*. Retrieved from: http://digital.aglmediagroup.com/display_article.php?id=2751558&view=396325.

CEPT-ECC (2017). *Studies under WRC-19 Agenda item 1.16 – Compliance with outdoor limit 5 150-5 250 MHz*. Retrieved from: https://cept.org/ecc/groups/ecc/cpg/cpg-pt-d/client/meeting-documents/file-history/?fid=38075.

Cisco (2017). Cisco Visual Networking Index: Global mobile data traffic forecast update, 2016-2021. Retrieved from: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html.

Cisco (2017). *Cisco solution for LoRaWAN*. Retrieved from: https://www.cisco.com/c/dam/en/us/products/collateral/se/internet-of-things/at-a-glance-c45-737308.pdf.

Cisco (2017). United States 2021 forecast highlights. Retrieved from: https://www.cisco.com/c/dam/m/en_us/solutions/service-provider/vni-forecast-highlights/pdf/United_States_2021_Forecast_Highlights.pdf.

Cooper, M. (2011). The consumer benefits of expanding shared used of unlicensed radio spectrum: Liberating long-term spectrum policy from short-term thinking. Washington, D.C.: Consumer Federation of America.

Corasaniti, N. (2017, Mar. 20). In New York, bringing broadband to everyone by 2018. *The New York Times*. Retrieved from: https://www.nytimes.com/2017/03/20/nyregion/new-york-broadband-cuomo-internet.html?_r=0.

Das, R. & Harrop, P. (2011). RFID forecasts, players and opportunities 2011-2021. *IDTechEx*. Retrieved from: http://www.idtechex.com/research/reports/rfid_forecasts_players_and_opportunities_2011_2021_000250.asp

Das, R. (2017). RFID forecasts, players and opportunities 2017-2027. *IDTechEx*. Retrieved from: https://www.idtechex.com/research/reports/rfid-forecasts-players-and-opportunities-2017-2027-000546.asp.

Datalogic (2014). *Benefits from warehouse automation: A comparative report*. Retrieved from: http://www.datalogic.com/upload/marketlit/wp/WP-WAREHOUSEAUTOMATION-ENA4.pdf.

Doig, S., Howard, A., & Ritter, R. (2003, Nov.). The hidden value in airline operations. McKinsey Quarterly. Retrieved from: https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/the-hidden-value-in-airline-operations

Faraci, G. and Lombardo, A. (2017). A simulative model of a 5G Telco Operator Network. *Procedia Computer Science*, 110, pp. 344-51. Retrieved from: https://ac.els-cdn.com/S1877050917312826/1-s2.0-S1877050917312826-main.pdf?_tid=daad0945-82a2-4000-a144-4811803b4603&acdnat=1523380497_738f0cec8049f463e16ff7c79f84d4a9.

Federal Trade Commission (2015). Internet of Things: Privacy and security in a connected world. Retrieved from: https://www.ftc.gov/system/files/documents/reports/federal-trade-commission-staff-report-november-2013-workshop-entitled-internet-things-privacy/150127iotrpt.pdf.

Gabriel, C. (2015). *Towards 2020: Emerging opportunities for Wi-Fi services*. Maravedis-Rethink. Retrieved from: https://cdn.shopify.com/s/files/1/0313/2473/files/wba-interim-report.pdf?12935325085178333557.

Gartner (2016, Apr. 11). Gartner says worldwide PC shipments declined 9.6 percent in first quarter of 2016. Retrieved from: https://www.gartner.com/newsroom/id/3280626.

Gillett, Frank E. et al. (2016, Nov. 2). Predictions 2017: Security and skills will temper growth of IoT. *Forrester*. Retrieved from: https://www.forrester.com/report/Predictions+2017+Security+And+Skills+Will+Temper+Growth+Of+IoT/-/E-RES136255.

Greenstein, S. & McDevitt, R. (2009). *The broadband bonus: Accounting for broadband Internet's impact on U.S. GDP*. Cambridge, M.A.: National Bureau of Economic Research, Working Paper No. 14758.

GSMA Intelligence (2014, December). Understanding 5G: Perspectives on future technological *advancements in mobile*.. Retrieved from: gsmaintelligence.com • info@gsmaintelligence.com • @GSMAi

Heater, B. (2017, Mar. 21). What happened to tablet sales? *TechCrunch*. Retrieved from: https://techcrunch.com/2017/03/21/what-happened-to-tablet-sales/.

Hesseldahl, A. (2014, Oct. 28). Apple's latest iPad costs about the same as the first but with slightly lower profits. *RECODE*. Retrieved from: https://www.recode.net/2014/10/28/11632352/apples-latest-ipad-costs-about-the-same-as-the-first-but-with.

