How Much Licensed Spectrum is Needed to Meet Future Demands for Network Capacity?

THE BRATTLE GROUP

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CTIA

APRIL 17, 2023

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- We would like to thank Ryan Taylor, Shea Peretz, Megan Sullivan and Natalie Selfie for their contribution to this paper.

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Executive Summary

Mobile data demand is exploding, with aggregate data downloaded quadrupling in the last seven years. New and innovative uses enabled by 5G, as well as the prospect of 6G applications, point towards further increases in expected demand for mobile network capacity. Unfortunately, the U.S. spectrum landscape appears to be stalled, with no clear prospects for significant spectrum reallocations this year and insufficient bands under consideration for reallocation in the coming years. This lack of a spectrum pipeline, coupled with the lapse of the Federal Communications Commission (FCC) auction authority, has raised the prospect of significant capacity constraints in the terrestrial wireless space, and concern that this may limit the U.S.'s ability to be a leader in this area. This paper investigates this capacity constraint and estimates the likely spectrum deficit the U.S. will face over the next decade absent policymakers allocating additional full-power, licensed spectrum.

We examine several potential mechanisms to ease the gap between projected demand for mobile data and estimated future capacity of mobile networks. Obviously one way to align supply and demand is simply through reducing network usage. Restricted offerings or higher prices could limit demand to maintain network performance in the face of inadequate supply of capacity. This approach would reduce the growth of innovative applications, ultimately restraining economic growth and potential U.S. leadership without any real benefit to users. We assume policymakers would seek to avoid this outcome.

Two historically effective avenues for increasing mobile network capacity include improvements in spectral efficiency and adding more physical infrastructure such as base stations or cell towers. Unfortunately, both of these options are approaching serious limitations, as we analyze below. Even under optimistic projected improvements in the areas of spectral efficiency and infrastructure deployment, the U.S. will still face a significant capacity deficit—leaving additional new mobile spectrum allocations as essential to meet projected future demand.

In 5 years, by the end of 2027, the U.S. is expected to have a capacity deficit of over 10 exabytes/month. In ten years, by 2032, this deficit could grow to approximately 17 exabytes/month.

Extrapolating from historical trends, we project that data traffic on the macro network is expected to increase by over 250% in the next 5 years and by over 500% in the next 10 years. If no new spectrum bands are allocated for wireless use in the next 5-10 years, we estimate that by 2027, the U.S. could face a spectrum deficit of approximately 400 megahertz, and by 2032, this deficit will have more than tripled to over 1,400 megahertz, normalized to lower mid-band equivalent spectrum, licensed at full power.[1] To avoid this deficit, work needs to begin now on filling the spectrum pipeline.[2]

Absent any new spectrum, in 5 years, by 2027, the U.S. is expected to have a spectrum deficit of nearly 400 megahertz. In ten years, by 2032, this deficit could more than triple to approximately 1,400 megahertz.

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[1] The report analyzes the spectrum deficit in terms of a normalized band of spectrum with propagation characteristics of 1-2 GHz frequency, average power limits, and free of encumbrances—bands with other characteristics will vary in the amount needed to cover the capacity deficit.

[2] The authors recognize that a lot can change over the studied time period, so we also calculated potential spectrum deficits using other demand projections. We found that under all plausible scenarios we examined, the United States will have a substantial spectrum deficit in 2027 and an even larger deficit in 2032.

I. Introduction

The global COVID pandemic moved a large part of the workforce and academia from physical to virtual work and learning spaces, leading to an explosion of demand for data in both wired and wireless networks.[3] Consumers and businesses large and small used mobile broadband networks at an unprecedented pace for a variety of uses, including schoolwork, shopping, entertainment, and telemedicine.[4] The trend continues with hybrid work options and people using more data-intensive applications on their mobile phones.

In seven years, from 2015 to 2022, global mobile traffic increased from five exabytes per month to 93 exabytes per month – a more than 18-fold increase.[5] Over that period, aggregate data demand in North America has more than quadrupled.[6] In 5 years, from 2021 to 2027, the average monthly data usage per smartphone in North America is expected to grow from 15 GB to 52 GB – more than tripling per device data consumption.[7] New and innovative uses enabled by 5G, the proliferation of Internet of Things (IoT) devices, enhanced mobile broadband, augmented and virtual reality applications, are dramatically increasing demand for mobile network capacity.[8] These trends have raised the specter of significant capacity constraints and spectrum shortfalls

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[3] Bruce Duysen, "5G and the age of pandemic: A look at the US," April 27, 2020, last accessed December 15, 2022, RCR Wireless News, https://www.rcrwireless.com/20200427/opinion/readerforum/5g-and-the-age-of-pandemic-reader-forum.

[4] Karthikeyan Iyengar, Gaurav K. Upadhyaya, Raju Vaishya, and Vijay Jain, "COVID-19 and Applications of Smartphone Technology in the Current Pandemic," Diabetes & Metabolic Syndrome: Clinical Research & Reviews, Vol. 14(5), September - October, 2020, https://www.sciencedirect.com/science/article/abs/pii/S1871402120301521?via%3Dihub.

[5] Ericsson, "Mobility Report," Ericsson, June, 2022, last accessed August 16, 2022, at p. 15, available at https://www.ericsson.com/49d3a0/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-june-2022.pdf ("Ericsson Mobility Report, June 2022"). Note: One exabyte equals one billion gigabytes. *See*, Alexander S. Gillis, "What is an Exabyte?" TechTarget, last accessed August 21, 2022, https://www.techtarget.com/searchstorage/definition/exabyte.

[6] *See,* Ericsson Mobility Report, June 2022, at pp. 17-19. Note that Ericsson reports the mobile traffic number for North America and not just the US. However the vast majority of the traffic is US-based.

[7] *See,* Ericsson Mobility Report, June 2022, at pp. 17-19. Note that Ericsson reports the mobile traffic number for North America and not just the US. However the vast majority of the traffic is US-based. *See also*, GSMA, "The Mobile Economy – North America 2022," accessed December 25, 2022, p. 13, https://www.gsma.com/mobileeconomy/wp-content/uploads/2022/09/290922-Mobile-Economy-North-America-2022.pdf.

[8] Ericsson, "Ericsson Mobility Report," November 2022, last accessed December 19, 2022, at p. 22, https://www.ericsson.com/4ae28d/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-november-2022.pdf ("Ericsson Mobility Report, November 2022"). *See also*, Noman M. Alam, Mark Racek, and Kumar Balachandran, "Mid-Band Spectrum – Laying a strong foundation for 5G," Ericsson, July 4, 2022, last accessed December 15, 2022, https://www.ericsson.com/en/blog/6/2022/mid-band-spectrum-in-the-us-a-strong-foundation-for-5g, ("Mid-Band spectrum – Laying a strong foundation for 5G").

in mobile networks and concern that this may constrain the U.S.'s ability to be a leader in data-intensive 5G applications.[9]

Engineers remind us that there are several ways to avoid capacity constraints on wireless networks, such as through installing more equipment or infusing more spectrum into the network.[10] In this paper we account for the interrelated and complementary tools that can help solve the gap between the demand for and supply of capacity in the mobile network, estimating how to what extent non-spectrum inputs can go toward meeting demand. We find non-spectrum avenues lacking even under highly optimistic scenarios, leaving more full-power, licensed spectrum as the most effective way to meet projected wireless demand.

This paper aims to identify how much additional full-power, licensed spectrum is needed to close the projected gap between demand for wireless services and network capacity projections. Section II discusses the demand for data and the expected growth in data demand for the next five to 10 years. Section III presents the available inventory of spectrum today, as well as briefly discussing various supply-side factors used to help meet demand. Section IV discusses the spectrum deficit estimation, concluding that even under optimistic scenarios the United States would face a deficit of approximately 400 megahertz in five years, growing to over 1,423 megahertz in ten years.[11]

This analysis indicates that additional mobile spectrum allocations are necessary if U.S. wireless networks are to be able to supply enough capacity to meet growing demand. It is infeasible to expect non-spectrum inputs to cover the capacity deficit, even using conservative inputs and under the most optimistic scenarios. With aggressive investment in infrastructure and reasonably expected improvements to spectral efficiency, we estimate that in order to meet demand in five years industry will still require approximately 400 megahertz of spectrum in the next 5 years, and over 1,400 megahertz in ten years. This estimate is normalized to exclusively licensed, wide-area, full-power spectrum, with propagation characteristics of 1-2 GHz. Spectrum with other characteristics would change the analysis—for example, if spectrum were only made available with lower power levels, much more would be required to meet demand.

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[9] Roger Entner, "The U.S. is Hamstrung by Spectrum Constraints," Fierce Wireless, April 22, 2022, Fierce Wireless, https://www.fiercewireless.com/wireless/us-hamstrung-spectrum-constraints-entner.

[10] Richard N Clark, "Expanding Mobile Wireless Capacity: The challenges presented by technology and economics," Telecommunications Policy 38(8-9) (September 2014): 693-708, pp. 694-695, https://www.sciencedirect.com/science/article/pii/S0308596113001900 ("Expanding Mobile Wireless Capacity"). *See also*, Ericsson Mobility Report, November 2022.

[11] We normalized these figures to the equivalence of lower mid-band spectrum licensed for full power, flexible mobile use.

II. Demand for Capacity

Analyzing historical growth in wireless traffic allows us to predict future trends. We estimate both the growth in traffic as well as its composition in terms of different generations of wireless technologies, which is important in analyzing expected efficiency gains over time, as well as the potential trends in network offloading.

