EMERGING TECHNOLOGIES AND THEIR EXPECTED IMPACT ON NON-FEDERAL SPECTRUM DEMAND

May 2019

Mr. President:

Wireless technology has the power to drive our economy, protect national security, and improve the lives of Americans in ways that are still being discovered. As a result of our Nation's leadership in 4G, we increased GDP by $100 billion in 2016, created more jobs, lowered consumer costs, and ensured that the United States was the home to the entrepreneurial revolution of advanced wireless applications.

5G networks can move massive amounts of data at exponentially faster speeds than existing 4G LTE networks, and will ensure American job growth, improve national security, and ensure American technological leadership in the 21st century. However, as our nation continues to innovate and create devices that are more capable, the demand for spectrum increases as well. To reap the benefits of 5G and the networks of the future, the Nation must have a forward-looking strategic policy to make spectrum use more efficient and make more spectrum available.

In your October 25, 2018 Presidential Memorandum, "Developing a Sustainable Spectrum Strategy for America's Future," you directed The White House Office of Science and Technology Policy to develop a report on emerging technologies and their expected impact on non-Federal spectrum demand. The attached report examines the foundation of 5G technologies and the critical importance of leveraging such technologies to expedite rollout of 5G networks, details the spectrum requirements of 5G and Wi-Fi, and reviews recent and ongoing activities across the government to meet the spectrum demand.

As you noted during the State of the Union address, the United States must "deliver new and important infrastructure investment, including investments in the cutting-edge industries of the future. This is not an option. This is a necessity." Leadership in the industries of the future, including artificial intelligence, quantum information science, 5G, advanced manufacturing, and space commerce, will be central to this Administration's economic, security, and infrastructure priorities.

The focus of this report is on emerging technologies in wireless networks, specifically 5G and Wi-Fi, and ensuring that America expeditiously reaps the benefits of the revolutionary impact that 5G is expected to have across industrial sectors and society in general.

5G will allow the connectivity necessary for autonomous vehicles to communicate, create improvements in technological innovations to improve manufacturing, and provide vast datasets for interpretation by quantum computers. The effects of 5G networks will be transformative, and facilitate American innovation in unprecedented levels. From smart cities to connected farms, Americans' entrepreneurship and innovation will utilize 5G connectivity and data rates to exponentially enhance our Nations technological leadership.

However, to ensure near and long-term success in 5G, our Nation must ensure access to adequate spectrum capacity and utilize new and innovative methods of spectrum use. The private sector plays a central role in the rollout of 5G technology, but the goal of reaching 5G first cannot be attained without partnership with the Federal government. Through investment in R&D for next generation capabilities, ensuring efficient allocation and use of spectrum, and removing regulatory barriers, the Government plays a critical role in 5G deployment. Through such an approach, we can maintain our Nation's global leadership in wireless technologies and the industries of the future.

Sincerely,

Michael Kratsios
Deputy Assistant to the President for Technology Policy

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Executive Summary

The Presidential Memorandum of October 25, 2018, "Developing a Sustainable Spectrum Strategy for America's Future," calls for the development of a National Spectrum Strategy. The development of the strategy is to be informed by three interim products, one of which is a report on emerging technologies and their expected impact on non-Federal spectrum demand, to be submitted to the President by the Director of the Office of Science and Technology Policy (OSTP) or the Director's designee. The purpose of this paper is to assist OSTP in developing the required report.

Fifth Generation (5G) Wireless Technology

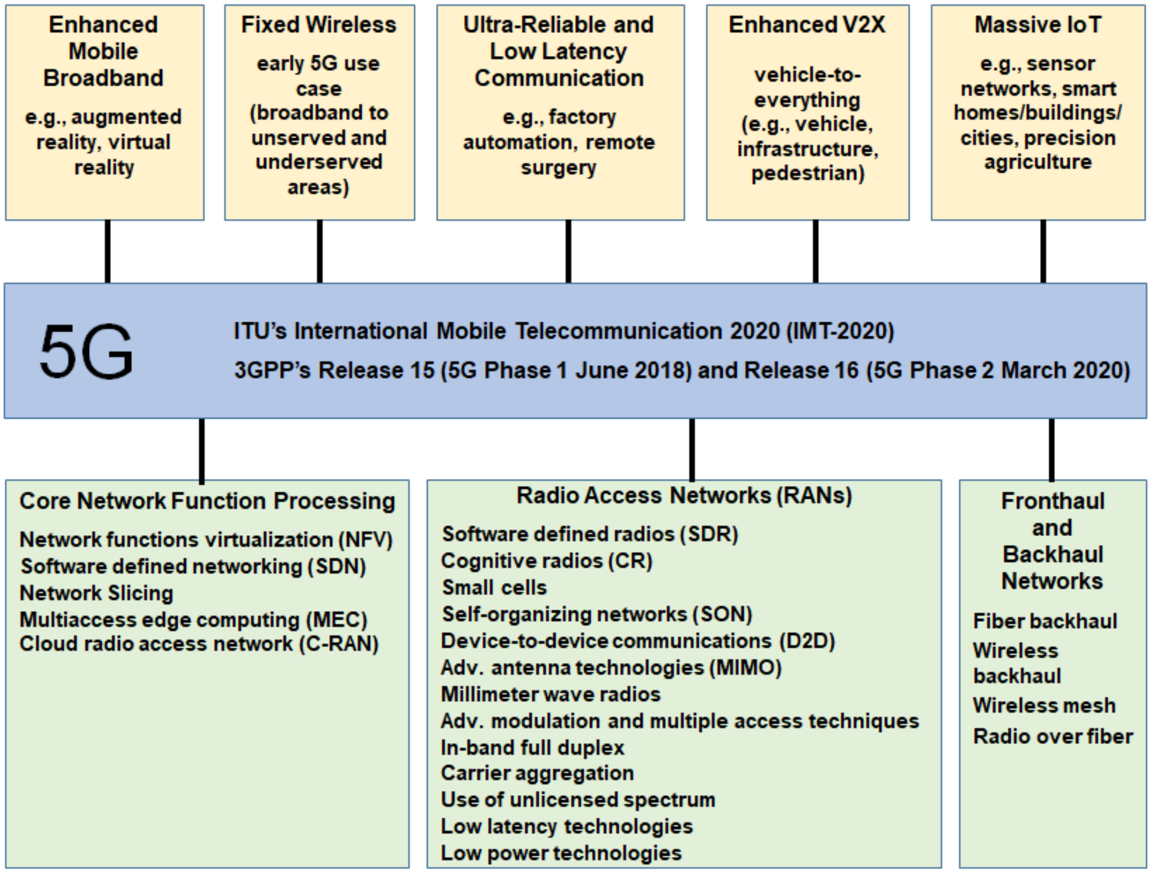
This study assesses the potential impact on spectrum demand of emerging 5G wireless technology and 5G enable applications, which is recognized by the Trump Administration as one of four "Industries of the Future" that will ensure American prosperity and national security. 5G is expected to be revolutionary in its impact. It will enhance mobile broadband performance with an order of magnitude increase in speed, which will enable new classes of applications—such as augmented reality and virtual reality—to emerge in offices, classrooms, museums, sports events, and retail premises. 5G will also accommodate crowd densities at the scale of Super Bowls and support broadband access for users moving at the speed of express trains. Moreover, 5G will enable applications—such as self-driving cars, factory automation, and remote surgery—that require ultra-high reliability and low latency. In addition, 5G will enable the world of the Internet of Things (IoT)—which will lay the foundation for smart homes, smart buildings, smart cities, precision agriculture, and more.

5G Standardization Status. 5G is the subject of international standardization activities led by the International Telecommunication Union (ITU) and the 3rd Generation Partnership Project (3GPP). ITU, which designates 5G as International Mobile Telecommunication 2020 (IMT-2020), laid out a vision for IMT-2020 in 2015 and has been developing and refining requirements for IMT-2020 since then. The ITU goal is to have an approved IMT-2020 standard in the year 2020.

The 3rd Generation Partnership Project (3GPP) is developing detailed specifications for 5G. 3GPP's Release 16, to be completed in early 2020, is expected to be fully compliant with IMT-2020 and to be approved by the ITU as an IMT-2020 standard. In the meantime, 3GPP has released a series of specifications in advance of Release 16. These releases are facilitating early 5G deployments and reducing risk for the full-scale 5G rollout. As in the case of LTE—which moved from LTE in 3GPP Releases 8 and 9, to LTE Advanced in Releases 10 through 12, to LTE Advanced Pro in Releases 13 and 14—3GPP will continue to add enhancements to 5G even after Release 16 is completed.

5G Deployment Status. In the U.S., carriers began rolling out 5G fixed wireless services and initial 5G mobile services in late 2018. For example, Verizon launched Verizon 5G Home, which uses its spectrum in the 28 gigahertz (GHz) band, in selected cities; and AT&T began rolling out 5G mobile services, using its spectrum in the 39 GHz band, in selected cities. 2019 will see additional launches of mobile 5G services in selected cities, including (1) Verizon's rollout of its 5G Ultra Wideband service, using its spectrum in the 28 GHz band; (2) Sprint's rollout of its mobile 5G network, using its spectrum in the 2.5 GHz band; and (3) T-Mobile' s rollout of its mobile 5G network, using its spectrum in the 600 megahertz (MHz) band. 2019 will also see the debut of 5G mobile phones, such as the Samsung Galaxy S10. Then, in 2020, the carriers will accelerate their 5G deployments, and Apple will offer a 5G iPhone.

5G-Enabled Technologies. As illustrated in the figure below, 5G will enable whole new classes of applications and use cases, which we refer to as *enabled technologies*.

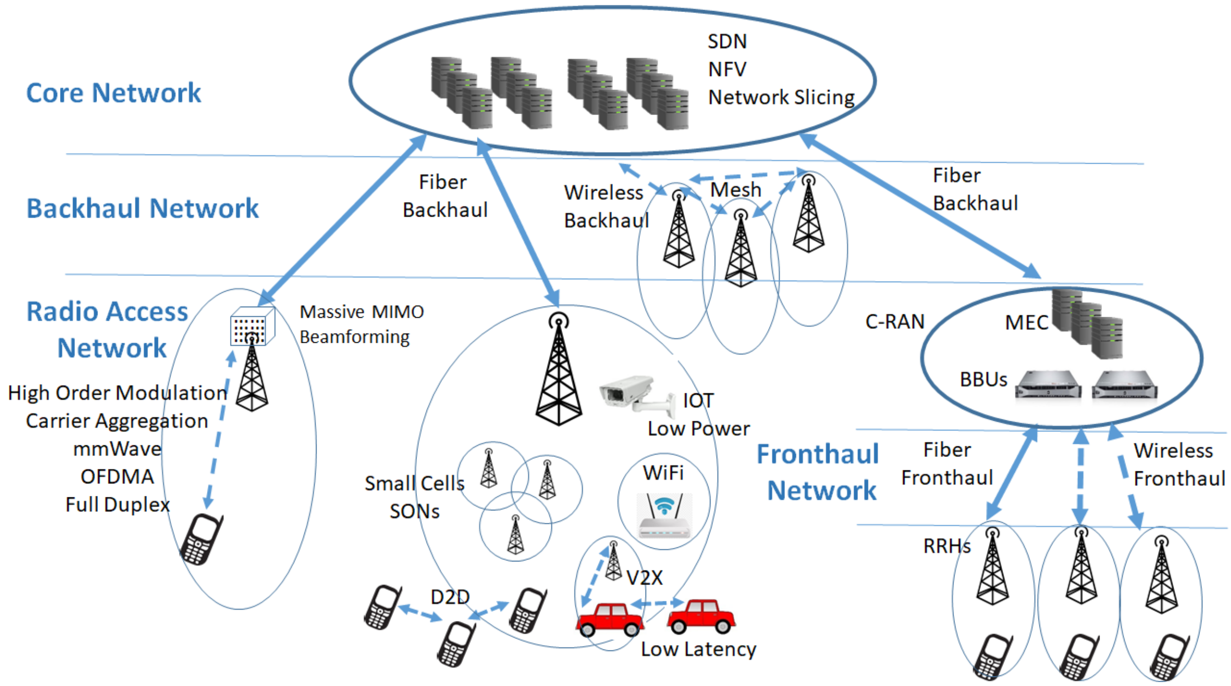


5G, 5G-Enabled Technologies (top), and 5G-Enabling Technologies (bottom)

Early work in the ITU laid out a vision of three broad classes of use cases for 5G: (1) enhanced mobile broadband; (2) ultrareliable and low latency communications; and (3) massive machine type communications, also known as massive IoT. More recently, two additional broad classes of use cases have been added to the discussion: (1) fixed wireless, an early 5G use case already being rolled out; and (2) enhanced vehicle-to-everything (V2X), a high-profile motivator for advanced 5G capabilities.

5G is expected to vastly outperform 4G. The improvements cover at least eight dimensions: (1) peak data rate, (2) user experienced data rate, (3) area traffic capacity, (4) spectrum efficiency, (5) mobility, (6) latency, (7) connection density, and (8) network energy efficiency. The identified use cases are driving research and development activities, as well as the standardization activities taking place in the ITU and 3GPP.

5G-Enabling Technologies. The challenges posed by the demanding use cases described above are being addressed by three categories of enabling technologies: (1) core network function processing, (2) backhaul and fronthaul networks, and (3) radio access networks. An architectural view of how these technologies work together is provided below. Arguably, the properties that most distinguish 5G from its predecessors are its flexibility and adaptability, which are required to meet the needs of the diverse applications that 5G is intended to support. The core network technologies that support these properties include software defined networking (SDN), network functions virtualization (NFV), network slicing, multi-access edge computing (MEC), and cloud radio access networks (C-RAN).



Architectural View of 5G-Enabling Technologies

Wi-Fi Role

Wi-Fi has been and remains a linchpin communications technology. According to Cisco, approximately half of all IP traffic is expected to be carried by Wi-Fi in 2022. In addition, well over half of the data traffic from mobile devices is expected to be offloaded to Wi-Fi. Thus, Wi-Fi is tightly coupled to 5G. Wi-Fi offloading of mobile traffic enables cellular networks to maintain their high data rates, not having to accommodate all the additional traffic they would otherwise face. With respect to the 5G-enabled technologies, Wi-Fi is expected to play a key role in forthcoming 5G fixed wireless services, with the cellular signal being converted to a Wi-Fi signal for delivery to the host of Wi-Fi-enabled devices on which individuals and corporations have come to rely. Moreover, 5G is being designed to make more use of unlicensed spectrum than previous generations of mobile wireless technology did, and to better integrate and coexist with Wi-Fi systems.

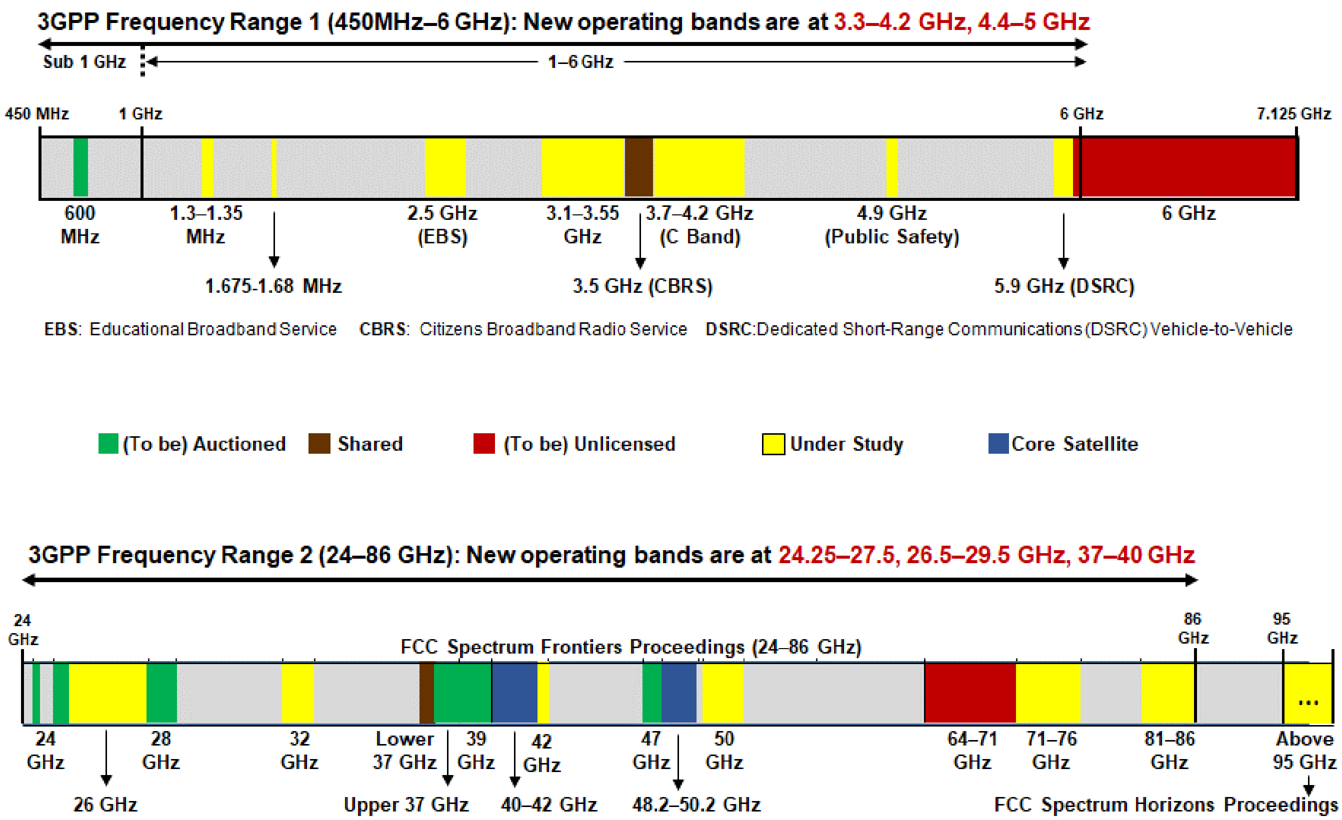
Satellite Role

To deploy 5G ubiquitously, the satellite transport conduit can and must be integrated into the overall available 5G architecture. Satellite technology has been included into 5G standards and will become an integral part of 5G.

Spectrum Demand

5G is expected to leverage millimeter wave bands at 24–86 GHz for applications requiring very high data rates. Low bands, below 1 GHz, will be leveraged for coverage. Mid bands, between 1 GHz and 6 GHz, which are highly sought after for their ability to offer both high data rates and good coverage, will bridge the gap between low bands and high bands. Due to unabated Wi-Fi growth, there is also demand for more unlicensed spectrum.

The figure on the next page provides a summary of recent activities—specifically, activities in 2016 and later—undertaken by the Federal Communications Commission (FCC) and NTIA in support of meeting commercial demands of 5G and Wi-Fi for spectrum. Existing FCC licenses and allocations can be employed to support 5G, as the industry "refarms" spectrum holdings and evolve networks from 3G and LTE to 5G. The FCC has made at least 715.5 megahertz of licensed spectrum below 3 GHz available for mobile wireless, with well over a gigahertz of spectrum licensed in higher bands that include fixed applications. Completed or in-process actions are adding 23,784 megahertz of spectrum to the market with more on the way:



- *Incentive auction.* The FCC concluded the 600 MHz auction—its first-ever incentive auction—in March 2017. The auction repurposed 84 megahertz of broadcasters' spectrum: 70 megahertz for licensed use and 14 megahertz for wireless microphones and unlicensed use.[1]
- *Millimeter wave band auctions.* The 28 GHz auction concluded in January 2019, and the 24 GHz auction kicked off in March 2019. The auction of the Upper 37 GHz, 39 GHz, and 47 GHz bands is expected to take place in 2019. Together the millimeter wave band auctions will make 4,950 megahertz available for 5G through the FCC's newly defined upper microwave flexible use service.

Recent FCC and NTIA Actions in Potential 5G Operating Bands

- *Shared bands.* The FCC defined an innovative three-tiered sharing scheme for the 3.5 GHz Citizens Broadband Radio Service (CBRS) band (150 megahertz of spectrum) in 2015, and it recently made some changes to the service to make it more viable for 5G. The FCC plans to demonstrate innovative spectrum sharing in the Lower 37 GHz band (600 megahertz of spectrum).
- *Unlicensed bands.* The FCC is heading toward allowing unlicensed access to 1200 megahertz of spectrum in the 6 GHz band, with protection for incumbents. The FCC has also provided for unlicensed access in the 64-71 GHz band. Together with the existing 57-64 GHz unlicensed band, this means that 14 gigahertz of millimeter wave spectrum are available for unlicensed access.
- *Core satellite bands.* In the context of 5G deliberations, the FCC has declared the 40-42 GHz and 48.2-50.2 GHz bands (4 gigahertz of spectrum total) to be core satellite bands.
- *Additional millimeter waves under consideration.* The FCC is considering additional millimeter wave bands-26 GHz, 32 GHz, 42 GHz, 50 GHz, 71-76 GHz, and 81-86 GHz-for 5G. Together, these bands total 16.15 gigahertz of spectrum.

As previously noted, mid band spectrum is highly sought after by 5G proponents, but the mid bands also have incumbents who value the spectrum:

- *2.496-2.69 GHz (Educational Broadband Service (EBS) band)*, 194 megahertz of spectrum. Use of this band has been strictly limited since 1995, but it is being considered by the FCC for more flexible use. Some educational institutions are advocating to keep it dedicated to educational purposes.
- *3.7-4.2 GHz (C band)*, 500 megahertz of spectrum. Globally, this is a leading 5G band, and so 5G stakeholders are advocating for at least a portion of it to be made available for commercial mobile service. In the U.S., the C Band Alliance of satellite incumbents came together to ensure that incumbents are protected.
- *4.9 GHz band (public safety band)*, 50 megahertz of spectrum. This band has been dedicated to public safety use since 2002 but is now being considered by the FCC for more flexible use. Public safety incumbents, as well as critical infrastructure stakeholders, are advocating for it to remain dedicated to their needs.
- *5.9 GHz band (Dedicated Short Range Communication (DSRC) band)*, 75 megahertz of spectrum. The 5.9 GHz band has been allocated for DSRC Vehicle-to-Everything (V2X), a short range communications service built on the IEEE 802.11 standard to support transportation safety. Significant differences from the IEEE 802.11 standard are to support high speed vehicles (closing speed greater than 150 mph), and a broadcast mode to reduce latency to near zero. The last action by the FCC was in 2006. DSRC V2V has been joined by another technology, Cellular Vehicle-to-Everything (C-V2X). The issue before the FCC is whether to allocate then band entirely to one or the

[1] This paper generally follows the convention of using abbreviations for band names and band boundaries: "GHz" for "gigahertz" and "MHz" for "megahertz." It spells out "gigahertz" and "megahertz" when talking about the width of a band or a quantity of spectrum.

other of these technologies with full interoperability, or to allow for certain channels to be dedicated to each technology to provide for a secure redundant system. Testing is currently underway to examine the safety impacts of the UNII sharing the band with DSRC.

- *1.3-1.35 MHz, 1.675-1.68 MHz, 3.1-3.55 MHz bands*. These bands have Federal incumbents who must be protected. However, in accordance with direction received from Congress in the Spectrum Pipeline Act of 2015 and the MOBILE NOW Act of 2018, NTIA is studying the bands and evaluating them for potential use, possibly on a shared basis, by commercial wireless systems.

Spectrum Management Challenge. As indicated above, the FCC and the NTIA are working to ensure that spectrum is available to sustain Wi-Fi growth and to facilitate 5G deployments. Congress and the Trump Administration are committed to making sure that the United States wins the race to 5G and secures the attendant economic gains. Globally, the bands most referenced for initial 5G deployments lie in the 3.3–4.2 GHz range, as well as in the millimeter wave bands. That is why, in the United States, mid-band spectrum—especially the 3.55–3.7 GHz CBRS band and the 3.47–4.2 GHz C band—are in such high demand by 5G stakeholders. The FCC and the NTIA have challenging work ahead as they seek to balance the needs of incumbents—both Federal and commercial—with the demands of 5G and Wi-Fi. Fortunately, analysis of these federal efforts reflect significant spectrum allocation for wireless terrestrial services to date, with much more planned for 5G upon completion of pending FCC and NTIA activities.

1. Introduction

Background

The Presidential Memorandum ("PM") of October 25, 2018, "Developing a Sustainable Spectrum Strategy for America's Future," calls for the development of a National Spectrum Strategy. As stated in Section 1 of the PM, the motivation behind the development of the strategy is two-fold—to enable economic activity and protect national security:

> *Wireless communications and associated data applications establish a foundation for high-wage jobs and national prosperity…. [E]ach technological leap also increases demands on [the usage of spectrum]. Those demands have never been greater than today, with the advent of autonomous vehicles and precision agriculture, the expansion of commercial space operations, and the burgeoning Internet of Things…. Moreover, it is imperative that America be first in fifth-generation (5G) wireless technologies – wireless technologies capable of meeting the high-capacity, low latency, and high-speed requirements that can unleash innovation broadly across diverse sectors of the economy and the public sector….*
>
> *The Nation can and will ensure security and safety through modern technology. America's national security depends on technological excellence and the U.S. Government must continue to have access to the spectrum resources needed to serve the national interest, from protecting the homeland and managing the national airspace, to forecasting severe weather and exploring the frontiers of space.*

According to the PM (Section 4), the National Spectrum Strategy is to include legislative, regulatory, or other policy recommendations to (1) increase spectrum access, including on a shared basis; (2) create flexible models for spectrum management; (3) use ongoing research, development, testing, and evaluation to develop advancements that increase spectrum access, efficiency, and effectiveness; (4) build a secure, automated capability to facilitate spectrum coordination and sharing; and (5) improve the global competitiveness of U.S. industries and augment the mission capabilities of Federal entities. The Secretary of Commerce, working through the National Telecommunications and Information Administration (NTIA) and in consultation with the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), the Federal Communications Commission (FCC), and other Federal entities, is responsible for submitting the National Spectrum Strategy to the President within 270 days of the date of the memorandum.

The development of the National Spectrum Strategy is to be informed by three interim products, identified in Section 2 of the Presidential Memorandum, which are each due within 180 days of the date of the PM:

1. Reports on anticipated future spectrum requirements of Executive departments and agencies, submitted to the Secretary of Commerce, through the NTIA, by the departments and agencies;
2. A report on emerging technologies and their expected impact on non-Federal spectrum demand, submitted to the President by the Director of the Office of Science and Technology Policy (OSTP) or the Director's designee; and
3. A report on recommendations for research and development priorities that advance spectrum access and efficiency, submitted to the President by the Director of OSTP or a designee of the Director.

Section 5 of the PM establishes a Spectrum Strategy Task Force, co-chaired by the Chief Technology Officer and the Director of the National Economic Council, or their designees, to work with the Secretary of Commerce and the NTIA in coordinating implementation of the memorandum. The Task Force is to include representatives from the OMB, OSTP, the National Security Council, the National Space Council, and the Council of Economic Advisors and is to consult with the FCC.

Purpose

Section 2(b) of the PM directs OSTP to submit to the President a report on emerging technologies and their expected impact on non-Federal spectrum demand. OSTP asked the IDA Science and Technology Policy Institute (STPI) to support the development of the required report by researching and summarizing the impact of 5G and related technologies on spectrum demand. The purpose of this paper is to respond the second interim report required by the PM.

Scope

This study focuses on the emerging technology Fifth Generation (5G) wireless technology. 5G is anticipated to have a revolutionary impact across industrial sectors and society in general. 5G is recognized by the Trump Administration as one of four "Industries of the Future"[2] that will ensure American prosperity and national security. The other three are artificial intelligence, advanced manufacturing, and quantum information science.

This report covers 5G, 5G-enabling technologies, and the applications and use cases that 5G in turn enables. It also covers Wi-Fi technologies, which are closely coupled to 5G and which are, in fact, projected to carry almost half the IP traffic in the U.S. within the next few years. The report examines spectrum demand of 5G and Wi-Fi, and it describes recent and ongoing activities—in Congress, at the Federal Communications Commission (FCC), and at the National Telecommunications and Information Administration (NTIA)—to meet the spectrum demand and ensure U.S. leadership in these important technologies.

In keeping with the assignment made in the Presidential Memorandum, this report focuses on non-Federal spectrum demand. The NTIA and Federal agencies are responsible for examining Federal demand.

Approach

The STPI team conducted an extensive review of the documentation available from the standards development organizations driving 5G and Wi-Fi. The team also reviewed (1) pending and enacted legislation; (2) recent FCC rulemakings; (3) statements from the FCC Chair and Commissioners; (4) statements from the Department of Commerce Assistant Secretary for Communications and Information and other information available on the NTIA website, including responses to a request for comments on the national spectrum strategy called for in the Presidential Memorandum; and (5) material emanating from recent symposia and conferences related to communications technologies. In addition, the team consulted subject matter experts in the Government and in industry associations, and it reviewed the academic literature as well as the trade press.

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[2] https://www.whitehouse.gov/briefings-statements/america-will-dominate-industries-future/

2. Emerging Wireless Technologies

In this chapter, we provide an overview of 5G and the underlying technologies that enable its capabilities. We also describe the latest Wi-Fi technologies.

5G Wireless Technologies

Introduction and Key Requirements

5G is the emerging next generation of mobile communications that will improve current systems and services by offering, among other things, increased data rates (up to 20 Gbps), lower latency, and better mobility (ITU 2018b). It will also broaden the scope of mobile communications to include new sets of applications such as Internet of Things, connected vehicles, and others.

Figure 1 summarizes the projected improvement of 5G, designated "IMT-2020" (ITU 2015a), over 4G, designated "IMT-Advanced" (ITU 2018a), along eight key dimensions.