IDC. *Worldwide quarterly tablet tracker*. Retrieved from: https://www.idc.com/getdoc.jsp?containerId=prUS43193717

IDC (2017, Feb. 2). Tablet market woes continue as growth in detachable tablets takes its first vacation during the holiday season, according to IDC. Retrieved from: https://www.idc.com/getdoc.jsp?containerId=prUS42272117.

Indepen Consulting Ltd (2006 Dec.). *The economic value of license exempt spectrum*. A final report to Ofcom from Indepen, Aegis, and Ovum. Retrieved from: http://www.aegis-systems.co.uk/download/1818/value.pdf.

IHS Markit (2011, Mar. 13). iPad 2 carries bill of materials of $326.60, ISH iSuppli teardown analysis shows. Retrieved from: https://technology.ihs.com/388971/ipad-2-carries-bill-of-materials-of-32660-ihs-isuppli-teardown-analysis-shows.

ITU (2017). *Measuring the information society*. Geneva: International Telecommunications Union.

Jones, C. (2013, Dec. 4). IDC predicts that tablet unit sales will slow to single-digits by 2017. Forbes. Retrieved from: https://www.forbes.com/sites/chuckjones/2013/12/04/idc-predicts-that-tablet-unit-sales-will-slow-to-single-digits-by-2017/#674059fc19a5.

Kang, C. (2017, July 11). To close the digital divide, Microsoft to harness unused television channels. *The New York Times*. Retrieved from: https://www.nytimes.com/2017/07/11/technology/to-close-digital-divide-microsoft-to-harness-unused-television-channels.html.

Katz, R. (2014). *Assessment of the economic value of unlicensed spectrum in the United States.* New York: Telecom Advisory Services. Retrieved from: Wi-Fiforward.org/resources. ("Katz (2014a)").

Katz, R. (2014). *Assessment of the future economic value of unlicensed spectrum in the United States.* New York: Telecom Advisory Services. Retrieved from: Wi-Fiforward.org/resources. ("Katz (2014b)").

Katz, R. and Berry, T. (2015). *Driving demand for broadband networks and services*. London: Springer.

Kishore, A. (2017, Oct. 17). Worried about bandwidth for 4K? Here comes 8K! *Light Reading*. Retrieved from: http://www.lightreading.com/video/4k-8k-video/worried-about-bandwidth-for-4k-here-comes-8k!/d/d-id/737330.

Knight, W. (2015, July 7). Inside Amazon's warehouse, human-robot symbiosis. *MIT Technology Review*. Retrieved from: https://www.technologyreview.com/s/538601/inside-amazons-warehouse-human-robot-symbiosis/.

Lella, A. (2017, Feb. 23). Unlocking mobile measurement for YouTube. *ComScore*. Retrieved from: https://www.comscore.com/Insights/Data-Mine/Unlocking-Mobile-Measurement-for-YouTube-in-the-US.

Lore M. (2017, June 15). How much will 5G cost? No one has a clue. *Light Reading*. Retrieved from: http://www.lightreading.com/mobile/5g/how-much-will-5g-cost-no-one-has-a-clue/a/d-id/733753.

Lowenberg-DeBoer, J. (2000). Economic analysis of precision farming. In: Borem, A. et al. (eds.), *Agricultura de Precisao*. Vicosa, Brazil: Federal University of Vicosa, pp. 147-80. Retrieved from: http://www.ufrrj.br/institutos/it/deng/varella/Downloads/IT190_principios_em_agricultura_de_precisao/livros/Capitulo_7.pdf.

Majithia, K. (2018, Jan. 4). AT&T trumps rivals with 2018 mobile 5G launch plans. Mobile World Live. Retrieved from: https://www.mobileworldlive.com/featured-content/home-banner/att-trumps-rivals-with-2018-mobile-5g-launch-plans/.

Markets and Markets (2017, Oct. 30). Wireless display market by offering (hardware, software & services), application (consumer, commercial - corporate, education, healthcare, signage, government), technology protocols (Miracast, WiDi), and geography - global forecast to 2023. Retrieved from: https://www.marketsandmarkets.com/Market-Reports/wireless-display-market-41146860.html.

Markets and Markets (2016). U.S. machine-to-machine connections market worth $7,262.76 million by 2020. Retrieved from: https://www.marketsandmarkets.com/PressReleases/united-states-m2m-communications.asp.

Markets and Markets (2017, June). Wireless sensor network market by offering (hardware, software, services), sensor type, connectivity type, end-user industry (building automation, wearable devices, healthcare, automotive & transportation, industrial), and region - global forecast to 2023. Retrieved from: https://www.marketsandmarkets.com/Market-Reports/wireless-sensor-networks-market-445.html.

McCue, D. and Herbert, S. (2016, Dec. 12). Updated household projections 2015-2035. *Joint Center for Housing Studies of Harvard University*. Retrieved from: http://www.jchs.harvard.edu/research/publications/updated-household-projections-2015-2035-methodology-and-results.