A. Growth in Wireless Traffic

Today, the ubiquity of mobile devices, increasing per-user data consumption, and more data-hungry applications have led to an explosion of mobile traffic and, consequently, a demand for greater capacity of the mobile networks to accommodate such increases in traffic. According to Ericsson, the growth in mobile data traffic per smartphone can be attributed to three main drivers: "improved device capabilities, an increase in data-intensive content and growth in data consumption due to continued improvements in the performance of deployed networks."[12] In North America, mobile data demand is expected to increase significantly, driven by new services such as "unlimited data plans and improved 5G network coverage and capacity" that will attract new 5G subscribers.[13]

To project the demand for capacity on the U.S. macro network of facilities-based operators, or the "on-network traffic," we turn to Cisco's Visual Networking Index (VNI) data to review historical data demand and use these to ground our estimates of mobile data demand going forward.[14] The VNI reports provide a geographic breakdown of Internet users, mobile users,

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[12] *See* Ericsson Mobility Report, November 2022, p. 22. This paper seeks to quantify the deficit in licensed spectrum from the mobile perspective, notwithstanding the explosive growth of fixed wireless access among home broadband subscribers. We exclude demand for fixed wireless for present purposes, as we understand fixed wireless services currently rely primarily on excess mobile capacity. Ultimately, however, the growing popularity of fixed wireless among consumers will cause the spectrum deficit to likewise grow.

[13] *See* Ericsson Mobility Report, November 2022, p. 22.

[14] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022," White Paper, Appendix A, Table 4, February 2019, last accessed December 18, 2022, http://media.mediapost.com/uploads/CiscoForecast.pdf, ("Cisco VNI: Global Mobile Data Traffic Forecast Update, 2017-2022"). *See also*, Cisco, "Cisco Annual Internet Report (2018–2023)," March 9, 2020, https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html, ("Cisco Annual Internet Report (2018–2023)"). *See also*, Sources and Notes for

We are interested in understanding long-term trends in traffic growth (2022 – 2032). However, the VNI data includes only five-year projections. For predicting traffic growth from 2023 – 2032, we use a combination of a projected CAGR and a regression analysis. We use the 2010-2022 Cisco mobile traffic data, which is comprised of actual data traffic forming the basis of each report from 2010 – 2018, as well as Cisco's 2018 forecasts for

Continued on next page

networked devices, speeds, and traffic for actual and forecasted traffic data from 2010 – 2022 for North America.[15]

The blue and teal bars in Figure 1 show that North American traffic has grown from 49 petabytes per month in 2010 to 1,804 petabytes in 2018 and is projected to reach over 5,800 petabytes per month in 2022.[16] The Ericsson numbers are slightly higher at around 6,000 petabytes in 2022.[17] Our data forecasts are shown in green and yellow and they project a roughly 2.5-fold increase in mobile traffic in the next 5 years and an almost six-fold increase in the next 10 years.[18]

2019 – 2022 North America traffic, as our baseline traffic numbers. For the years 2023 – 2028, we use Ericsson's predicted 2022 – 2028 CAGR (23%) to generate forecasted traffic. We then use the actual and predicted traffic data from 2010 – 2028 as the dependent variable in a regression analysis, predicting data traffic for 2029 – 2032 based on a quadratic time trend, a COVID indicator, and the previous year's population as covariates. The results are presented in Table A1.

Table A1. Note that we could have used the Ericsson traffic forecasts, which are in general higher than the Cisco forecasts, although the data availability for earlier years is better for Cisco. However, to be conservative, we use the Cisco forecasts in the base model for 2023, and then use a 23% CAGR from the Ericsson data forecasts. Also note, that the mobile traffic forecasts by Cisco and Ericsson are for the mobile traffic on the macro network of wireless operators. Facilities-based carriers are those with a nation-wide or regional cell site infrastructure that use licensed spectrum.

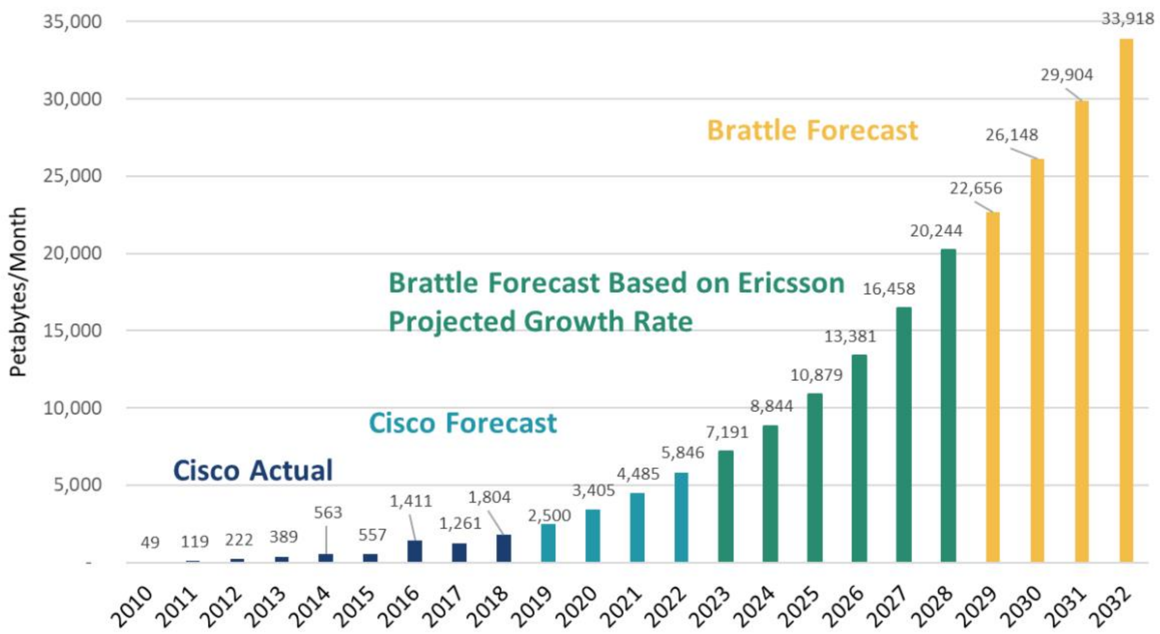
[15] *See* Cisco Annual Internet Report (2018–2023). *See also* Cisco VNI: Global Mobile Data Traffic Forecast Update, 2017-2022.

[16] See Figure 1. Note that the traffic forecasts are for North America which includes the U.S. and Canada. We use this as the aggregate U.S. forecasts and the Canadian data traffic is a very small fraction of the North American traffic volume.

[17] Ericsson Mobility Report, November 2022, p. 39. The monthly data traffic for North America is reported in EB/month or exabytes/month. We have converted these to PB (petabytes) using 1EB=1000 PB. See https://www.coolstuffshub.com/data-storage/convert/exabytes-to-petabytes/.

[18] The detailed methodology and data sources are described in 0 and the regression estimates are shown in Table 1.

FIGURE 1: NORTH AMERICA WIRELESS DATA DEMAND, 2010-2032



Sources and Notes: *See*, Appendix
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Table A1.

This aggregate trend masks the changing composition of traffic on a network – that is, it does not show how the traffic moves between generations of cellular technology, from 2G to 3G, 4G, 5G and beyond. As technology progresses, traffic will decline on the older generations of technology, through consumers upgrading to newer technology and operators shutting down older generation networks, while traffic on the newer technology increases. The next sub-section discusses how the traffic composition has changed.

B. Mobile Traffic Composition

The changing composition of traffic has implications for how efficiently a network is used, as described later in Section III, and for understanding the relationship between technology evolution and data demand.

We use subscriber data from the Ericsson Mobility Visualizer to analyze how data traffic patterns change as a cellular technology moves from its nascent form to maturity and then to obsolescence.[19] This dataset lists the number of mobile subscriptions for each technology generation through 2028.[20] Figure 2 below shows the composition of traffic over the years. From Figure 2, we see that the inflection point for LTE and 5G almost mirror each other, with LTE declining from its peak and 5G subscriptions increasing after 2019, and 5G subscriptions expected to be greater than 4G subscriptions after 2023.[21]

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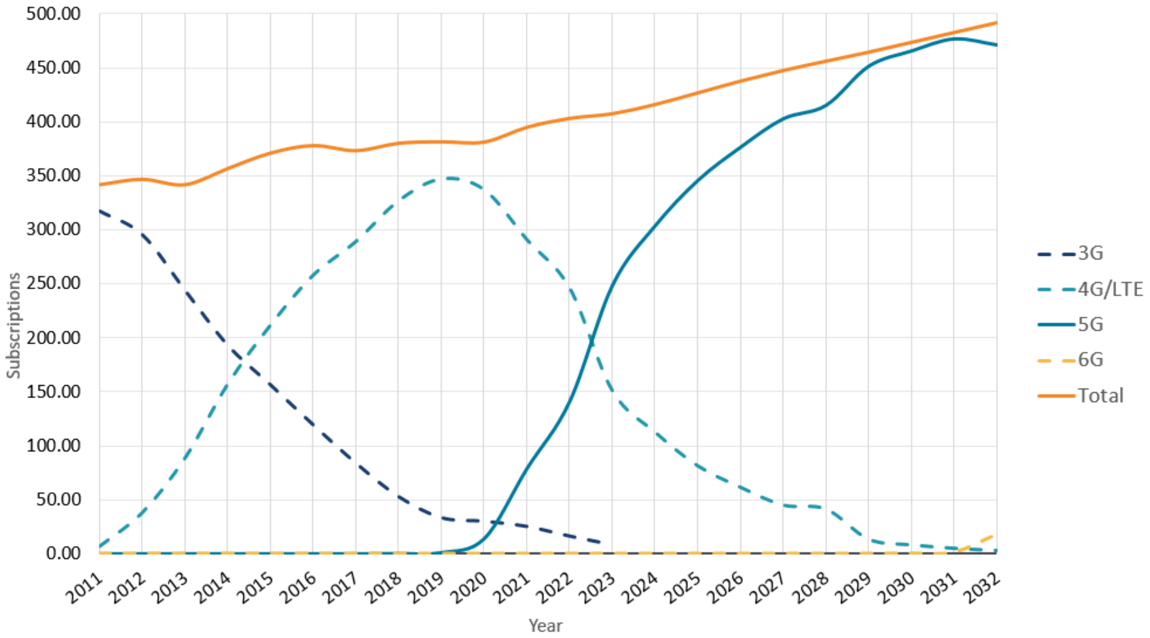
[19] Ericsson, "Ericsson Mobility Visualizer," Mobile Subscriptions, last accessed December 9, 2022, https://www.ericsson.com/en/reports-and-papers/mobility-report/mobility-visualizer?f=1&ft=2&r=2,3,4,5,6,7,8,9&t=1,2,3,4,5,6,7&s=4&u=1&y=2022,2028&c=3.