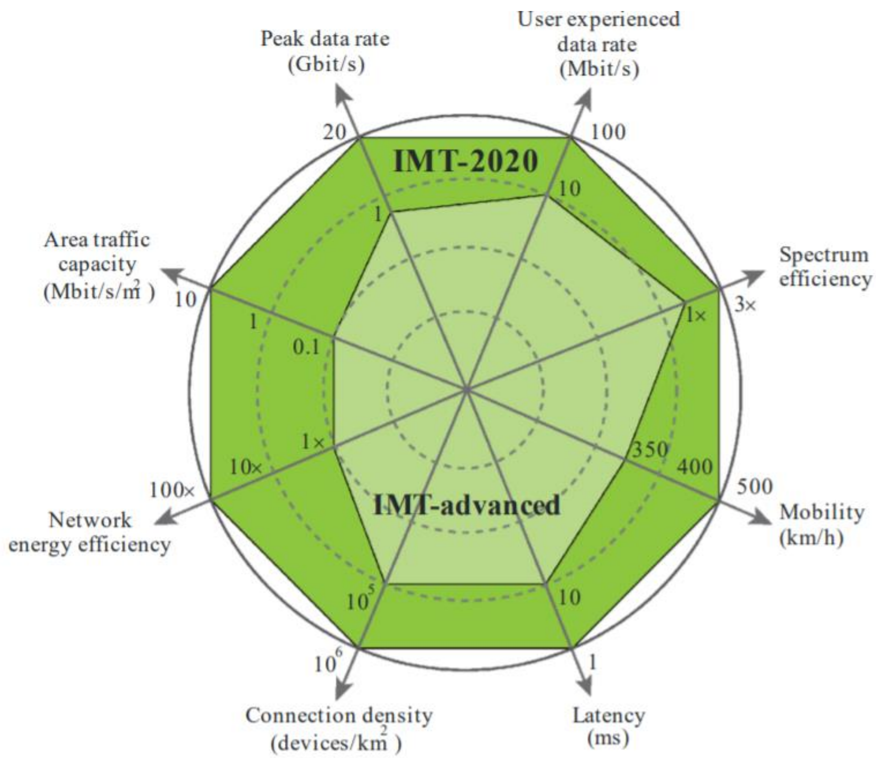


Figure 1. Improvement of 5G (IMT-2020) over 4G (IMT-Advanced)

Table 1 provides required values for several performance parameters in more detail.

Table 1. Minimum Performance Requirements for IMT-2020 Radio Interfaces

Parameter	Comments	Requirement
Peak Data Rate	Achievable under ideal conditions	20 Gbps downlink; 10 Gbps uplink
User-Experienced Data Rate	Ubiquitously achievable data rate. Corresponds to 5% point of cumulative distribution function of user throughput	100 Mbps downlink; 50 Mbps uplink
Peak Spectral Efficiency	Maximum data rate under ideal conditions normalized by channel bandwidth	30 bps/Hz downlink; 15 bps/Hz uplink
5th Percentile User Spectral Efficiency	5% point of cumulative distribution function of user throughput normalized by channel bandwidth	0.3 bps/Hz downlink; 0.21 bps/Hz uplink (Indoor Hotspot) 0.225 bps/Hz downlink; 0.15 bps/Hz uplink (Dense Urban) 0.12 bps/Hz downlink; 0.045 bps/Hz uplink (Rural)
Average Spectral Efficiency	Average data throughput per unit of spectrum resource per cell	9 bps/Hz/cell downlink; 6.75 bps/Hz/cell uplink (Indoor Hotspot) 7.8 bps/Hz/cell downlink; 5.4 bps/Hz/cell uplink (Dense Urban) 3.3 bps/Hz/cell downlink; 1.6 bps/Hz/cell uplink (Rural)
Area Traffic Capacity	Total traffic throughput served per geographic area. Thus far ITU-R has defined this objective only for the indoor hotspot case.	10 Mbps/m^2 downlink
User Plane Latency	Contribution of the radio network to the time lag from when the source sends a packet to when the destination receives it	4 ms for eMBB(*) services 1 ms for URLCC(*) services
Control Plane Latency	Transition time between idle state to active state	<20 ms (10 ms encouraged)
Connection Density	Total number of connected and/or accessible devices per unit area	1,000,000 devices per km^2 for mMTC(*) services
Energy Efficiency	Not specified precisely: air interfaces must support a high sleep ratio and long sleep duration	
Reliability	Success probability of transmitting a packet by a given deadline	99.999% probability of success in transmitting 32-byte packet in 1 ms
Mobility	Maximum speed of moving user at which a defined quality of service and seamless transfer between radio nodes can be achieved.	0.45 bps/Hz normalized traffic channel uplink data rate when moving at 500 km/hr (rural environment)
Mobility Interruption Time	Time during which device cannot exchange data packets because of handoff procedures	0 ms—connection to new cell must be made before old one is dropped
Bandwidth	Maximum aggregated system bandwidth	At least 100 megahertz, up to 1 gigahertz for bands above 6 GHz

* eMBB = Enhanced Mobile Broadband, URLCC = Ultra-reliable and low latency communications, mMTC = Massive Machine Type Communications

Source: Adapted from El Ayoubi, et al. 2018 (based on information in ITU 2017a)

Generations of Mobile Communications

To place 5G in perspective, it is useful to describe previous generations of wireless mobile communications systems. In brief, these are (adapted from a summary by Safdar, Ali, and Rehman 2018):

- *1G (First Generation)*. This cellular telephony system was known as AMPS (Advanced Mobile Radio System) and mostly provided analog voice communication over a radio frequency with fairly large handsets communicating through base stations. 1G was first implemented in North America in the early 1980s and saw widespread consumer use in the 1990s. The equivalent achievable data rate of 1G technology was 14.4 kilobits per second (kbps).
- 2G (Second Generation). 2G was based on GSM (Global System for Mobile Communication), a digital cellular system using a type of time division multiple access (TDMA) technology. 2G allowed for digital voice and data transmission. It saw widespread global use beginning in the late 1990s and early 2000s.
- Interim Generations between 2G and 3G. There were two “bridging” systems between 2G and 3G mobile communications systems. These are sometimes dubbed “2.5G” and “2.75G.”
  - *2.5G*. This involved GPRS (Generalized Packet Radio Service), which superimposed a packet-switched air interface for data on the GSM system. 2.5G allowed for mobile connections to the Internet and data rates of 40 kbps.
  - *2.75G*. This involved a technology called EDGE (Enhanced Data Rates for GSM Evolution). It allowed faster data rates of up to 500 kbps.
- *3G (Third Generation)*. This generation enabled services such as web browsing, multimedia, and navigation. It was based on CDMA (Code Division Multiple Access), allowing multiple users to use a single channel. 3G technology allowed typical data rates of 500-700 kbps with a peak rate of about 3 megabits per second (Mbps). 3G is also known as IMT-2000 (ITU 2019).
- *3.5G*. This interim generation introduced HSPA (High-Speed Packet Access) technology to improve data speeds and achieved typical rates of 1-3 Mbps and a peak rate of 14.4 Mbps.
- *4G (Fourth Generation)*. 4G is based on LTE (Long Term Evolution) and LTE Advanced (LTE-A), standards developed by the 3rd Generation Partnership Project (3GPP) and codified in ITU (2018a). The LTE standards are based on OFDMA (Orthogonal Frequency Division Multiple Access) and offer higher throughput, low latency, and improved quality of service. 4G systems can achieve typical data rates of 3-5 Mbps and peak rates of 100-300 Mbps.
- *4.5G or LTE Advanced Pro,* also known as Pre-5G, is based on the 3GPP's Release g13 (3GPP 2015) and Release 14 (3GPP 2014) (see also 5G Americas 2018). It incorporates a number of new technologies now associated with 5G, such as Massive MIMO (Multiple Input Multiple Output). This, along with carrier aggregation, allows data rates up to 3 gigabits per second (Gbps).

5G Development and Standardization

A significant number of entities are involved in the development of a 5G vision, as well as exploring system characteristics, setting requirements, and formulating standards, including the following:

- *Regulatory institutions*, notably the ITU (International Telecommunication Union), particularly ITU-R (ITU Radiocommunication Sector). ITU is developing the International Mobile Telecommunication-2020 (IMT-2020) standard for 5G, to be completed in 2020. Current documentation relevant to the IMT-2020 effort includes ITU 2014 and ITU 2015 (a,b). The ITU previously issued IMT-2000 (3G) and IMT-Advanced (4G). The latest revisions of these standards are in ITU 2019 and ITU 2018a, respectively.
- *Industrial alliances and standards associations*, such as the following:

    - 3rd Generation Partnership Project (3GPP), an umbrella body consisting of seven telecommunication standards development organizations.[3] 3GPP's Release 16, to be issued in March 2020, is expected to be fully compliant with the ITU's IMT-2020 (5G Americas 2018).
    - Next Generation Mobile Networks (NGMN) Alliance,[4] a mobile telecommunications association headquartered in Frankfurt, Germany. It represents a global partnership of mobile network operators (members), manufacturers and vendors (contributors), and research institutes (advisors). In relation to 5G, NGMN has been particularly focused on the needs and concerns of mobile network operators.
    - 5G Americas,[5] an alliance of telecommunication service providers and manufacturers headquartered in Bellevue, Washington, and focused on 5G development for the Americas. 5G Americas has produced useful documents on 5G spectrum demands (5G Americas 2017b).
- *Public-private partnership associations*, such as 5G PPP (5G Infrastructure Public Private Partnership),[6] headquartered in Brussels, Belgium. 5G PPP is a joint initiative between the European Commission (the public side of the partnership) and the 5G Infrastructure Association (5G IA) (the private side). 5G IA has members from several segments of the European information and communications technology (ICT) industry—ICT manufacturers, telecommunications operators, service providers, research institutes, universities, related vertical industries, and subject matter experts. The 5G PPP is associated with the METIS projects, beginning with METIS2020 (Mobile and wireless communications Enablers for the Twenty-twenty Information Society). This produced significant studies on multiple aspects of 5G by 2015. METIS2020 was succeeded by METIS II, which lasted until 2017, and activities continue under the 5G PPP.

5G Usage Scenarios

5G is envisioned to be both an evolutionary improvement over the best current (4G, 4.5G) wireless communications systems and a revolutionary broadening in the uses of such systems. The following three broad classes of uses cases, referred by ITU as "usage scenarios," are desired and projected for 5G (El Ayoubi et al. 2018):

- Enhanced Mobile Broadband (eMBB). This usage scenario, or rather a subset of it, is the most similar to the services currently offered by 4G and 4.5G mobile systems. It involves faster data rates, more universal spatial coverage, and more tolerance for mobility. It also covers use cases such as hotspots with low mobility and high user density.
- Ultrareliable and low-latency communications (URLLC). This usage scenario includes such applications as distributed automation, industrial control, vehicle safety, remote medical practice, and others. Such applications may not need very high data rates, but require very low latency, high reliability, and must often accommodate high mobility.
- Massive machine-type communications (mMTC). This usage scenario includes Internet-of-Things applications, such as distributed wireless sensor networks transmitting relatively small amounts of data, for example, in industrial logistics or precision agriculture, or in support of smart homes, buildings, cities, utilities. This family of use cases may not require high data rates or low latency but requires energy efficiency and high connection density.

[3] https://www.3gpp.org/about-3gpp/partners
[4] https://www.ngmn.org/home.html
[5] http://www.5gamericas.org/en/
[6] https://5g-ppp.eu/ and https://5g-ia.eu/

Various entities, including 3GPP, 5G Americas, NGNM, and 5G PPP, have developed more detailed sets of use cases that can be classified into the broad usage scenarios listed above. Chapter 3 discusses these.

Figure 2 shows the relative importance of several key performance parameters for the three families of use cases, and Figure 3 depicts several notional applications in terms of their bandwidth and latency requirements. Many such applications cannot currently be delivered by mobile communications systems and will be enabled by 5G. These applications can be considered to be higher-level emerging technologies.

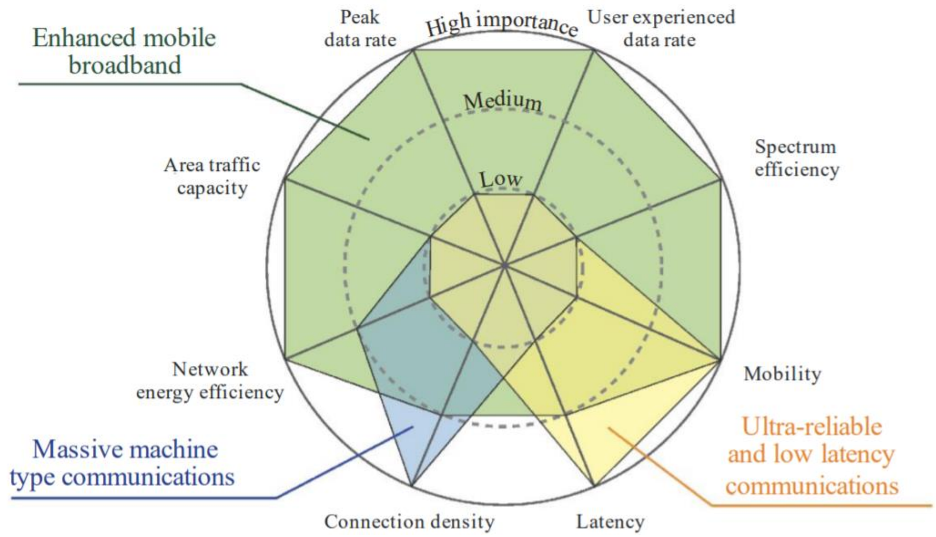
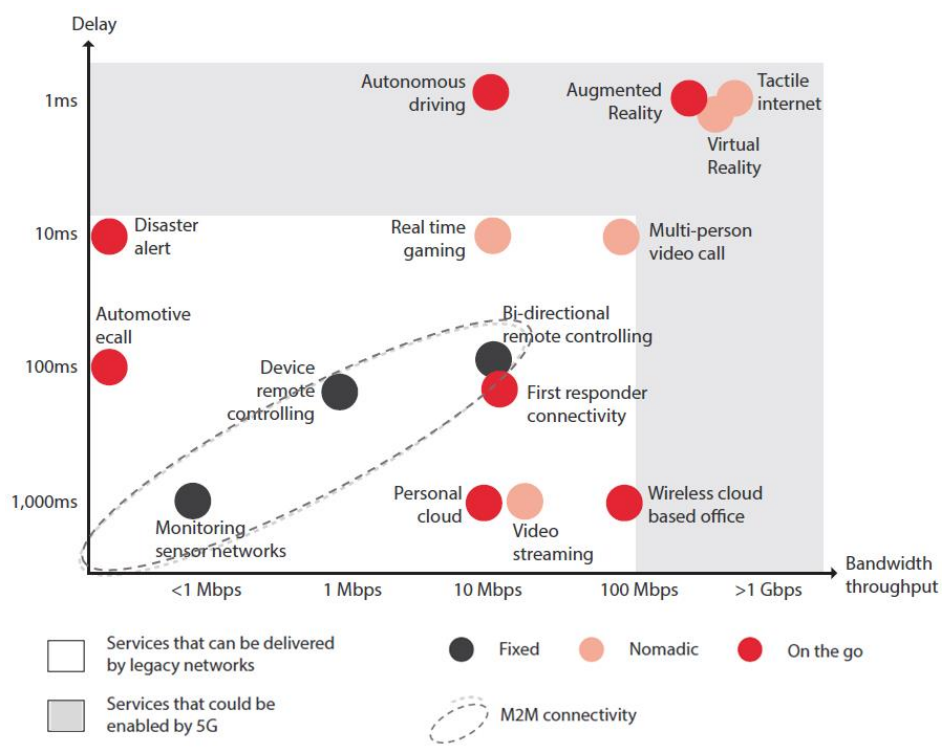


Figure 2. Importance of Key Performance Parameters for the ITU Usage Scenarios

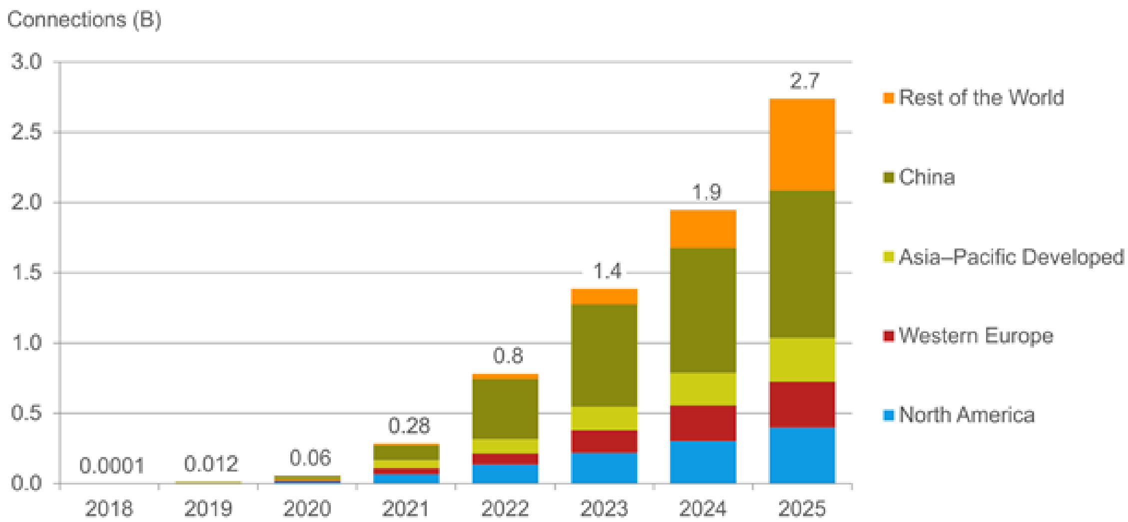


Source: GSMA Intelligence 2014

Figure 3. Notional applications in terms of their bandwidth and latency requirements

5G Deployment Projections

CCS Insight Projections. As shown in Figure 4, CCS Insight projects that 5G connections will reach 1 billion in mid-2023 and 2.7 billion in 2025 (CCS Insight 2018a).



Source: CCS Insight 2018a

Figure 4. 5G Connections by Region

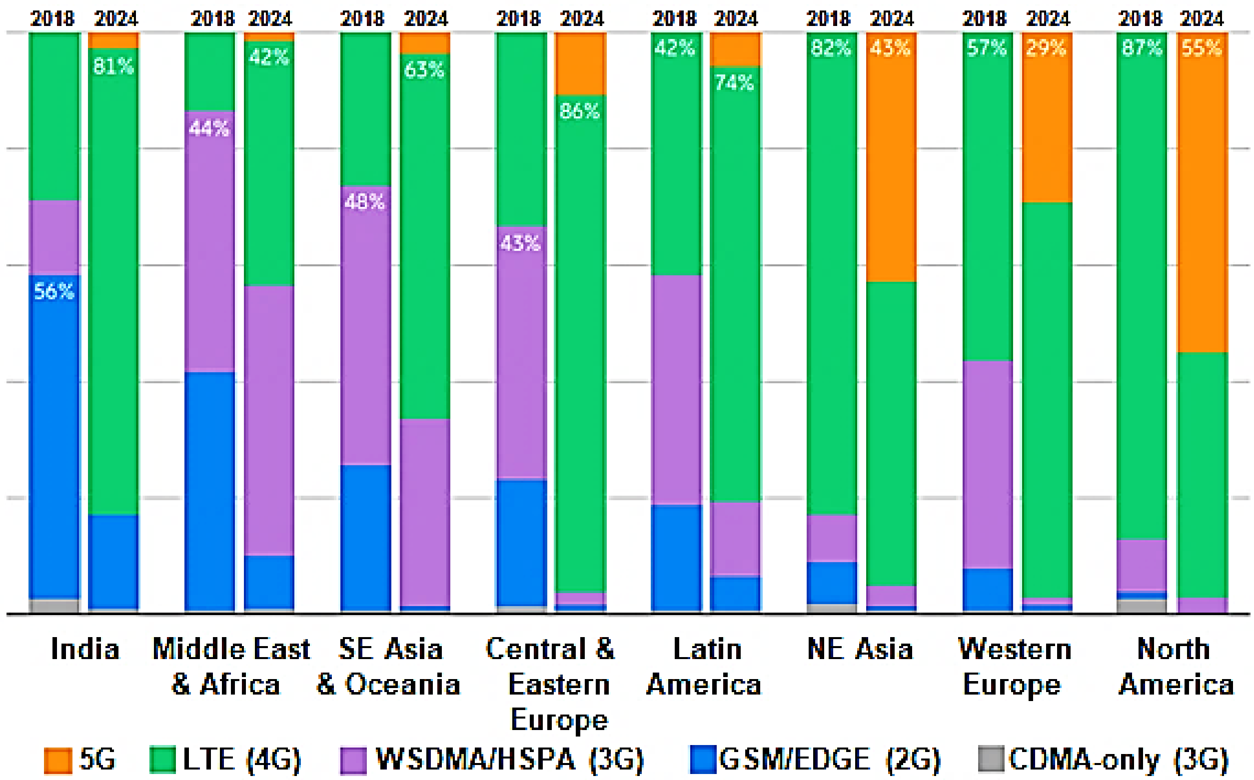
The CCS Insight analysis looks at 5G connections by use cases. They make the following points (CCS Insight 2018b):

- *eMBB.* From 2021 to 2025, fast deployment will occur in developed markets. In 2021, deployment will start, with low numbers, in emerging markets.
- *mMTC.* Deployment faces a slow start, with narrowband still not standardized in 5G. The year 2024 will see early commercial launches of narrowband 5G, and the pace will pick up in 2025.
- *URLLC.* Even in 2025, there will only be isolated commercial implementations, led by automotive use cases.
- *Fixed wireless access (FWA)*. In 2018, FWA is launched as an early 5G use case in the U.S. From 2019-2020, there will be a slow roll-out in the U.S., as well as in some developed markets of Asia-Pacific. The growth will pick up in 2021. However, in 2025, FWA is still niche compared with fiber broadband.

CCS Insight sums up their deployment projections as follow (CCS Insight 2018a):

> *Autonomous driving and remote healthcare are still being touted as "killer" applications for new 5G networks, but CCS Insight predicts adoption will be pushed by the growing need for higher speeds and bandwidth to support video consumption on mobile devices. The forecast shows that even in 2025, mobile broadband will still represent 98 percent of all 5G connections.*

Ericsson Projections. In its November 2018 Mobility Report, Ericsson projects 1.5 billion 5G subscriptions for enhanced mobile broadband service by the end of 2024. This will represent approximately 17 percent of all mobile subscriptions at that time. The evolution to 5G is depicted in Figure 5. As shown in the figure, North East Asia and North America will lead in 5G (Ericsson 2018).



Source: Adapted from Ericsson 2018

Figure 5. Mobile Subscriptions by Region and Technology

Ericsson estimates that, as of 2018, LTE penetration is 87 percent in North America, which is closely followed by North East Asia at 82 percent. Ericsson predicts that by the end of 2024, there will be over 250 million 5G subscriptions in North America, representing 55 percent of all mobile subscriptions. In North East Asia, 5G subscriptions will represent 43 percent of all mobile subscriptions (Ericsson 2018).

5G Enabling Technologies

Realization of 5G will require the development, refinement, and application of a number of new technologies (many such underlying technologies are summarized by Gupta and Jha 2015; ITU 2018b; Reed, Vassiliou, and Shah 2016; Sexton et al. 2017; and Vannithamby and Talwar 2017).

We classify these underlying technologies as (1) Core Network Function Processing, (2) Backhaul and Fronthaul Networks, or (3) Radio Access Networks (RANs) and discuss some of the main approaches being developed for 5G deployment.[7] Figure 6 depicts an overview of these categories and some of the emerging technologies under consideration.

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[7] Note that some of the enabling technologies described here also apply to the Wi-Fi (IEEE 802.11) technologies discussed in the following section. Where this is the case, we state which IEEE 802.11 standards leverage the specified enabling technology.

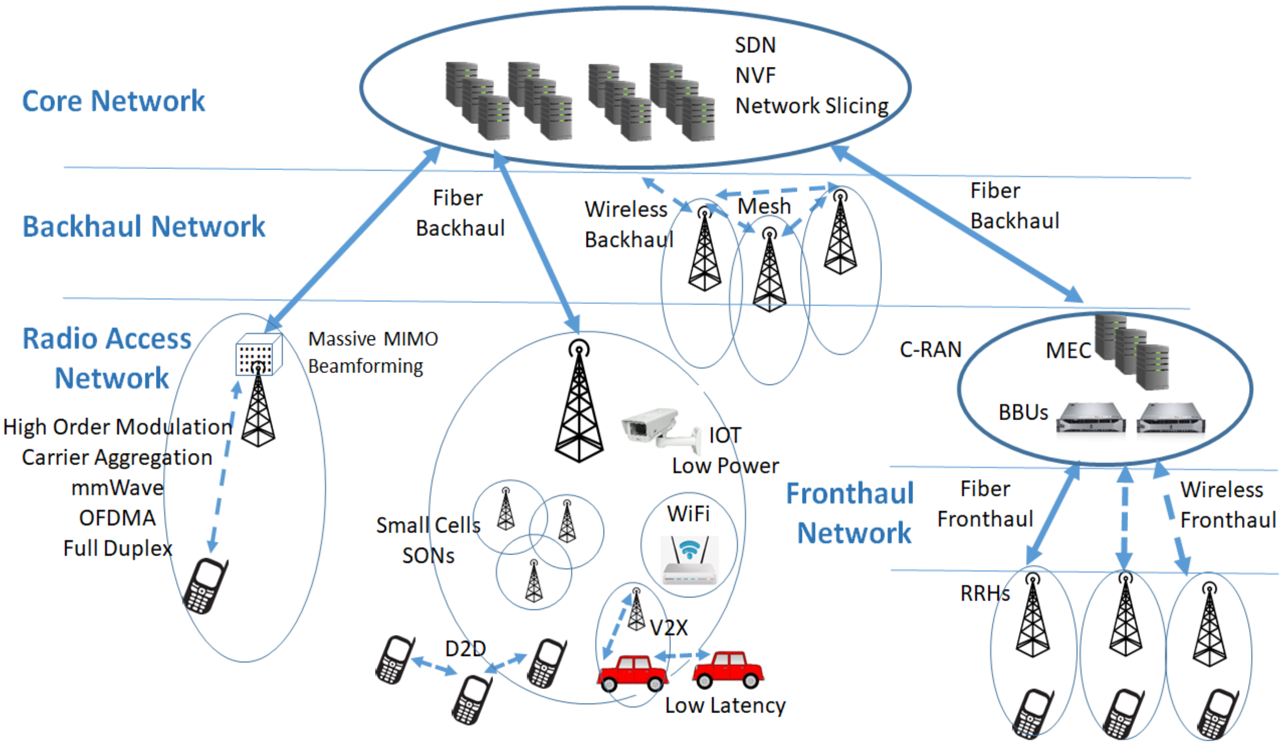


Figure 6. 5G-Enabling Technologies

Core Network Function Processing

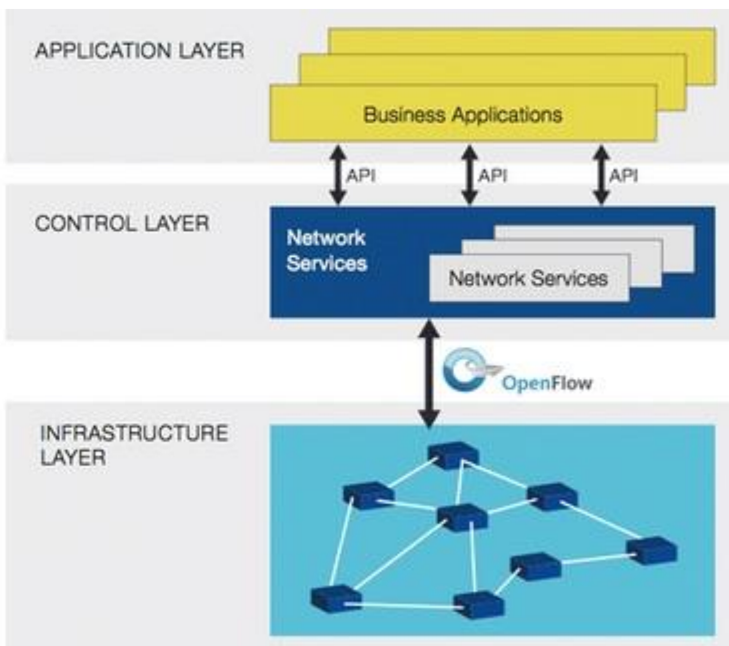
For core network function processing, important technologies that will supply the flexibility and adaptability required to satisfy the expanded set of use cases by 5G include the following (ITU 2018b):

- *Network Functions Virtualization (NFV)*, which replaces dedicated network hardware on appliances such as routers with commercial-of-the-shelf hardware running virtualized instances of network function.
- *Software Defined Networking (SDN)*, which permits rapid dynamic reconfiguration of networks and allows 5G to be controlled by software.
- *Network Slicing*, which separates a physical network into several virtual networks that support different radio access networks.
- *Multiaccess Edge Computing (MEC)*, which brings data and computing closer to the end user and thus provides low latency for certain applications.
- *Cloud Radio Access Network (C-RAN)*, which is a cloud-based network architecture replacing distributed signal processing units at mobile base stations and reducing the cost of deploying large numbers of small cells.

Network Functions Virtualization (NFV) – *The use of IT virtualization technology to implement network functions into software so that they can be run on commercial commodity computing devices and can be easily instantiated and relocated as needed*. Implementing network functions as virtual machines or virtual appliances on standard computing devices or white boxes, providing rapid provisioning, scalability, mobility, and reduces capital expenses (capex) and operating expenses (opex). NFV is being advanced by the European Telecommunication Standards Institute (ETSI) Industry Specification Group for Network Functions Virtualization (ETSI 2019b), which represents an international group of carriers that see value in standardizing the use of virtualized network functions. They have defined a framework and use cases including several related to mobile networks. Some candidate network functions for virtualization include (Jain 2014): (1) Switches, (e.g., Open vSwitch); (2) Routers, (e.g., Click); (3) Home Location Register (HLR); (4) Serving GPRS Support Node (SGSN); (5) Gateway GPRS Support Node (GGSN); (6) Combined GPRS Support Node (CGSN); (7) Radio Network Controller (RNC); (8) Serving Gateway (SGW); (9) Packet Data Network Gateway (PGW); (10) Residential Gateway (RGW); (11) Broadband Remote Access Server (BRAS); (12) Carrier Grade Network Address Translator (CGNAT); (13) Deep Packet Inspection (DPI); (14) Provider Edge (PE) Router; (15) Mobility Management Entity (MME); and (16) Element Management System (EMS).

NFV is independent of SDN and can be used separately or in conjunction with SDN.

Software Defined Networking (SDN) – *A design approach to networking in which the network infrastructure layer (also called the data plane) is separated from the control layer (also called the control plane)* (shown in Figure 7 below). The two layers are connected by an interface standard, such as OpenFLow.[8] OpenFLow was first proposed in 2012 and was the first open protocol for interconnecting the data and control planes. SDN allows offloading the control of the network onto commercial commodity computing devices and centralized control of network resources under programmatic control. The control layer is typically implemented by an SDN controller. The infrastructure layer is typically thought of as a switch. Southbound APIs relay information between the SDN controller and the switches, such as through OpenFLow, and Northbound APIs relay information between the SDN controller and the applications.