Mensah, E. & Wohlgenant, M. (2014). A market impact analysis of soybean technology adoption. *Research in Business and Economics Journal*. Retrieved from: https://s3.amazonaws.com/academia.edu.documents/44442541/09228.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1516294366&Signature=bWnFRJlBrCMK3IF94edj4IFjixY%3D&response-content-disposition=inline%3B%20filename%3DA_Market_Impact_Analysis_of_Soybean_Tech.pdf.

Meola, A. (2016, June 3). Smartphone growth is slowing to a possible tipping point. *Business Insider*. Retrieved from: http://www.businessinsider.com/smartphone-growth-is-slowing-to-tipping-point-2016-6.

Methley, S. & Webb, W. (2017). *Wi-Fi spectrum needs study*. Wi-Fi Alliance. Retrieved from: https://www.Wi-Fi.org/downloads-registered-guest/Wi-Fi%2BSpectrum%2BNeeds%2BStudy_0.pdf/33364.

MicroMarketMonitor. *Global Wireless HART market research report.* Advance online publication. Retrieved from: http://www.micromarketmonitor.com/market-report/wireless-hart-reports-4636290505.html.

Milgrom, P., Levin, J., & Eilat, A. (2011). *The case for unlicensed spectrum*. Stanford Institute for Economic Policy Research Discussion, Paper No. 10-036. Retrieved from: https://web.stanford.edu/~jdlevin/Papers/UnlicensedSpectrum.pdf.

Mordor Intelligence (2017, Oct.). WiGig market - by devices (network infrastructure devices, communication or display devices), applications (point to point IP applications, HDMI data streaming, cordless computing, Internet support), usage models (instant wireless sync, wire). Retrieved from: https://www.mordorintelligence.com/industry-reports/global-wigig-market-industry.

Murdock, J. N., Ben-Dor, E., Qiao, Y., Tamir, J. I., & Rappaport, T. S. (2012). A 38 GHz cellular outage study for an urban outdoor campus environment. *2012 IEEE Wireless Communications and Networking Conference: Mobile and Wireless Networks*, pp. 3085–90. Retrieved from: http://ieeexplore.ieee.org/xpls/abs_all.jsp? arnumber1/46214335.

Norton, G. and Swinton, S. (2000). *Precision* agriculture: Global prospects and environmental i*mplications*. International Association of Agricultural Economists. Retrieved from: http://ageconsearch.umn.edu/record/197207/files/agecon-024conf-1997-016.pdf.

NPD (2016, July 28). Bluetooth capable headphone sales surpass non-Bluetooth sales. Retrieved from: https://www.npd.com/wps/portal/npd/us/news/press-releases/2016/bluetooth-capable-headphone-sales-surpass-non-bluetooth-sales/.

Oughton, E. & Frias, Z. (2016). Exploring the cost, coverage and rollout implications of 5G in Britain. Engineering and Physical Sciences Research Council. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/577965/Exploring_the_Cost_Coverage_and_Rollout_Implications_of_5G_in_Britain_-_Oughton_and_Frias_report_for_the_NIC.pdf.

Oughton, E.J. and Frias, Z. (2017). The cost, coverage and rollout implications of 5G in Britain. *Telecommunications Policy*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0308596117302781.

Park Associates (2017, Jan. 10). 71% of U.S. broadband households have Wi-Fi or Apple AirPort access. Retrieved from: http://www.parksassociates.com/blog/article/pr-01102017.

Paaske, S., Bauer, A., Moser, T., & Seckman, C. (2017). The benefits and barriers to RFID technology in healthcare. *Online Journal of Nursing Informatics*, 21(2). Retrieved from http://www.himss.org/library/benefits-and-barriers-rfid-technology-healthcare.

Machina Research (2016, Aug. 3). Press release: global Internet of Things market to grow to 27 billion devices, generating US$3 trillion in revenue by 2025. Retrieved from: https://machinaresearch.com/news/press-release-global-internet-of-things-market-to-grow-to-27-billion-devices-generating-usd3-trillion-revenue-in-2025/.

Markets and Markets (2017) Augmented Reality Market by Offering (Hardware (Sensor, Displays & Projectors, Cameras), and Software), Device Type (Head-Mounted, Head-Up, Handheld), Application (Enterprise, Consumer, Commercial, Automotive) and Geography - Global forecast to 2023. Retrieved from: https://www.marketsandmarkets.com/Market-Reports/augmented-reality-market-82758548.html.

Prest, G. & Sopher, S. (2016). The 2015 MHI annual industry report. Deloitte. Retrieved from: https://www2.deloitte.com/content/dam/Deloitte/dk/Documents/process-and-operations/2015%20MHI%20Industry%20Report.pdf.