[20] Ericsson reports the following technology categories for North America – CDMA, WCDMA/HSPA, GSM/EDGE, LTE, 5G and Other. We classify CDMA and GSM/EDGE under 3G and WCDMA/HSPA under 4G. The 'Other" category is classified as 2G.

[21] *See* Figure 2.

FIGURE 2: SUBSCRIBER COUNT BY TECHNOLOGY



Sources and Notes: *Ericsson, "Ericsson Mobility Visualizer," last accessed December 14, 2022, https://www.ericsson.com/en/reports-and-papers/mobility-report/mobility-visualizer?f=1&ft=2&r=2,3,4,5,6,7,8,9&t=1,2,3,4,5,6,7&s=4&u=1&y=2021,2027&c=3.*

To complete the data composition patterns from 2022 – 2032, we generate predictions for 2029 – 2032, using the historical data. We construct subscriber shares by technology, and use these to predict subscriber shares for LTE and 5G, using a linear time trend to project the total number of future subscriptions in each category through 2032.[22] However, since we are projecting for a period 10 years from now, we have to factor in the evolution of 6G. The Ericsson data does not include any 6G subscription predictions. Therefore, we assume that 6G subscriptions will likely take off later and we predict the 6G trend in 2030 – 2032 using historical 5G customer patterns. Thus, for 6G we apply the same share of traffic that 5G experienced when it was in its infancy. We then apply these shares by technology to the total subscribers to obtain the number of customers by technology. Our projections show that for 2029 – 2032, LTE subscriptions are almost zero, 5G subscriptions have reached their peak, and 6G starts gaining market share.

Next, we discuss another factor affecting demand trend – traffic off-loading.[23]

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[22] We assume that 4G (HSPA) will be phased out by 2024 so the subsequent years have 0% traffic share. Note, that we rescale the shares after prediction to ensure that the shares add up to one.

[23] Rashmi Bharadwaj, "What is Wi-Fi Offload? An Overview," last accessed December 20, 2022, !https://ipwithease.com/what-is-wi-fi-offload-an-overview/, ("What is Wi-Fi Offload? An Overview").

C. Traffic Offloading

Offloading traffic generally refers to the situation when a mobile subscriber elects to connect using Wi-Fi over unlicensed spectrum rather than rely on the mobile network. Trends in Wi-Fi offloading featured prominently in our earlier analysis, which was done before the popularity of unlimited mobile broadband plans. In 2017 Cisco reported that 54% of total data traffic on mobile devices was over Wi-Fi, and estimated that in 2022, this figure would rise to 59%.[24] Unfortunately, Cisco no longer provides these statistics, making analysis of recent offloading trends difficult. The historic level of offloading is incorporated into the base for our demand projection, thus the important question for our analysis is whether offloading will change dramatically from prior years.

Recent trends indicate it is unlikely we will see a significant increase in Wi-Fi offloading. Improvements in mobile network capacity and latency mean consumers often do not see a material gain in network performance when switching to Wi-Fi. Furthermore, with the widespread prevalence of unlimited plans, users do not face the same cost incentive to seek out Wi-Fi access.[25] Finally, recent growth in popularity of fixed wireless access, which provides home broadband over licensed mobile spectrum, will increase the capacity load on licensed networks.[26] Again, our demand projections maintain historic rates of traffic offloading, so our estimated deficit is likely conservative in this regard.

In the next section, we turn to the supply side of the network capacity issue and explore how technological solutions (increasing spectral efficiency), infrastructure deployments (deploying more cell sites), and increased spectrum availability can ease capacity constraints.

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[24] Cisco, "Cisco: Global Mobile Networks Will Support More Than 12 Billion Mobile Devices and IoT Connections by 2022; Mobile Traffic Approaching The Zettabyte Milestone," February 19, 2019, last accessed December 13, 2022, https://newsroom.cisco.com/c/r/newsroom/en/us/a/y2019/m02/cisco-global-mobile-networks-will-support-more-than-12-billion-mobile-devices-and-iot-connections-by-2022-mobile-traffic-approaching-the-zettabyte-mil.html.

[25] Unlimited plans gained popularity after Cisco's most recent offloading data, complicating analysis. *See* e.g., Chaim Gartenberg, "Why every US carrier has a new unlimited plan," *The Verge* (Feb 2017), https://www.theverge.com/2017/2/17/14647870/us-carrier-unlimited-plans-competition-tmobile-verizon-att-sprint.

[26] Furthermore, fixed wireless home broadband access will complicate future offloading measurements, as analytics captured from devices may show them connected to a Wi-Fi network, when nevertheless licensed spectrum is ultimately carrying the traffic.

III. The Supply Side Inputs

A. Spectrum Availability

When it comes to spectrum, there are two broad types of regulatory constructs – licensed spectrum and unlicensed spectrum. Licensed spectrum is a part of the frequency assigned for terrestrial wireless use to an array of nationwide and regional cellular operators, cable companies, and others who pay a licensing fee for the "right to transmit on an assigned frequency within a certain geographic area so that nothing interferes with transmissions."[27] Unlicensed spectrum are frequencies that the FCC assigns for non-exclusive usage without the need for a license, *i.e.*, any entity can use it, subject to some regulatory restrictions.[28] Wi-Fi is one of the prime examples of the use of unlicensed spectrum. In this section, we discuss the availability of the licensed spectrum that is used for the traffic of cellular operators.[29]

1. Current Spectrum Inventory

The composition of the U.S. spectrum inventory grew slowly but steadily until 2019, with spectrum bands mostly below 3 GHz available for use for mobile terrestrial networks. However, with the advent of 5G, for the first time, carriers could utilize low, medium, and high frequencies in the same integrated, optimized network. In particular, with this "multi-layered" network, 5G is able to utilize the mmW spectrum, which has extremely short coverage capabilities and was previously not viable for use, along with mid- and low-band spectrum.[30] This resulted in a dramatic increase in the total stock of spectrum available for wireless networks, a development that coincides with a new focus on capacity by carriers. Importantly, much of this spectrum is licensed for full-power exclusive use, with larger geographic license sizes, all of which enhances the efficiency of network deployments.

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[27] Christopher Trick, "Licensed vs. Unlicensed Spectrum: Key Differences and 5G Use Cases," November 7, 2022, last accessed December 29, 2022, https://www.trentonsystems.com/blog/licensed-vs-unlicensed-spectrum, ("Licensed vs. Unlicensed Spectrum: Key Differences and 5G Use Cases").

[28] *See* Licensed vs. Unlicensed Spectrum: Key Differences and 5G Use Cases.

[29] It is beyond the scope of the current analysis to evaluate any needs for additional unlicensed spectrum.

[30] OmniSci "5G's Data Science Challenge," at p. 4, 2021, last accessed August 1, 2022, https://www2.omnisci.com/resources/whitepaper/5g-data-science-challenge/lp.

The spectrum inventory table (Table 1) lists the frequencies that are available to be integrated into mobile broadband networks.[31]

- *3 GHz and Below (Low Band)*: Currently, the licensed sub-1 GHz frequencies – 600 MHz, 700 MHz and 800 MHz (cellular and SMR) Bands – have a total of 204 megahertz licensed. Between 1-3 GHz, the AWS-1, AWS-3, AWS-4, PCS, and H-Block, in total, comprise 335 megahertz of licensed spectrum.[32] The licensed frequencies in the 2 - 3 GHz range are WCS and BRS/EBS. In aggregate, these comprise 743 megahertz of low and low mid-band spectrum.[33]

- *Between 3 GHz and 8.4 GHz (Mid Band)*: The licensed frequencies in these bands are CBRS, C-Band, and the 3.45 GHz Band, which total 450 megahertz of licensed spectrum, although 180 MHz of the C-Band spectrum will not be available for use until later this year.[34] These bands were added to the inventory in the past three years.

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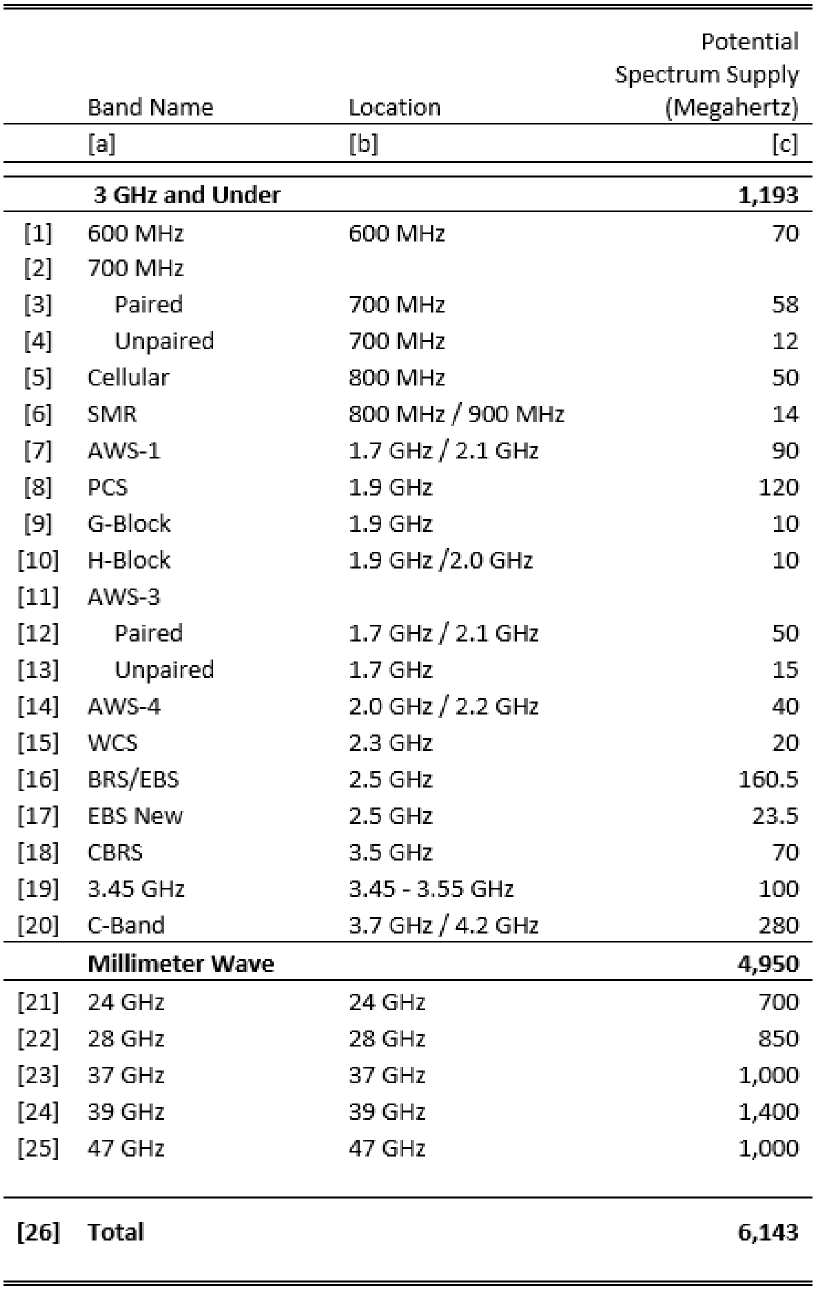
[31] "While there is no set rule for dividing between low-, mid-, and high-band spectrum, we have chosen dividing lines that best reflect recent allocation decisions made by policymakers with knowledge of forthcoming 5G service deployments. To further expand on one such delineation we made: while we selected 3 GHz as the dividing line between low- and the lower mid-band, the 2.5 GHz band - first allocated about two decades ago shares many of the same characteristics of the identified lower mid-band spectrum (e.g., large bandwidth, use of time division duplexing, and propagation ability.)" *See* Accenture, "Spectrum Allocation in the United States," CTIA, September 28, 2022, https://api.ctia.org/wp-content/uploads/2022/09/Spectrum-Allocation-in-the-United-States-2022.09.pdf. Note that the table lists all spectrum made available by the FCC for terrestrial mobile use and is different from the spectrum screen.