Source: SDxCentral 2019b

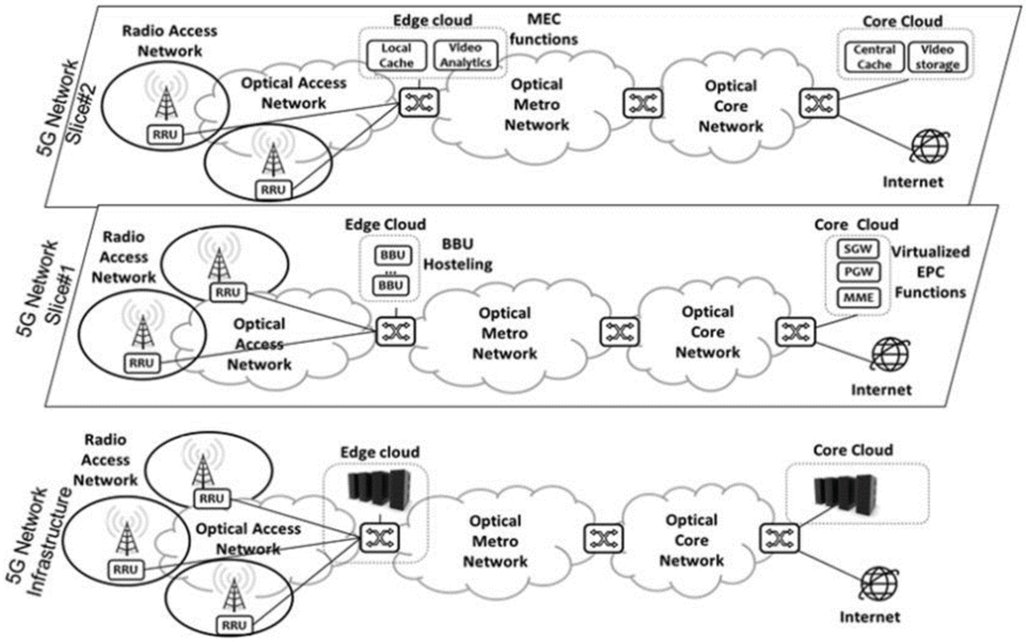
Figure 7. SDN Architecture

SDN provides benefits of increased flexibility in design, use of open source tools, centralized management, reduced capex and opex, and increased innovation.

Network Slicing – A set of virtualized network and cloud functions and resources that are used to satisfy an application use case, such as a monitoring application. The overall network can support multiple

[8] https://www.opennetworking.org/software-defined-standards/specifications

network slices running simultaneously. Figure 8 shows an example of network slicing with two network slices over a 5G network infrastructure (Mayoral et al. 2016). The slices include MEC resources and functions.



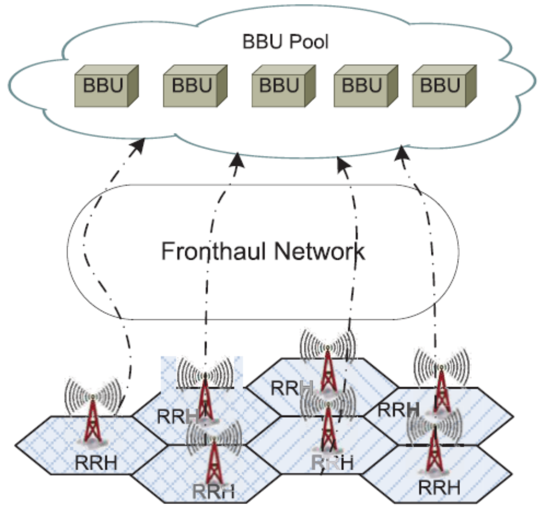
Source: Mayoral et al. 2016

Figure 8. Network Slicing

Network slicing is considered to be essential to the 5G architecture for delivering the use cases of enhanced mobile broadband (EMB), massive machine type (MMT) communications, and ultra-reliable low-latency (URLL) communications, each of which would be given a very different network slice of a 5G network deployment.

Multi-access Edge Computing (MEC) – *A cloud-based IT compute and storage environment that is positioned at the edge of the network*. MEC, formerly known as mobile edge computing, enables applications that require low-latency, high bandwidth, or real-time by residing at the edge, close to the users. "This allows for a new class of cloud-native applications and for network operators to open their networks to a new ecosystem and value chain. MEC permits multiple types of access at the edge, including wireline" (SDxCentral 2019a). The MEC is envisioned as providing a number of opportunities to provide value added services such as data analytics, location services, artificial reality, and data caching for carriers to provide their mobile subscribers. Standardization for MEC including frameworks, architectures, and use cases is undertaken by MEC ETSI Industry Specification Group (ETSI 2019a).

Cloud Radio Access Network (C-RAN) – *Implementation of the radio access network functions in software as virtual functions and deploy them in standard cloud environments*. The concept of the C-RAN has evolved from the original concept of the centralized RAN (I et al. 2014), and the objectives are to provide design flexibility, computational scalability, energy efficiency, and reduced integration costs. In a C-RAN, the traditional functions of the base stations are distributed so that remote radio heads (RRHs) are placed with the antennas in the field, and baseband units (BBUs) are placed at centralized cloud-processing sites. The RRHs are connected to the BBU pool through a front haul network, as shown in Figure 9. The BBU functions are virtualized and can be shared to process the signals from various RRUs on an as-needed basis. This leads to efficiencies in processing and cooling, as well as more advanced joint optimization schemes (e.g., coordinated multipoint operation [CoMP]), multiple radio access technologies (multi-RAT), and dynamic cell reconfiguration.



Source: Wang, Hu, and Yang 2014

Figure 9. C-RAN Architecture

A challenge of C-RAN is the design and implementation of the fronthaul network, which must carry the radio signals from the RRH to the BBUs.

Backhaul and Fronthaul Networks

Backhaul networks connect the radio access network to the core network. Fiber is a good choice for backhaul networks; however, where fiber is hard to deploy or too costly, a number of wireless technologies become critical: These include point-to-multipoint (PMP) microwave, millimeter wave, High Altitude Platform Systems (HAPS), and satellites (ITU 2018b). Wireless mesh technologies, which will forward backhaul traffic from remote base stations toward the core network, have also been proposed. 5G itself is envisioned as a possible technology for wireless backhaul links in many scenarios. A novel technology from AT&T called AirGig, which employs millimeter wave wireless transmission that follow electric utility power lines as a backhaul link for fixed wireless-to-the-home applications, is being tested for deployment (AT&T 2019).

The fronthaul link connects centralized radio controllers to remote radio units as described in the C-RAN discussion and shown in Figure 9. The latency and throughput requirements of the data that travel over these fronthaul links are a function of the number of the antennas and the radio data rates, both of which are increasing in 5G systems. Fronthaul networks typically use the Common Public Radio Interface (CPRI) protocol in existing fronthaul links in 4G networks. The current implementation of CPRI cannot cope with the expected 5G data rates. Some processing power can be reallocated to the remote radio units to improve latency and throughput, but this comes at a cost of reducing simplified centralized management. The ITU and other entities are actively working on identifying technologies that can improve fronthaul links, including radio-over-fiber technologies (ITU 2018b) such as an Ethernet-based version. However, 5G deployments will require additional technical advancements over these protocols to meet the throughput and cost demands.

Radio Access Networks (RANs)

For RANs, many key technologies are being pursued to reach the 5G goals for increasing capacity, spectral efficiency, and throughput, as well as for meeting low latency and energy efficiency objectives. Here, the following technologies are highlighted:

- Software defined radios and cognitive radios
- Small cells and self-organizing networks
- Device-to-device communications
- Advanced antenna technologies
- Millimeter wave radios
- Advanced modulation and access techniques
- In-band full duplex transceivers
- Carrier aggregation
- Use of unlicensed spectrum
- Low latency technologies
- Low power technologies

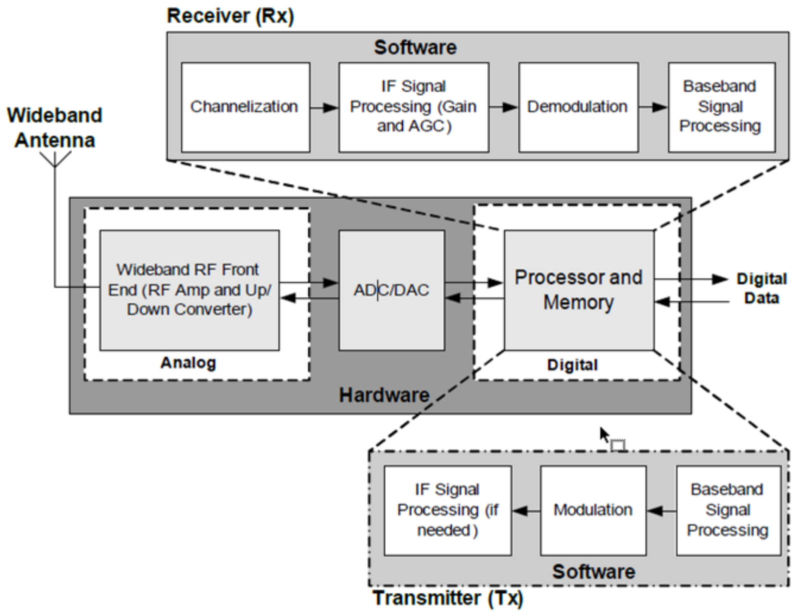
Software Defined Radio (SDR) – *A radio in which some or all of the physical layer functions are defined in software.*[9] This is typically contrasted with a software-controlled radio in which the physical layer functions are only controlled by software. SDRs modify the RF processing chain on the receive side by converting the RF signal to the digital domain early using high speed analog to digital converters (ADCs) near the antenna, then processing the signals in the digital domain. They modify the RF processing chain on the transmit side, by doing the processing and then reconstructing the analog signals using digital to analog converters (DACs) later near the antenna. The software computations can be done on general purpose computers, digital signal processors, FPGAs, GPUs, or other special purpose chips. Some of the traditional physical layer functions implemented in an SDR include modulation, demodulation, filtering, channel gain, and frequency selection.

Figure 10 illustrates a typical architecture of an SDR showing the hardware and many of the traditional radio functions that are implemented in software (Cho et al. 2014). This allows the SDR flexibility to support capabilities like multimode, multicarrier, multirate, and variable rate transmissions. An SDR also provides flexibility in that new waveforms or other modifications can be made to the radio without changing the hardware that are expected to be used in 5G systems. The primary technical limitations to SDRs are the sampling rates of the ADCs that limit the top frequencies that the SDRs can process and also the computational needs of some of the digital signal processing algorithms.

Cognitive Radio (CR) – *A radio that is aware of its internal state and its environment, such as its location or the utilization of the local spectrum and is able to make decisions to modify its behavior to achieve operational objectives.* SDR is considered an enabling technology for CR, and CR is enabling for many technologies, such as cognitive networks and advanced spectrum management and sharing schemes. Several new applications can be enabled by CR, including the following (Bambang et al. 2019):

- Dynamic spectrum access (DSA)
- Self-organizing networks
- Cognitive jamming systems
- Cognitive gateways / bridges
- Real-time spectrum markets
- Synthetic (Cooperative) MIMO
- Cognitive spectrum management
- Cognitive routing

[9] Defined by the Wireless Innovation Forum and IEEE P1900.1, https://www.wirelessinnovation.org/Introduction_to_SDR.



Source: Bambang et al. 2019

Figure 10. Radio Functions Implemented in Hardware and Software

Small Cells – *An umbrella term for operator controlled, low-powered, radio-access nodes, including those that operate in licensed spectrum and unlicensed carrier-grade WiFi* (Small Cell Forum 2014). This refers to the use of smaller cells, served by more base stations and operating at lower power, to help avoid interference and thereby increase spectrum efficiency and area traffic capacity. Small-cell technology essentially amounts to taking the key principle of cellular technology (i.e., cells) to a greater extreme.

Small cells typically have a range from 10 meters to several hundred meters. Small cells are added to macro cellular networks to increase capacity in selected locations with high user demand or to reach indoor or outdoor areas not covered by the macro network. The mix of traditional base stations (or macro cells) and small cells leads to heterogeneous networks (HetNets) that results in improved capacity and quality of service for less cost by offloading the macro base stations. Small cell technology is primarily categorized by the range and capacity (number of users) of the base stations:

- Femtocell – coverage of approximately 10 meters used in homes or small businesses
- Picocell – coverage of a small building, hotel, stadium, or airplane
- Microcell – coverage of a defined area up to several hundred meters, such as a shopping center

Small cells are a key technology enabling the densification of the 5G where there will be a proliferation of small cells using combinations of both licensed and unlicensed approaches. It is also worth noting that millimeter-wave technologies being considered for 5G are well suited for small cell deployment because of propagation limitations in that band, allowing closer placement of base stations. Small cells have been used in previous generations of cellular networks; however, 5G is envisioning hyperdense deployments. The profusion of cells can complicate system management. HetNet deployments must deal with the problem of intercell interference, especially when using the same frequencies, and with frequency coordination in general. Coordinating a large-scale deployment of small cells is challenging. Also, there are regulatory and implementation barriers involved with siting the large number of small cell base stations anticipated in 5G deployments and arranging the backhaul networks.

Self-Organizing Network (SON) – *A collection of base stations and relay stations that can automatically configure and optimize themselves and coordinate with their neighboring cells to mitigate interference and to operate efficiently.* Also called self-optimizing networks, SON methods have been developed for 3G systems, and 4G LTE standards are being tested. As noted above, coordination of many small cells to minimize interference is difficult. Cognitive radio techniques can be used to deal with this interference in an intelligent manner without requiring carefully planned cellular deployment (Sexton et al. 2017).

Device-to-Device (D2D) – A method that allows a cellular end-device to directly communicate with another cellular end-device without the data passing through a base station. D2D capabilities were first proposed in LTE Advanced as the Proximity Service (ProSe) for public safety applications and consists of two synergistic capabilities (Yasukawa et al. 2015):

- D2D communications – data and voice exchange among proximate equipment
- D2D discovery – discovery of proximate equipment and/or services

A ProSe link between two end-devices is called a *side link*. Figure 11 shows the possible cases of D2D and base station interaction. Each case requires its own method of coordination and interference mitigation.

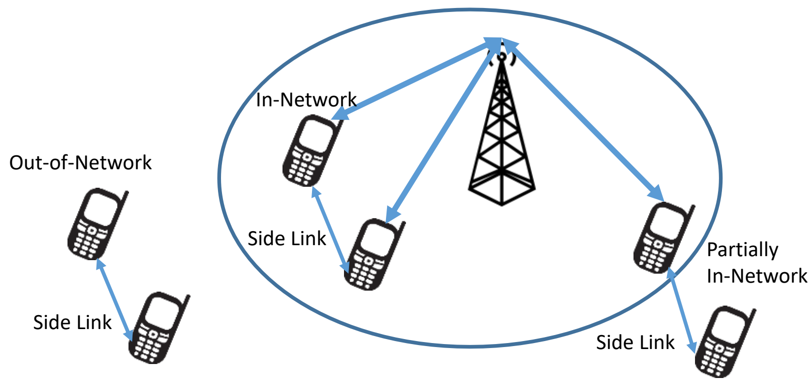


Figure 11. D2D Communication Situations

The important use cases for D2D in 5G include proximity services, public safety, vehicle to everything communications, autonomous vehicles, IoT devices, and wearables, as well as potential for offloading to the wireline networks. For example, IoT devices could directly communicate to end-user devices to relay data to the network to save power. Challenges include security, compensation schemes, and ensuring fairness of resource usage.

Advanced Antenna Technologies. Many of the capacity improvements have been due to the use of multiple antenna technologies. If multiple antennas are used at the base station and at the terminal or end devices, then Multiple Input-Multiple Output (MIMO) schemes are possible where multiple transmitting antennas are used to input signals into space and multiple receiving antennas are used to receive and output the signals.

MIMO systems are characterized as MxN where M is the number of transmitting antennas and N is the number of receiving antennas at a device (e.g., 4x2 MIMO). If a MIMO device is transmitting to a single other MIMO device then this is a single user MIMO scheme (SU-MIMO). Under good channel conditions, an end terminal can receive multiple data streams on separate antennas resulting from multipath reflections, effectively multiplying the effective data rate by the number of streams. In LTE-A, there are 10 base station downlink transmission modes corresponding to several different MIMO schemes using up to 8 transmit and receive antennas. The terminal devices provide feedback on the channel conditions.

If a MIMO device is transmitting to multiple MIMO devices or multiple MIMO devices are transmitting to a single MIMO device, then this is referred to as multi-user MIMO (MU-MIMO), and additional efficiency gains are possible. Figure 12 shows a downlink MU-MIMO channel where multipath streams from a base station are shown. Through channel state feedback from the terminal devices, the base station can make use of the multipath signals to send simultaneous data streams to multiple users using its separate RF chains. Both uplink and downlink MU-MIMO is planned for 5G and 802.11ax (802.11ac is downlink only).

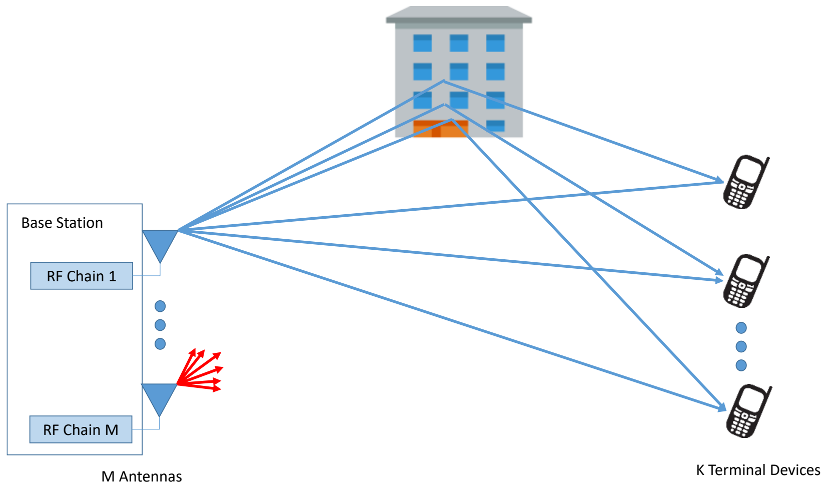


Figure 12. MU-MIMO Downlink Channel State

The multiple antennas can also be used for beamforming where the transmitted or received radiation pattern is given a particular shape and direction by modifying the amplitude and phase of the signal to/from each antenna. This is used to direct the transmitted signal to a specifics area or to null (lessen) the effects of an interference source on the received signal. In LTE-A (also 802.11ac and 802.11 ax) beamforming is used to improve the signals sent and received by the MIMO antenna arrays through the use of a set of precomputed patterns chosen using channel feedback.

Massive-MIMO involves increasing the number of antennas for transmission and reception (usually more than 12 and scaling up to the thousands) and developing beam forming techniques to allow for more propagation paths to be used and hence increase the amount of data that can be transmitted in a given amount of spectrum. Massive-MIMO systems are being designed for 5G, WiMAX, and newer IEEE 802.11ax systems and recent trials have demonstrated improvements with 64x64 MIMO arrays (Nordrum 2016). Challenges with massive-MIMO include accurate channel estimation (especially for high mobility operation), synchronization of multiple terminals, calibration of the antenna array, power consumption, and computational complexity of the signal processing schemes.

Millimeter Wave (mmWave) Radios. The RF frequencies between around 30 GHz and 300 GHz are generally referred to as the mmWave frequencies as their wave lengths range from 1 mm to 10 mm. 5G will depend on operating at frequencies greater than 24 GHz, and frequencies above 24 GHz are often included as mmWave technologies. The mmWave signals tend to have a high signal attenuation and propagation loss, requiring near line-of-sight visibility and limiting their range. They also do not penetrate solid structures well. However, this makes them suitable for small cell deployment, and the shorter wave lengths allow antennas to be smaller and packed closer together, leading to larger antenna arrays in a smaller form factor. This allows mmWave radios to take advantage of MU-MIMO and beamforming, increasing the antenna gain and thus the range and efficiency of mmWave radios (Rappaport et al. 2013). In addition, power amplifiers for mmWave radios require relatively high antenna gains, as power amplifiers at mmWave frequencies are not efficient; efficiencies can be as low as 8%. (Reed, Vassiliou, and Shah 2016).

The ITU and many countries are making relatively large frequency bands above 24 GHz for licensed and unlicensed use, which can support larger bandwidth channels for short range, high data rate transmissions. The 28 GHz frequency band is used in the 3GPP New Radio (NR) release 15, and the 60 GHz unlicensed band is used by IEEE 802.11ad (WiGig). Use cases for mmWave include small cells, wireless backhaul link, fixed wireless, virtual reality, multimedia streaming, vehicle-to-vehicle communications and other short range, high rate applications (Sakaguchi et al. 2017).

Advanced Modulation and Multiple Access Techniques. The expected primary use cases for 5G—enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable low latency communication (uRLLC)—impose a new set of requirements on the modulation and access methods that are needed for 5G systems. These schemes impact the throughput, coverage, latency, and reliability of the systems and effect the spectral efficiency, signaling overhead, ability to support multiple types of services, number of end devices simultaneously active, and multiple frequencies employed (Nekovee et al. 2016). In 4G systems, the modulation scheme widely employed is a cyclic prefix, orthogonal frequency division multiplexing (OFDM). OFDM has several advantages:

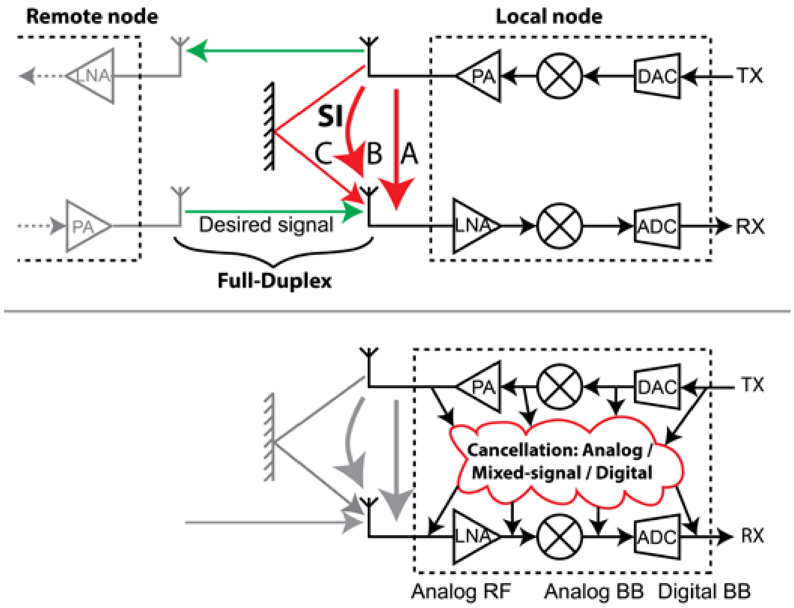
- Reduced intercell interference through use of orthogonality of subcarriers
- The ability to counteract multipath distortion
- Adaptable power control and modulation cardinality
- Lower complexity of implementation of transmitter and receiver
- Compatibility with multi-antenna systems

In OFDM, the multiple subcarriers are shaped with a modulation scheme such as quadrature amplitude modulation (QAM) or phase shift keying (PSK) to code each symbol so that, in total, a high data rate is maintained. By using higher cardinality QAM schemes, such as 256-QAM, that can transmit more bits per symbol (e.g., 8 bits per symbol for 256-QAM), data rates can be increased; however, the decoding is more complex and sensitive to received signal strength. The modulation scheme is also paired with a multiple access scheme to serve a number of end devices simultaneously, such as orthogonal frequency division multiple access (OFDMA), which allocates different subsets of subcarriers to different users or a time division multiple access (TDMA) scheme.

The 5G requirements of higher spectral efficiency and loose synchronization require improvements over the current modulation and access schemes. The released 3GPP NR (3GPP 38 series) standard will use a form of OFDM similar to, but modified from, that used in 4G systems: cyclic prefix OFDM (CP-OFDM) on the downlink and discrete Fourier transform spread OFDM (DFT-S-OFDM) on the uplink. These schemes have a flexible subcarrier spacing to support the various bands and deployment models and are coupled with up to 256-QAM. The modulation schemes for the next phase of 3GPP and 5G are still under study. In addition to various modulation options (Pirinen 2014), several access schemes are under consideration, including orthogonal frequency division multiple access (OFDMA), sparse code multiple access (SCMA), and other non-orthogonal multiple access (NOMA) schemes that use power or code multiplexing (Banelli et al. 2014; Wu, Wang and Bayesteh 2017).

In-band Full Duplex (IBFD). IBFD communication allows simultaneous transmission and reception in the same frequency band and can increase the transmission rate by up to factor of two when compared to half-duplex schemes, but this results in strong self-interference that must be compensated. Frequency division duplex (FDD) communication, which uses two separate carriers to carry the signal in each direction, has been used in previous cellular generations, but IBFD is a relatively newer capability.

In Figure 13, the upper diagram shows the sources of self-interference with IBFD: A is circuit leakage, B is antenna spillover, and C is reflected signals (B and C are also called co-channel interference). The lower portion of the diagram shows where the transmitted information can be tapped and provided to the receiver circuit as reference signals to reduce the interference (Debaillie et al. 2015).



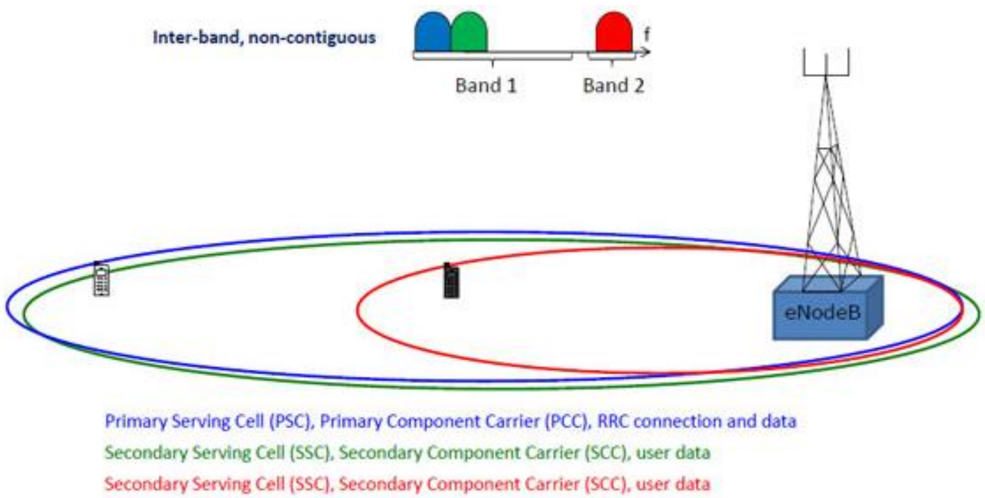
Source: Debaillie et al. 2015

Figure 13. Full Duplex Sources of Interference and Cancellation Options

Recent advances in self-interference cancellation show promise of realizable throughput gains under favorable traffic conditions. Several studies of IBFD in small cell scenarios illustrate the effects of inter-cell interference and show promise of improved performance (Mahmood et al. 2017). However, IBFD increases the complexity of the radios, and it is challenging to implement low-cost designs for 5G systems.

Carrier Aggregation (CA) – A method for a radio system to combine a number of separate carrier channels across fragmented spectrum allocations to increase the attainable data rates and capacity. Carrier aggregation can be applied to several cases of carrier separation: (1) intra-band contiguous, (2) intra-band non-contiguous, and (3) interband noncontiguous, with increasing complexity of implementation. It can be applied to FDD or TDD channels, licensed and unlicensed bands, and on either the uplink or downlink. In IEEE 802.11 systems, a similar concept, called channel bonding, is employed to increase bandwidth and data rates by combining contiguous channels and using a common waveform. For example, in 802.11ac, it is possible to bond contiguous 20 MHz channels into a 160 MHz channel or two non-contiguous 80 MHz channels. Carrier aggregation is a generalization that can support differing waveforms in the non-contiguous channels. IEEE 802.11ay supports bot channel bonding and carrier aggregation.

Different carriers have different physical properties that must be compensated in the control mechanism for the aggregation, as shown in Figure 14. As the carriers at different frequency ranges have different propagation and attenuation properties, the coverage areas can be divided into primary and secondary cells for the different end terminals. The primary serving cell and primary component carrier has the largest coverage and is used convey the control information while the secondary cells are used to augment the capacity.

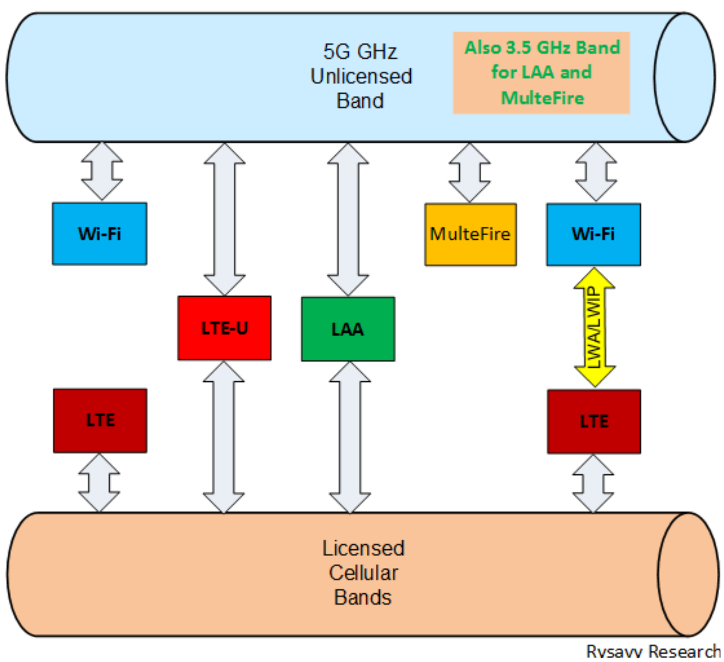


Source: Wannstrom 2013

Figure 14. Carrier Aggregation with Primary and Secondary Cells

CA has been used in LTE systems since release 10 and will be an important feature in 5G. In 5G, a method of combining LTE and 5G carriers using a technique called dual connectivity is under consideration.

Use of Unlicensed Spectrum. Cellular carriers have been employing various schemes to use the unlicensed spectrum bands to augment the capacity of their systems by offloading traffic to unlicensed spectrum. The evolution of these schemes is shown in Figure 15, where LTE and WiFi (802.11ac/11ad/11ax/11ay) exist or are evolving as separate entities in separate bands on the left.