Richter, F. (2017, Feb. 14). The U.S. wireless headphone market. *Manufacturing.net*. Retrieved from: https://www.manufacturing.net/data-focus/2017/02/us-wireless-headphone-market.

Rivera, J. & Van der Muelen, R. (2015, Aug. 20). Gartner says worldwide smartphone sales recorded slowest growth rate since 2013. *Gartner*. Retrieved from: https://www.gartner.com/newsroom/id/3115517.

Roberti, M. (2017, Oct. 2). Is retail approaching the tipping point for RFID? *RFID Journal*. Retrieved from: http://www.rfidjournal.com/articles/view?16668.

Robertson, M, Carberry, P. & Brennan, L. (2008). *Economic benefits of precision agriculture: case studies from Australian grain farms*. Grains Research and Development Corporation. Retrieved from: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2008/02/economic-benefits-of-precision-agriculture-case-studies-from-australian-grain-farms.

Schimmelpfennig, D. (2016). *Farm profits and adoption of precision agriculture.* USDA Economic Research Report No. 217. Retrieved from: https://www.ers.usda.gov/publications/pub-details/?pubid=80325.

Schimmelpfennig, D. & Ebel, R. (2011). *On the doorstep of the information age: Recent adoption of precision agriculture*. USDA Economic Information Bulletin No. (EIB-80). Retrieved from: https://www.ers.usda.gov/publications/pub-details/?pubid=44576.

Statista (2017, Nov.). Worldwide tablet shipments from 2nd quarter 2010 to 3rd quarter 2017. Retrieved from: https://www.statista.com/statistics/272070/global-tablet-shipments-by-quarter/.

Statista (2018). Forecast unit shipments of tablets worldwide from 2010 to 2022. Retrieved from: https://www.statista.com/statistics/269912/worldwide-tablet-shipments-forecast/.

Statista (2018). Global tablet operating systems' market share from 2013 to 2020. Retrieved from: https://www.statista.com/statistics/272446/global-market-share-held-by-tablet-operating-systems/.

Statista (2018). Global smartphone shipments forecast from 2010 to 2021. Retrieved from: https://www.statista.com/statistics/263441/global-smartphone-shipments-forecast/.

Szymanski, C. (2014, July 14). Why unlicensed spectrum allocation is critical to the next wave of innovation. *Broadcom*. Retrieved from: https://www.broadcom.com/blog/why-unlicensed-spectrum-allocation-is-critical-to-the-next-wave.

Taylor, D. (2014). RFID in the pharmaceutical industry: Addressing counterfeits with technology. *Journal of Medical Systems*, 38(141). Retrieved from: https://doi.org/10.1007/s10916-014-0141-y.

Technavio (2016, Jan.). Global ZigBee enabled devices market 2016-2020. Retrieved from: https://www.technavio.com/report/global-computing-devices-zigbee-enabled-devices-market.

Thanki, R. (2009). *The economic value generated by current and future allocations of unlicensed spectrum*. Perspective Associates. Retrieved from: https://ecfsapi.fcc.gov/file/7020039036.pdf.

Transportation Research Board (2013, Oct.). *ACRP impacts on practice—Maximizing airport facility utilization and efficiency with common-use resources*. Retrieved from: http://www.trb.org/Publications/Blurbs/169730.aspx.

Tullberg, H., Fallgren, M., Kusume, K., & Hoglund, A. (2016). 5G use cases and system concept. In: A. Osseiran, J. Monserrat, & P. Marsch, (eds.), *5G Mobile and Wireless Communications Technology*. Cambridge: Cambridge University Press, pp. 21-49. Retrieved from: http://ebooks.cambridge.org/ref/id/CBO9781316417744A014.

Van Bloem, J.W.H. & Schiphorst, R. (2011). *Measuring the service level in the 2.4 GHz ISM band.* Enschede: University of Twente, Centre for Telematics and Information Technology, Report No. SAS2011. Retrieved from: https://research.utwente.nl/en/publications/measuring-the-service-level-in-the-24-ghz-ism-band.

U.S. Bureau of Transportation Statistics (2017, June 19). First quarter 2017 airline financial data. Retrieved from: https://www.bts.gov/newsroom/1st-quarter-2017-airline-financial-data.

USDA Census (2017, June 30). Acreage. Retrieved from: https://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2017.pdf.

Vaughan-Nichols, S. (2013, Feb. 5). What is "Super-Wi-Fi"?. *ZDNet*. Retrieved from http://www.zdnet.com/article/what-is-super-wi-fi/.

Valerio, P. (2015, Sept. 28). Amazon robotics: IoT in the warehouse. *Information Week*. Retrieved from: https://www.informationweek.com/strategic-cio/amazon-robotics-iot-in-the-warehouse/d/d-id/1322366?.