[32] There is one possible addition to this band expected in the near-term: 10 megahertz of spectrum from the NOAA/Ligado Band (1670 MHz – 1680 MHz band).

[33] We use 156.5 megahertz for the BRS/EBS spectrum to match the bands excluded from the FCC's updated spectrum screen. *See*, "Policies Regarding Mobile Spectrum Holdings," Federal Communications Commission, WT Docket No. 12-269, June 2, 2014, at ¶¶ 107-125, available at https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-63A1.pdf. *See also*, "Mobile Broadband Spectrum," at p. 7. *See also*, "FCC Establishes Procedures for 3.5 GHz Band Auction," Federal Communications Commission, FCC-20-18, 35 FCC Rcd 2140 (3), March 2, 2020, available at https://www.fcc.gov/document/fcc-establishes-procedures-35-ghz-band-auction-0. *See also*, "FCC Acts To Free Up C-band Spectrum For 5G Services," Federal Communications Commission, GN Docket # 18-122, February 28, 2020, available at https://www.fcc.gov/document/fcc-expands-flexible-use-C-band-5g. *See also*, Coleman Bazelon and Paroma Sanyal, "Mobile Broadband Spectrum: A Revaluation in a 5G World," CTIA, May 20, 2019, ("Mobile Broadband Spectrum: A Revaluation in a 5G World").

[34] Although wireless providers have obtained licenses to use CBRS spectrum, the low power levels and a new spectrum sharing regime made CBRS spectrum less valuable at auction than other licensed spectrum bands. We have accounted for this through adjustments made to how much CBRS spectrum to count as usable, as discussed below.

TABLE 1: SPECTRUM INVENTORY 2022



	Band Name	Location	Potential Spectrum Supply (Megahertz)
	[a]	[b]	[c]
	3 GHz and Under		**1,193**
[1]	600 MHz	600 MHz	70
[2]	700 MHz		
[3]	Paired	700 MHz	58
[4]	Unpaired	700 MHz	12
[5]	Cellular	800 MHz	50
[6]	SMR	800 MHz / 900 MHz	14
[7]	AWS-1	1.7 GHz / 2.1 GHz	90
[8]	PCS	1.9 GHz	120
[9]	G-Block	1.9 GHz	10
[10]	H-Block	1.9 GHz /2.0 GHz	10
[11]	AWS-3		
[12]	Paired	1.7 GHz / 2.1 GHz	50
[13]	Unpaired	1.7 GHz	15
[14]	AWS-4	2.0 GHz / 2.2 GHz	40
[15]	WCS	2.3 GHz	20
[16]	BRS/EBS	2.5 GHz	160.5
[17]	EBS New	2.5 GHz	23.5
[18]	CBRS	3.5 GHz	70
[19]	3.45 GHz	3.45 - 3.55 GHz	100
[20]	C-Band	3.7 GHz / 4.2 GHz	280
	Millimeter Wave		**4,950**
[21]	24 GHz	24 GHz	700
[22]	28 GHz	28 GHz	850
[23]	37 GHz	37 GHz	1,000
[24]	39 GHz	39 GHz	1,400
[25]	47 GHz	47 GHz	1,000
[26]	**Total**		**6,143**

Sources and Notes: FCC's 2022 Communications Marketplace Report.[35]

- *Above 24 GHz (mmW Bands)*: The total millimeter wave (mmW) spectrum licensed for use through Auctions 101 – 103 is 4,950 megahertz, which includes 850 megahertz of the 28

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[35] FCC, "2022 Communications Marketplace Report," DA/FCC #: FCC-22-103, adopted December 30, 2022, https://www.fcc.gov/document/2022-communications-marketplace-report.

GHz Band, 700 megahertz of the 24 GHz Band, along with 2,400 megahertz in the Upper 37 GHz and 39 GHz spectrum bands, and 1,000 megahertz in the 47 GHz Band.[36]

2. Spectrum Used and Relative Effectiveness

While there are several spectrum allocations available for licensed use, not all frequencies are of equal usefulness, given different propagation characteristics, power levels, geographic license sizes, or sharing obligations. For example, over 80 percent of the total 6143 megahertz licensed spectrum inventory is mmW spectrum with highly limited propagation. We adjust to account for the estimated relative usefulness of bands. Furthermore, some of frequencies are not yet actually deployed, so we estimate when they will come into service and contribute to supporting network capacity. In the end, these adjustments allow us to represent network capacity and needs relative to full-power, mid-band spectrum because it is the prime workhorse used in networks today. For example, the coverage and capacity characteristics, and hence value, of 1 megahertz of low-mid band spectrum is not the same as 1 megahertz of say, 3.45 GHz spectrum. We use the 1 – 2 GHz frequencies as the base band and determine the other frequency bands' equivalent amount of spectrum to this base.[37] Additionally, the year that some spectrum bands would become available is uncertain. Therefore, in our base model of spectrum availability, we only include the quantity of frequencies in use, *i.e.,* the bands outlined in Table 2. There are several adjustments we make to the spectrum inventory to reflect availability and the coverage characteristics of higher bands to create low-band equivalents.

Available for Use

- *2.5 GHz*: 23.5 megahertz of 2.5 GHz is considered available and usable immediately after the auction in 2022.
- *28 GHz and 24 GHz*: Auction 101 and 102 ended in 2019.[38] We assume that it takes around 1 year to 18 months to start integrating this new mmW spectrum into the network.

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[36] The FCC allocated the 37.0 to 37.6 GHz mmW frequency band (the "Lower 37 GHz band") as a shared licensed band in July 2016. *See*, FCC, "In the Matter of Use of Spectrum Bands Above 24 GHz For Mobile Radio Services," GN Docket No. 14-177, adopted April 12, 2019, ¶¶ 2, 5, https://docs.fcc.gov/public/attachments/FCC-19-30A1.pdf.

[37] We use the term mid-band equivalent when converting the higher frequencies to be comparable to this range.

[38] FCC, "Auction 101: Spectrum Frontiers – 28 GHz," https://www.fcc.gov/auction/101/factsheet; FCC, "Auction 102: Spectrum Frontiers – 24 GHz," https://www.fcc.gov/auction/102/factsheet.

Therefore, 25% is available for use in 2021, 50% will be in 2022-2023, and 75% in 2024-2027. All the spectrum would become fully integrated in 2032.[39]

- *Upper 37, 39 and 47 GHz*: Auction 103 ended in early 2020.[40] We assume that 25% is available for use in 2021-2022, 50% will be available for use in 2023-2024, and 75% in 2025-2027. All the spectrum would become fully integrated in 2032.
- *CBRS (3.5 GHz):* Auction 105 ended in late 2020.[41] We assume that 25%, 50%, and 75% of the band is available in 2021, 2022 and 2023, respectively.
- *C-Band (3.7 GHz)*: Auction 107 ended in early 2021.[42] We assume that 25% , 50%, and 75% of the band is used or will be available for use in 2022, 2023, and 2024 respectively, and the band will be fully available for use from 2025.
- *3.45 GHz*: Auction 110 concluded in late 2021.[43] Given the coordination requirement with the Department of Defense, we assume that 25% of the band is used in 2022, 50% and 75% of 3.45 GHz will be available for use in 2023 and 2024 respectively, and that the band becomes fully available for use in 2025.

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[39] The 10-year roll out of mmW spectrum reflects the uncertainty around its use cases.

[40] FCC, "Auction 103: Spectrum Frontiers – Upper 37 GHz, 39 GHz, and 47 GHz," https://www.fcc.gov/auction/103/factsheet.

[41] FCC, "Auction 105: 3.5 GHz Band," https://www.fcc.gov/auction/105/factsheet.

[42] FCC, "Auction 107: 3.7 GHz Service," https://www.fcc.gov/auction/107/factsheet.

[43] FCC, "Auction 110: 3.45 GHz Service," https://www.fcc.gov/auction/110/factsheet.