Source: Rysavy Research 2017

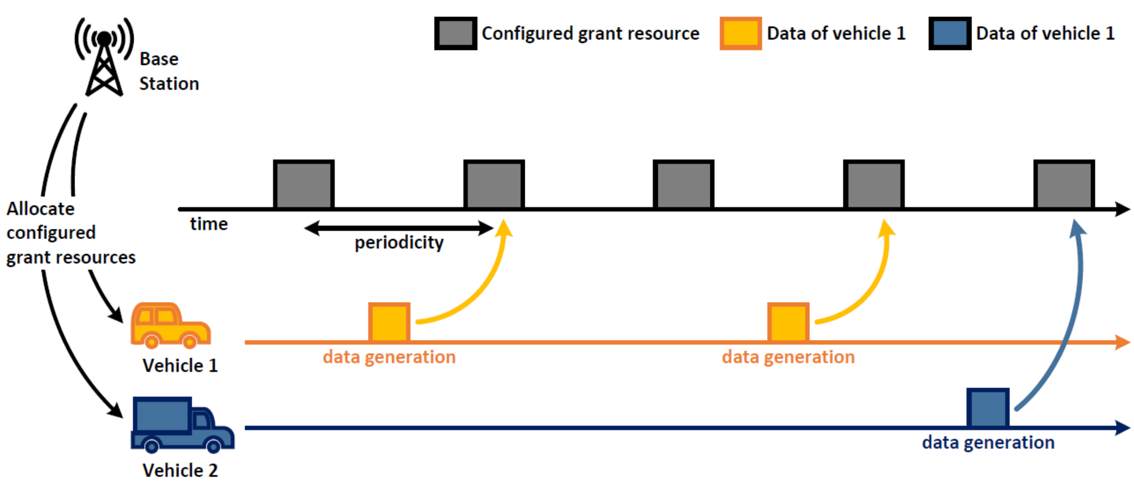
Figure 15. Approaches to Using Licensed and Unlicensed Spectrum

LTE-U, Licensed Assisted Access (LAA) schemes require both licensed and unlicensed spectrum to be combined using carrier aggregation and channel bonding. The licensed or anchored portion carries the control information, which is used to provide a more stable user experience. More recently in 3GPP Release 13, LTE/Wi-Fi Aggregation (LWA) leverages newer carrier WiFi (802.11ac, 11ax) and link aggregation, and LTE WAN Integration with IPSec tunnel (LWIP) performs aggregation and switching at the IP layer (GSA 2019; Qualcomm 2017). MulteFire, building on LAA, will provide LTE-like performance in the 5GHz unlicensed band without requiring a licensed-carrier anchor. All these schemes will coexist in the unlicensed band, and challenges remain to provide seamless handover between the regimes and to maintain fairness in the use of the unlicensed band.

Low Latency Technologies. Satisfying the low latency requirements for packet transmission is critical for many envisioned 5G use cases such as V2X for autonomous vehicles. 5G has a target value of 1 ms for packet latency. In order to reduce the latency in 4G systems, three general approaches are being investigated: (1) reducing the minimum size of a time slot for transmission of a packet, (2) increasing the opportunities to transmit through improved scheduling algorithms, (3) using multi-access edge processing to perform computation functions closer to the end devices (covered in the section on core function processing), and allow devices to communicate without establishing a network connection (allow broadcast without network infrastructure and no network subscription).

In existing LTE systems, a subframe slot size of 1 ms is used to transport packets (and this is before considering processing time at devices and transmission latency in the network). In order to reduce the response time, 5G will use a scalable orthogonal frequency-division multiplexing (OFDM) framework with different numerologies, so that various sub-slot configurations are possible within a 1-ms time slot, resulting in a minimum size transmission sub-slot of 0.03125 ms (Park 2018).

In order to send a packet, the terminal must be granted permission from the base station scheduler using a resource grant procedure, which can take at least 8 ms in LTE systems. A semi-persistent scheduling (SPS) method was implemented in LTE for periodic traffic (e.g., voice over IP) to reduce this delay by pre-allocating dedicated time slots; however, this can only be used by a single terminal device. If the terminal device does not have anything to send, then the dedicated slots are wasted. In 5G systems, multiple devices are allowed to share the dedicated periodic slots using a configured grant, as shown in Figure 16, where a base station scheduler allocates the configured grant resources to several vehicles. The vehicles can then use the dedicated slots when they have data to transmit. The configured grant eliminates the delay from a scheduling request and also increases the link utilization.



Source: Park 2018

Figure 16. Use of Configured Grant to reduce latency

Low Power Technologies. Satisfying the requirements for low power operations is critical for the expected 5G MMC use cases, especially considering the expected increase in the number of devices for IoT applications such as sensor networks. A collection of technologies, called *low-power wide area* (LPWA),[10] are being considered for machine-to-machine (M2M) communication, providing inexpensive, broad area coverage for many IoT applications. LPWA technologies are primarily focused on low-power, low-cost devices that are transmitting relatively short messages at lower data rates at intermittent times over a wide area (e.g., up to 10 km). LPWA technologies are also concerned with the ability to transmit through walls and other physical barriers, security, mobility/roaming support, ease of deployment, and other services that can be provided with low power and increased range (e.g., voice). For penetration capability, many LPWA technologies tend to use spectrum in the lower frequency bands (e.g., under 1 GHz). LPWA networks (LP-WANs) generally fit in between the short-range wireless technologies such as Bluetooth, Zigbee, or WiFi and the cellular technologies.

Several LPWA technologies are in various stages of development, deployment, and standardization and represent different tradeoffs and capabilities that are tailored for different use case requirements. At a coarse level, they can be divided into proprietary, standard cellular, and standard/open technologies as shown in Table 2. The proprietary and standard/open protocols operate in the unlicensed ISM spectrum bands and must coexist with the other users in those bands. The standard cellular schemes operate in licensed bands and thus can achieve more predictable capacity and latency—at potentially higher cost.

Table 2. LPWA Technologies

Technology	Type	Frequency	Data Rate Max	Range	Power	Cost
Ingenu	Proprietary Random Phase Multiple Access	2.4 GHz	624 Kbps Uplink/downlink	2-5 km, up to 15 km	Low	Medium
LoRaWAN Alliance (Semtech)	Proprietary Ultra Narrow Band (UNB)	915 MHz in U.S.	50 Kbps Mainly uplink	15 km	Low	Low
Sigfox	Proprietary (UNB)	868 and 915 MHz	1 Kbps Mainly uplink	Up to 50 km	Low	Medium
Symphony (LinkLabs)	Proprietary (LoRa Phy, Open Symphony MAC)	915 MHz	50 Kbps Mainly uplink	10 km	Low	Medium
LTE-M	Standard Cellular	Cellular bands	1 Mbps	Several km	Medium	High
NB-IoT	Standard Cellular	Cellular bands	250 Kbps	Several km	Medium	High
Weightless–W Technology UNB	Open Protocol, Proprietary HW	470-790 MHz TV White Space	10 Mbps	5 km	Low	Low
DASH7 (Weyn et al. 2015)	Open protocol, derived from ISO/IEC 18000-7 for RFID	<1 GHz (433, 868, 915 MHz)	166 Kbps	Several km	Low	Low
Wi-Fi (802.11af)	Standard Unlicensed	54-790 MHz TV White Space	.1 -24 Mbps (569 Mbps max)	Several km, up to 16 km for lower frequencies	Medium	Low
WiFi (802.11ah) HaLow	Standard Unlicensed	<1 GHz (902-928 MHz in US)	.1-1 Mbps (347 Mbps max)	1 km	Medium	Low

Source: Frenzel 2017 and McClelland 2016

[10] These are also known as *low-power wide-area networking* (LP-WAN) technologies.

LPWAs are typically compared by performance on battery life, coverage, equipment cost, and capacity. Long battery life (e.g., up to a few years) is achieved through methods that reduce power consumption, such as efficient sleep cycles and smaller cells. However, the coverage and range is enhanced by increasing the power used per bit and slowing the data rate (reducing effects of noise), so the various LPWA technologies balance this tradeoff.

The proprietary schemes have reached the market faster than the cellular-based schemes, as they were not slowed by the standardization process. Of the proprietary schemes, the Sigfox LP-WAN is the most widely deployed, particularly in Europe. Cellular IoT technologies are the three 3GPP standardized cellular technologies (in releases 14 and 15): LTE-M, Narrow-Band IoT (NB-IoT), and extended range GSM (EC-GSM). LTE-M (also called CAT-M1) and NB-IoT (CAT-NB1) use the existing LTE network and benefit from LTE's extensive existing infrastructure and global product market. LTE-M is designed with more features (e.g., voice, mobility) and supports higher data rates and lower latencies at higher cost, while NB-IoT targets lower data rate applications that can tolerate higher latency. The EC-GSM technology is designed for the GSM networks and provides similar capabilities as LTE-M.

5G LPWA is still evolving the cellular LPWA technologies. It is likely there will be more than one scheme to address the different use cases and IoT applications, and they will need to coexist with the surviving proprietary and open/unlicensed schemes. For 5G reduced power consumption, capacity improvements and coexistence of LTE-M and NB-IoT are expected.

Use of Satellite

Satellite technology has been included into 5G standards and will become an integral part of 5G if we aspire to bring 5G to all areas of the nation. The satellite transport conduit can be integrated into the overall available 5G architecture; compared to previous technology generations, 5G is "a network of networks" enabling a higher level of interconnectedness of satellite, terrestrial wireless, and other telecom infrastructure. Service providers will need to provide seamless connectivity between terrestrial and satellite; 5G traffic will be dynamically steered to the best transport options available, including satellite, according to bandwidth, latency, network conditions and other application-specific requirements. Use of Satellite

Wi-Fi Technologies

Existing and Emerging Wi-Fi Technologies

The IEEE 802.11 wireless local area network (WLAN) protocol standard was first released in 1997, and the initial standard has evolved through many amendments and revisions. The initial IEEE 802.11-1997 standard provided a data rate of up to 2 Mbps in the 2.4 GHz range. The development of the IEEE 802.11 protocols is done through working groups, which define the medium access protocol and physical layer protocol to meet specific objectives. Periodically, the IEEE 802.11 body will combine a series of working group outputs into a revision. The IEEE 802.11 working groups are continuing to make improvements and several new protocols are actively being developed. A summary of the IEEE 802.11 family of standards is given in Table 3, which includes some of the key performance parameters of the existing and evolving protocols.

Wi-Fi is a term trademarked by the Wi-Fi Alliance[11] for a collection of wireless technologies that meet the IEEE 802.11 wireless standards. The Wi-Fi Alliance, now 20 years old, is a consortium of companies

[11] https://www.wi-fi.org/

that certifies 802.11 products. The Wi-Fi Alliance also gives names to many of the 802,11 versions, such as Wi-Fi 4 for IEEE 802.11n, Wi-Fi 5 for 802.11ac, and Wi-Fi 6 for 802.11ax.

In 1999, the 802.11b standard was released with a top data rate of 11 Mbps in the 2.4 GHz band. This was followed by the release of the 802.11a protocol, which achieved data rates of up to 54 Mbps in the 5 GHz band. The 802.11b protocol was improved with the 802.11g protocol in 2003, which provided a 54 Mbps data rate in the 2.4 GHz band, matching the 802.11a data rate. The 802.11n protocol (Wi-Fi 4), released in 2009, operated in both the 2.4 and 5 GHz bands, achieved data rates up to 600 Mbps, and included MIMO and channel bonding to achieve these rates. A brief description of some of the other 802.11 family of protocols is provided.

Table 3. Existing and Emerging Wi-Fi Technologies

IEEE 802.11 Amendment	Year	Band	Maximum Rate	Range	Maximum Bandwidth	Waveform	MIMO	Channel Bonding (CB)
Low Band: Low Power Wide Area Network (LPWAN)								
11af (White-Fi)	2014	700 MHz	569 Mbps	1 Km	8 MHz	OFDM + 256-QAM	DL MU-MIMO (4x4)	
11ah (HaLow)	2016	<1 GHz	347 Mbps	1 Km	16 MHz	OFDM + 256-QAM	DL MU-MIMO (4x4)	
Mid Band: Wi-Fi								
11a	1999	5 GHz	54 Mbps	100 m	20 MHz	OFDM + 64-QAM		
11b	1999	2.4 GHz	11 Mbps	100 m	22 MHz	DSSS		
11g	2003	2.4 GHz	54 Mbps	100 m	20 MHz	OFDM + 64-QAM		
11n (Wi-Fi 4)	2009	2.4/5 GHz	600 Mbps	100 m	40 MHz	OFDM + 64-QAM	SU-MIMO (4x4)	up to two 20 MHz channels
11ac (Wi-Fi 5)	2013	5 GHz	6.93 Gbps	100 m	160 MHz	OFDM + 256-QAM	DL MU-MIMO (8x8)	up to eight 20 MHz channels
11ax (Wi-Fi 6)	2020 (expected)	2.4/5 GHz	9.6 Gbps	100 m	160 MHz	OFDMA + 1024 QAM	UL & DL MU-MIMO (8x8)	up to eight 20 MHz channels
High Band: WiGig								
11ad	2012	60 GHz	8 Gbps	10 m	2.16 GHz	OFDM or Single Carrier + 64-QAM		
11ay	2020 (expected)	60 GHz	100 Gbps	10 m	8.64 GHz	OFDM or Single Carrier + 64-QAM	DL MU-MIMO (4x4)	up to four 2.16 GHz channels

IEEE 802.11af TV White Space Band Devices. This standard defines CR-based spectrum sharing between unlicensed TV white space band devices (WSBDs) and licensed TV services, where sharing is coordinated by a geolocation database that depends on the regulatory domain proposed by different countries (Flores et al. 2013).

IEEE 802.11ah Sub 1 GHz License Exempt Operation. This standard, also known as HaLow and released in 2016, defines the use of unlicensed band below 1 GHz, excluding those used for TV white space. The purpose is to create extended range, low data rates and low power consumption in order to support IoT devices and other machine to machine applications (Adame et al. 2014).

IEEE 802.11ac High Speed Wireless Local Area Network (WLAN). Also known as Gigabit Wi-Fi and Wi-Fi 5, and operating in the 5 GHz Spectrum, 802.11ac defines a high-speed WLAN using smart antennas (e.g., downlink MU-MIMO), higher order modulation (256-QAM) and wider channels to achieve multi-user throughput of up to 7 Gbps and dynamic spectrum sensing to share with Federal systems (Aruba Networks 2014; Bejarno, Knightly, and Park 2013).

IEEE 802.11ad Very High Throughput WLAN in 60 GHz. This standard, also called WiGig, was released in 2012 and defines a high speed WLAN that operates in the 57.05–64.00 GHz band in the U.S. The standard supports short-range communications at up to 8 Gbps using 2.16 gigahertz channels and beamforming by antenna arrays with 16 to 32 elements. However, the range is reduced to under 10 meters. The medium access control (MAC) layer is compatible with other current 802.11 standards and supports multi-mode operations (Nguyen et al. 2019; Schulz 2013; Zhu, Doufexi, and Kocak 2011).

IEEE 802.11ax Enhancements for High Efficiency WLAN. This pending standard is intended to support dense deployments such as stadiums or airports and operates in the 2.4 GHz and 5 GHz bands with promised data rates of up to 9.6 Gbps using higher order modulation (1024 QAM), uplink and downlink MU-MIMO, and wide channels. Approval is now expected in 2020 (Khorov et al. 2018).

IEEE 802.11ay Enhanced Throughput for Operation in License-Exempt Bands above 45 GHz. This protocol, also known as Next Generation 60 GHz, is currently actively defining the protocol to support up to 100 Gbps data rates in the 60 GHz band, and to increase the range and reliability over the 802.ad protocol. The protocol will use downlink MU-MIMO and very wide channels and is expected to be released in 2020 (Zhou et al. 2018). In addition, there are several other ongoing related working groups:

- *802.11aj Enhancements for Very High Throughput to Support Chinese Millimeter Wave Frequency Bands (60 GHz and 45 GHz)*. This protocol, also known as China Millimeter Wave, is a modification to the 802.11ad specifically for the China frequency bands and was recently approved in 2018 (H. Wang et al. 2014).
- *802.11az Enhancements for Positioning*. This protocol, also known as Next Generation Positioning, enables the determination of absolute and relative positions and improves timing accuracy. It is expected in 2021 (Banin et al. 2017).
- *802.11ba Wake-up Radio operation*. This protocol is intended to improve battery life of IoT devices and is expected in 2020 (Hwang et al. 2018).
- *802.11bd Enhancements for Next Generation V2X*. This group is working on updating the IEEE 802.11p (DSRC) protocol for vehicular communications to account for higher throughput applications, better reliability/efficiency, and extended range WLAN technologies (Kenney 2018).

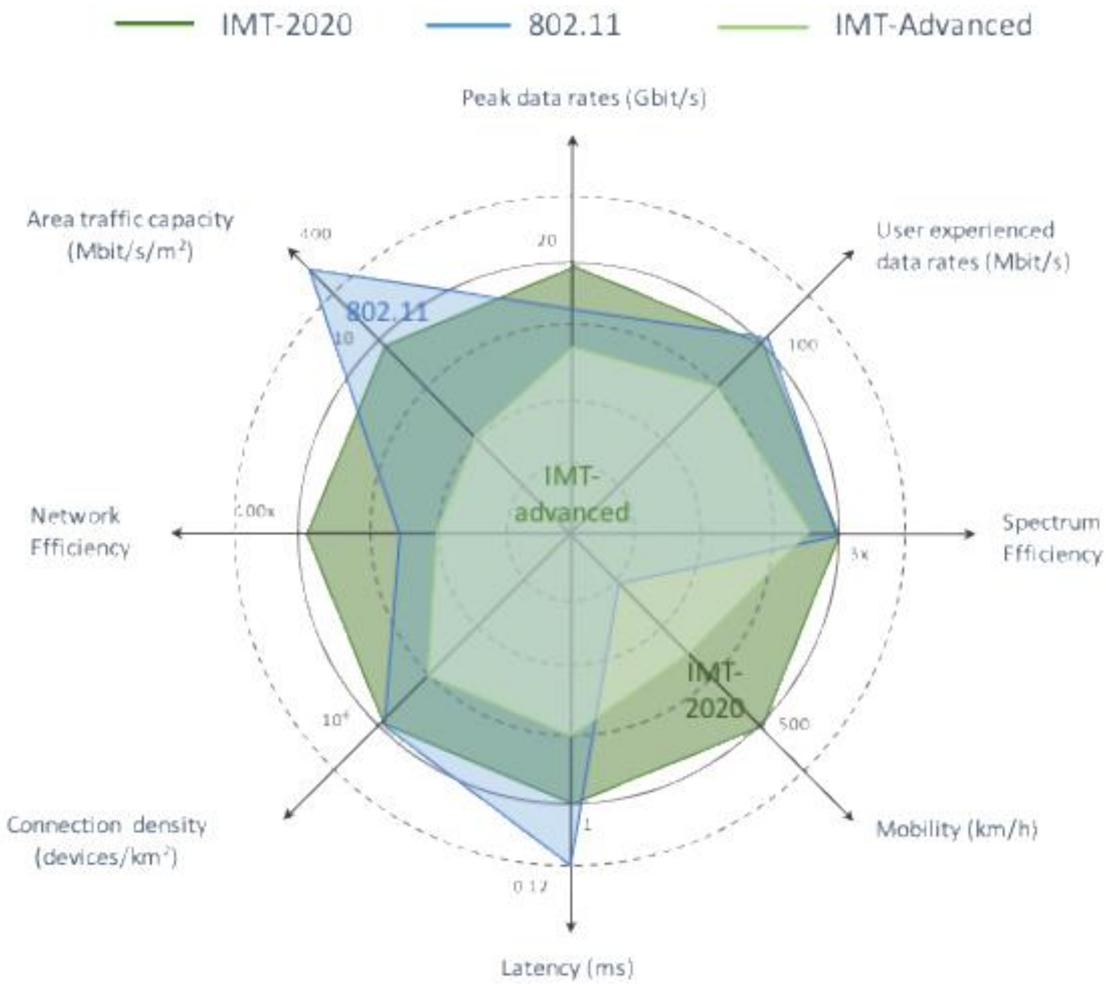
Wi-Fi Capabilities vs. 5G Capabilities

Wi-Fi systems are now viewed as complementary to the current and future cellular systems. As shown in Figure 17, the capabilities of the combined 802.11 WLAN technologies exceed or are close to the goals of 5G. The major exception is in the mobility domain, which has not been the focus of IEEE 802.11. Some of these key parameters are derived from the following 802.11 protocols (Wireless Broadband Alliance 2017):

- Peak data rate from 802.11ax
- User experienced data rate from 802.11ac
- Latency from 802.11ax
- Mobility is addressed in the 802.11p protocol for vehicular communications
- Connection density from 802.11ax
- Energy efficiency from 802.11ax
- Spectrum efficiency from 802.11ax
- Area traffic capacity from 802.11ad

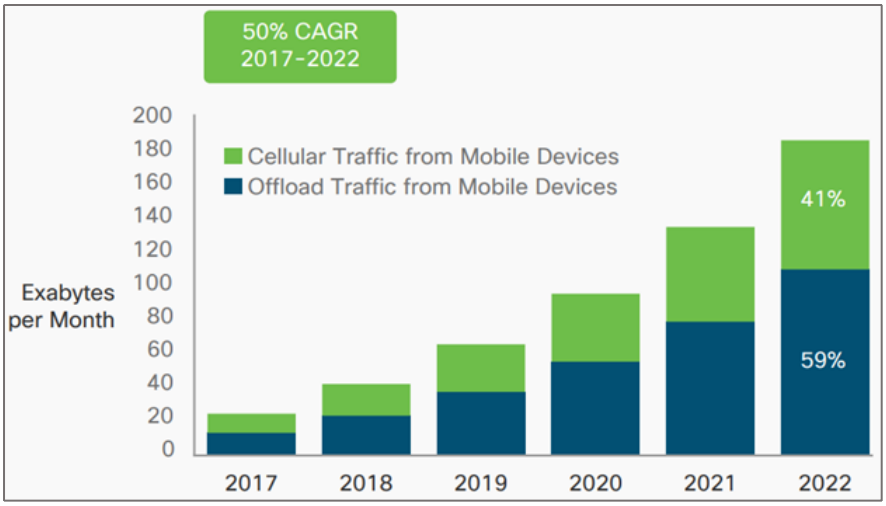
Wi-Fi Offloading of Cellular Traffic

As mentioned in the earlier section, cellular systems are using Wi-Fi and other fixed wireless networks to offload traffic from their cellular systems. Mobile devices are accessing fixed wireless broadband, Wi-Fi public or home access points, or operator-owned femtocells or picocells, and then offloading significant amounts of data from the cellular network onto the fixed networks. In (Cisco 2019a), offload is defined as traffic from dual-mode mobile devices onto Wi-Fi or small-cell networks. The offloading occurs when the device switches from a cellular connection to a fixed connection. The extent to which this is occurring is shown in Figure 18, where the mobile offload increases from 54 percent (13.4 exabytes/month) in 2017 to 59 percent (111.4 exabytes/month) by 2022.



Source: Wireless Broadband Alliance (2017).

Figure 17. Wi-Fi (802.11) Capabilities vs. IMT-Advanced and IMT-2020



Source: Cisco 2019a

Figure 18. Global Mobile Data Traffic Offload to Wi-Fi

In Cisco 2019a, Wi-Fi offload is projected to be higher on 4G and 5G networks than on the lower-speed networks, where the amount of traffic offloaded from 4G was 57% in 2017 and is expected to be 59% by 2022. The amount of traffic offloaded is driven by the data caps on cellular plans and lower data rates that encourage users to access the fixed wireless points. Offloading in 5G networks is expected to increase in the near term but may reduce as 5G matures and data rates are increased.

3. Emerging Application-Level Technologies

In this chapter, we describe the wealth of applications and use cases that are driving the development of 5G. These are, in essence, higher level emerging technologies; many of which could not come to fruition without the communication capabilities of 5G. We consider these higher-level emerging technologies to be *5G-enabled technologies*.

Specifically, we describe the use case categorizations defined by the following organizations:

- International Telecommunication Union (ITU)
- 3rd Generation Partnership Project (3GPP)
- 5G Americas
- Next Generation Mobile Networks (NGMN) Alliance
- 5G Infrastructure Public Private Partnership (5G PPP)

We conclude with a summary that maps the three broad classes of ITU usage scenarios to the top-level categorizations of 3GPP, 5G Americas, NGNM, and 5G PPP.

ITU Use Cases

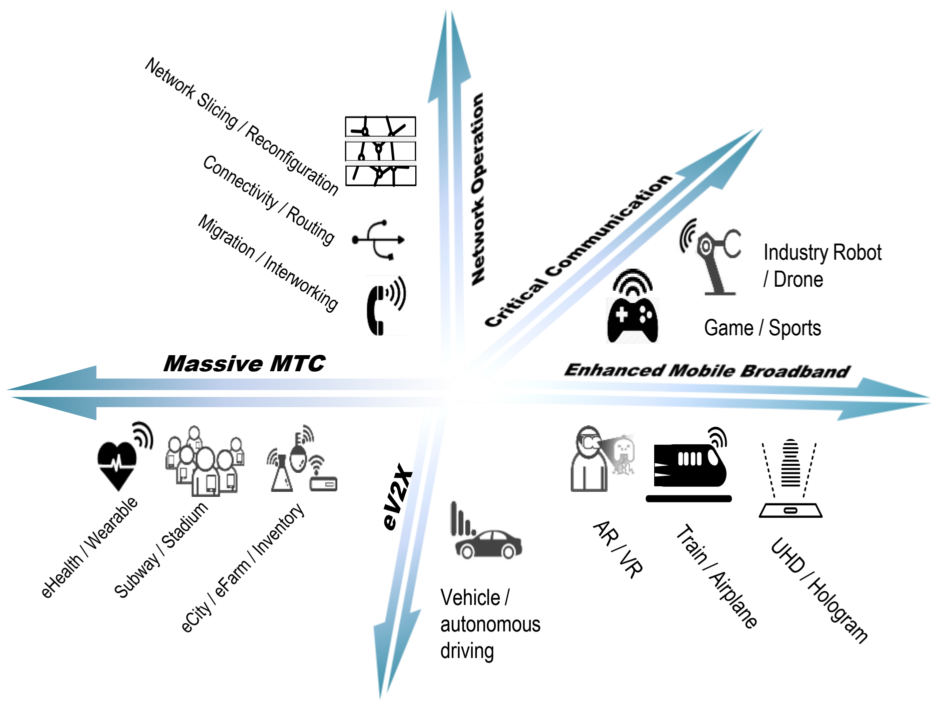
As described in Chapter 2, the ITU envisions 5G as laying a foundation for three broad classes of usage scenarios or use cases:

1. Enhanced Mobile Broadband (eMBB)
2. Ultra-Reliable and Low Latency Communications (URLLC)
3. Massive Machine-Type Communications (MTC) (often referred to as massive IoT)

The 3rd Generation Partnership Project (3GPP) and stakeholders such as 5G Americas, the Next Generation Mobile Networks (NGMN) Alliance, and the 5G Infrastructure Public Private Partnership (5G PPP) have taken the ITU vision and developed rich categorizations of use cases based on the three broad classes of ITU usage scenarios. Highlights of their work are presented below. Appendix A provides details.

3GPP Use Cases

As shown in Figure 19, 3GPP has added two categories of use cases—*Network Operations* and *Enhanced Vehicle-to-Everything (eV2X)*—to the three top-level usage scenarios in the ITU vision. Note that 3GPP refers to URLCC as *Critical Communication*, and, in some cases, it refers to Massive MTC as *Massive IoT*.



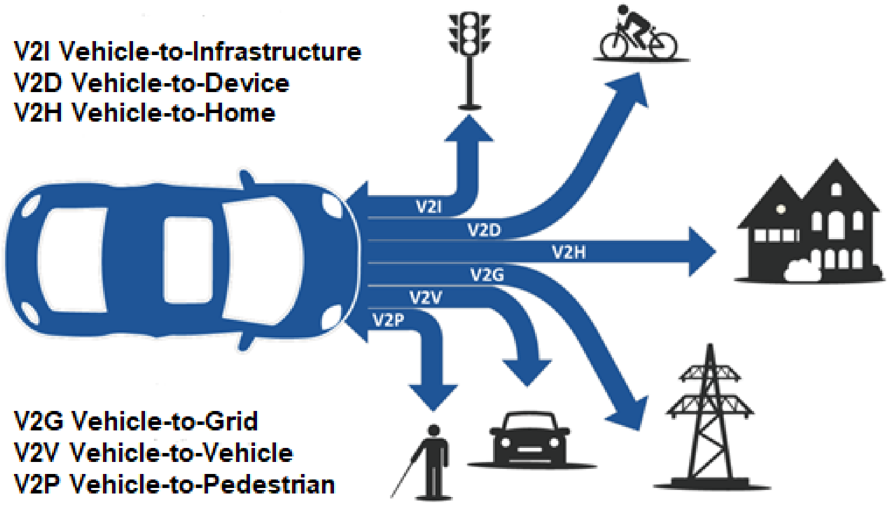
Source: 3GPP 2016

Figure 19. 3GPP Use Case Categories

In the latest draft of the 3GPP Technical Report TR 22.891 on use cases and requirements (September 2016), 3GPP describes 74 separate use cases in detail. To aid in the analysis of use case requirements, 3GPP breaks down its five top-level use case categories into 22 use case families as follows:

1. *Enhanced Mobile Broadband.* This category comprises four use case families: (1) higher date rates, (2) higher density, (3) deployment and coverage, and (4) higher user mobility.
2. *Critical Communications*. This category comprises six use case families: (1) higher reliability and lower latency; (2) higher reliability, higher availability, and lower latency; (3) very low latency, (4) higher accuracy positioning; (5) higher availability; and (6) mission critical services.
3. *Massive IoT*. This category comprises three use case families: (1) operational aspects, (2) connectivity aspects, and (3) resource efficiency aspects.
4. *Enhanced V2X (eV2X)*. eV2X, illustrated in Figure 20, is a highly anticipated, important, and demanding 5G use case family. While eV2X could be considered to be part of the Critical Communication category, 3GPP has elevated it to top-level category status. 3GPP has identified 25 use cases for eV2X services and they are categorized into 4 use case groups: vehicles platooning, extended sensors, advanced driving and remote driving.

5. *Network Operation*. This category—which is considered to be a horizontal use case category that *covers* system aspects of 5G networks [12]—comprises eight use case families: (1) system flexibility, (2) scalability, (3) mobility support, (4) efficient content delivery, (5) self-backhauling, (6) access, (7) security, and (8) migration and interworking.