Wagstaff, A. (2009, Apr.). *Estimating the utilization of key license-exempt spectrum bands*. Mass Consultants Limited. Retrieved from: https://www.ofcom.org.uk/__data/assets/pdf_file/0013/40333/wfiutilisation.pdf.

Wang, N; Li, Z; Franzen, A & Taher, P. (2009). Development of wireless sensor network for precision agriculture applications. Agricultural Technologies in a Changing Climate: The 2009 CIGR International Symposium of the Australian Society for Engineering in Agriculture. Brisbane, Queensland: Engineers Australia, pp. 414-21. Retrieved from: https://search.informit.com.au/documentSummary;dn=643024819734502;res=IELENG.

Weissberger, A. (2017, June 2). Parks Associates: >75% of U.S. households use Wi-Fi for in home connectivity. *IEEE Communications Society Technology Blog*. Retrieved from: http://techblog.comsoc.org/2017/06/02/parks-associates-75-of-u-s-households-use-Wi-Fi-for-in-home-connectivity/.

Westphal, C. (2017). *Challenges in networking to support augmented reality and virtual reality*. Santa Cruz, CA: Huawei Technologies & University of California, Santa Cruz. Retrieved from: https://users.soe.ucsc.edu/~cedric/papers/westphal2017challenges.pdf.

Williamson, B., Punton, T. & Hansell, P. (2013, Jan.). *Future proofing Wi-Fi – The case for more spectrum*. Plum Consulting. Retrieved from: http://www.plumconsulting.co.uk/pdfs/Plum_Jan2013_Future_proofing_Wi-Fi.pdf.

Wireless Broadband Alliance (2016, Nov.). *The unlicensed road to 5G: WBA industry report 2016*. Retrieved from: https://www.wballiance.com/resource/the-unlicensed-road-to-5g-wba-industry-report-2016/.

Wireless 20|20, LLC (2015). *ROI analysis of Wi-Fi off-loading*. [PowerPoint presentation]. Retrieved from: www.wireless2020.com/Wi-Fioffloading/ROIAnalysisofWi-FiOffloading.ppsx.

WISPA (2017). Ready for take-off: Broadband Wireless Access providers prepare to soar with fixed wireless. Retrieved from: http://www.wispa.org/News/wispa_news_09-25-17_Fixed_Wireless_Broadband_Industry_Projected_to_Nearly_Double_in_Five_Years.

WiseGuyReports (2017, Nov. 29). Bluetooth in automotive 2017 global market to reach USD 1,09,979.0 million and growing at CAGR of 34.65% by 2023. *ABNewswire*. Retrieved from: http://www.abnewswire.com/pressreleases/bluetooth-in-automotive-2017-global-market-to-reach-usd-1-099790-million-and-growing-at-cagr-of-3465-by-2023_165039.html.

Wolverton, T. (2017, Mar. 30). Super Wi-Fi may finally be coming your way. *The Mercury News*. Retrieved from: https://www.mercurynews.com/2017/03/30/super-Wi-Fi-may-finally-be-coming-your-way/.

WirelessHD (2018). Specification Summary. Retrieved from: www.wirelesshd.org/about/specification-summary/.