TABLE 2: SPECTRUM BANDS AND USABLE MEGAHERTZ WITH NO NEW SPECTRUM ALLOCATION

	2022	2027	2032
Spectrum Band		**In Use**	
Cellular	50.0	50.0	50.0
SMR	14.0	14.0	14.0
Broadband PCS	130.0	130.0	130.0
H Block	10.0	10.0	10.0
AWS-1	90.0	90.0	90.0
700 MHz	70.0	70.0	70.0
AWS-3	65.0	65.0	65.0
AWS-4	40.0	40.0	40.0
WCS	20.0	20.0	20.0
BRS	54.0	54.0	54.0
EBS	93.2	93.2	93.2
600 MHz	70.0	70.0	70.0
24 GHz	350	525	700
28 GHz	425	638	850
Upper 37 GHz	250	750	1,000
39 GHz	350	1,050	1,400
47 GHz	250	750	1,000
CBRS	7	14	14
C-Band	52.5	210	210
3.45 GHz	0	50	50
Low / Mid-Band Pre-2020	706	706	706
Adjusted for EBS	687	706	706
Mid-Band 2020-2022	60	274	274
mmWave	1,625	3,713	4,950
mmWave Equivalent (at 5%)	81	186	248
Spectrum Usable	862	1,166	1,228

Sources and Notes: *See* Brattle calculations.

Coverage Adjustment

- To compare like-to-like, we estimate the amount of spectrum in each band that should be counted in the usable inventory by creating a “mid-band” equivalent by calibrating the greater than 2 GHz bands to the 1-2 GHz frequency bands.
- Based on prior work, the relative band value of 2.5 GHz band vis-a-vis the 1-2 GHz bands is 80%, *i.e.*, it has a 20% discount due to coverage and hence value characteristics.
- We estimate the C-Band is similar in coverage to other lower mid-band spectrum. In prior work, we have shown that the C-Band covers approximately 75% of the population of the

U.S. compared to near 100% coverage by 1 – 2 GHz bands; thus, we use a relative band value of 75% vis-a-vis the 1 – 2 GHz bands.[44]

- The 3.45 GHz band, although similar to the C-Band, has a higher discount due to the encumbrances that are present in this band.[45] We use a relative band value of 50%.[46]
- The CBRS band (3.5 GHz) has a discount of 80% compared to the 1 - 2 GHz bands due to their lower coverage characteristics and lower power limits.
- Only 5% of the mmW spectrum is counted in the effective 1-2 GHz equivalent inventory due to propagation characteristics. [47]

The subset of licensed spectrum bands and megahertz that are being used today are shown in terms of their mid-band equivalents in Table 2.

B. Spectral Efficiency

Historically, technological improvements allowed wireless operators to do more with a given quantity of spectrum. Spectral efficiency is a measure of how much data can be transmitted over a given amount of spectrum, and as such, is an important factor in meeting growing demand. For the purposes of communications networks, efficiency is measured as a ratio of "the amount (or bits) of information transmitted" and "the amount of spectrum (or Hertz) impacted or made unavailable for use."[48] It is usually expressed as "bits per second per hertz," or bps/Hz, *i.e.*, the

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[44] Coleman Bazelon and Paroma Sanyal, "Valuing the 12 GHz Spectrum Band with Flexible Use Rights," Prepared for RS Access, filed on the docket "In the Matter of Expanding Flexible Use of the 12.2-12.7 GHz Band," WTB 20-443, GN 17-183, filed May 7, 2021, p. 18, Table 1,https://www.fcc.gov/ecfs/document/10508241713847/3; ZTE, "APT 700 MHz: Best Choice for Nationwide Coverage," June 2013, https://www.gsma.com/spectrum/wp-content/uploads/2013/07/ZTE-LTE-APT-700MHz-Network-White-Paper-ZTE-June-2013.pdf

[45] FCC, "Correction of Select Inventory Announced for the Auction of Flexible-Use Service Licenses in the in the 3.45–3.55 GHz Band for Next-Generation Wireless Services (Auction 110)," DA/FCC #: DA-21-1132, issued on September 10, 2021, https://www.fcc.gov/document/correction-auction-110-inventory.

[46] The C-Band is 80% of the 1 – 2 GHz bands. At $0.74 MHz/Pop, the 3.45 GHz band was valued at approximately 70% of the C-Band values ($1.10/ MHZ-pops). This the 3.45 GHz band is 50% of the 1 – 2 GHz band ((0.51 = 0.74/1.10)*0.75). For auction prices, see Sasha Javid, "Post Auction Analysis for Auction 110," accessed January 11, 2023, https://www.sashajavid.com/FCC_Auction110.php. See also, Sasha Javid, "Post Auction Analysis for Auction 107," accessed January 11, 2023, https://www.sashajavid.com/FCC_Auction107.php.

[47] This is done to adjust for the limited coverage property of mmW compared to low and mid-band spectrum.

[48] Richard Engelman et. al., "Federal Communications Commission Spectrum Policy Task Force," Federal Communications Commission, November 15, 2002, last accessed December 13, 2022, https://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf.

"net data rate in bits per second (bps) divided by the bandwidth in hertz."[49] Increasing spectral efficiency allows the same amount of spectrum and same number of cell sites to provide greater overall capacity.[50] Unfortunately improvements in spectral efficiency are approaching their theoretical limit.

To estimate rates of spectral efficiency for the aggregate U.S. mobile data traffic through 2032 we use the spectral efficiency rates for different technologies predicted by analysts as discussed earlier. To implement this we make some assumptions about the applicability of rates to various technologies and the composition of mobile traffic over the next 10 years as estimated earlier in Section II.B. We understand that peak efficiency numbers can only be met when there is a confluence of several ideal conditions, and is not feasible across the entire network.[51] Thus in a very real sense, any projections we make to account for efficiencies are purely theoretical and may overstate the ability of efficiencies to decrease spectrum demand.[52]

As the demand for data continues to grow, any increase in the throughput of data over spectrum that allows for faster, less costly and ubiquitous deployment of 5G services is of significant value. Despite the fact wireless technology has seen great advancements in the last 50 years, there is a hard mathematical limit to how much spectral efficiency can improve.[53] Furthermore, future gains in spectral efficiency will increasingly depend on costly deployments of additional physical infrastructure.

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[49] "Spectral Efficiency," Techplayon, last accessed December 12, 2022, https://www.techplayon.com/spectral-efficiency-5g-nr-and-4g-lte/, ("Spectral Efficiency").

[50] *See,* Spectral Efficiency. *See also*, Mike Eddy, "Overcoming a Spectrum Deficit in a 5G World," Electronic Design, April 3, 2021, last accessed December 13, 2022, https://www.electronicdesign.com/industrial-automation/article/21159765/resonant-overcoming-a-spectrum-deficit-in-a-5g-world.

[51] To achieve peak efficiency the device must be directly in front of the base station under perfect RF, the base station is transmitting all resources and power to the device, it is using the most efficient data transfer method, for example.

[52] For 3G we use 2.6 bps/MHz, for 4G we use 3.5 bps/MHz, for 5G we use 6 bps/MHz, and for 6G we use 10 bps/MHz.

[53] Shannon's Law: This theorem "sets an upper limit on the rate at which data can be transmitted over any communications channel, whether wired or wireless." Shannon's law measures channel capacity as a function of the radio frequency of spectrum used, the number of antennas on uncorrelated signal paths, and the signal-to-noise ratio on the channel. *See* Larry Hardesty, "Explained: The Shannon Limit," MIT News, January 19, 2010, available at https://news.mit.edu/2010/explained-shannon-0115. *See also*, Waveform, "5G's Faster Data Rates and Shannon's Law," April 27, 2022, last accessed December 14, 2022, https://www.waveform.com/a/b/guides/5g-and-shannons-law, ("5G's Faster Data Rates and Shannon's Law").

C. Building Cell Sites

Deploying more cell sites, including small cells, is another way to increase the capacity of a wireless network. Increasing the number of cell sites increases the capacity of a given network by dividing or splitting cells to reduce cell size. This functionally allows for the reuse of existing spectrum, thereby increasing the overall capacity. Ideally, each cell would continue to deploy the full set of frequencies available for the market area, but this is only feasible up to a certain point.[54] Unfortunately, this approach also has natural limitations, as discussed below.

After successive deployments of macro cells throughout earlier network generations, macro coverage is beginning to reach maturation, with small cells anticipated to play a key complementary role to macro cells in the deployment of 5G.[55] As such, we anticipate the growth of macro cells over the next decade to occur at a lower rate than when the rollouts of 3G and 4G occurred. This is shown in Appendix Table B1.

When 4G/LTE subscriptions started accelerating around 2013-2014, and the industry had positioned itself to service the increased traffic by deploying more cell sites, the YoY average growth rate of macro sites was approximately 3.5% (2011-2015).[56] Given not all 5G site growth will be on macro towers, we assume that 5G sites will grow at half that rate, 1.75%, and use this to forecast the macro cell sites from 2022 – 2032. We estimate that by 2032 there will be approximately 354,000 macro sites, or a total additional deployment of approximately 61,000 sites between 2022 – 2032. This can be seen in Figure 3.