Source: Alam 2018

Figure 20. Overview of the V2X Concept

Table A-1 of Appendix A provides a complete mapping of the 74 use cases to the 22 use case families and the five top-level 3GPP use case categories. Each of the 74 use cases is assigned to one or more of the use case families. For example, the use case "mobile broadband services with seamless wide-area coverage" is assigned to the "deployment and coverage" and the "higher user mobility" families in the eMBB category; it is also assigned to the eV2X category/family.

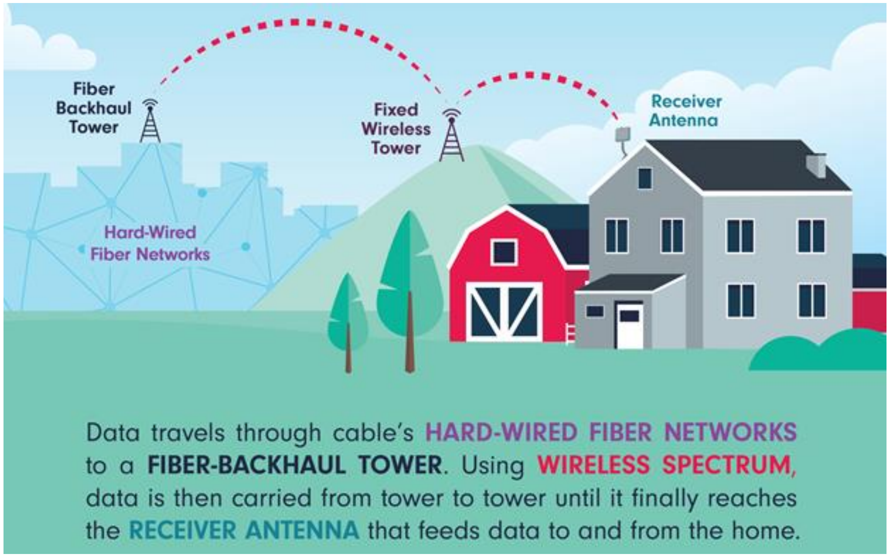
5G Americas Use Cases

5G Americas has a slightly different perspective from the ITU and 3GPP. Namely, 5G Americas breaks out the broad ITU eMBB category into three separate categories—eMBB, enhanced multimedia, and fixed wireless access (FWA)—and thus ends up with six top-level use case categories:

1. eMBB.
2. URLCC.
3. Massive IoT.
4. *Connected Vehicles*. Like 3GPP, 5G Americas considers this use case category significant enough to break it out separately from the URLLC use case category.
5. *Enhanced Multimedia*. This use case category is broken out from the broad ITU eMBB category. Specific use cases include live TV, on-demand multimedia, and mobile TV.
6. *FWA*. This use case is also broken out from the broad ITU eMBB category. 5G Americas calls out fixed wireless access, illustrated in Figure 21, as a separate top-level category, in part due to its prominence as an early 5G deployment case and its potential to help close the digital divide. Instead of laying fiber to customers' premises—which could entail laying miles and miles of fiber to sparsely populated remote regions, sometimes across treacherous terrain—FWA leverages

[12] The other four use case categories are considered to represent market segments or vertical industries.

wireless communication for "last-mile" connectivity. Already, Verizon is marketing Verizon 5G Home,[13] and AT&T is marketing AT&T Fixed Wireless Internet.[14]



Source: NCTA 2018

Figure 21. Overview of Fixed Wireless Access

As shown in the figure, data travels over a fiber network to a fiber backhaul tower. From there, the data is relayed from tower to tower via over-the-air hops of up to five miles, until it reaches a receiver antenna (fixed wireless antenna) at a customer's premises (say, on a rooftop). Once the wireless signal is received at a customer's home or business, it can be converted to conventional Wi-Fi with the use of devices such as fixed wireless 5G routers or Wi-Fi gateways.

5G Americas goes further than 3GPP in terms of identifying specific requirements for its use cases. As shown in Table A-2 of Appendix A, 5G Americas cites user data rate, latency, and mobility requirements for each of the 22 use cases identified for its six top-level use case categories. The most stringent requirements are as follows:

- *User data rate*. Some eMBB use cases (e.g., 5G-enabled homes and offices) require down-link data rates of as high as 1 to 5 Gbps. Other use cases—hotspots in dense areas, live TV, and on-demand multimedia—require data rates of 50-500 Mbps.
- *Latency*. The V2X use cases, as well as certain Massive IoT use cases, require latencies of as low as 1 ms. Several URLLC use cases require latencies of below 1 ms.
- *Mobility*. The V2X use cases require mobility up to 160 km/h. In certain contexts, (e.g., high-speed trains), the mobile TV and sensor networks require mobility up to 500 km/h.

NGNM Use Cases

NGNM starts out with eight top-level groups, the first four of which can be viewed as a breakout of the broad ITU eMBB category, and the next three of which can be viewed as a breakout of the broad ITU MTC category:

1. *Broadband Access in Dense Areas*

[13] https://www.verizonwireless.com/5g/home/

[14] https://www.att.com/internet/fixed-wireless.html

2. *Higher User Mobility*
3. *Broadcast-like Services*
4. *Broadband Access Everywhere*
5. *Extreme Realtime Communications* (e.g., tactile Internet), with emphasis on latency vs. reliability
6. *Lifeline Communications* (e.g., communications associated with natural disasters), with emphasis on reliability vs. latency
7. *Ultra-Reliable Communications* (e.g., automatic traffic control/driving, remote surgery), with emphasis on both latency and reliability
8. *Massive IoT*

As shown in A-3 of Appendix A, NGMN provides a further breakdown of its eight top-level groups into a total of 14 subgroups[15] and lists sample use cases for each subgroup. Like 5G Americas, NGMN identifies user requirements—namely, user experienced data rate, latency, and mobility—for its subgroups. In addition, NGMN identifies system performance requirements—connection density and traffic density—for the subgroups. Highlights from this perspective are as follows:

- The "indoor ultra-high broadband access" subgroup (exemplified by the smart office use case) has extremely demanding requirements, including (1) user data rates of 1 Gbps, (2) connection density of 75,000/km^2, and (3) traffic density of 15 Tbps/km^2 for uplink and 2 Tbps/km^2 for downlink.[16]
- The "broadband access in a crowd" subgroup (exemplified by the HD video/photo sharing in a stadium use case) has even higher demands for connection density—150,000/km^2—as well as for uplink traffic density—7.5 Tbps/km^2.
- The "airplanes connectivity" subgroup (exemplified by 3D connectivity for aircraft, as well as for balloonists, gliders, and skydivers) has mobility requirements of up to 1,000 km/h.
- The massive low-cost/long-range/low-power MTC subgroup (exemplified by smart wearables and sensor networks) has demands up to 200,000/km^2 for connection density.

5G PPP Use Cases

5G PPP defines six use case families, the first three of which are broken out from the ITU eMBB category:

- Future Smart Office
- Dense Urban
- Broadband (50+ Mbps) Everywhere
- Tactile Internet / Automation
- Connected Vehicles
- Low Bandwidth IoT

As shown in Table A-4, 5G PPP also considers five vertical use cases—Automotive, eHealth, Energy, Media and Entertainment, and Factories of the Future—and maps them to the above use case families. Upon reviewing the mapping, 5G PPP basically concludes that the use case families are comprehensive enough to cover the vertical use cases.

Summary

Table 4 provides a mapping from the ITU usage scenarios to the top-level categorizations developed by 3GPP, 5G Americas, NGMN, and 5G PPP. There seems to be a consensus that the ITU usage are too broad to support requirements analysis. There is also a developing consensus that eV2X is a leading 5G use case with high network demands but also high societal returns.

[15] NGMN refers to its eight top-level groups as "families" and to its 14 lower-level groups as "categories." The terms are not used here because they do not align with the concepts of categories and families discussed in previous sections.

[16] Tbps/km^2 stands for terabits per second per square kilometer.

Table 4. ITU Usage Scenarios Mapped to 3GPP, 5G Americas, NGMN, and 5G PPP Use Cases

<table>
<tr><th>ITU Usage Scenarios</th><th>3GPP Use Case Category</th><th>5G Americas Use Case Category</th><th>NGMN Use Case Family</th><th>5G PPP Use Case Family</th></tr>
<tr><td rowspan="6">Enhanced Mobile Broadband
e.g., enhanced video (4K, 8K, 3D, 360-degree video, UHD live streaming), virtual and/or augmented reality)</td><td rowspan="6">Enhanced Mobile Broadband
Drivers: data rate, latency, traffic density, connection density, mobility</td><td rowspan="2">Enhanced Mobile Broadband</td><td>Broadband Access in Dense Areas</td><td rowspan="2">Future Smart Office</td></tr>
<tr><td rowspan="2">Higher User Mobility</td></tr>
<tr><td rowspan="2">Enhanced Multimedia</td><td rowspan="2">Dense Urban</td></tr>
<tr><td rowspan="2">Broadcast-Like Services</td></tr>
<tr><td rowspan="2">Fixed Wireless Access (early 5G deployment)</td><td rowspan="2">Broadband (50+ Mbps) Everywhere</td></tr>
<tr><td>Broadband Access Everywhere</td></tr>
<tr><td rowspan="4">Ultrareliable and Low Latency Communications
e.g., factory automation, remote surgery, self-driving cars</td><td rowspan="2">Critical Communication
Drivers: latency, reliability, position accuracy, connection density</td><td rowspan="2">Ultrareliable Low Latency Communications</td><td>Extreme Realtime Communications (emphasis on latency vs. reliability)</td><td rowspan="2">Tactile Internet / Automation</td></tr>
<tr><td rowspan="2">Lifeline Communications (emphasis on reliability vs. latency)</td></tr>
<tr><td rowspan="2">Enhanced Vehicle-to-Everything (eV2X)
Drivers: latency, reliability, position accuracy, mobility</td><td rowspan="2">Connected Vehicles</td><td rowspan="2">Connected Vehicles</td></tr>
<tr><td>Ultrareliable Communications (emphasis on ultrareliability and low latency</td></tr>
<tr><td>Massive Machine Type Communications
e.g., smart homes, cities, buildings, farms, utilities</td><td>Massive MTC (also known as Massive IoT)
Drivers: communication efficiency, connection density, position accuracy</td><td>Massive IoT</td><td>Massive IoT</td><td>Low Bandwidth IoT</td></tr>
<tr><td>Not covered as use case*</td><td>Network Operation (requirements for 5G system aspects)
e.g., network slicing, routing, migration and interworking, energy saving</td><td>Not covered as use case*</td><td>Not covered as use case*</td><td>Not covered as use case*</td></tr>
</table>

***** Network operation is covered as a use case by 3GPP, but not by ITU, 5G Americas, NGMN, or 5G PPP.

4. Spectrum Demand

In this chapter, we examine the spectrum demand of 5G and Wi-Fi technologies. We begin by providing overviews of the following:

- Spectrum bands (low, mid, high, millimeter wave, etc.) and characteristics
- Spectrum management, namely, (1) the functions of spectrum management in general; (2) spectrum management in the U.S. (i.e., the roles of the FCC and NTIA); and (3) the FCC classes of spectrum use rights)
- Current spectrum holdings in the U.S.

We then present anticipated spectrum demand from various perspectives:

- Forecasts of growth in the number of connected devices and the amount of data traffic
- Qualitative summaries of the 5G requirements for low, mid, and high band spectrum, by application type
- Quantitative estimates of spectrum demands for 5G and Wi-Fi

We close with a review of the responses to an NTIA Request for Comments on spectrum issues.

Spectrum Bands and Characteristics

As noted in a recent report by the Commerce Spectrum Management Advisory Committee (CSMAC), there is no consensus on what constitutes low-, mid-, and high- band spectrum. Historically, spectrum in the 300 MHz to 3 GHz range was considered "beachfront" property due to its favorable characteristics with respect to range, penetration, and resistance to rain fade. Within that frequency range, low-band spectrum was considered to be below 1 GHz, mid-band spectrum was considered to be between 1 and 2 GHz, and high-band spectrum was considered to be between 2 and 3 GHz (CSMAC 2017).

Now, as illustrated in Figure 22, mid-band spectrum is generally considered to cover frequencies up to 6 GHz and sometimes as high as 20 or 24 GHz; likewise, high-band spectrum is generally considered to cover frequencies above 20 to 24 GHz. There are discrepancies with respect to the boundary between mid-band and high-band spectrum. The CSMAC report points out that the definitions are not fixed (p. 9):

> *The definitions of low-, medium-, and high-band spectrum are very dynamic and will continue to evolve over time. The definitions could continue to develop upward as new technologies and approaches for overcoming some of the physical obstacles are advanced which could, for instance, leverage terahertz communications or free-space optics for some applications.*

Table 8, which is drawn from material in the CSMAC report, summarizes the characteristics of spectrum bands in terms of frequency range; data rate; distance; free-space, foliage, and building-penetration losses; antenna directionality; and use cases. In general, lower frequencies have longer range, better penetration, and more resistance to rain fade, while higher frequencies have higher data rates and higher antenna directionality.

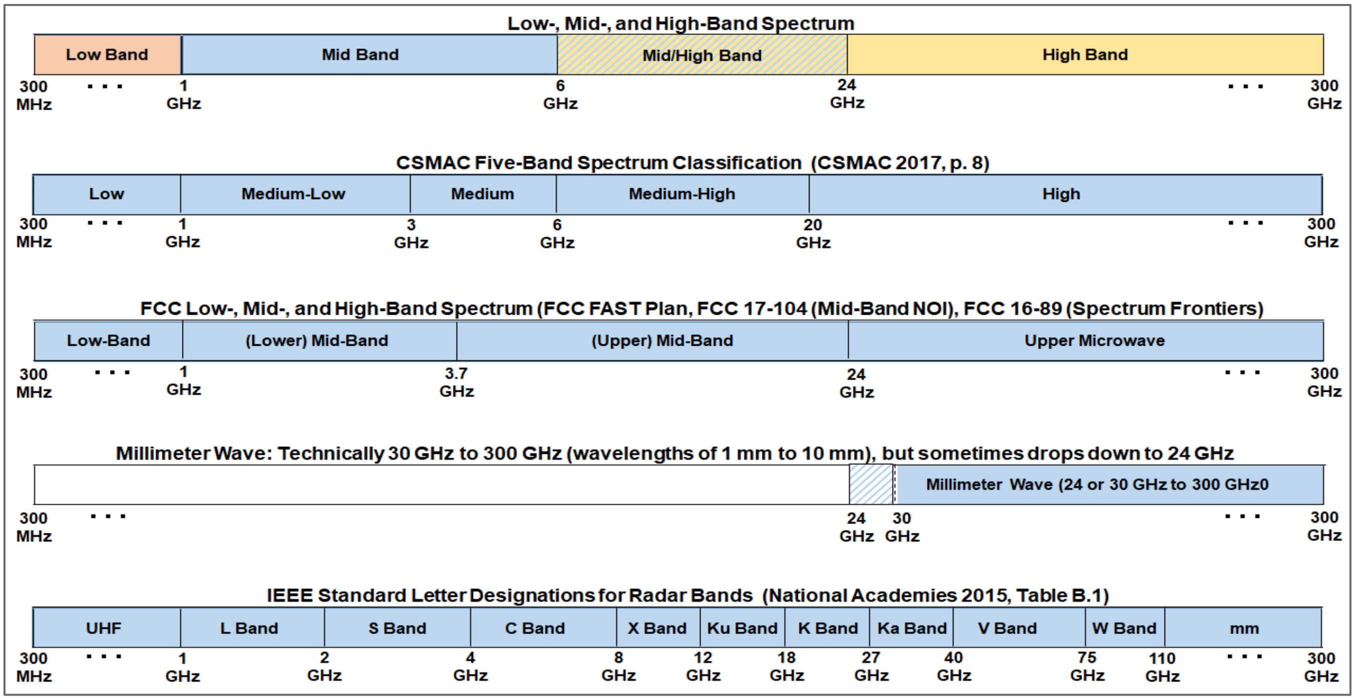


Figure 22. Sample Definitions of Spectrum Bands

Table 5. Spectrum Bands – General Characteristics and Use Cases

Spectrum Band		Characteristics			
CSMAC Designation	Frequency	Data Rate	Distance	Free-Space, Foliage, & Building-Penetration Losses and Antenna Directionality	Use Cases
Low	<1GHz	low	5-50 miles	1. low free-space, foliage, and building-penetration losses 2. virtually invulnerable to rain 3. limited antenna directionality	• 50 MHz and even 20 MHz channels infeasible • Low latency applications can be supported, but not high bandwidth • Can support rural broadband at limited speeds • Good for low bandwidth IoT applications
Medium-low	1–3 GHz	medium	up to 5 miles	1. free-space, foliage, and building-penetration losses increase 2. rain losses increase 3. antenna size decreases; antenna directionality increases	• 50–100 MHz channels possible • Well suited for high availability satellite applications due to propagation characteristics and resistance to rain fade • Fixed wireless broadband could be supported, but new 5G applications (8K video, VR/AR) could quickly exhaust available bandwidth
Medium	3–6 GHz	medium-high	<5 miles		
Medium-high	6–20 GHz	high	<5 miles		• Large contiguous spectrum blocks available (100 – 200 or more MHz per channel) for multiple operators • Gbps speeds/user possible • VR/AR/other low latency, high bandwidth applications can be supported
High	>20 GHz	very high	<2 miles	1. very high losses →line of sight (LOS) 2. very high rain and/or humidity losses 3. extremely high antenna directionality	

Source: Adapted from material on pages 8–11 of CSMAC 2017

Spectrum Management[17]

Functions of Spectrum Management

Spectrum management has, for most of its history, centered around three primary functions:

1. *Allocating bands of spectrum for specific services*. The characteristics of the service demand and the available technology drive the allocations. For example, in response to technological advances and associated 5G demand, the FCC recently created the Upper Microwave Flexible Use Service (UMFUS) and allocated several millimeter wave bands (24 GHz band, 28 GHz band, Upper 37 GHz band, 39 GHz band, 47 GHz band) for the service.[18,19]
2. *Granting spectrum use rights* (e.g., licenses, frequency assignments, unlicensed access). Conventional spectrum management involves dividing the spectrum along the dimensions of frequency, space, and time. Licensed users have protection against interference from other users. Both the FCC and NTIA also authorize the use of "unlicensed devices" in some frequency bands, but they may not cause harmful interference to systems with licenses or assignments, and they must accept interference from them.
3. *Defining rules of use to protect against harmful interference*. Licenses and other authorizations to use spectrum typically require adherence to limits on the transmission power and bandwidth in a band, along with the power emitted outside that bandwidth. Spectrum management also frequently involves creating guard bands between the frequency authorizations to further protect against interference. The rules for authorizing use of a frequency band are based on the state of the art of the technology at the time the rules are made.

Spectrum Management in the United States

In the U.S., the NTIA and the FCC jointly manage spectrum. They collaboratively decide which spectrum is allocated to Federal users, which to non-Federal users, and which to shared use. The NTIA is responsible for managing Federal use of spectrum, while the FCC is responsible for managing non-Federal use of spectrum. The NTIA and the FCC have to coordinate on spectrum shared among Federal and non-Federal users. Federal agencies provide input to NTIA and FCC deliberations through the Interdepartment Radio Advisory Committee (IRAC).

The international and U.S. allocations are listed in the FCC Online Table of Frequency Allocations[20] for frequencies ranging from 0 kHz to 3000 GHz.[21] For the U.S., the table gives the most current Federal and non-Federal allocations, as well as references to relevant rules. The table is also published by the Federal Register and codified in the Code of Federal Regulations at Title 47 (Telecommunication), §2.106 (Table of Frequency Allocations).

FCC Classes of Spectrum Use Rights

Exclusive-Use Licenses. Licenses for spectrum partitions are granted to individual entities and, importantly, contain regulatory protections against interference from other users. The FCC manages a variety of spectrum and services including satellite, amateur radio, and public safety, as well as the fixed

[17] The material in this section is drawn from *A Summary of Recent Federal Government Activities to Promote Spectrum Sharing*, by the Institute for Defense Analyses Science and Technology Policy Institute (Agre and Gordon 2015).

[18] 47 CFR Part 30 – Upper Microwave Flexible Use Service, §30.4 Frequencies.

[19] Note that a band can be allocated for multiple services. For example, the 28 GHz band is also allocated for RF devices, satellite communications, and fixed microwave services.

[20] https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf

[21] Note that there are no allocations below 8.3 kHz or above 275 GHz.

and mobile wireless broadband services, and employs different schemes for licensing decisions. *Exclusive use licensing* of bands with interference protection and geographic limitations is the most prevalent form of assignment in use below 3 GHz. For example, a cellular carrier may be granted a license for exclusive use of a 20 megahertz frequency band centered at a particular frequency within a certain Cellular Market Area (i.e., Metropolitan Statistical Area or Rural Service Area), while other carriers are granted licenses for exclusive use of the same band in other Cellular Market Areas.

Licenses are typically granted on a long-term basis, often for 10 or more years, with renewals possible. This is desirable from the commercial perspective to justify the large capital investment required to create cellular or other services infrastructure. Typically, in return for the license, the licensee must utilize the spectrum by building out the infrastructure or the license may be revoked.

Until the 1980s, the FCC administratively assigned cellular wireless licenses based on comparative hearings, where the Commission weighed the relative merit of competing proposals (Copps 2002, Wynns 2004). However, since 1993, when Congress authorized the FCC to award licenses through competitive bidding,[22] spectrum auctions have generally been accepted as a best practice for assigning wireless broadband spectrum where demand exceeds availability. Auctions are a market-based mechanism and, as such, are used to help assign the spectrum in optimal ways from an economic perspective. Auctions have tended to favor assignment of exclusive licenses, because they are deemed to have the highest value by terrestrial wireless carriers. Between 1994 and January 2019, the FCC conducted 92 spectrum auctions, which together raised over $120 billion for the U.S. Treasury.[23,24]

Priority-Access Licenses (PALs). In April 2015, the FCC established rules for the Citizens Broadband Radio Service (CBRS), which represents an innovative scheme to facilitate shared access between Federal and non-Federal use of the 3.5 GHz band (3.55–3.7 GHz). The scheme defines three tiers of users: (1) first tier (Incumbents), (2) second tier (Priority Access Licenses (PALs)), and (3) third tier (General Authorized Access (GAA) users). Incumbents receive protection from all other users. Priority Access Licenses (PALs) receive protection from GAA users but must avoid causing harmful interference to Incumbents and also accept interference from them. GAA users are licensed by rule and must avoid causing harmful interference to higher tier users as well as accept interference from all other users. Operations among the three tiers of users are to be coordinated by an automated coordinator known as a Spectrum Access System (SAS). PAL commercial operations require (1) a PAL auction and (2) availability of certified SAS. Both could have happened as early as 2019 (CBRS WInnForum 2019; Schaubach 2018).

Licensed by Rule Services. There is a special category of licensed services—known as "licensed by rule" services—that allow users to operate without acquiring individual licenses. The basis of license by rule services lies in 47 U.S.C. 903(e), which authorizes the citizens band radio service and certain other services to operate without individual licenses and, furthermore, gives the FCC discretion in defining the meaning of "citizens band radio service" and other relevant services. In 47 CFR §95.401, the FCC exercises its authority to define the scope of the term citizens band radio service and declares that the citizens band radio services include not only the original Citizens Band (CB) Radio Service, but also several other services such as Medical Device Radiocommunication Service (MedRadio).

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[22] Congress authorized the FCC to award licenses for rights to use the radio spectrum through competitive bidding as part of the 1993 Budget Act (Omnibus Budget Reconciliation Act of 1993).

[23] FCC Auctions Summary, https://www.fcc.gov/auctions-summary

[24] These totals include the first Spectrum Frontiers auction, for the 28 GHz band, which concluded on January 24, 2019. It was the 92nd auction and has a total of $702.572 million in provisionally winning bids (PWB) listed in the FCC Auctions Summary as of March 4, 2019. Additional Spectrum Frontiers auctions—the 24 GHz band, the Upper 37 GHz band, the 39 GHz band, and the 47 GHz band—are expected to be conducted in 2019.

Unlicensed Access. In 1985, the FCC began to allow unlicensed access to specified spectrum bands—beginning with the industrial, scientific, and medical (ISM) bands at 902–928 MHz, 2400–2483.5 MHz, and 5725–5850 GHz—under Part 15 of its rules governing radio frequency (RF) devices. Under Part 15, devices meeting certain technical specifications, administrative requirements, and other conditions are permitted to access spectrum in an unlicensed mode, i.e., without individual licenses. Part 15 applications include Wi-Fi, Bluetooth, Zigbee, cordless phones, baby monitors, and wireless garage door openers.

Unlicensed users are not granted the same kinds of rights and protections as licensed users. They, in fact, have no vested right to continue using any frequency. They must accept any interference generated by other users, and they may not cause harmful interference. If notified by the FCC that they are causing harmful interference, they must cease operation.

To reduce harmful interference, unlicensed users typically have restrictions placed on them, such as limited power levels, geolocation database-controlled access, and/or sensing (e.g., to avoid radars in the 5 GHz Wi-Fi band).

Current Spectrum Holdings in the United States

Low and Mid Bands

The U.S., through FCC action, has allocated 673 MHz for wireless service – more than any other country.[25] Table 9 shows spectrum holdings of AT&T, Sprint, T-Mobile, Verizon Wireless, US Cellular, and DISH in spectrum bands below 3 GHz—the high end of what was known as “beach front” spectrum until recently. The table was derived from Figures A-23 and A-24 of the FCC's first *Communications Marketplace Report,* published in accordance with RAY BAUM'S Act of 2018. The report was released on 26 December 2018 as FCC 18-181.

With respect to 5G, the following facts are noteworthy:

- *T-Mobile, through its participation in the incentive auction, gained significant holdings in the 600 MHz band.* According to a recent Wireless 20|20 report, T-Mobile had deployed an Extended Range LTE network using its 600 MHz spectrum in more than 1,250 cities and towns across the U.S. by the end of 2018. T-Mobile has also been working with Nokia on plans for a broad and potentially fast rollout of 5G services using this spectrum (Ayvazian, Campbell, and Sarkissian 2019).
- *Sprint holds an overwhelming percentage of the spectrum in the 2.5 GHz band.* According to the Wireless 20|20 report, “Only Sprint has the 100 MHz of bandwidth in the 2.5 GHz spectrum band that could support 5G deployment with user downlink speeds that could deliver 1 Gbps service. Sprint controls around 120 MHz of 2.5 GHz spectrum in 90 percent of the top 100 U.S. markets, and the 2.5 GHz spectrum band is included in the Non-Standalone 3GPP 5G NR specification” (Ayvazian, Campbell, and Sarkissian 2019, p. 5).

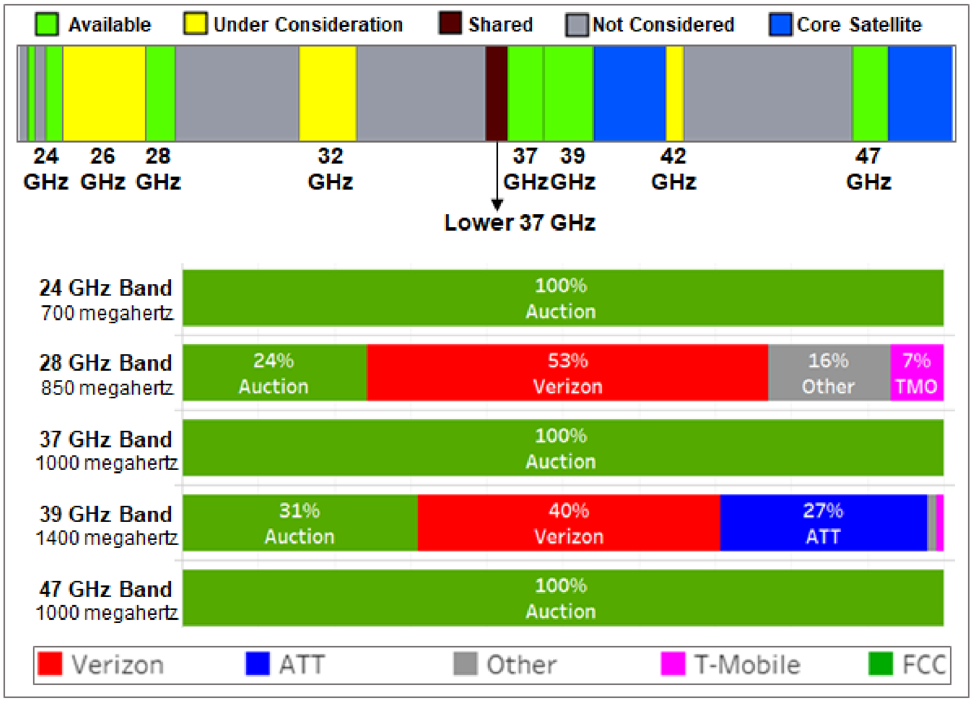
Millimeter Wave Bands

The millimeter wave bands, lying in the 24 GHz–300 GHz range, are important to 5G because of the very high data rates they enable. As shown in Figure 26, Verizon and AT&T are the dominant spectrum

[25] See The Spectrum Handbook 2018, SUMMIT RIDGE GROUP (Oct. 2018, 31), 234 (2018 Spectrum Handbook), available at: https://ssrn.com/abstract=3259782.

holders at this time, with T-Mobile being the only other significant holder. The holdings are largely a result of the following acquisitions (Ayvazian, Campbell, and Sarkissian 2019):

- Verizon acquired XO Communications in early 2017, thus gaining licenses in the 28 GHz and 39 GHz bands. It also acquired Straight Path, gaining more licenses in both bands.
- AT&T acquired FiberTower in early 2018, thus gaining spectrum in the 39 GHz band.
- T-Mobile acquired MetroPCS in 2013, gaining spectrum in the 28 GHz band.

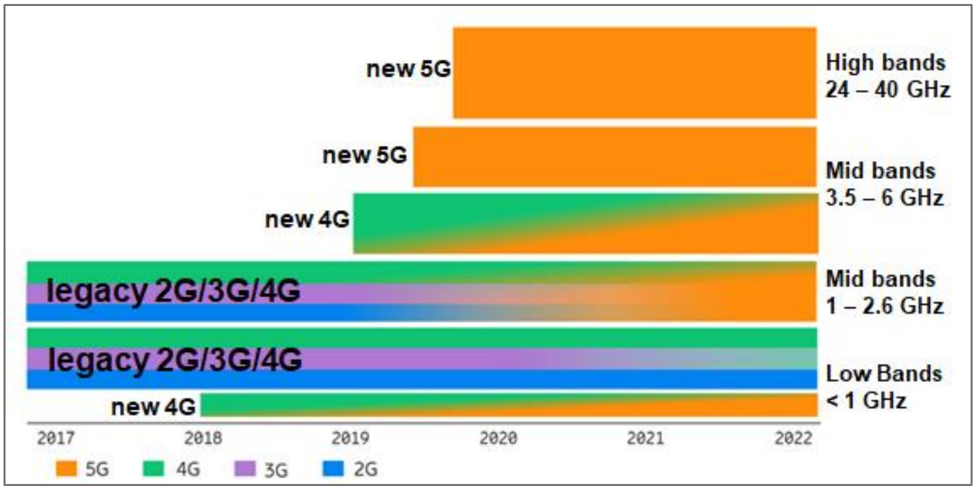


Source: Adapted from T-Mobile 2018

Figure 23. Millimeter Wave Bands: Status and Current Holdings in the United States

Evolution of 2G/3G/4G Bands to 5G

As noted in Ericsson's June 2018 Mobility Report, spectrum bands currently dedicated to 2G, 3G, and 4G services can be expected to evolve to 5G services in the future. Figure 24 illustrates the concept known as "refarming," by which operators transition operations in a given spectrum band from one technology to another (e.g., legacy 2G/3G/4G low and mid bands to 5G, new 4G bands to 5G).