Appendices

A. United States: Free WiFi Traffic (2010-2020)

1.#Devices	2010	2011	2012
Smartphones	112,888,596	139,344,317	172,000,000
Smartphone (Penetration)	36.00%	44.07%	53.96%
Tablets	26,407,591	35,008,499	46,410,709
Tablets (Penetration)	8.42%	11.07%	14.56%
Laptops	235,184,576	237,156,382	239,083,493
Laptops (Penetration)	75.00%	75.00%	75.00%
Total Devices (Smartphones+Tablets+Laptops)	**374,480,763**	**411,509,198**	**457,494,202**
Total Devices Per Capita	**1.19**	**1.30**	**1.44**
Portable Gaming Console	42,615,887	46,954,004	51,733,724
Portable Gaming Console (Penetration)	13.59%	14.85%	16.23%
PC	329,082,731	329,082,731	329,082,731
PC (Penetration)	105%	104%	103%
Phone	289,085,114	292,640,736	296,240,090
Phone (Penetration)	92.19%	92.55%	92.93%
M2M Connections	31,,	46,666,667	70,000,000
M2M Connections (Penetration)	9.92%	14.76%	21.96%
2. Average Traffic per Device (Gb per month)	**2010**	**2011**	**2012**
Smartphones	0.28	0.40	0.56
Tablets	1.74	2.68	4.12
Laptops	1.43	2.08	2.44
Portable Gaming Console	0.24	0.31	0.39
PC	15.40	17.68	20.31
Phone	0.31	0.49	0.79
M2M	0.04	0.05	0.07
3. Total Traffic per device (Gb per month)	**2010**	**2011**	**2012**
Smartphones	31,723,574	55,448,934	96,917,969
Tablets	45,985,183	93,735,136	91,067,541
Laptops	335,321,758	493,535,400	584,400,375
Portable Gaming Console	10,154,567	4,535,566	20,372,953
PC	5,066,567,473	5,819,415,328	6,684,129,826
Phone	88,706,552	44,528,663	235,479,049
M2M	1,194,306	2,490,943	5,195,313
Total Traffic (Gb per Month)	**413,030,514**	**642,719,470**	**872,385,884**
(Smartphones+Tablets+Laptops)	**5,579,653,413**	**6,623,689,970**	**7,817,563,024**
3.1. Total Traffic per device (Exabytes per month)	**2010**	**2011**	**2012**
Smartphones	0.03	0.05	0.09
Tablets (Model) Laptop (Model)	0.04	0.09	0.18
Portable Gaming Console (Model)	0.31	0.46	0.54
PC	0.01	0.01	0.02
Phone M2M (Model)	4.72	5.42	6.23
Total Traffic (Exabytes per Month)	**0.08**	**0.13**	**0.22**
(Smartphones+Tablets)	**0.00**	**0.00**	**0.00**
Total Traffic (Exabytes per Month)	**0.07**	**0.14**	**0.27**
(Smartphones+Tablets+Laptops)	**0.38**	**0.60**	**0.81**
Total Traffic (Exabytes per Month)	**5.20**	**6.17**	**7.28**
Total Trafifc (CISCO)	**4.84**	**5.64**	**6.62**
Mobile devices like smartphones or tablets (CISCO)	**0.11**	**0.21**	**0.39**

2013	2014	2015	2016	2017	Source	CAGR 2010-2013
192,751,370	216,006,342	242,066,967	271,271,742	304,000,000	Cisco	19.52%
59.99%	66.70%	74.16%	82.46%	91.69%	Cisco	18.56%
61,526,599	81,565,710	108,131,526	143,349,784	190,038,569	Cisco (Mail)	32.57%
19.15%	25.19%	33.13%	43.57%	57.32%	TAS	31.50%
240,987,646	242,891,490	244,806,660	246,732,252	248,663,732	Deloitte	0.82%
75.00%	75.00%	75.00%	75.00%	75.00%	Deloitte	0.00%
495,265,616	**540,463,542**	**595,005,153**	**661,353,778**	**742,702,301**	**TAS**	**9.77%**
1.54	**1.67**	**1.82**	**2.01**	**2.24**	**TAS**	**8.88%**
57,000,000	62,802,360	69,195,376	76,239,173	84,000,000	Park Associates	10.18%
17.74%	19.39%	21.20%	23.17%	25.34%	Park Associates	9.29%
316,501,079	304,400,454	292,762,467	281,569,428	270,804,328	Cisco (Mail)	N/A
99%	94%	90%	86%	82%	TAS	N/A
299,883,715	303,572,155	307,305,961	311,085,691	314,911,910	Cisco (Mail)	1.23%
93.33%	93.74%	94.15%	94.56%	94.98%	TAS	0.41%
95,042,737	129,044,599	175,210,742	237,892,980	323,000,000	Cisco	45.10%
29.58%	39.85%	53.68%	72.31%	97.42%	TAS	43.93%

2013	2014	2015	2016	2017	Source	CAGR 2010-2013
0.80	1.13	1.60	2.27	3.21	Cisco	41.60%
6.33	9.73	14.97	23.01	35.38	Cisco (Mail)	53.76%
2.88	3.40	4.02	4.74	5.60	Cisco	26.48%
0.50	0.64	0.81	1.03	1.31	Cisco	28.11%
23.33	26.80	30.78	35.35	40.60	Cisco (Mail)	14.86%
1.28	2.06	3.31	5.33	8.59	Cisco (Mail)	60.95%
0.10	0.14	0.20	0.28	0.39	Cisco	39.05%

2013	2014	2015	2016	2017	Source	CAGR 2010-2013
53,796,072	244,054,142	387,281,830	614,565,337	975,234,375		69.25%
389,467,671	793,881,922	1,618,230,608	1,298,563,967	1,723,716,751		103.84%
695,199,712	826,953,359	983,661,915	1,170,044,724	1,391,691,259		27.51%
28,554,596	40,021,933	56,094,477	78,621,647	110,195,581		41.15%
7,383,809,800	8,156,730,733	19,010,559,324	19,953,764,811	10,995,702,968		13.38%
383,663,567	625,099,064	1,018,467,409	1,659,378,367	2,703,607,931		62.93%
9,808,199	8,516,840	34,957,830	65,996,676	24,594,727		101.76%
1,238,463,455	**1,864,889,422**	**2,989,174,353**	**5,083,174,029**	**9,090,642,385**		
9,044,299,618	**10,705,257,992**	**13,109,253,394**	**16,840,935,530**	**23,024,743,592**		