Next, we turn to the growth in small cells. While the macro cell infrastructure is mature, small cells are still at their nascent stage. Industry analysts report upwards of 80% of all future

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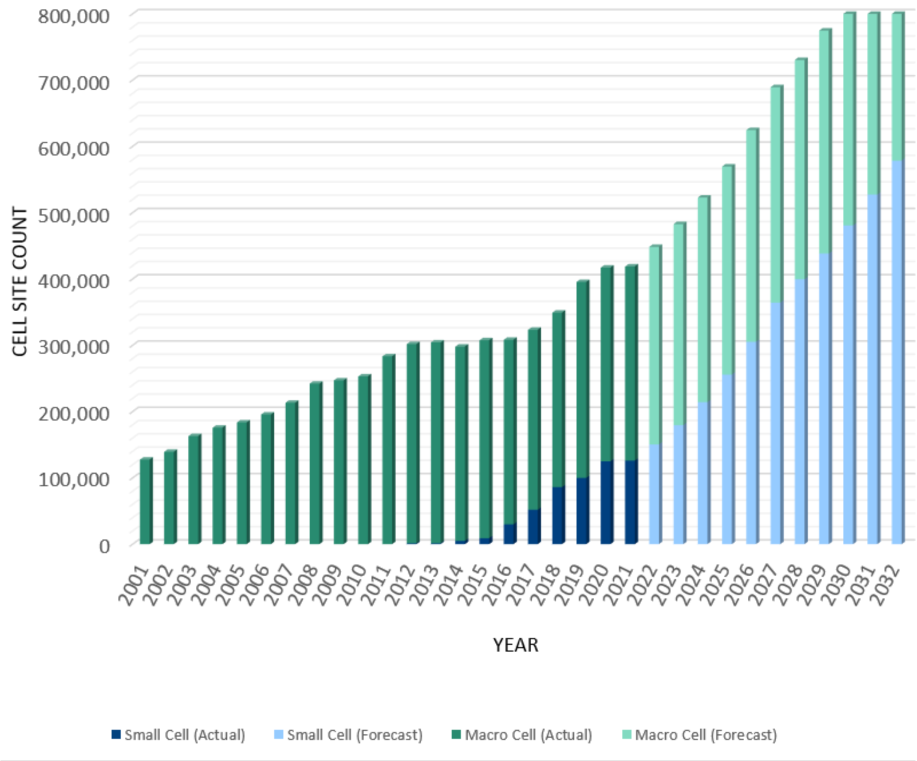
[54] This ideal scenario is not realistically achievable after cells are shrunk to a certain size, as self-interference concerns limit the ability to re-use the same bands in directly adjacent cells. Additional infrastructure in the form of small cells typically use a limited sub-set of spectrum bands licensed to an operator.

[55] *See*, Scott Bergmann, "A Year of Accelerated Wireless Infrastructure Investment," CTIA, March 22, 2019, last accessed December 6, 2022, https://www.ctia.org/news/a-year-of-accelerated-wireless-infrastructure-investment, ("CTIA: Accelerated Wireless Infrastructure"). *See also*, "Smart Cities: How 5G Can Help Municipalities Become Vibrant Smart Cities," Accenture, 2017, https://api.ctia.org/docs/default-source/default-document-library/how-5g-can-help-municipalities-become-vibrant-smart-cities-accenture.pdf. *See also*, "Impact of Federal Regulatory Reviews on Small Cell Deployment," Accenture, March 12, 2018, https://api.ctia.org/docs/default-source/default-document-library/small-cell-deployment-regulatory-review-costs_3-12-2018.pdf ("Accenture: 2018 Small Cell Report").

[56] CTIA data on macro cell sites.

deployments will be small cells.[57] Our forecast suggests that by 2027, the United States will have around 365,000 small cells deployed and this will increase to about 580,000 by 2032. Keeping in mind initial over-estimates of small cell deployment, we believe our ten-year forecast is a reasonable one, expecting an optimistic level of small cell deployment. Figure 3 shows a composite chart of macro and small cell sites till 2032.

FIGURE 3: ACTUAL AND FORECASTED CELL SITES 2001-2032: SMALL VERSUS MACRO CELL



Sources and Notes: *See*, Appendix Table B1
2001-2021 data based upon CTIA data.
Macro cells: 2022 onwards based on Brattle forecast using 1.75% YoY growth rate.
Small cell forecast: 2022-2027 based on Brattle forecast using a 19.4% annual growth rate and 2028-2032 based on half of that rate.

While additional infrastructure may be desirable to provide additional capacity, deploying new sites is expensive, time consuming, and has a natural limit, “requiring the construction of extra

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[57] FCC, “FCC Facilitates Wireless Infrastructure Deployment for 5G,” FCC-18-133, 33 FCC Rcd 9088 (14), September 27, 2018, https://www.fcc.gov/document/fcc-facilitates-wireless-infrastructure-deployment-5g. “From a regulatory perspective, these raise different issues than the construction of large, 200-foot towers that marked the 3G and 4G deployments of the past. Indeed, estimates predict that upwards of 80 percent of all new deployments will be small cells going forward. To support advanced 4G or 5G offerings, providers must build out small cells at a faster pace and at a far greater density of deployment than before” (at p. 2).

towers/antennas, deploying more radios and base station equipment; as well as extending additional backhaul links to link new towers back into the mobile operator's core network."[58] Investments in additional macro cell sites include capital expenditures, such as the cost of the land, towers, radios and backhaul, and operating expenditures, such as electricity, maintenance, security, etc. These capital and operating expenditures cost billions of dollars in capex.[59]

In sum, keeping up the pace of new cell site construction comes with practical challenges including site acquisition, acquiring fiber backhaul and reliable power, and a shortage of trained work force talent. Site acquisition gets more challenging in urban and even suburban areas, as providers seek to find the right site locations to provide capacity relief, while minimizing interference from surrounding sites and navigating the state and local approval processes. Operators work to obtain the best site locations while balancing the costs of leasing new space for towers and sites in order to provide quality service for their customers. Regardless, there are real limits about the ability for operators to rely on additional infrastructure to meet capacity demand. Regulators functionally limit the number and location of sites, so the needed sites might not be available regardless of the carrier's willingness to invest. This and other natural limits on the number of available sites is compounded by the fact that multiple carriers are all competing for ideal locations, particularly for small cell deployments. Therefore, if historical technology trends hold and forecasted traffic patterns are realized, these solutions are unlikely to be sufficient to meet rapidly growing traffic demand.

Controlling for advancements in technology and deployments, we estimate that there will be an almost four-fold increase in traffic per site in the next 10 years, putting continued strain on existing networks and adding pressure for mobile operators to find new spectrum to ease capacity constraints. To meet the growing demands of wireless networks, additional frequencies will be a necessary part of the solution.

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[58] *See* Expanding Mobile Wireless Capacity, at p. 695.

[59] One analyst source estimates that "between 2022 and 2025, mobile operators will need to invest more than USD 600 billion in capex." *See* Mordor Intelligence, "United States Telecom Towers Market – Growth, Trends, COVID-19 Impact, and Forecasts (2023-2028)," accessed January 6, 2023, https://www.mordorintelligence.com/industry-reports/united-states-telecom-towers-market

IV. Absent Capacity from More Full-Powered, Licensed Spectrum Macro Networks Will Likely Be Constrained

A. Capacity Constraint and Spectrum Deficit if No New Spectrum is Made Available

To estimate the spectrum deficit, we use a model of supply and demand for macro network data capacity. Our data projections already exclude Wi-Fi offload.[60] To project macro network demand, we estimate the amount of traffic that will be carried by small cells, and remove that from our demand projections. We then calibrate the model assuming that network capacity will just meet demand in 2025. This assumption recognizes that, with several auctions in the past few years, there is, or shortly will be, more spectrum licensed than will be needed to meet near-term demand. That this current inventory of licensed spectrum will be exhausted by 2025 is based in part on judgement, but is informed by the recognition that 2025 provides the carriers two years to fully deploy the complete set of their licensed C-Band frequencies.

We use our calibrated model to project network capacity. This project takes into account improvements in spectrum efficiency, growth of cell sites, and the integration of licensed, but not yet deployed, spectrum into mobile networks. By comparing projected network capacity and demand, we can estimate any shortfalls in the ability of capacity to meet demand.[61] We then estimate how much additional spectrum is needed to make up that capacity shortfall.

We find that if no new spectrum bands are allocated for terrestrial mobile use in the next 5 years, then the U.S. is expected to have a capacity deficit of roughly 10 exabytes per month and a spectrum deficit of roughly 400 megahertz. In ten years, without new mobile spectrum, the capacity deficit will increase to almost 17 exabytes per month and the spectrum deficit will more than triple to approximately 1,400 megahertz. See Table 3 and Appendix C, Table C1.

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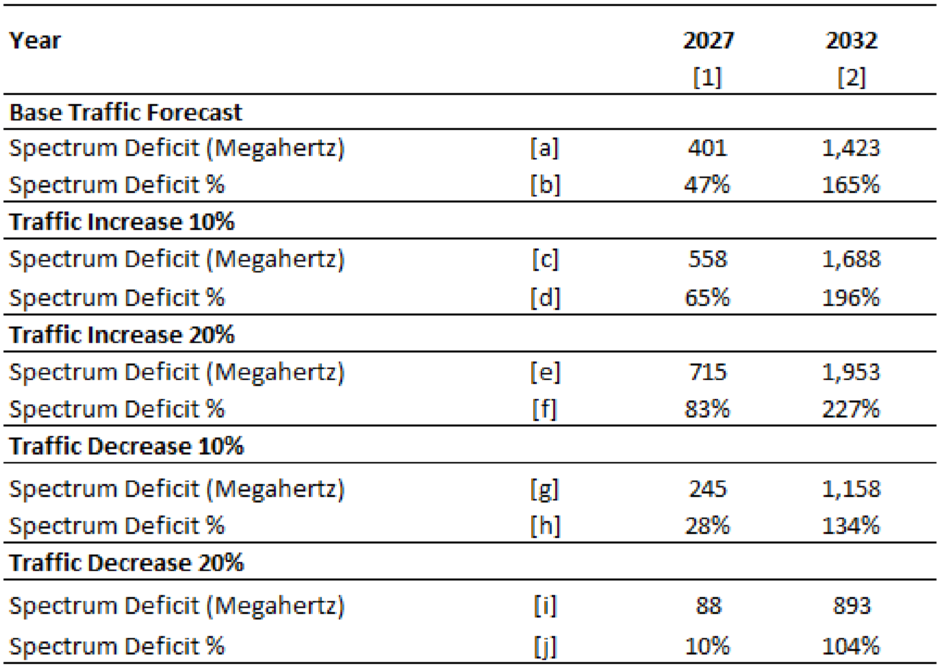
[60] As noted above in Section II.C, we assume that MVNO non-WiFi offload is carried via licensed spectrum and this does not reduce demand for that spectrum.

[61] Any projected network capacity surpluses do not cause any significant policy concerns.