Source: Adapted from (Ericsson 2018).

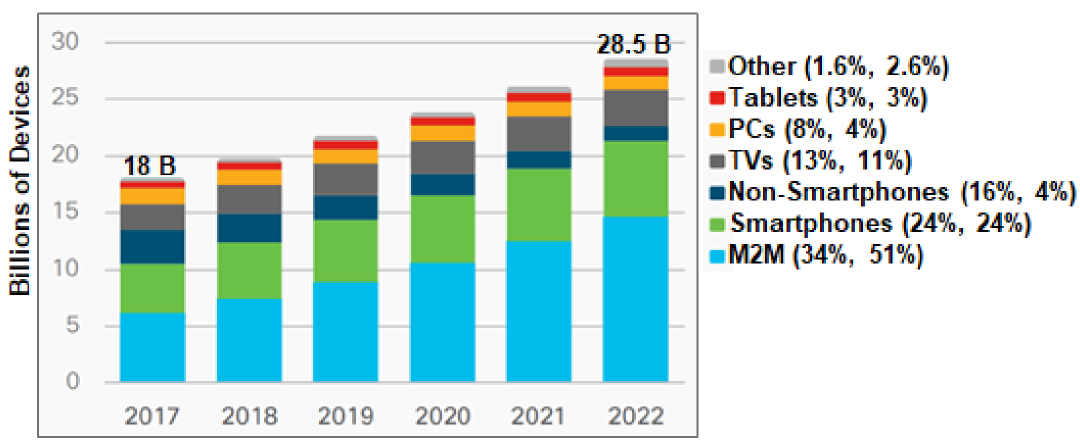
Figure 24. Refarming of Spectrum over Time

Forecasts of Demand in Terms of Devices and Traffic

In this section, we present forecasts of demand in terms of number of devices and amount of data traffic. The ever-increasing numbers of devices and amount of traffic drives the demand for greater commercial access to more and more spectrum. The forecasts are drawn from the highly regarded and widely cited Cisco Visual Networking Index (VNI) Forecast (Cisco 2019a, Cisco 2019b, Cisco VNI Forecast Highlights Tool). Cisco started preparing the VNI Forecast in 2006 and began publicly releasing the results on an annual basis in 2007. According to Cisco, “The Cisco VNI Forecast has been characterized as conservative by some industry analysts and academicians. In general, the actual growth rate has been within 10 percent of the projected growth rate” (Cisco 2018).

Networked Devices by Type

Globally, the number of networked devices is expected to grow from 18 billion in 2017 to 28.5 billion in 2022, as shown in Figure 25. Machine-to-machine (M2M) devices (or modules) will be the fastest growing device type and will represent 51 percent of total devices by 2022. (Cisco 2019b).



Note: Figures in parentheses refer to 2017 and 2022 device share.

Source: Adapted from Cisco 2019b

Figure 25. Global Growth in Devices and Connections by Device Type

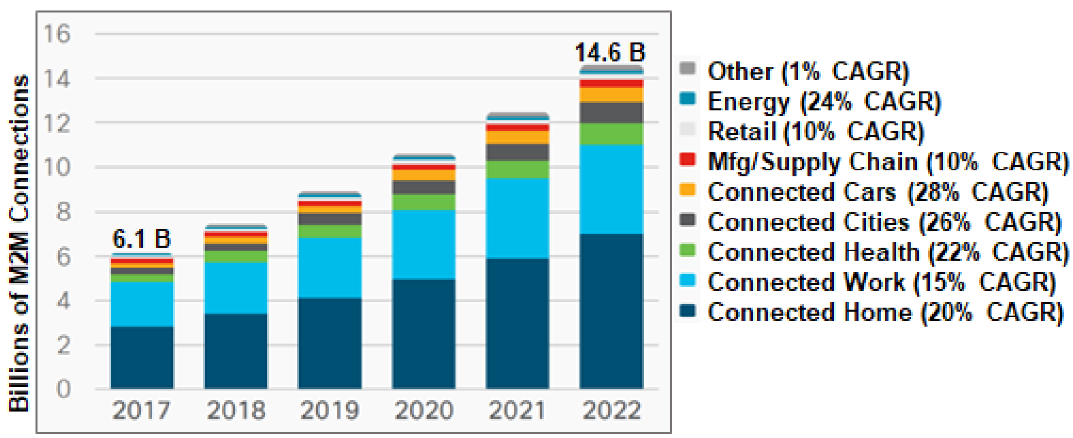
In the U.S., the number of networked devices is expected to increase 1.8-fold, from 2.6 billion devices in 2017 to 4.6 billion in 2022, according to the online Cisco VNI Forecast Highlights Tool.[26] The mix of devices will more heavily weighted toward M2M modules and TVs in the U.S. than it will be globally (Cisco VNI Forecast Highlights Tool, accessed March 20, 2019).

In 2022, the breakdown by device type in the U.S. is projected to be as follows (Cisco VNI Forecast Highlights Tool, accessed March 20, 2019):

- M2M modules – 64% of networked devices and 6% of IP traffic
- Smartphones – 7% of networked devices and 20% of IP traffic
- Connected TVs – 15% of networked devices and 42% of IP traffic
- PCs – 6% of networked devices and 24% of IP traffic
- Tablets – 3% of networked devices and 8% of IP traffic
- Other – 5% of networked devices and less than 1% of IP traffic

Connected Machine-to-Machine (M2M) Connections by Sector

As noted above, Cisco projects that M2M networked connections will account for over half of all connections globally in 2022, growing from 6.1 billion connections in 2017 to 14.6 billion in 2022. Figure 26 breaks out the M2M connections by sector. Connected home applications (e.g., home automation, home security and video surveillance, smart appliances, and tracking applications) will account for 48 percent of M2M connections. Connected cars, cities, energy, and health will be the fastest growing sectors, with their numbers of networked connections having compound annual growth rates of 28%, 26%, 24%, and 22%, respectively (Cisco 2019b).



Source: Adapted from Cisco 2019b

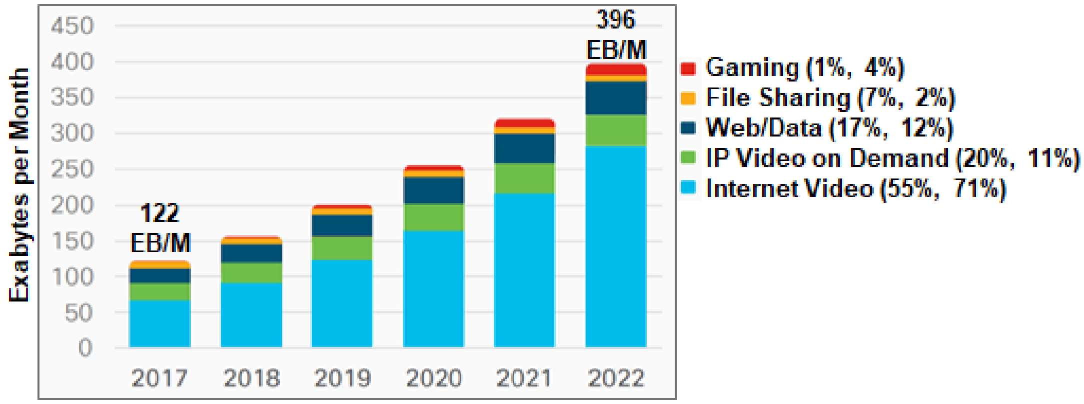
Figure 26. Global Growth in M2M Connections by Sector

IP Traffic by Application Type

Globally, IP traffic is expected to experience a *3-fold increase* between 2017 and 2022, growing from 122 exabytes[27] per month to 346 exabytes per month. As shown in Figure 27, IP video traffic, which includes Internet video and IP video on demand (VOD), will account for the bulk of the traffic—82 percent of all IP traffic in 2022, up from 75 percent in 2017 (Cisco 2019b).

[26] https://www.cisco.com/c/m/en_us/solutions/service-provider/vni-forecast-highlights.html

[27] An exabtye is 10^{18} bytes; it is equivalent to one billion gigabytes, one million terabytes, and one thousand petabtyes.



Note: Figures in () refer to 2017 and 2022 traffic share

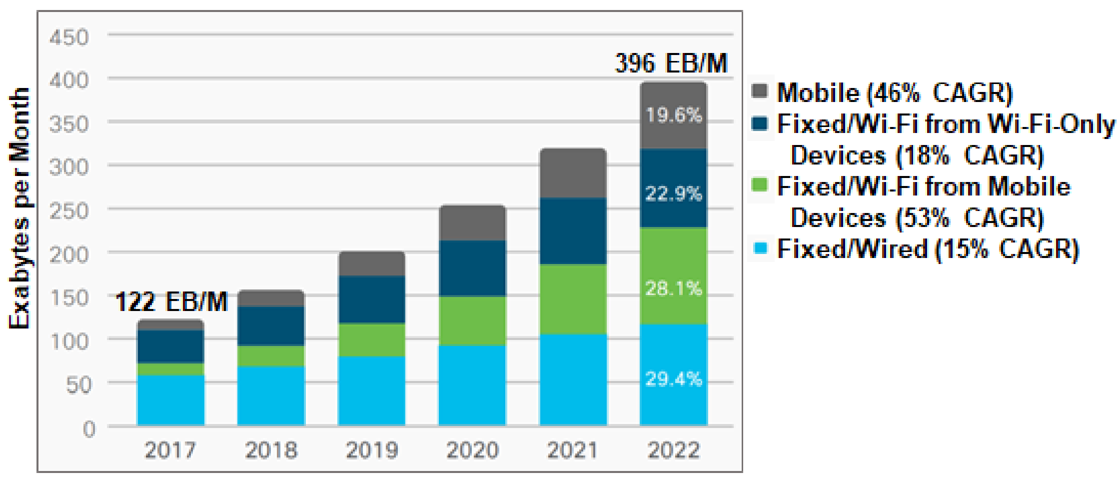
Source: Adapted from Cisco 2019b

Figure 27. Global Growth in IP Traffic by Application

Between 2017 and 2022, IP traffic in the U.S. is projected to grow from 39 exabytes per month to 102.4 exabytes per month. IP video traffic will represent over 80 percent of that traffic—31.6 exabytes per month (81 percent of all IP traffic) in 2017 and 83.8 exabytes per month (82 percent) (Cisco VNI Forecast Highlights Tool, accessed March 20, 2019).

IP Traffic by Network Type and Device Type

Figure 28 looks at IP traffic from another perspective—network type (wired, Wi-Fi, or mobile) and device type (Wi-Fi only or mobile).



Source: Adapted from Cisco 2019b

Figure 28. Global Growth in IP Traffic, Wired, and Wireless

The data underlying the graph tells a more complete story (Cisco VNI Forecast Highlights Tool, accessed March 20, 2019):

- Fixed/wired traffic will experience a twofold increase (58.3 exabytes/month to 116.8 exabytes/month) between 2017 and 2022 but will decrease as a percentage of total IP traffic, falling from 48% in 2017 to 29% in 2022.

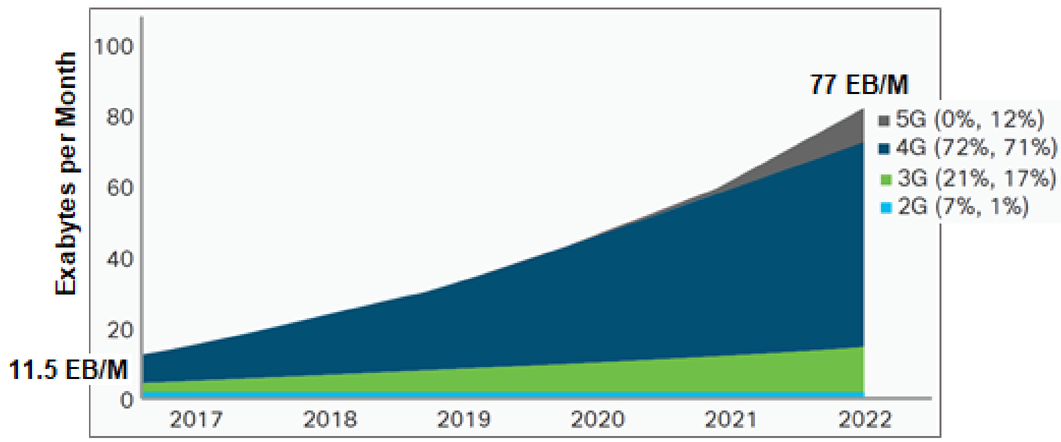
- Fixed/Wi-Fi traffic will experience a fourfold increase (52.5 exabytes/month to 201.8 exabytes/month) between 2017 and 2022 and will therefore increase as a percentage of total IP traffic, rising from 43% in 2017 to 51% in 2022.
- Mobile traffic will experience a sevenfold increase (11.5 exabytes/month to 77 exabytes/month) between 2017 and 2022 and will therefore increase as a percentage of total IP traffic, rising from 9% of total IP traffic in 2017 to 20% in 2022.

The projections for the U.S. are as follows (Cisco VNI Forecast Highlights Tool, accessed March 20, 2019):

- Fixed/wired traffic will fall from 59% to 46% of total IP traffic between 2017 and 2022.
- Fixed/Wi-Fi traffic will rise from 38% to 49% of total IP traffic between 2017 and 2022.
- Mobile traffic will grow fivefold from 2017 to 2022, rising from 1.2 exabytes/month (3% of total IP traffic) in 2017 to 5.7 exabytes/month (6% of total IP traffic) in 2022.

Mobile Traffic by Network Type, Device Type, and Application Type

As noted above and as shown in Figure 29, mobile traffic is projected to increase sevenfold from 11.5 exabytes/month in 2017 to 77 exabytes/month in 2022 (Cisco 2019a).



Source: Adapted from Cisco 2019a

Figure 29. Global Growth in Mobile Traffic by Network Type

The percentages in the legend indicate the percentage of mobile traffic estimated to be attributed to 2G, 3G, 4G, and 5G in 2017 and 2022, respectively. For example, 5G will be non-existent in 2017, but it will rise to 3 percent of mobile connections and 12 percent of total mobile traffic by 2022. In 2022, 4G will still account for the bulk of the devices (54%), as well as the bulk of the traffic (71%) (Cisco 2019a).

The Cisco VNI Global Mobile Data Traffic Forecast breaks out the mobile traffic by application and device type. Noteworthy points are as follows (Cisco 2019a):

- With respect to application, video traffic is expected to rise from 59% of total mobile traffic in 2017 to 79% in 2022.
- With respect to device, smartphones are expected to account for the bulk of mobile traffic in 2022—93%, up from 88% in 2017.

5G Requirements for Low-, Mid-, and High-Band Spectrum

Frequencies above 24 GHz are currently being studied for eMBB use. mMTC applications will need spectrum below 6 GHz, and also spectrum below 1 GHz for spatial coverage. URLCC services will also require spectrum below 6 GHz, but with guaranteed availability. Table 6–Table 8, adapted from 5G America's 2017 report, *Spectrum Landscape for Mobile Services*, show suitable spectrum ranges for various application scenarios in greater detail.

Table 6. Spectrum Ranges for 5G eMBB Applications

Application Type	Suitable Spectral Range
Ultra-high data rates	>24 GHz
High data rates	3–6 GHz
High mobility	All ranges
Ultra-low latency	3–6 GHz, >24 GHz
Low latency	3–6 GHz
Ultra-high reliability links	<6 GHz

Source: Adapted from (5G Americas 2017b)

Table 7. Spectrum Ranges for 5G URLLC Applications

Application Type	Suitable Spectral Range
Short range	>24 GHz
Medium-long range	<6 GHz
Ground or obstacle penetration	<1.5 GHz

Source: Adapted from (5G Americas 2017b)

Table 8. Spectrum Ranges for 5G mMTC Applications

Application Type	Suitable Spectral Range
Cluttered environments	All ranges
Operation near fast-moving obstacles	Mostly <6GHz
Mesh networking	>24 GHz

Source: Adapted from (5G Americas 2017b)

Estimates of Spectrum Demand

Demands of Pre-5G Wireless Technologies

In 2013, the ITU published a report, *Future Spectrum Requirements Estimate for Terrestrial IMT*, which estimated the spectrum requirements for Pre-5G technologies in the year 2020. Generations up to and including IMT-2000, that is, 2G and 3G, will require between 440 and 540 megahertz of spectrum, depending on user density. IMT-Advanced (4G) will require between 900 and 1420 megahertz (ITU 2013).

Demands of 5G

The demands of 5G services will be even greater. The 5G PPP METIS II project analyzed spectrum demand in its Deliverable D3.2, *Enablers to Secure Sufficient Access to Adequate Spectrum for 5G*, in 2017. METIS II examined three enhanced mobile broadband use cases in detail: (1) Dense Urban Scenario, (2) Virtual Reality Office, and (3) Broadband Access Everywhere, as described in Table 9 (5G METISS II 2017).

Table 9. Enhanced Mobile Broadband Use Cases for Spectrum Analysis

	UC1 Dense urban information society	UC2 Virtual reality office	UC3 Broadband access everywhere
Base station deployment	HetNet (macro layer with ISD of 200 m and micro layer with multiple small cells per macro sector)	12 sites per floor with ISD of 20 m	Macro layer with ISD of 1732 m
Carrier frequency	Below 6 GHz for macro layer and above 6 GHz for micro layer	Both below and above 6 GHz	Below 6 GHz
Experienced user throughput (requirement)	DL: 300 Mbps, UL: 50 Mbps	DL: 1 Gbps, UL: 1 Gbps	DL: 50 Mbps, UL: 20 Mbps

Note: ISD = Inter-Site Distance

Source: 5G PPP METIS II 2017

The METIS II analysis derives the spectrum demand estimates, shown in Table 14, for these three uses, assuming that bands below 6 GHz and above 6 GHz are available and used.

Table 10. Spectrum Demand Estimates for Enhance Mobile Broadband Use Cases

Use Case	Spectrum Below 6 GHz	Spectrum Above 6 GHz
Dense urban information society	2.4 gigahertz	2.2–6.6 gigahertz, depending on spectral efficiency
Virtual reality office	630 megahertz	3.4–10.3 gigahertz, depending on spectral efficiency
Broadband access everywhere	875 megahertz	(not suitable)

Source: 5G PPP METIS II 2017

METIS II acknowledges that estimated demand is dependent on many factors, including the assumed deployment scenarios, user density, and spectral efficiency (5G PPP METIS II 2017).

Demands of Wi-Fi

Quotient Associates examined Wi-Fi needs for spectrum in a recent study commissioned by the Wi-Fi Alliance. Their focus was on the 5 GHz band because (1) IEEE 802.11ac, the current generation of Wi-Fi, targets 5 GHz exclusively, and (2) IEEE 802.11ac and its successor, 802.11ax, provide a combination of range and data rate that is not met by 2.4 GHz or 60 GHz bands.

The Quotient Associates analysis took into account existing and future Wi-Fi device capabilities and deployment needs for business, residential, and public locations. They concluded that more unlicensed spectrum is needed for Wi-Fi in all regions of the world; for the U.S., more than the 580 megahertz currently allocated for unlicensed access in the 5 GHz band is needed. Their specific findings for the U.S. were as follows (Quotient Associates Limited 2017):

- Wi-Fi data traffic will exceed the capacity of spectrum currently available in the 5 GHz band by 2020.

- Between 220 and 470 megahertz of additional spectrum may be needed to support expected growth in Wi-Fi by 2020.
- If demand for Wi-Fi exceeds expected growth, then between 1.3 and 1.6 gigahertz of additional spectrum may be required by 2025.
- Wi-Fi spectrum needs to be sufficiently contiguous to support 160-megahertz channels, which are required to support a growing number of bandwidth-intensive applications and to allow maximum Wi-Fi benefits to be attained.

The Quotient Associates analysis suggests that spectrum in the 2–10 GHz range could meet the shortfall.

As detailed below, the FCC has taken steps to address this issue; it is estimated that at additional 5080 MHz of spectrum is planned by the FCC for use for wireless technologies including 5G. This 5G pipeline is far wider than that of any other country, as reflected in the table below:

Figure 18-2: Licensed Spectrum Available for Mobile (MHz)

Country	Current	Pipeline	Current+ Pipeline
U.S.	673	5080	5753
Australia	478	230	708
Brazil	554	0	554
China	227	360	587
France	555	50	605
Italy	540	20	560
Japan	500	10	510
Spain	540	60	600
U.K.	353	265	618

Source: FCC[245] and Summit Ridge Group, LLL analysis. [28]

Themes from Responses to NTIA's Request for Comments

On December 21, 2018, the NTIA published a notice and request for comments (RFC) in the Federal Register.[29] The notice was titled "Developing a Sustainable Spectrum Strategy for America's Future." The RFC received over 50 responses.[30] Below, we identify some themes that emerged from the responses:

- Prioritize licensed spectrum for 5G, especially mid-band spectrum (and do not favor unlicensed spectrum too heavily);
- Give more priority to unlicensed spectrum;
- Prioritize sharing;
- Facilitate sharing via data and automation;
- Share, but test first to protect incumbents;
- Perform compatibility studies to protect incumbents;
- Support flexible use;
- Recognize the special needs of public safety and critical infrastructure;

[28] 2018 Spectrum Handbook at 234.

[29] https://www.ntia.doc.gov/files/ntia/publications/2018-27690_3.pdf

[30] https://www.ntia.doc.gov/federal-register-notice/2019/comments-developing-sustainable-spectrum-strategy-america-s-future

- Balance the needs of all industries (e.g., aerospace, satellite, stratospheric based communications, broadcasters);
- Consider licensing of small geographic areas;
- Increase commercial access to Federal spectrum;
- Enable bi-directional sharing (Federal use of commercial spectrum).

Clearly, different stakeholders support different positions. For example, some stakeholders advocate for more spectrum for 5G, while others say the 5G demands should not necessarily be put ahead of other industries' needs for spectrum. Some stakeholders advocate spectrum sharing, while others say sharing should be done with caution so that incumbents remain protected. These varying opinions are what makes spectrum management so challenging. See Appendix C for details. There, we offer selected quotes from the responses to illustrate the themes.

5. Legislative and Regulatory Initiatives

In this chapter, we review recent actions by Congress, the FCC, and the NTIA to make more spectrum available for commercial use, including licensed spectrum for 5G and unlicensed spectrum for Wi-Fi and other technologies. To provide some context for those actions, we begin by giving an overview of spectrum bands under consideration for 5G at the international level.

Spectrum Bands Under Consideration for 5G at the International Level

World Radiocommunication Conferences

World Radiocommunication Conferences (WRC) are held every three to four years under the auspices of the ITU. As stated on the ITU website, "It is the job of WRC to review, and, if necessary, revise the Radio Regulations, the international treaty governing the use of the radio-frequency spectrum and the geostationary-satellite and non-geostationary-satellite orbits."[31] The last conference, WRC-15, was held in November 2015 in Geneva, Switzerland; the next conference, WRC-19, will be held in November 2019 in Sharm el-Sheikh, Egypt.

At WRC-15, Resolution 238, "Studies on frequency-related matters for International Mobile Telecommunications identification including possible additional allocations to the mobile services on a primary basis in portion(s) of the frequency range between 24.25 and 86 GHz for the future development of International Mobile Telecommunications for 2020 and beyond," was passed. The resolution states that WRC-15 resolves to invite ITU-R "to conduct and complete in time for WRC-19 the appropriate sharing and compatibility studies, taking into account the protection of services to which the band is allocated on a primary basis, for the frequency bands" shown in Table 11. WRC-19 will consider these bands in Agenda Item 1.13 (ITU 2015c, ITU 2017b).

[31] https://www.itu.int/en/ITU-R/conferences/wrc/Pages/default.aspx.

Table 11. Bands under Study for WRC-19 for 5G

Bands already allocated to mobile		Bands lacking mobile allocations	
24.25–27.5 GHz	(3,25 gigahertz)	31.8–33.4 GHz	(1.6 gigahertz)
37–40.5 GHz	(3.5 gigahertz)	40.5–42.5 GHz	(2 gigahertz)
42.5–43.5 GHz	(1 gigahertz)	47–47.2 GHz	(0.2 gigahertz)
45.5–47 GHz	(1.5 gigahertz)		
47.2–50.2 GHz	(3 gigahertz)		
50.4–52.6 GHz	(2.2 gigahertz)		
66–76 GHz	(10 gigahertz)		
81–86 GHz	(5 gigahertz)		

Source: ITU 2015c

Near-Term Global Outlook

A recent Analysys Mason report looked at 5G readiness in the U.S. and nine other countries—Canada, China, France, Germany, Japan, Russia, Singapore, South Korea, and the United Kingdom. The report found that, globally, the most referenced spectrum for initial 5G deployments is in the following bands (Abecassis, Nickerson, and Stewart 2018):

- 3.4–3.8 GHz
- 24.25–29.5 GHz (namely, the 26 GHz band in some countries and the 28 GHz band in others)

Not surprisingly, global equipment vendors are targeting these bands for early deployments. The Analysys Mason report found that 5G network equipment and devices that will be ready for use in the near term falls into two areas of spectrum (Abecassis, Nickerson, and Stewart 2018):

- Mid-band, around 3.5 GHz
- Millimeter wave, between 24.25 GHz and 29.5 GHz, as well as several higher bands

Legislation[32]

Spectrum Pipeline Act of 2015

The Spectrum Pipeline Act of 2015 is Title X of the Bipartisan Budget Act of 2015 (Public Law 114-74). It requires the Secretary of Commerce (through NTIA and in consultation with Federal agencies) to submit a report identifying **30 megahertz of spectrum below 3 GHz** for an auction to begin by July 1, 2024. In addition, the FCC must identify **two additional tranches of spectrum, of 50 megahertz each and below 6 GHz**, for non-Federal use, either licensed or unlicensed. The FCC is to provide corresponding reports to Congressional committees by January 1, 2022, and January 1, 2024.

[32] The 2014 IDA STPI report, *A Review of Approaches to Sharing or Relinquishing Agency-Assigned Spectrum*, reviewed previous legislation relevant to making more spectrum available for commercial use. It also described nine general approaches to give agencies greater incentive to share or relinquish spectrum, while protecting the mission capabilities of existing and future systems that rely on spectrum use (Gordon et al. 2014).

RAY BAUM'S Act of 2018

RAY BAUM'S[33] Act of 2018 is Division P of the Consolidated Appropriations Act of 2018 (Public Law 115-141). RAY BAUM'S Act reauthorizes the FCC for the first time in 28 years. Among the provisions of RAY BAUM'S Act is a requirement for the FCC to bring several of its reports together into a single comprehensive report on the state of the communications marketplace. The consolidated report is to be published the last quarter of every even-numbered year. The FCC published its first *Communications Marketplace Report* on December 26, 2018 (FCC 18-181).

RAY BAUM'S Act also incorporates the MOBILE NOW Act, discussed below, as Title VI.

MOBILE NOW Act of 2018

The MOBILE NOW[34] Act of 2018 is Title VI of RAY BAUM's Act of 2018. Its key provisions include the following (Connected Nation 2018a):

- By December 31, 2022, the NTIA and the FCC must identify a total of at least **255 megahertz of Federal and non-Federal spectrum for mobile and fixed wireless broadband use.** At least 100 megahertz must be below 8 GHz for unlicensed use; at least 100 megahertz must be below 6 GHz for exclusive, licensed commercial wireless use; and at least 55 megahertz must be below 8 GHz for either licensed, unlicensed, or a combination thereof.
- Within two years, the FCC must issue a notice of proposed rulemaking for mobile or fixed terrestrial wireless operations in the **42–42.5 GHz band.**
- Within 18 months, the FCC, in consultation with the NTIA, must submit a report to Congress evaluating the feasibility of allowing commercial wireless services, licensed or unlicensed, to use or share spectrum in the **3700–4200 MHz band.**
- Within 18 months, the FCC, in consultation with the NTIA, must submit a national plan to Congress for making **additional spectrum available for unlicensed or licensed by rule operations.**

Within two years, NTIA, in consultation with the FCC, must submit a report to Congress evaluating the feasibility of allowing commercial wireless services, licensed or unlicensed, to use or share the frequencies between **3100–3550 MHz band.**

Rural eConnectivity Pilot Program

The Rural eConnectivity Pilot Program (ReConnect Program) is Division A, Title VII, Section 779 of the Consolidated Appropriations Act of 2018. The ReConnect Program provides **$600 million** to the U.S. Department of Agriculture's Rural Utilities Service for a **new broadband loan and grant pilot program.** At least 90 percent of the households to be served by a project receiving funding under the program must be in a rural area without "sufficient" access to broadband, which is defined for now as 10 Mbps download, 1 Mbps upload (but is subject to redefinition by the Secretary of Agriculture) (Connected Nation 2018a).

This pilot program and the provisions of the 2018 Farm Bill, described below, are relevant to spectrum allocations due to the potential role of satellite and fixed wireless companies in helping to close the digital divide.

[33] Repack Airwaves Yielding Better Access for Users of Modern Services (RAY BAUM'S)

[34] Making Opportunities for Broadband Investment and Limiting Excessive and Needless Obstacles to Wireless (MOBILE NOW)

Connecting Rural Americans to High Speed Broadband

Connecting Rural Americans to High Speed Broadband is Subtitle B of Title VI of the Agriculture Improvement Act of 2018 (Public Law 115-334), commonly referred to as the 2018 Farm Bill. The Farm Bill adds **$350 million in broadband-related funding** over five years for high-speed Internet access in rural unserved or underserved areas. The three broadband funding mechanisms—which take the form of amendments to the Rural Electrification Act of 1936—that are discussed in the Farm Bill include: (1) Middle Mile Infrastructure Grants, Loans, and Loan Guarantees; (2) Innovative Broadband Advancement Grants and Loans; and (3) the Community Connect Grant Program (Connected Nation 2018b).