2013	2014	2015	2016	2017	Source	CAGR 2010-2013
0.14	0.23	0.36	0.57	0.91		69.25%
0.36	0.74	1.51	3.07	6.26		103.84%
0.65	0.77	0.92	1.09	1.30		27.51%
0.03	0.04	0.05	0.07	0.10		41.15%
6.88	7.60	8.39	9.27	10.24		13.38%
0.36	**0.58**	**0.95**	**1.55**	**2.52**		**62.93%**
0.01	**0.02**	**0.03**	**0.06**	**0.12**		**101.76%**
0.51	**0.97**	**1.87**	**3.64**	**7.17**		**91.21%**
1.15	**1.74**	**2.78**	**4.73**	**8.47**		**44.20%**
8.42	**9.97**	**12.21**	**15.68**	**21.44**		**17.47%**
7.60	**8.92**	**10.85**	**13.89**	**19.02**		**16.18%**
0.75	**1.41**	**2.68**	**5.09**	**9.65**	**Cisco**	**89.67%**

A. United States: Free WiFi Traffic (2010-2020)

4. Percent Wi-Fi Offloading	2010	2011	2012
Smartphones	57.11%	58.05%	59.00%
Tablets	76.60%	76.80%	77%
Laptop	41.03%	43.91%	47.00%
Average	41.03%	43.91%	47%
5. Total Wi-Fi Traffic per device (Exabytes per month)	**2010**	**2011**	**2012**
Smartphones	0.02	0.03	0.05
Tablets	0.03	0.07	0.14
Laptop	0.15	0.22	0.26
Total Wi-Fi (Exabytes per month)	**0.20**	**0.31**	**0.45**
No cost Wi-Fi (%)	**4.32%**	**4.32%**	**4.32%**
No cost Wi-Fi (Exabytes per month)	**0.01**	**0.01**	**0.02**
No cost Wi-Fi (Exabytes per Year)	**0.10**	**0.16**	**0.23**
No cost Wi-Fi (Million Gb Per year)	**109.83**	**174.74**	**248.46**
6. Pricing per Gb	**2010**	**2011**	**2012**
ATT	$10.00	$10.00	$10.00
Verizon	$10.81	$9.62	$8.37
Sprint	$10.15	$9.03	$7.86
t-Mobile	$10.15	$9.03	$7.86
Verizon (Price Evolution)	12.36%	14.89%	17.95%
Average price per Gb	$10.28	$9.42	$8.52
Average cost of Wi-Fi provision	$2.50	$2.50	$2.50
7. Economic Impact of Free Wi-Fi	**2010**	**2011**	**2012**
Economic1impact1(Million1USD1per1year)	854.19	1,209.51	1,496.87

2013	2014	2015	2016	2017	Source	CAGR 2010-2013
59.97%	60.95%	61.95%	62.97%	64.00%	Cisco	1.64%
77%	77%	78%	78%	78%	Cisco	0.26%
50.30%	53.84%	57.62%	61.67%	66.00%	TAS	7.03%
50%	54%	58%	62%	66%	Cisco	7.03%
2013	**2014**	**2015**	**2016**	**2017**	**Source**	**CAGR 2010-2013**
0.08	0.13	0.21	0.34	0.54	69.25%	
0.28	0.57	1.16	2.37	4.82	103.84%	
0.30	0.36	0.43	0.51	0.61	27.51%	
0.67	**1.07**	**1.80**	**3.22**	**5.97**	**50.20%**	
4.32%	**4.32%**	**4.32%**	**4.32%**	**4.32%**		
0.03	**0.05**	**0.08**	**0.14**	**0.26**	**50.20%**	
0.35	**0.55**	**0.94**	**1.67**	**3.10**	**50.20%**	
372.12	**593.40**	**1004.71**	**1790.87**	**3323.38**	**50.20%**	
2013	**2014**	**2015**	**2016**	**2017**	**Source**	**CAGR 2010-2013**
$10.00						
$7.10	$6.57	$6.24	$5.96	$5.74		
$6.67						
$6.67						
$7.61	$7.05	$6.68	$6.39	$6.15		
$2.50	$2.50	$2.50	$2.50	$2.50		
2013	**2014**	**2015**	**2016**	**2017**		
1,900.86	2,697.07	4,201.96	6,966.73	12,121.72		