B. The Effect of Demand Shock and New Spectrum Availability on Capacity Constraint and Spectrum Deficit

To understand the sensitivity of our model to various uncertainties, we calculate the spectrum deficit under alternative demand assumptions. Many factors can influence the spectrum deficit. Variations in macro network demand can come from many sources, such as analysts' expectations about the mobile traffic not being realized and the share of realized offload being higher or lower than expected. Similarly, supply expectations also contain uncertainty. For example, spectral efficiency could be higher or lower than predictions; technology transitions might not happen according to expectations, and macro and small cell growth could fall short or exceed our forecasts. Rather than modeling all these variations separately, we incorporate the uncertainties they represent into four broad scenarios – a ±10% and ±20% change in demand. A summary of the results is presented below in Table 3, and details are in presented in Appendix C Tables C1-C5.

TABLE 3: SPECTRUM DEFICIT AND SENSITIVITY TO DEMAND CHANGES



Year		**2027** [1]	**2032** [2]
Base Traffic Forecast			
Spectrum Deficit (Megahertz)	[a]	401	1,423
Spectrum Deficit %	[b]	47%	165%
Traffic Increase 10%			
Spectrum Deficit (Megahertz)	[c]	558	1,688
Spectrum Deficit %	[d]	65%	196%
Traffic Increase 20%			
Spectrum Deficit (Megahertz)	[e]	715	1,953
Spectrum Deficit %	[f]	83%	227%
Traffic Decrease 10%			
Spectrum Deficit (Megahertz)	[g]	245	1,158
Spectrum Deficit %	[h]	28%	134%
Traffic Decrease 20%			
Spectrum Deficit (Megahertz)	[i]	88	893
Spectrum Deficit %	[j]	10%	104%

Notes and Sources:
[a]-[b]: Table C1: Capacity and Spectrum Deficit in 5 and 10 years if no new Spectrum is Available in 2027 and 2032.
[c]-[d]: Table C2: Demand Increase 10%.
[e]-[f]: Table C3: Demand Increase 20%.
[g]-[h]: Table C4: Demand Decrease 10%.
[i]-[j]: Table C5: Demand Decrease 20%.

We conclude that even with a significant decrease in demand (or, equivalently, unexpected increase in supply), the current spectrum availability is not adequate. Even with a 20% decrease in demand, which all else being equal is highly unlikely, there is going to be a spectrum deficit in 2032 if no new spectrum is allocated to mobile uses. By contrast, a 20% *increase* in demand would obviously exacerbate the deficit and the follow-on, downstream negative effects. Given the possibility of accelerating data-intensive 5G applications such as fixed wireless home broadband access, AR/VR, aggregate IoT connections, or other unforeseen popular use cases, a 20% increase in demand is not an unreasonable possibility (particularly over the projected 10-year window).

V. Conclusion

Our analysis indicates that, given the pace of the demand growth, technological solutions and deploying more cell sites are insufficient to ease the capacity constraint currently facing the U.S. cellular networks. Spectrum availability is the key to solving the capacity shortfall and Congress, the FCC, and other policymakers should work to allocate more spectrum for licensed mobile uses in a timely manner. Otherwise, the U.S. may run the risk of losing leadership in the international wireless space due to unavailability of licensed spectrum.[62]

A lack of additional high-power licensed spectrum would have several effects throughout the wireless ecosystem. Wireless service is a highly competitive industry, with firms making massive investments to compete in providing as much value to consumers as possible. Without cost-effective means to increase capacity—additional spectrum—operators would have to effectively limit use of their network. Given the dynamic nature of wireless competition, it is difficult to anticipate exactly what form these limitations would take, but certainly consumers would face a less reliable, robust, or consistently improving experience than they have from mobile wireless networks today.

Fixed wireless access would likely be the first service to be impacted—already today home broadband over 5G is only offered in locations where operators have available capacity in the network to provide sufficient quality of service for a home connection. Without additional

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[62] *See, e.g.* for example: Janette Stewart, Chris Nickerson, Juliette Welham, "Comparison of Total Mobile Spectrum in Different Markets," Analysis Mason, CTIA, September, 2022, https://api.ctia.org/wp-content/uploads/2022/09/Comparison-of-total-mobile-spectrum-28-09-22.pdf. See also, "Data Demand is Causing Spectrum Deficit; What Can Operators Do?" RCR Wireless, May 5, 2021, last accessed December 9, 2022, https://www.rcrwireless.com/20210505/5g/data-demand-is-causing-spectrum-deficit-what-can-operators-do.

spectrum, fixed wireless access will not be able to reach its potential scale, limiting the opportunity for additional competition to be injected into the home broadband market.

Operators may also look to continue or further limit the data-intensity of specific applications, such as streaming video, or otherwise manage their networks to ration limited capacity. The long trend of declining prices for unlimited wireless service may slow or stall as operator turn to more expensive options to increase supply. In short, the progress toward wireless connectivity abundance would slow, with knock-on effects throughout the economy. Spectrum repurposing is a difficult and time-consuming process, and unfortunately there is not an adequate pipeline of spectrum anticipated to meet mobile demand today. Our analysis gives a glimpse of the stunted wireless future if policymakers do not act.

In five years, the U.S. is expected to have a spectrum deficit of about 400 megahertz, which could more than triple to approximately 1,400 megahertz over another five years, even accounting for optimistic improvements in spectral efficiency and new infrastructure deployment. Additional spectrum is the only realistic option for meeting this gap.

Appendices

Appendix A: Demand and Traffic Growth

We are interested in understanding long-term trends in traffic growth (2022 – 2032). However, the VNI data includes only five-year projections. For predicting traffic growth from 2023 – 2032, we use a combination of a projected CAGR and a regression analysis. We use the 2010-2022 Cisco mobile traffic data, which is comprised of actual data traffic forming the basis of each report from 2010 – 2018, as well as Cisco's 2018 forecasts for 2019 – 2022 North America traffic, as our baseline traffic numbers.[63] For the years 2023 – 2028, we use Ericsson's predicted 2022 – 2028 CAGR (23%) to generate forecasted traffic.[64] We then use the actual and predicted traffic data from 2010 – 2028 as the dependent variable in a regression analysis, predicting data traffic for 2029 – 2032 based on a quadratic time trend, a COVID indicator, and the previous year's population as covariates. The results are presented in Table A1.

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[63] See Cisco Annual Internet Report (2018–2023). *See also* Cisco VNI: Global Mobile Data Traffic Forecast Update.

[64] *See* Ericsson Mobility Report, November 2022, p. 39. The Cisco data is a little more conservative than the Ericsson data so we use it for our baseline of actual data usage. The Ericsson data have projections longer into the future, so we use the growth rates from those projections.

TABLE A1: NORTH AMERICAN MOBILE DATA TRAFFIC (ACTUALS AND FORECAST)

Year [1]	North America Mobile Data Traffic (PB/month) [2]
2010	49
2011	119
2012	222
2013	389
2014	563
2015	557
2016	1,411
2017	1,261
2018	1,804
2019	2,500
2020	3,405
2021	4,485
2022	5,846
2023	7,191
2024	8,844
2025	10,879
2026	13,381
2027	16,458
2028	20,244
2029	22,656
2030	26,148
2031	29,904
2032	33,918

Sources and Notes:
[B]: For 2010 data, *see,* "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015," Cisco, February 1, 2011, Table 9. For 2011 data, *see,* "Cisco Visual Networking Index: Forecast and Methodology, 2011-2016," Cisco, May 30, 2012, Table 16. For 2012 data, *see*, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012-2017,” February 6, 2013, Table 6. For 2013 data, *see,* "Cisco Visual Networking Index: Forecast and Methodology, 2013-2018," Cisco, June 10, 2014, Table 16. For 2014 data, *see,* "Cisco Visual Networking Index: Forecast and Methodology, 2014-2019," Cisco, May 27, 2015, Table 16. For 2015 data, *see*, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2020," Cisco, February 3, 2016, Table 5. For 2016 data, *see*, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021," Cisco, February 7, 2017, Table 4. For 2017-2022 data, *see*, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022," Cisco, February 2019, Table 3. Note that values for 2019-2022 are Cisco forecasts. Also, note that for years 2010, 2012, 2015, and 2016, values in source are given in TB per month, so they have been multiplied by .001 to convert to PB. Data for 2023-2032 were predicted using the regression methodology outlines in Appendix A.

Appendix B: Infrastructure

TABLE B1: FORECASTED AND ACTUAL CELL SITE GROWTH IN THE UNITED STATES 2022-2032

Year [1]	Total Cell Sites [2]	Macro Sites [3]	Small Cell [4]
2001	127,540	127,540	
2002	139,338	139,338	
2003	162,986	162,986	
2004	175,725	175,725	
2005	183,689	183,689	
2006	195,613	195,613	
2007	213,299	213,299	
2008	242,130	242,130	
2009	247,081	247,081	
2010	253,086	253,086	
2011	283,385	283,385	
2012	301,779	300,479	1,300
2013	304,360	302,960	1,400
2014	298,055	293,055	5,000
2015	307,626	298,626	9,000
2016	308,334	278,334	30,000
2017	323,448	271,448	52,000
2018	349,344	263,344	86,000
2019	395,562	295,562	100,000
2020	417,215	292,215	125,000
2021	418,887	292,887	126,000
2022		298,001	150,399
2023		303,205	179,522
2024		308,499	214,285
2025		313,886	255,779
2026		319,366	305,308
2027		324,943	364,428
2028		330,617	399,711
2029		336,390	438,412
2030		342,264	480,859
2031		348,240	527,415
2032		354,321	578,480

Sources and Notes:

[1]-[2]: CTIA 2022 Survey provides actuals for all cells from 2001-2021. For 2022 onwards, assume macro cells grow yearly at 20% of the 5-year CAGR, where the CAGR is 6.68%.