FCC Actions

The FCC has aggressively advanced prioritizing spectrum allocation for 5G. As noted above, the initiatives detailed below are estimated to allocate 5080 MHz of additional spectrum for wireless services. In fact, with the conclusion of the C Band proceeding detailed below, it is predicted that the spectrum crunch long feared will have been addressed.[35]

The FCC 5G FAST Plan

On September 28, 2018, the FCC released its plan to "Facilitate America's Superiority in 5G Technology," known as the 5G FAST Plan. The plan had a three-pronged approach: (1) making more spectrum available for commercial use, (2) updating infrastructure policy, and (3) modernizing outdated regulations. With respect to spectrum, the 5G FAST Plan laid out the following actions (quoting from FCC 2018a):

- *High-band*. The FCC has made auctioning high-band, millimeter-wave spectrum a priority. The FCC will hold its first 5G spectrum auctions this year in the 28 GHz and 24 GHz bands. In 2019, the FCC will auction the upper 37 GHz, 39 GHz, and 47 GHz bands. With these auctions, the FCC will release almost 5 gigahertz of 5G spectrum into the market—more than all other flexible use bands combined. And we are working to free up another 2.75 gigahertz of 5G spectrum in the 26 and 42 GHz bands.
- *Mid-band*. Mid-band spectrum has become a target for 5G buildout given its balanced coverage and capacity characteristics. With our work on the 2.5 GHz, 3.5 GHz, and 3.7-4.2 GHz bands, we could make up to 844 megahertz available for 5G deployments.
- *Low-band*. The FCC is acting to improve use of low-band spectrum (useful for wider coverage) for 5G services, with targeted changes to the 600 MHz, 800 MHz, and 900 MHz bands.
- *Unlicensed*. Recognizing that unlicensed spectrum will be important for 5G, the agency is creating new opportunities for the next generation of Wi-Fi in the 6 GHz and above 95 GHz band.

FCC Actions

Highlights of recent and upcoming auction activity are as follows:

- The 600 MHz auction, the FCC's first incentive auction, began on March 29, 2016, and closed on March 30, 2017, repurposing 84 megahertz of spectrum (70 megahertz for licensed use and 14 megahertz for unlicensed use). The auction yielded $19.8 billion in revenue, including $10.05 billion for 175 winning stations and more than $7 billion to be deposited to the U.S. Treasury for deficit reduction.[36]
- The 28 GHz auction (labeled Auction 101) began on November 13, 2018, with the initiation of bidding, and concluded on January 24, 2019. There were 3,072 county-based licenses of two 425-

[35] See 2018 Spectrum Handbook at 92.

[36] https://www.fcc.gov/about-fcc/fcc-initiatives/incentive-auctions#block-menu-block-4; https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf

megahertz blocks (27.5–27.925 GHz and 27.925–28.35 GHz) up for auction. 2,965 licenses were won, with a total provisional winning bids (PWB) amount of $702.57 million.

- The 24 GHz auction (labeled Auction 102) began on March 14, 2019. 2,909 Partial Economic Area (PEA) licenses are set to be auctioned in 7 100-megahertz blocks (2 between 24.25–24.45 GHz and 5 between 24.75–25.25 GHz).
- An auction of the Upper 37 GHz, 39 GHz, and 47 GHz bands is planned for 2019.

Table 12 summarizes other recent FCC actions in terms of the following categories:

- Low bands. In addition to auctioning 600 MHz band spectrum, the FCC has released rulemakings for the 800 MHz and 900 MHz bands.
- Mid bands. These are the most contested bands. The Spectrum Pipeline Act and the MOBILE NOW Act are both driving action here. The FCC 5G FAST Plan singles out the 2.5 GHz (EBS) band, 3.5 GHz (CBRS) band, and 3.7–4.2 GHz band (the C band) as priorities.
- 6 GHz band. This is the subject of FCC 17-104 and FCC 18-147.
- 24–86 GHz bands. These are the subject of the Spectrum Frontiers proceedings (FCC 16-89, FCC 17-152, FCC 18-73, FCC 18-110, FCC-180).
- Above 95 GHz bands. These are the subject of the Spectrum Horizons proceedings (FCC 18-17).

Note that in the rows for the 24–86 GHz bands, the left-most column identifies the bands that are the subject of WRC-15 Resolution and WRC-19 Action Item 1.13 (described above in Section 0). The FCC has recent or ongoing activity in all the bands called out by the ITU for WRC action.

As shown in Appendix D, 3GPP has defined operating bands for 5G NR in the millimeter range (which 3GPP calls Frequency Range 2 or FR2) (3GPP 2018). The FR2 bands cover the 24 GHz, 26 GHz, 28 GHz, 37 GHz, and 39 GHz bands that are the subject of ongoing FCC and NTIA activity.

Regarding bands below 6 GHz, several of the bands shown in Table 12 align with bands specified by 3GPP as operating bands for 5G NR in Frequency Range 1 (FR1), which is the sub 6 GHz range at 450 MHz–6 GHz (3GPP 2018). For example, as shown in Appendix D:

- The 600 MHz band falls in FR1 n71.
- The 2.5 GHz (EBS) band falls in FR1 band n41.
- The 3.7-4.2 GHz (C Band) falls in FR1 band 77.
- The 3.1–3.55 GHz, 3.45–3.55 GHz, and 3.5 GHz (CBRS) bands fall in FR1 band n78.
- The 4.9 GHz (public safety) falls in the FR1 band n79.

Table 12. Recent Activity on Frequency Bands for 5G and Wi-Fi

	Frequency Band addressed by FCC or NTIA	Amount of Spectrum	Status (green=auctioned; yellow=shared; blue=unlicensed)	Notes	FCC Proceedings
Low Bands (subjects of FCC 5G FAST Plan)					
	600 MHz 617-698 MHz	70 megahertz	Auctioned via incentive auction	FCC 5G FAST Plan	
	800 MHz 824-894 MHz		Transitioned 800 MHz Cellular Service (dating to 1981) to more flexible use model	FCC 5G FAST Plan	FCC 17-27, 24 Mar 2017
	900 MHz: 896–901/935–940 MHz	10 megahertz	Under study by FCC—NOI seeks to increase access, improve efficiency, and expand flexibility	FCC 5G FAST Plan	FCC 17-108, 4 Aug 2017
Mid Bands (subjects of FCC 5G FAST Plan, Spectrum Pipeline Act, MOBILE NOW Act, etc.)					
	1300–1350 MHz	50 megahertz	Under study by NTIA	Spectrum Pipeline Act	
	1675–1680 MHz	5 megahertz	Under study by NTIA	Spectrum Pipeline Act	
	2.5 GHz (EBS): 2496–2690 MHz)	194 megahertz	Under study by FCC—NPRM proposes to modernize and rationalize the EBS spectrum to allow more flexible use (5G)	FCC 5G FAST Plan	FCC 18-59, 10 May 2018
	3.1–3.55 GHz	450 megahertz	Under study by NTIA	MOBILE NOW Act	
	3.45–3.55 GHz (subset of above)	100 megahertz	Under study by NTIA	Spectrum Pipeline Act	
	3.5 GHz (CBRS) 3.55–3.7 GHz	150 megahertz	Citizens Broadband Radio Service (CBRS)—FPRM proposes longer license terms with possibility of renewal, larger geographic areas, etc., to facilitate 5G deployments	FCC 5G FAST Plan	FCC 17-134, 24 Oct 2017
	3.7–4.2 GHz (Fixed Satellite Service – C Band)	500 megahertz	Under study by FCC—NPRM proposes to add a mobile allocation to the band and seeks comment on various proposals for transitioning part or all of the band for flexible use	MOBILE NOW Act; FCC 5G FAST Plan;	FCC 17-104, 3 Aug 2017; FCC 18-91, 13 Jul 2018
	4.9 GHz (Public Safety): 4.94–4.99 GHz	50 megahertz	Seeking comment on alternatives for the band, including redesignating it, wholly or partially, to support commercial wireless use		FCC 18-33, 23 Mar 2018

	Frequency Band addressed by FCC or NTIA	Amount of Spectrum	Status (green=auctioned; yellow=shared; blue=unlicensed)	Notes	FCC Proceedings
	5.9 GHz (DSRC V2V): 5.85–5.925 GHz	75 megahertz	Seeking comment on approaches that would facilitate unlicensed use of the band without causing harmful interference to Dedicated Short Range Communications (DSRC) operations, or that would allow for multiple uses for traffic safety and efficiency		FCC 16-68, 1 Jun 2016
6 GHz Band (subject of FCC FAST Plan)					
	6 GHz: 5.925–7.125 GHz	1200 megahertz	Unlicensed (proposed)—seeking comment on methods of protecting incumbents	FCC 5G FAST Plan	FCC 17-104, 3 Aug 2017; FCC 18-147, 24 Oct 2018
24 – 86 MHz Bands (subjects of FCC Spectrum Frontiers proceedings) *left column indicates band named in WRC-15 Resolution 238*					
24.25-27.5 GHz	**24 GHz**: 24.25–24.45 GHz; 24.75–25.25 GHz	700 megahertz	To be auctioned (bidding to begin in Mar 2019)	FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016; FCC 17-152, 22 Nov 2017; FCC 18-73, 8 Jun 2018
	26 GHz: 25.25–27.5	2250 megahertz	Under study. May be shared: seeking comment on sharing framework	FCC 5G FAST Plan	FCC 18-73, 8 Jun 2018
Not available for 5G globally, since Europe has harmonized the 27.5–29.5 GHz band for broadband satellite and is supportive of the worldwide use of this band for Earth Stations in Motion (ESIM)	**28 GHz**: 27.5–28.35 GHz	850 megahertz	To be auctioned (concluded Jan 2019)	FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016
31.8–33.4 GHz	**32 GHz**: 31.8–33 GHz	1200 megahertz	Under study		FCC 16-89, 14 Jul 2016
37–40.5 GHz	**Lower 37 GHz**: 37–37.6 GHz	600 megahertz	To be shared (envisioned as innovation band in mmW spectrum)	FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016; FCC 18-73, 8 Jun 2018
	Upper 37 GHz: 37.6–38.6 GHz	1000 megahertz	To be auctioned in 2019 with 39 GHz and 47 GHz	FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016; FCC 18-110, 3 Aug 2018

	Frequency Band addressed by FCC or NTIA	Amount of Spectrum	Status (green=auctioned; yellow=shared; blue=unlicensed)	Notes	FCC Proceedings
	39 GHz: 38.6–40 GHz	1400 megahertz	To be auctioned in 2019 with Upper 37 GHz and 47 GHz (with incentive mechanism for 39 GHz incumbents)	FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016; FCC 18-110, 3 Aug 2018; FCC 18-180, 12 Dec 2018
	40–40.5 GHz		Maintain as core satellite bands, including end user devices		FCC 17-152, 22 Nov 2017
40.5–42.5 GHz	40.5–42 GHz		Maintain as core satellite bands, including end user devices		FCC 17-152, 22 Nov 2017
	42 GHz: 42–42.5 GHz	500 megahertz	Under study. May be shared: seeking comment on sharing framework	MOBILE NOW Act; FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016; FCC 18-73, 8 Jun 2018
42.5–43.5 GHz					
45.5–47 GHz					
47–47.2 GHz					
47.2-50.2 GHz	**47 GHz**: 47.2–48.2 GHz	1000 megahertz	To be auctioned in 2019 with Upper 37 GHz and 39 GHz	FCC 5G FAST Plan	FCC 16-89, 14 Jul 2016; FCC 17-152, 22 Nov 2017; FCC 18-110, 3 Aug 2018
	48.2–50.2 GHz		Maintain as core satellite bands, including end user devices		FCC 17-152, 22 Nov 2017
50.4-52.6 GHz	**50 GHz**; 50.4–52.6 GHz	2200 megahertz	Under study by FCC		FCC 16-89, 14 Jul 2016
	50.4–51.4 GHz (subset of above)	1000 megahertz	Under study by FCC – may permit limited number of FSS earth stations (FSS allocation already exists in this band)		FCC 18-73, 8 Jun 2018
66-76 GHz	**64–71 GHz**	7000 megahertz	Unlicensed		FCC 16-89, 14 Jul 2016; FCC 17-152, 22 Nov 2017
	70 GHz: 71–76 GHz	5000 megahertz	Development to be focused on fixed (vs. mobile), e.g., 5G backhaul		FCC 16-89, 14 Jul 2016; FCC 17-152, 22 Nov 2017
81-86 GHz	**80 GHz**: 81–86 GHz	5000 megahertz	Development to be focused on fixed (vs. mobile), e.g., 5G backhaul		FCC 16-89, 14 Jul 2016; FCC 17-152, 22 Nov 2017

	Frequency Band addressed by FCC or NTIA	Amount of Spectrum	Status (green=auctioned; yellow=shared; blue=unlicensed)	Notes	FCC Proceedings
Above 95 GHz (subject of FCC Spectrum Horizons proceedings)					
	Above 95 GHz		Seeking comment on proposed rules to permit licensed and unlicensed spectrum use opportunities in the 95 GHz to 275 GHz range, with additional provisions for experimental licensing up to 3000 GHz	FCC 5G FAST Plan (promises to create unlicensed opportunities above 95 GHz)	FCC 18-17, 28 Feb 2018

NTIA and Federal Agency Actions

As part of its obligations under the Spectrum Pipeline Act of 2015, NTIA and the Federal agencies submitted pipeline plans, which have been approved for funding, for the following bands:

- *1300–1350 MHz band*. The Spectrum Efficient National Surveillance Radar (SNSR)—a cross-agency team representing the Federal Aviation Administration, the Department of Defense, the Department of Homeland Security, and the National Oceanic and Atmospheric Administration—is studying combining surveillance, air safety, and weather radar applications into a single, spectrum-conserving "system of systems" by 2024. This would allow the agencies to vacate 30 megahertz of spectrum in the 1300–1350 band, thus making it available for reallocation for shared Federal and non-Federal use. The FAA is leading the feasibility assessment to find a technology solution that meets the needs of all stakeholders (Olson 2018; Redl 2018b; Rockwell 2018).
- *1675–1680 MHz band*. NOAA is studying the potential of shared access to the 1675–1680 MHz band, which it currently operates meteorological satellites in support of weather data distribution activities. (Redl 2018c).

3450–3550 MHz band. Military radar systems currently operate in this band. The Department of Defense plans to conduct a comprehensive engineering study to determine the potential for introducing advanced wireless services in this band without harming critical government operations (Moorefield 2018; Redl 2018a).

6. Conclusion

The emerging technology at the core of this study is 5G wireless technology. 5G is expected to be revolutionary in its impact. It will enhance mobile broadband performance with an order of magnitude increase in speed, which will enable new classes of applications—such as augmented reality and virtual reality—to emerge in offices, classrooms, museums, sports events, and retail premises. 5G will also accommodate crowd densities at the scale of Super Bowls and support broadband access for users moving at the speed of express trains. Moreover, 5G will enable applications—such as self-driving cars, factory automation, and remote surgery—that require ultra-high reliability and low latency. In addition, 5G will enable the world of the Internet of Things—which will lay the foundation for smart homes, smart buildings, smart cities, precision agriculture, and more.

5G Standardization Status. 5G is the subject of international standardization activities led by the International Telecommunication Union (ITU) and the 3rd Generation Partnership Project (3GPP). ITU, which designates 5G as International Mobile Telecommunication 2020 (IMT-2020), laid out a vision for

IMT-2020 in 2015 and has been developing and refining requirements for IMT-2020 since then. The ITU goal is to have an approved IMT-2020 standard in the year 2020.

The 3rd Generation Partnership Project (3GPP) is developing detailed specifications for 5G. 3GPP's Release 16, to be completed in early 2020, is expected to be fully compliant with IMT-2020 and to be approved by the ITU as an IMT-2020 standard. In the meantime, 3GPP has released a series of specifications in advance of Release 16:

- Releases 13 and 14 (released in March 2016 and June 2017, respectively), which are considered pre-5G releases because they add 5G-related features to LTE.
- Release 15 Non-Standalone Access (released in December 2017), the first 3GPP 5G release, which defines the 5G radio access network but relies on the LTE core network.
- Release 15 Standalone Access (released in June 2018), which adds a definition of the 5G core network.
- Release15 "Late Drop" (expected in June 2019), which adds additional migration architectures.

These releases are facilitating early 5G deployments and reducing risk for the full-scale 5G rollout. As in the case of LTE—which moved from LTE in 3GPP Releases 8 and 9, to LTE Advanced in Releases 10 through 12, to LTE Advanced Pro in Releases 13 and 14—3GPP will continue to add enhancements to 5G even after Release 16 is completed.

5G Deployment Status. In the U.S., carriers began rolling out 5G fixed wireless services and initial 5G mobile services in late 2018:

- Verizon launched Verizon 5G Home, which operates on its 28 GHz spectrum, in selected cities.
- AT&T began rolling out 5G mobile services, using its 39 GHz spectrum, in selected cities, providing mobile services to users via the Netgear Nighthawk 5G Mobile Hotspot.

2019 will see additional launches of mobile 5G services in selected cities, as well as the debut of 5G mobile phones, such as the Samsung Galaxy S10:

- Verizon plans to begin rolling out its 5G Ultra Wideband service, using its 28 GHz spectrum, in the first half of 2019.
- Sprint plans to begin rolling out its mobile 5G network, using its 2.5 GHz spectrum, in mid 2019.
- T-Mobile plans to begin rolling out its mobile 5G network, using its 600 MHz spectrum, in the second half of 2019.

The carriers will accelerate 5G deployments in 2020. In addition, Apple plans to offer a 5G iPhone in 2020.

5G-Enabled Technologies. As illustrated in Figure 30, 5G will enable whole new classes of applications and use cases, which we refer to as *enabled technologies*. Early work in the ITU laid out a vision of three broad classes of use cases for 5G:

- Enhanced mobile broadband
- Ultra-reliable and low latency communications
- Massive machine type communications, also known as massive IoT

More recently, two additional broad classes of use cases have been added to the discussion:

- Fixed wireless, also called broadband wireless access, is an early 5G use case already being rolled out.
- Enhanced vehicle-to-everything (V2X), a high-profile motivator for advanced 5G capabilities that encompasses vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-pedestrian communications.

5G is expected to vastly outperform 4G. The improvements cover at least eight dimensions: (1) peak data rate, (2) user experienced data rate, (3) area traffic capacity, (4) spectrum efficiency, (5) mobility, (6) latency, (7) connection density, and (8) network energy efficiency. The identified use cases are driving research and development activities, as well as the standardization activities taking place in the ITU and 3GPP.

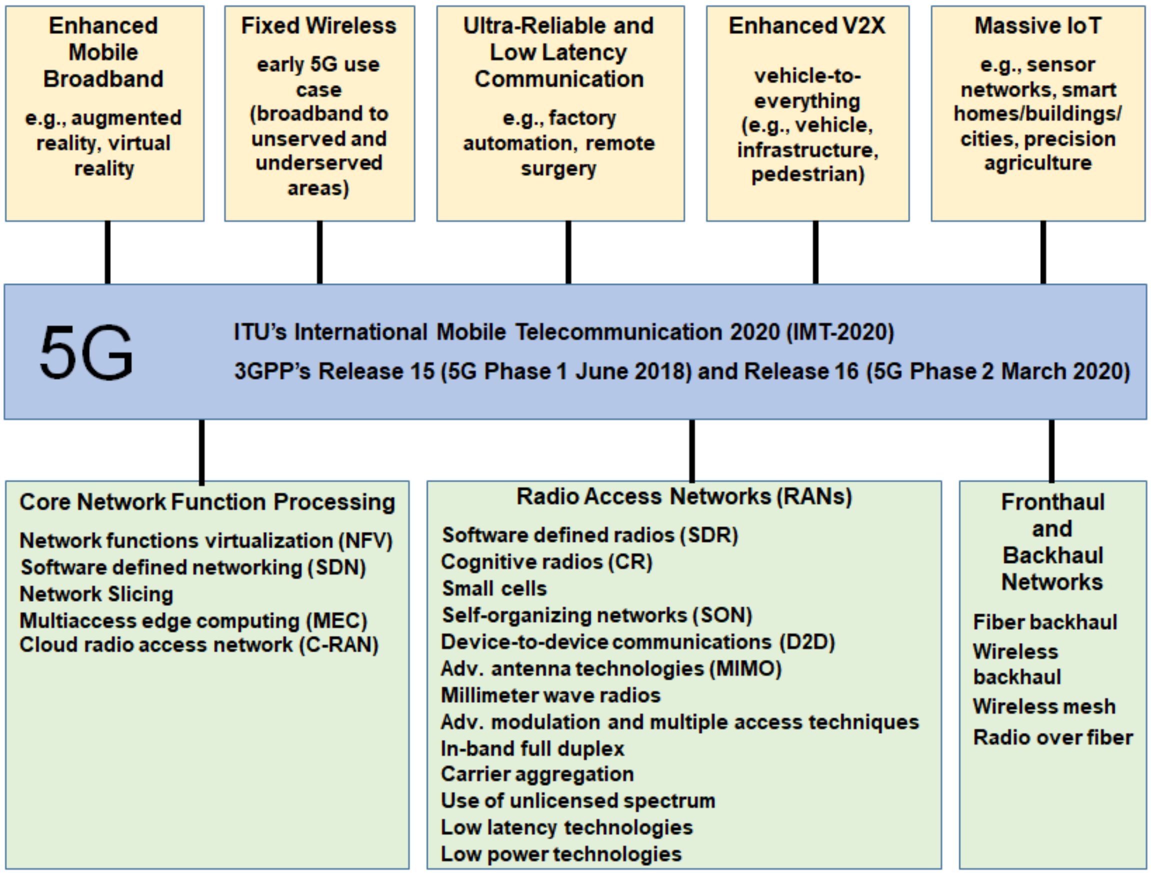


Figure 30. 5G, 5G-Enabled Technologies (top), and 5G-Enabling Technologies (bottom)

5G-Enabling Technologies. The challenges posed by the demanding use cases described above are being addressed by three categories of enabling technologies:

- Core network function processing
- Backhaul and fronthaul networks
- Radio access networks

Figure 30 lists many of the specific technologies that we highlighted in Chapter 2. Arguably, the properties that most distinguish 5G from its predecessors are its flexibility and adaptability, which are required to meet the needs of the diverse applications that 5G is intended to support. The core network technologies that support these properties include network functions virtualization, software defined networking, network slicing, multi-access edge computing, and cloud radio access networks.

Wi-Fi role. Wi-Fi has been and remains a linchpin communications technology. According to Cisco, approximately half of all IP traffic is expected to be carried by Wi-Fi in 2022. In addition, well over half of the data traffic from mobile devices is expected to be offloaded to Wi-Fi. Thus, Wi-Fi is tightly coupled to 5G. Wi-Fi offloading of mobile traffic enables cellular networks to maintain their high data rates, not having to accommodate all the additional traffic they would otherwise face. With respect to the 5G-enabled technologies, Wi-Fi is expected to play a key role in forthcoming 5G fixed wireless services, with the cellular signal being converted to a Wi-Fi signal for delivery to the host of Wi-Fi-enabled devices on which individuals and corporations have come to rely. Moreover, 5G is being designed to make more use of unlicensed spectrum than previous generations of mobile wireless technology did, and to better integrate and coexist with Wi-Fi systems.

Spectrum demand. 5G is expected to leverage millimeter wave bands, at 24–86 GHz, for applications requiring very high data rates. Low bands, below 1 GHz, will be leveraged for coverage. Mid bands, between 1 GHz and 6 GHz, are highly sought after for their ability to offer both high data rates and good coverage, thus bridging the gap between low bands and high bands. Due to unabated Wi-Fi growth, there is also demand for more unlicensed spectrum.

Figure 31 provides a summary of recent FCC and NTIA activities—specifically, activities in 2016 and later—undertaken in support of meeting commercial demands of 5G and Wi-Fi for spectrum:

- *Incentive auction*. The FCC concluded the 600 MHz auction—its first-ever incentive auction—in March 2017. The auction repurposed 84 megahertz of broadcasters' spectrum: 70 megahertz for licensed use and 14 megahertz for wireless microphones and unlicensed use.
- *Millimeter wave band auctions*. The 28 GHz auction (850 megahertz of spectrum) concluded in January 2019, and the 24 GHz auction (700 megahertz of spectrum) kicked off in March 2019. The auction of the Upper 37 GHz, 39 GHz, and 47 GHz bands (1000 megahertz, 1400 megahertz, and 1000 megahertz of spectrum, respectively) is expected to take place in 2019. Together the millimeter wave band auctions will make 4,950 megahertz available for 5G through the FCC's newly defined upper microwave flexible use service.
- *Shared bands.* The FCC defined an innovative three-tiered sharing scheme for the 3.5 GHz Citizens Broadband Radio Service (CBRS) band (150 megahertz of spectrum) in 2015, and it recently made some changes to the service to make it more viable for 5G. The FCC plans to demonstrate innovative spectrum sharing in millimeter wave spectrum in the Lower 37 GHz band (600 megahertz of spectrum).
- *Unlicensed bands.* The FCC is heading toward allowing unlicensed access to 1200 megahertz of spectrum in the 6 GHz band, with protection for incumbents. The FCC has also provided for unlicensed access in the 64-71 GHz band. Together with the existing 57-64 GHz unlicensed band, this means that 14 gigahertz of millimeter wave spectrum are available for unlicensed access.
- *Core satellite bands*. In the context of 5G deliberations, the FCC has declared the 40–42 GHz and 48.2–50.2 GHz bands (4 gigahertz of spectrum total) to be core satellite bands.
- *Additional millimeter waves under consideration*. The FCC is considering additional millimeter wave bands in the 3GPP FR2 range—26 GHz, 32 GHz, 42 GHz, 50 GHz, 71–76 GHz, and 81–86 GHz—for 5G. Together, these bands total 16.15 gigahertz of spectrum.

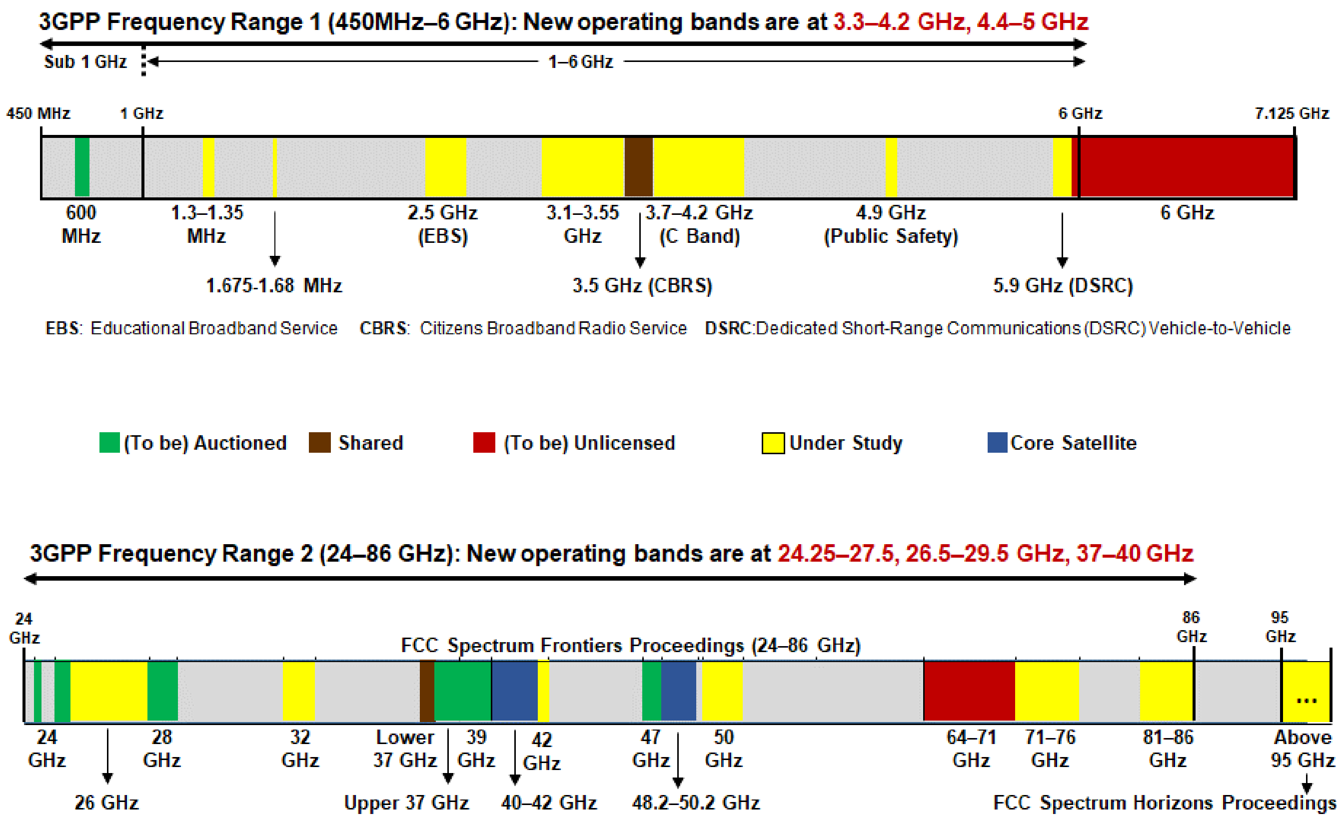


Figure 31. Recent FCC and NTIA Actions in Potential 5G Operating Bands

As previously noted, mid band spectrum is highly sought after by 5G proponents, but the mid bands also have incumbents who value the spectrum:

- *2.496–2.69 GHz (Educational Broadband Service (EBS) band),* 194 megahertz of spectrum. The use of this band has been strictly limited since 1995, but it is being considered by the FCC for more flexible use. Some educational institutions are advocating to keep it dedicated to educational purposes.
- *3.7–4.2 GHz (C band),* 500 megahertz of spectrum. Globally, this is a leading 5G band, and so 5G stakeholders are advocating for at least a portion of it to be made accessible to commercial mobile service. In the U.S., the C band has satellite incumbents, and they have formed the C Band Alliance to ensure that incumbents are protected.
- *4.9 GHz band (public safety band),* 50 megahertz of spectrum. This band has been dedicated to public safety use since 2002 but is now being considered by the FCC for more flexible use. Public safety incumbents, as well as critical infrastructure stakeholders, are advocating for it to remain dedicated to their needs.
- *5.9 GHz band (Dedicated Short Range Communication (DSRC) band)*, 75 megahertz of spectrum. The 5.9 GHz band has been allocated for DSRC Vehicle-to-Everything (V2X), a short range communications service built on the IEEE 802.11 standard to support transportation safety. Significant differences from the IEEE 802.11 standard are to support high speed vehicles (closing speed greater than 150 mph), and a broadcast mode to reduce latency to near zero. The last action by the FCC was in 2006. DSRC V2V has been joined by another technology, Cellular Vehicle-to-Everything (C-V2X). The issue before the FCC is whether to allocate the band entirely to one or the other of these technologies with full interoperability, or to allow for certain channels to be dedicated

to each technology to provide for a secure redundant system. Testing is currently underway to examine the safety impacts of UNII sharing the band with DSRC.