B. Return to Speed

1. Mobile/Wi-Fi Traffic								
	2012	2013	2014	2015	2016	2017	2020	Source
Average Mobile Connection Speed (Mbps)	2.41	3.40	4.81	6.59	11.41	13.52	18.59	Cisco
Wi-Fi Speeds from Mobile Device (Mbps)	11.50	14.60	18.54	17.78	28.15	37.93	56.00	Cisco
Speed Gap Wi -Fi VS Mobile (Mbps)	9.09	11.20	13.73	11.19	16.74	24.41	37.41	TAS
Average Speed (Mbps)	9.40	11.04	13.42	14.26	22.98	30.20	40.93	TAS
Mobile Traffic (Exabytes per month)	0.13	0.29	0.54	0.94	1.32	1.82	5.60	Cisco
Total Wi-Fi (Exabytes per month)	0.411	0.62	0.92	2.04	2.96	3.93	8.30	TAS
Total Traffic (Exabytes per month)	0.57	0.91	1.46	2.98	4.29	5.74	13.90	TAS
Mobile Traffic (Exabytes per year)	1.59	3.46	6.53	11.25	15.86	21.83	67.20	TAS
Total Wi-Fi (Exabytes per year)	5.30	7.41	10.98	24.45	35.57	47.11	99.64	TAS
Total Traffic(Exabytes per month)	6.89	10.87	17.51	35.71	51.43	58.94	166.84	TAS
2. Economic Impact of Wi-Fi Speed								
	2012	2013	2014	2015	2016	2017	2020	Source
Speed Wi-Fi over Mobile Speed (Mbps)	9.09	11.20	13.73	11.19	16.74	24.41	37.41	TAS
Speed decrease(%)	-74.36%	-69.16%	-64.18%	-53.76%	-50.36%	-55.22%	-54.59%	TAS
Wi-Fi Traffic(% Total Traffic)	6.67%	7.98%	10.00%	22.53%	21.94%	23.01%	27.20%	TAS
Coefficient of Bohl in	0.30% Growth in GDP per capita							
Decrease in GDP Per Capita	-0.22%	-0.21%	-0.19%	-0.16%	- 0.15%	-0.17%	-0.16%	TAS
GDP Per Capita (Current Prices)	49,922.11	51,248.21	53,327.98	55,837.31	58,436.31	61,690.00	65,465.48	USA Bureau
Population	315,967,692	318,292,277	320,611,133	322,946,209	325,296,400	327,654,888	334,716,138	USA Bureau
GDP Reduction (Current Prices)	-2,346,895,333	-2,699,596,449	-3,291,253,664	-6,551,149,919	-6,302,352, 758	-7,703,385,707	-9,761,245,925	TAS

C. Residential Wi-Fi

Total Annual Traffic	2010	2011	2012	2013	2014	2015	2016	2017	2020
Smartphones	148,191,904	445,022,139	1,116,075,767	2,597,033,761	5,674,527,472	24,996,536,363	35,491,295,668	47,637,761,853	114,757,268,270
Gaming Consoles	121,854,802	174,426,788	142,751,947	116,829,065	99,771,880	63,105,161	79,333,213	93,219,911	141,025,009
Tablets	921,274,714	1,453,378,247	2,292,810,490	3,617,076,252	5,706,202,353	11,476,414,134	16,617,564,754	22,403,490,182	42,501,361,810
Total	1,101,321,421	2,072,827,175	3,551,638,204	6,330,939,078	11,480,501,705	36,536,055,658	52,100,103,634	70,134,471,057	157,399,655,090

Split per location

Location	Hours	Share
Home	2.60	43.12%
Friend's home	0.35	5.80%
At work	0.80	13.27%
At work remote location	0.40	6.63%
Retail location (stores, restaurants)	0.38	6.30%
Public location (parks, schools)	0.45	7.46%
Travel locations	0.45	7.45%
On The Go	0.60	9.95%
Total	6.03	100%

Total Annual Traffic at Home	2010	2011	2012	2013	2014	2015	2016	2017	2020
Smartphones	63,897,007	191,883,509	481,226,699	1,119,782,384	2,446,728,263	10,777,942,710	15,303,046,225	20,540,328,494	49,480,745,854
Gaming Consoles	52,541,042	75,208,897	61,551,420	50,374,058	43,019,384	27,209,522	34,206,692	40,194,318	60,806,803
Tablets	397,232,879	626,663,921	988,608,172	1,559,601,701	2,460,385, 758	4,948,370,937	7,165,119,131	9,659,879,681	18,325,628,641
Total	513,670,928	893,756,327	1,531,386,290	2,729,758,143	4,950,133,405	15,753,523,169	22,502,372,048	30,240,402,502	67,867,181,299
Average Price per Gb									
	$10.28	$9.42	$8.52	$7.61	$6.67	$5.84	$5.49	$5.16	$3.77
Price per home traffic									
	$5,279,229,066	$ 8,420,910,502	$13,054,522,492	$20,768,341,173	$33,017,389,811	$92,000,575,308	$123,538,022,544	$156,040,476,9101	$255,859,273,497

Notes

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