Appendix C: Calculating Spectrum Deficit Under Alternative Scenarios

TABLE CI: CAPACITY AND SPECTRUM DEFICIT IN 5 AND 10 YEARS IF NO NEW SPECTRUM IS AVAILABLE IN 2027 AND 2032

Year		**2022** [1]	**2027** [2]	**2032** [3]
Aggregate Demand For Capacity				
Data Traffic Forecast (PB/month)	[a]	5,846	16,458	33,918
Traffic Growth	[b]		282%	580%
Adjustments in Demand for Capacity				
Adjustment for Traffic on Small Cells				
Number of Small cell	[c]	150,399	364,428	578,480
Macro Cell Equivalent Small Cell Sites	[d]	15,040	36,443	57,848
Total Macro Cell Sites	[e]	298,001	324,943	354,321
Macro Cell + Macro Cell Equivalent Sites	[f]	313,041	361,386	412,169
Traffic on Small Cells (PB/month)	[g]	280.87	1,660	4,760
Small Cell & Wi-Fi Adjusted Traffic on Macro Cells (PB/month)	[h]	5,565	14,799	29,157
Adjusted Traffic Growth on Macro Cells	[i]		266%	524%
Supply Side Adjustments				
Spectral Efficiency				
Average Spectral Efficiency (bps/Hz)	[j]	4.28	5.74	6.13
Spectral Efficiency Growth	[k]	111%	134%	143%
Cell Sites				
Total Macro Cell Sites	[l]	298,001	324,943	354,321
Total Cell Site Growth	[m]		109%	119%
Spectrum				
Spectrum Licensed	[n]	1,081	1,840	2,010
Spectrum Available/ Usable	[o]	862	1,166	1,228
Deficit				
Traffic per Site Growth	[p]		244%	441%
Tech Adjusted Traffic/Site Growth	[q]		182%	308%
Excess Traffic After Technology & Infrastructure Adjustment (PB/month)	[r]		10,123	17,123
Total Spectrum Required	[s]		1,567	2,651
Spectrum Deficit	[t]		401	1,423
% Deficit	[u]		47%	165%

Sources and Notes:
[a]: North American Mobile Traffic (PB/month)
[b]: 2027: [a][2] / [a][1]; 2032: [a][3] / [a][1].
[c]: Forecasted and Actual Cell site Growth in the United States 2022-2032
[d]: [c] / 10; Note, we assume there are roughly 10 small cells per macro cell, hence the adjusted value.
[e]: Total Actual and Forecasted Macro Cell Sites.
[f]: [d] + [l].
[g]: ([a] / [f]) *[d].
[h]: [a] - [g].
[i]: 2027: [h][2] / [h][1]; 2032: [h][3] / [h][1].
[j]: Spectral Efficiency Table.
[k]: 2022: [j][1] / 3.87 (average spectral efficiency in 2021); 2027: [j][2] / [j][1]; 2032: [j][3] / [j][1].
[l]: Total Actual and Forecasted Macro Cell Sites.
[m]: 2027: [l][2] / [l][1]; 2032: [l][3] / [l][1].
[n]: Megahertz of Spectrum by Year Table.
[o]: Spectrum Deficit Model Table.
[p]: [i] / [m].
[q]: [p] / [k].
[r]: [q] * [h][1].
[s]: [o][1] * [q].
[t]: [s] - [o].
[u]:[t] / [o].

TABLE C2: DEMAND INCREASE 10%

Year		**2022** [1]	**2027** [2]	**2032** [3]
Aggregate Demand For Capacity				
Data Traffic Forecast (PB/month)	[a]	5,846	18,104	37,310
Traffic Growth	[b]		310%	638%
Adjustments in Demand for Capacity				
Adjustment for Traffic on Small Cells				
Number of Small cell	[c]	150,399	364,428	578,480
Macro Cell Equivalent Small Cell Sites	[d]	15,040	36,443	57,848
Total Macro Cell Sites	[e]	298,001	324,943	354,321
Macro Cell + Macro Cell Equivalent Sites	[f]	313,041	361,386	412,169
Traffic on Small Cells (PB/month)	[g]	280.87	1,826	5,236
Small Cell & Wi-Fi Adjusted Traffic on Macro Cells (PB/month)	[h]	5,565	16,278	32,073
Adjusted Traffic Growth on Macro Cells	[i]		293%	576%
Supply Side Adjustments				
Spectral Efficiency				
Average Spectral Efficiency (bps/Hz)	[j]	4.28	5.74	6.13
Spectral Efficiency Growth	[k]	111%	134%	143%
Cell Sites				
Total Macro Cell Sites	[l]	298,001	324,943	354,321
Total Cell Site Growth	[m]		109%	119%
Spectrum				
Spectrum Licensed	[n]	1,081	1,840	2,010
Spectrum Available/ Usable	[o]	862	1,166	1,228
Deficit				
Traffic per Site Growth	[p]		268%	485%
Tech Adjusted Traffic/Site Growth	[q]		200%	338%
Excess Traffic After Technology & Infrastructure Adjustment (PB/month)	[r]		11,135	18,835
Total Spectrum Required	[s]		1,724	2,916
Spectrum Deficit	[t]		558	1,688
% Deficit	[u]		65%	196%

Sources and Notes:
See Table C1

TABLE C3: DEMAND INCREASE 20%

Year		**2022** [1]	**2027** [2]	**2032** [3]
Aggregate Demand For Capacity				
Data Traffic Forecast (PB/month)	[a]	5,846	19,750	40,701
Traffic Growth	[b]		338%	696%
Adjustments in Demand for Capacity				
Adjustment for Traffic on Small Cells				
Number of Small cell	[c]	150,399	364,428	578,480
Macro Cell Equivalent Small Cell Sites	[d]	15,040	36,443	57,848
Total Macro Cell Sites	[e]	298,001	324,943	354,321
Macro Cell + Macro Cell Equivalent Sites	[f]	313,041	361,386	412,169
Traffic on Small Cells (PB/month)	[g]	280.87	1,992	5,712
Small Cell & Wi-Fi Adjusted Traffic on Macro Cells (PB/month)	[h]	5,565	17,758	34,989
Adjusted Traffic Growth on Macro Cells	[i]		319%	629%
Supply Side Adjustments				
Spectral Efficiency				
Average Spectral Efficiency (bps/Hz)	[j]	4.28	5.74	6.13
Spectral Efficiency Growth	[k]	111%	134%	143%
Cell Sites				
Total Macro Cell Sites	[l]	298,001	324,943	354,321
Total Cell Site Growth	[m]		109%	119%
Spectrum				
Spectrum Licensed	[n]	1,081	1,840	2,010
Spectrum Available/ Usable	[o]	862	1,166	1,228
Deficit				
Traffic per Site Growth	[p]		293%	529%
Tech Adjusted Traffic/Site Growth	[q]		218%	369%
Excess Traffic After Technology & Infrastructure Adjustment (PB/month)	[r]		12,148	20,547
Total Spectrum Required	[s]		1,881	3,181
Spectrum Deficit	[t]		715	1,953
% Deficit	[u]		83%	227%

Sources and Notes:
See Table C1

TABLE C4: DEMAND DECREASE 10%

Year		2022 [1]	2027 [2]	2032 [3]
Aggregate Demand For Capacity				
Data Traffic Forecast (PB/month)	[a]	5,846	14,812	30,526
Traffic Growth	[b]		253%	522%
Adjustments in Demand for Capacity				
Adjustment for Traffic on Small Cells				
Number of Small cell	[c]	150,399	364,428	578,480
Macro Cell Equivalent Small Cell Sites	[d]	15,040	36,443	57,848
Total Macro Cell Sites	[e]	298,001	324,943	354,321
Macro Cell + Macro Cell Equivalent Sites	[f]	313,041	361,386	412,169
Traffic on Small Cells (PB/month)	[g]	280.87	1,494	4,284
Small Cell & Wi-Fi Adjusted Traffic on Macro Cells (PB/month)	[h]	5,565	13,319	26,242
Adjusted Traffic Growth on Macro Cells	[i]		239%	472%
Supply Side Adjustments				
Spectral Efficiency				
Average Spectral Efficiency (bps/Hz)	[j]	4.28	5.74	6.13
Spectral Efficiency Growth	[k]	111%	134%	143%
Cell Sites				
Total Macro Cell Sites	[l]	298,001	324,943	354,321
Total Cell Site Growth	[m]		109%	119%
Spectrum				
Spectrum Licensed	[n]	1,081	1,840	2,010
Spectrum Available/ Usable	[o]	862	1,166	1,228
Deficit				
Traffic per Site Growth	[p]		219%	397%
Tech Adjusted Traffic/Site Growth	[q]		164%	277%
Excess Traffic After Technology & Infrastructure Adjustment (PB/month)	[r]		9,111	15,410
Total Spectrum Required	[s]		1,410	2,386
Spectrum Deficit	[t]		245	1,158
% Deficit	[u]		28%	134%

Sources and Notes:
See Table C1

TABLE C5: DEMAND DECREASE 20%

Year		**2022** [1]	**2027** [2]	**2032** [3]
Aggregate Demand For Capacity				
Data Traffic Forecast (PB/month)	[a]	5,846	13,167	27,134
Traffic Growth	[b]		225%	464%
Adjustments in Demand for Capacity				
Adjustment for Traffic on Small Cells				
Number of Small cell	[c]	150,399	364,428	578,480
Macro Cell Equivalent Small Cell Sites	[d]	15,040	36,443	57,848
Total Macro Cell Sites	[e]	298,001	324,943	354,321
Macro Cell + Macro Cell Equivalent Sites	[f]	313,041	361,386	412,169
Traffic on Small Cells (PB/month)	[g]	280.87	1,328	3,808
Small Cell & Wi-Fi Adjusted Traffic on Macro Cells (PB/month)	[h]	5,565	11,839	23,326
Adjusted Traffic Growth on Macro Cells	[i]		213%	419%
Supply Side Adjustments				
Spectral Efficiency				
Average Spectral Efficiency (bps/Hz)	[j]	4.28	5.74	6.13
Spectral Efficiency Growth	[k]	111%	134%	143%
Cell Sites				
Total Macro Cell Sites	[l]	298,001	324,943	354,321
Total Cell Site Growth	[m]		109%	119%
Spectrum				
Spectrum Licensed	[n]	1,081	1,840	2,010
Spectrum Available/ Usable	[o]	862	1,166	1,228
Deficit				
Traffic per Site Growth	[p]		195%	353%
Tech Adjusted Traffic/Site Growth	[q]		146%	246%
Excess Traffic After Technology & Infrastructure Adjustment (PB/month)	[r]		8,098	13,698
Total Spectrum Required	[s]		1,254	2,121
Spectrum Deficit	[t]		88	893
% Deficit	[u]		10%	104%

Sources and Notes:
See Table C1