- *1.3–1.35 MHz, 1.675–1.68 MHz, 3.1–3.55 MHz bands.* These bands have Federal incumbents who must be protected. However, in accordance with direction received from Congress in the Spectrum Pipeline Act of 2015 and the MOBILE NOW Act of 2018, NTIA is studying the bands and evaluating them for potential use, possibly on a shared basis, by commercial wireless systems.

Spectrum Management Challenge. As demonstrated by Figure 31 and the above discussion, the FCC and the NTIA are working to ensure that spectrum is available to sustain Wi-Fi growth and to facilitate 5G deployments. The current proceedings will significantly address Congressional concerns. The Trump Administration is committed to making sure that the U.S. wins the race to 5G and secures the attendant economic gains. Globally, the bands most referenced for initial 5G deployments lie in the 3.3–4.2 GHz range, as well as in the millimeter wave bands. That is why, in the U.S., mid-band spectrum—especially the 3.55–3.7 GHz CBRS band and the 3.4–4.2 GHz C band—are in such high demand by 5G stakeholders. The FCC and the NTIA have challenging work ahead as they seek to balance the needs of incumbents—both Federal and commercial—with the demands of 5G and Wi-Fi.

Appendix A. 5G Use Case Categorizations and Requirements

This appendix provides the following tabular summaries of use case categorizations and requirements from key organizations participating in the development of 5G standards:

- Table A 1. 3GPP Use Cases by Top-Level Category and Use Case Family
- Table A 2. 5G Americas Use Cases by Category: User Data Rate, Latency, and Mobility Requirements
- Table A 3. NGMN Use Cases by Family and Category: User and System Performance Requirements
- Table A 4. 5G PPP Mapping of Vertical Use Cases to Use Case Families

In the tables, some cells are highlighted in shades of blue. The shading is meant to simply call the reader's attention to the most demanding requirements.

Table A-1. 3GPP Use Cases by Top-Level Category and Use Case Family

Use Case Family	Use Cases (numbered 1 through 74)
Enhanced Mobile Broadband (eMBB): Drivers are data rate, latency, traffic density, connection density, and mobility	
Higher data rates	5 Mobile broadband for indoor scenario; 6 Mobile broadband for hotspots scenario; 56 Broadcasting Support; 71 Wireless Local Loop
Higher density	5 Mobile broadband for indoor scenario; 6 Mobile broadband for hotspots scenario; 7 On-demand networking; 32 Improvement of network capabilities for vehicular case
Deployment and coverage	5 Mobile broadband for indoor scenario; 10 Mobile broadband services with seamless wide-area coverage; 11 Virtual presence; 30 Connectivity Everywhere; 66 Broadband Direct Air to Ground Communications; 71 Wireless Local Loop; 72 5G Connectivity Using Satellites
Higher user mobility	6 Mobile broadband for hotspots scenario; 10 Mobile broadband services with seamless wide-area coverage; 29 Higher User Mobility; 53 Vehicular Internet & Infotainment 66 Broadband Direct Air to Ground Communications
Critical Communications (CriC): Drivers are latency, reliability, connection density, and position accuracy	
Higher reliability and lower latency	1 Ultra reliable communication; 11 Virtual presence; 18 Remote control; 44 Cloud Robotics; 45 Industrial Factory Automation; 46 Industrial Process Automation; 50 Low-delay speech coding; 54 Local UAV Collaboration; 68 Telemedicine Support
Higher reliability, higher availability, and lower latency	12 Connectivity for drones; 13 Industrial control; 65 Moving ambulance and bio-connectivity
Very low latency	14 Tactile internet; 15 Localized real-time control; 17 Extreme real-time communications
Higher accuracy positioning	12 Connectivity for drones; 18 Remote control; 43 Materials and inventory management and location tracking; 54 Local UAV Collaboration; 55 High Accuracy Enhanced Positioning
Higher availability	72 5G Connectivity Using Satellites (duplicate with eMBB & NEO)
Mission-critical services	1 Ultra reliable communication; 2 Network Slicing; 3 Lifeline communications / natural disaster; 12 Connectivity for drones; 31 Temporary Service for Users of Other Operators in Emergency Case; 54 Local UAV Collaboration; 65 Moving ambulance and bio-connectivity; 68 Telemedicine Support; 72 5G Connectivity Using Satellites

Use Case Family	Use Cases (numbered 1 through 74)
Massive Internet of Things (MIOT): Drivers are communication efficiency, connection density, and position accuracy	
Operational aspects	19 Light weight device configuration; 21 IoT Device Initialization; 22 Subscription security credentials update; 24 Bio-connectivity; 25 Wearable Device Communication; 40 Devices with variable data; 41 Domestic Home Monitoring; 59 Massive Internet of Things M2M and device identification; 63 Diversified Connectivity; 67 Wearable Device Charging
Connectivity aspects	24 Bio-connectivity; 25 Wearable Device Communication
Resource efficiency aspects	20 Wide area monitoring and event driven alarms; 24 Bio-connectivity; 25 Wearable Device Communication; 40 Devices with variable data; 41 Domestic Home Monitoring; 42 Low mobility devices; 43 Materials and inventory management and location tracking; 60 Light weight device communication
Enhanced Vehicle-to-Everything Communication (eV2X): Drivers are latency, reliability, mobility, position accuracy	
eV2X	10 Mobile broadband services with seamless wide-area coverage; 32 Improvement of network capabilities for vehicular case; 33 Connected vehicles
Network Operation (NEO): This group covers the horizontal system aspects of 5G systems	
System flexibility	2 Network slicing; 8 Flexible application traffic routing; 37 Routing path optimization when server changes; 48 Provision of essential services for very low-ARPU areas; 49 Network capability exposure; 56 Broadcasting Support; 57 Ad-Hoc Broadcasting; 64 User Multi-Connectivity across operators; 69 Network Slicing – Roaming; 70 Broadcast/ Multicast Services using a Dedicated Radio Carrier; 73 Delivery Assurance for High Latency Tolerant Services; 74 Priority, QoS and Policy Control
Scalability	7 On-demand networking; 9 Flexibility and scalability; 35 Context Awareness to support network elasticity; 51 Network enhancements to support scalability and automation
Mobility support	34 Mobility on demand; 47 SMARTER Service Continuity; 42 Low mobility devices (duplicate with mIoT)
Efficient content delivery	36 In-network & device caching; 38 ICN Based Content Retrieval; 39 Wireless Briefcase
Self-backhauling	6 Mobile broadband for hotspots scenario; 52 Wireless Self-Backhauling; 61 Fronthaul/Backhaul Network Sharing
Access	3 Lifeline communications / natural disaster; 23 Access from less trusted networks; 26 Best Connection per Traffic Type; 27 Multi Access network integration; 28 Multiple RAT connectivity and RAT selection; 31 Temporary Service for Users of Other Operators in Emergency Case; 55 High Accuracy Enhanced Positioning; 58 Green Radio; 71 Wireless Local Loop; 72 5G Connectivity Using Satellites
Security	62 Device Theft Preventions / Stolen Device Recovery
Migration and interworking	4 Migration of services from earlier generations; 16 Coexistence with legacy systems

Source: Derived from 3GPP 2016 (Table 6.3.2, Section 6.2)

Table A-2. 5G Americas Use Cases by Category: User Data Rate, Latency, and Mobility Requirements

Use Case Category	Use Case	User Data Rate	Latency	Mobility
Enhanced Mobile Broadband (eMBB)	Hotspots: Broadband Access in Dense Areas	DL: 300–500 Mbps UL: 50–100 Mbps	NA	60 km/h
	Broadband Everywhere	DL: 25–50 Mbps UL: 10–25 Mbps	NA	0–120 km/h
	Homes and Offices	DL: 1–5 Gbps UL: 100 - 500 Mbps	NA	Pedestrian
	Public Transport, MBB in Cars, High Speed Trains	DL: 25–50 Mbps UL: 10–25 Mbps	NA	Up to 120 km/h
	Broadband Access in Events & Large Gatherings	DL: 10–25 Mbps UL: 25–50 Mbps	NA	Pedestrian
Connected Vehicles (Vehicle-to-Everything [V2X])	Connected Vehicles: Vehicle-to-Vehicle (V2V)	DL: 1–5 Mbps UL: 1–5 Mbps	1 ms	0–160 km/h
	Connected Vehicles: Vehicle-to-Infrastructure (V2I)I	DL: 1–5 Mbps UL: 1–5 Mbps	5 ms	0–160 km/h
	Connected Vehicles: Vehicle-to-Pedestrian (V2P)	DL: 1–5 Mbps UL: 100 kbps–1 Mbps	1 ms	0–160 km/h
	Moving Hotspots	DL: 10–50 Mbps UL: 5–25 Mbps	10 ms	0–160 km/h
Enhanced Multi-Media	Live TV	DL: 50–200 Mbps UL: 500 kbps	10 - 50 ms	0–8 km/h
	On Demand	DL: 50–200 Mbps UL: 500 kbps	10 - 50 ms	0 – 80 km/h
	Mobile TV	DL: 10–50 Mbps UL: 500 kbps	10 - 50 ms	250–500 km/h
Massive IoT	Sensor Networks (Connected Roads, Railways, Buildings, Smart Cities, Parking, Lighting, Environment Monitoring)	DL: 1–100 kbps UL: 1–100 kbps	50 ms–hours	0–500 km/h
	Smart Grid/Utilities	DL: 1–100 kbps UL: 1–100 kbps	50 ms–hours	Pedestrian
	Wearables	DL: 100 kbps–5 Mbps UL: 100 kbps–5 Mbps	1–5 ms	0–120 km/h
	Agriculture	DL: 1–100 kbps UL: 1–100 kbps	1–5 ms	Pedestrian
Ultra Reliable Low Latency	Industry Process Automation	DL: 100 kbps–10 Mbps UL: 100 kbps–10 Mbps	0.5–1 ms	Pedestrian
	Automated Factories	DL: 100 kbps–10 Mbps	0.5–1 ms	Pedestrian

Use Case Category	Use Case	User Data Rate	Latency	Mobility
Communications (URLLC) Ultra Reliable Low Latency Communications (URLLC) (cont.)		UL: 100 kbps–10 Mbps		
	Tactile Interaction	DL: 100 kbps–10 Mbps UL: 100 kbps–10 Mbps	0.5–1 ms	Pedestrian
	Emergency Services, Disasters, Public Safety	DL: 100 kbps–10 Mbps UL: 100 kbps–10 Mbps	1–5 ms	0–120 km/h
	Urgent Healthcare, Remote Surgery	DL: 100 kbps–10 Mbps UL: 100 kbps–10 Mbps	1–5 ms	0–120 km/h
Fixed Wireless Access	Fixed Wireless	DL: 100 kbps–5 Mbps UL: 100 kbps–1 Mbps	10 ms	Pedestrian

Source: Derived from 5G Americas 2017a (Table 1)

Table A-3. NGMN Use Cases by Family and Category: User and System Performance Requirements

Use Case Category and Sample Use Cases	User Experience Requirements			System Performance Requirements	
	User Experienced	Latency	Mobility	Connection Density	Traffic Density
Broadband Access in Dense Areas Use Case Family					
Broadband access in dense areas →Pervasive video →Operator cloud services →Dense urban society	DL: 300 Mbps UL: 50 Mbps	10 ms	On demand: 0–100 km/h	200-2500 /km^2	DL: 750 Gbps / km^2 UL: 125 Gbps / km^2
Indoor ultra-high broadband access →Smart Office	DL: 1 Gbps UL: 500 Mbps	10 ms	Pedestrian	75,000 / km^2 (75/1000 m^2 office)	DL: 15 Tbps/km^2 (15 Gbps/1000 m^2) UL: 2 Tbps/km^2 (2 Gbps/1000 m^2)
Broadband access in a crowd →HD video/photo sharing in stadium/open-air gathering	DL: 25 Mbps UL: 50 Mbps	10 ms	Pedestrian	150,000 / km2 (30.000 / stadium)	DL: 3.75 Tbps / km^2 (DL: 0.75 Tbps / stadium) UL: 7.5 Tbps / km^2 (1.5 Tbps / stadium)
Broadband Access Everywhere Use Case Family					
50+ Mbps everywhere →50 Mbps everywhere	DL: 50 Mbps UL: 25 Mbps	10 ms	0–120 km/h	400 / km^2 in suburban 100 / km^2 in rural	DL: 20 Gbps / km^2 in suburban UL: 10 Gbps / km^2 in suburban DL: 5 Gbps / km^2 in rural UL: 2.5 Gbps / km^2 in rural
Ultralow-cost broadband access for low average revenue per user (ARPU) areas Ultra-low cost networks	DL: 10 Mbps UL: 10 Mbps	50 ms	On demand: 0–50 km/h	16 / km^2	16 Mbps / km^2
Broadcast-like Services Use Case Family					
Broadcast like services →News and information →Local broadcast like services →Regional broadcast-like services →National broadcast-like services	DL: Up to 200 Mbps UL: Modest (e.g., 500 kbps)	<100 ms	On demand: 0–500 km/h	Not relevant	Not relevant
Higher User Mobility Use Case Family					
Mobile broadband in vehicles (cars, trains) →High speed train →Moving hot spots →Remote computing	DL: 50 Mbps UL: 25 Mbps	10 ms	On demand: up to 500 km/h	2000 / km^2 (500 active users per train x 4 trains, or 1 active user per car x 2000 cars)	DL: 100 Gbps / km^2 (25 Gbps per train, 50 Mbps per car) UL: 50 Gbps / km^2 (12.5 Gbps per train, 25 Mbps per car)

Use Case Category and Sample Use Cases	User Experience Requirements			System Performance Requirements	
	User Experienced	Latency	Mobility	Connection Density	Traffic Density
Airplanes connectivity →3D Connectivity: Aircrafts (and balloonists, gliders, skydivers)	DL: 15 Mbps per user UL: 7.5 Mbps per user	10 ms	Up to 1000 km/h	80 per plane 60 airplanes per 18,000 km²	DL: 1.2 Gbps / plane UL: 600 Mbps / plane
Massive Internet of Things Use Case Family					
Massive low- cost/long-range/low- power MTC →Smart wearables (clothes) →Sensor networks	Low (typically 1–100 kbps)	Seconds to hours	On demand: 0–500 km/h	Up to 200,000 / km²	Noncritical
Broadband MTC →Mobile video surveillance	See the requirements for the Broadband access in dense areas and 50+ Mbps everywhere categories				
Extreme Realtime Communication (without demand for ultra-reliability)					
Ultra-low latency →Tactile internet	DL: 50 Mbps UL: 25 Mbps	<1 ms	Pedestrian	Not critical	Potentially high
Lifeline Communication (without demand for ultralow latency)					
Resilience and traffic surge →Natural disaster	DL: 0.1–1 Mbps	Not critical	0–120 km/h	10,000 / km²	Potentially high
Ultrareliable Communication (with demand for low to ultralow latency)					
Ultra-high reliability & Ultra-low latency →Automatic traffic control/driving →Collaborative robots →Remote object manipulation – Remote surgery	DL: From 50 kbps to 10 Mbps UL: From a few bps to 10 Mbps	1 ms	On demand: 0–500 km/h	Not critical	Potentially high
Ultra-high availability & reliability →eHealth: Extreme Life Critical →Public safety →3D Connectivity: Drones	DL: 10 Mbps UL: 10 Mbps	10 ms	On demand: 0–500 km/h	Not critical	Potentially high

Source: Derived from NGNM 2015 (Figure 5, Table1, Table 2)

Table A-4. 5G PPP Mapping of Vertical Use Cases to Use Case Families

Vertical Use Cases	5G PPP Use Case Families					
	Dense urban	Broadband (50+ Mbps) Everywhere	Connected vehicles	Future smart offices	Low bandwidth IoT	Tactile Internet / automation
Automotive: Most demanding vertical with respect to mobility (speed), position accuracy (location)						
A1-Automated driving			X			
A2-Road safety and traffic efficiency services			X			
A3-Digitalization of transport and logistics			X			
A4-Intelligent navigation			X			
A5-Information society on the road			X			
A6-Nomadic nodes						
eHealth: Most demanding vertical with respect to mobility (speed), reliability						
H1-Assets and interventions management in hospitals						
H2-Robotics (remote surgery, cloud service robotics for assisted living)						X
H3-Remote monitoring of health or wellness data	X	X			X	X
H4-Smarter medication	X	X				
Energy						
E1-Grid access	X				X	
E2-Grid backhaul						X
E3-Grid backbone		X				X
Media and Entertainment: Most demanding vertical with respect to data rate						
ME1-Ultra high fidelity media		X				
ME2-On-site live event experience	X					
ME3-User generated content & machine generated content		X				
ME4-Immersive and integrated media		X				
ME5-Cooperative media production				X		
ME6-Collaborative gaming	X					

Vertical Use Cases	5G PPP Use Case Families					
	Dense urban	Broadband (50+ Mbps) Everywhere	Connected vehicles	Future smart offices	Low bandwidth IoT	Tactile Internet / automation
Factories of the Future: Most demanding with respect to latency, density (number of devices)						
F1-Time-critical process optimization inside factory to support zero-defect manufacturing						X
F2-Non time-critical optimizations inside factory to realize increased flexibility and ecosustainability, and to increase operational efficiency	X	X				
F3-Remote maintenance and control optimizing the cost of operation while increasing uptime	X					X
F4-Seamless intra-/inter-enterprise communication, allowing the monitoring of assets distributed in larger areas, the efficient coordination of cross value chain activities and the optimization of logistic flows	X	X				
F5-Connected goods, to facilitate the creation of new value-added services	X				X	

Source: Derived from Maternia and El Ayoubi 2016 (Table 1, Table 2, discussion on pp. 11-12)

Appendix B. FCC Auctions: Results to Date

Table B-1. FCC Auctions: Licenses Won and Net Winning Bids[37,38,39]

Auction Number and Name	Year Concluded	Licenses Won	Net Winning Bids ($M)
1: Nationwide Narrowband (PCS)	1994	10	$617.01
2: Interactive Video and Data Services (IVDS)	1994	594	$213.89
3: Regional Narrowband (PCS)	1994	30	$392.71
4: Broadband PCS A and B Block	1995	99	$7,019.40
5: Broadband PCS C Block	1996	493	$10,071.71
6: Multipoint/Multichannel Distribution Services	1996	493	$216.24
7: 900 MHz Specialized Mobile Radio Service	1996	1,020	$204.27
8: Direct Broadcast Satellite 110 Degrees (DBS)	1996	1	$682.50
9: Direct Broadcast Satellite 148 Degrees (DBS)	1996	1	$52.30
10: Broadband PCS C Block Re	1996	18	$904.61
11: Broadband PCS D, E, & F Block	1997	1,472	$2,517.44
12: Cellular Unserved	1997	14	$1.84
14: Wireless Communications Service (WCS)	1997	126	$13.64
15: Digital Audio Radio Service (DARS)	1997	2	$173.24
16: 800 MHz Specialized Mobile Radio Service (SMR)	1997	524	$96.23
17: Local Multipoint Distribution System (LMDS)	1998	864	$578.66
18: 220 MHz	1998	693	$21.65
20: VHF Public Coast	1998	26	$7.46
21: Location and Monitoring Services (LMS)	1999	289	$3.44
22: C, D, E, and F Block Broadband PCS	1999	302	$412.84
23: Local Multipoint Distribution Service (LMDS) Re-auction	1999	161	$45.06
24: 220 MHz	1999	222	$1.93
25: Closed Broadcast	1999	115	$57.82
27: Broadcast Auction	1999	1	$0.17
26: 929 and 931 MHz Paging Service	2000	985	$4.12

[37] Source: Derived from FCC Auction Summary, https://www.fcc.gov/auctions-summary. The FCC Auction Summary also provides the following information for each auction: (1) a link to details on the auction, (2) the number of licenses auctioned (in addition to the number won), and (3) the number of rounds in the auction.

[38] Highlighted auctions had net winning bids of greater than $1 billion.

[39] The broadcast incentive auction of 600 MHz spectrum that concluded in March 2017 is not included in this summary. The Reverse Auction 1001 provided $10.05 billion in revenue to 175 winning broadcast stations. The Forward Auction 1002 resulted in 2, 776 licenses won for 70 megahertz of spectrum. Gross proceeds totaled $19.8 billion; of that, $7.3 billion went to the U.S. Treasury for deficit reduction. See https://auctiondata.fcc.gov/public/projects/1000 and https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf for details.

Auction Number and Name	Year Concluded	Licenses Won	Net Winning Bids ($M)
28: Broadcast	2000	2	$1.21
30: 39GHz	2000	2,173	$410.65
33: Upper 700 MHz Guard Bands	2000	96	$519.89
34: 800 MHz SMR General Category Service	2000	1,030	$319.45
36: 800 MHz SMR Lower 80 Channels Service	2000	2,800	$28.98
80: Blanco Texas Broadcast	2000	1	$18.80
35: C and F Block Broadband PCS	2001	422	$16,857.05
38: Upper 700 MHz Guard Bands	2001	8	$20.96
39: VHF Public Coast and Location and Monitoring Services	2001	217	$1.15
40: Paging	2001	5,323	$12.90
41: Narrowband PCS	2001	317	$8.29
42: Multiple Address Systems Spectrum	2001	878	$1.20
32: New AM Broadcast Stations	2002	3	$1.52
43: Multi-Radio Service	2002	27	$1.55
44: Lower 700 MHz Band	2002	484	$88.65
45: Cellular RSA	2002	3	$15.87
82: New Analog Television Stations	2002	4	$5.03
46: 1670-1675 MHz Band Nationwide License	2003	1	$12.63
48: Lower and Upper Paging Bands	2003	2,832	$2.45
49: Lower 700 MHz Band	2003	251	$56.82
50: Narrowband PCS	2003	48	$0.43
51: Regional Narrowband PCS	2003	5	$0.13
54: Closed Broadcast	2003	4	$4.66
37: FM Broadcast	2004	258	$147.88
52: Direct Broadcast Satellite Service	2004	3	$12.20
53: Multichannel Video Distribution & Data Service (MVDDS)	2004	192	$118.72
55: 900 MHz Specialized Mobile Radio Service	2004	55	$4.86
56: 24 GHz Service	2004	7	$0.22
57: Automated Maritime Telecommunications System	2004	10	$1.06
58: Broadband PCS	2005	217	$2,043.23
59: Multiple Address Systems Spectrum	2005	2,223	$3.87
60: Lower 700 MHz Band	2005	5	$0.31
61: Automated Maritime Telecommunications System	2005	10	$7.09
63: Multichannel Video Distribution & Data Service (MVDDS)	2005	22	$0.13
81: Low Power Television (LPTV)	2005	90	$0.84

Auction Number and Name	Year Concluded	Licenses Won	Net Winning Bids ($M)
62: FM Broadcast	2006	163	$54.26
64: Full Power Television Station Construction Permits	2006	10	$23.37
65: 800 MHz Air-Ground Radiotelephone Service	2006	2	$38.34
66: Advanced Wireless Services (AWS-1)	2006	1,087	$13,700.27
68: FM Broadcast	2007	9	$3.26
69: 1.4 GHz Bands	2007	64	$123.60
70: FM Broadcast	2007	111	$21.30
71: Broadband PCS	2007	33	$13.93
72: 220 MHz	2007	76	$0.19
73: 700 MHz Band	2008	1,090	$18,957.58
77: Closed Cellular Unserved	2008	1	$0.03
78: AWS-1 and Broadband PCS	2008	53	$21.28
85: LPTV and TV Translator Digital Companion Channels	2008	30	$0.14
79: FM Broadcast	2009	85	$5.25
86: Broadband Radio Service	2009	61	$19.43
87: Lower and Upper Paging Bands	2010	4,714	$5.40
88: Closed Broadcast	2010	13	$1.44
90: VHF Commercial Television	2011	2	$2.63
91: FM Broadcast	2011	108	$8.54
92: 700 MHz Band	2011	16	$19.77
93: FM Broadcast	2012	93	$3.83
901: Mobility Fund Phase I	2012	0	$0.00
94: FM Broadcast	2013	93	$4.12
95: Lower and Upper Paging Bands	2013	3,104	$1.66
84: Closed AM Broadcast	2014	10	$0.60
96: H Block	2014	176	$1,564.00
902: Tribal Mobility Fund Phase I	2014	0	$0.00
97: Advanced Wireless Services (AWS-3)	2015	1,611	$41,329.67
98: FM Broadcast	2015	102	$4.12
83: FM Translator	2018	30	$0.58
99: AM Revitalization/FM Translators	2018	11	$0.23
101: Spectrum Frontiers – 28 GHz*	2019	2,965	$702.57
Total			**$121,672.18**

* For Auction 101, the total provisional winning bids (PWB) amount is shown until Auction 102 (Spectrum Frontiers – 24 GHz) concludes and the full results are released for Auctions 101 and 102.

Appendix C. Selected Responses to NTIA Request for Comments

On December 21, 2018, the NTIA published a notice and request for comments (RFC) in the Federal Register. The notice was titled "Developing a Sustainable Spectrum Strategy for America's Future."[40] The RFC received over 50 responses.[41] Here, we identify some themes that emerged from the responses and offer selected quotes from the responses to illustrate the themes.

Prioritize licensed spectrum for 5G, especially mid-band spectrum

T-Mobile. [A]ccess to exclusively-licensed spectrum is the best way to ensure investment by wireless communications providers.

Verizon. As Verizon and others have noted, allocating additional licensed mid-band spectrum is particularly critical for U.S. 5G interests.

CTIA. The U.S. Government Should Ensure that Future Allocations are Appropriately Balanced Between Unlicensed and Licensed. Today, in the mid-band, the U-NII bands offer 580 megahertz for unlicensed use, while there is no flexible-use licensed spectrum today and a commitment of only 70 megahertz of 3.5 GHz CBRS PAL spectrum in the future (which itself is subject to opportunistic sharing). Further, while the current proposal from incumbent satellite licensees holding spectrum in the 3.7-4.2 GHz C-band involves repurposing 180 megahertz of that band for flexible-use licensed services, the FCC has initiated a separate proceeding on the 6 GHz band, where it proposes to allow unlicensed access to more than six times that amount—1.2 gigahertz. As for high-band spectrum, 5.5 gigahertz has been committed to flexible-use licensing while nearly twice that amount—14 gigahertz—is reserved for unlicensed….

Google. [For 5G], the United States should maximize access to mid-band spectrum, including in CBRS and underutilized C-Band spectrum, which offers both significant coverage potential and sufficient bandwidth to accommodate high-capacity services…. Indeed, because mid-band spectrum is "where most of the rest of the world will deploy 5G," keeping pace with the European Union, China, Japan, and South Korea as they allocate mid-band spectrum is essential. Failure to focus on international harmonization would put the United States on a path to isolation to the detriment of American service providers, manufacturers, and consumers. Availability of equipment and semiconductors would be more limited, prices would be higher, and network coverage would suffer. Rather than over-emphasizing much higher-frequency spectrum with challenging propagation characteristics that will play a more limited role in 5G, therefore, the National Spectrum Strategy should prioritize unleashing the power of mid-band spectrum for both fixed and mobile 5G services.

MVDDS (Multichannel Video Distribution and Data Service) 5G Coalition. Given the clear potential for increasing 5G services using the 12 GHz Band – and the need to allocate new spectrum for such services – the Coalition urges the NTIA to consider the 12 GHz Band spectrum as part of the United States' national spectrum strategy going forward. The FCC's current rules are understandably out of date and have undermined the band's broadband potential, despite significant investment in the band. As a result, MVDDS spectrum today remains underutilized. Modifying the rules to permit sharing between DBS [Direct Broadcast System] and a viable two-way mobile broadband service will bring vast public interest benefits, including: (i) making an additional 500 MHz of contiguous spectrum available

[40] https://www.ntia.doc.gov/files/ntia/publications/2018-27690_3.pdf

[41] https://www.ntia.doc.gov/Federal-register-notice/2019/comments-developing-sustainable-spectrum-strategy-america-s-future

to help meet mobile broadband demand and foster 5G, and (ii) adapting the current regulatory approach to reflect today's technologies and the trend toward more flexible uses.

Do not favor unlicensed spectrum too heavily

CTIA. The U.S. Government Should Ensure that Future Allocations are Appropriately Balanced Between Unlicensed and Licensed…. Today, in the mid-band, the U-NII bands offer 580 megahertz for unlicensed use, while there is no flexible-use licensed spectrum today and a commitment of only 70 megahertz of 3.5 GHz CBRS PAL spectrum in the future (which itself is subject to opportunistic sharing)…. As for high-band spectrum, 5.5 gigahertz has been committed to flexible-use licensing while nearly twice that amount – 14 gigahertz – is reserved for unlicensed….

Verizon. But in light of the substantial swaths of spectrum the FCC already has earmarked for unlicensed use, identifying additional spectrum for licensed, exclusive-use is all the more important.

Give more priority to unlicensed spectrum

Apple. [I]n the past the U.S. has too heavily preferenced the identification of licensed bands over unlicensed bands. This is especially true when accounting for the leading role unlicensed technologies play in internet access for Americans—far more data travels over unlicensed bands than over any other frequency range…. Apple recommends that the strategy favor larger unlicensed bandwidths whenever possible, including in the pending Spectrum Horizons bands ranging from 95 GHz to 275 GHz.

Robert Bosch, LLC (Bosch). Expanding the amount of spectrum [in the bands below 10 GHz] that is available for unlicensed devices and permitting flexible use in these bands will decrease the pressure on the existing unlicensed bands below 10 GHz, including 902-298 MHz, 2450-2483.5 MHz, and 5725-5850 MHz. But new unlicensed spectrum for wide bandwidth digital devices should not all be in the bands below 10 GHz. Bands above 95 GHz generally, and specifically around 120 GHz offer excellent short-range opportunities for American manufacturing and for the Internet of Things.

NCTA—The Internet & Television Association. [U]nlicensed spectrum's low barriers to entry promote efficiency by supporting the development of innovative new technologies and applications that otherwise would not have access to spectrum resources…. Fixed wireless Internet service providers, known as WISPs, for example, offer broadband Internet access in rural areas using point-to-point and multipoint unlicensed networks.

Ruckus. As the world's most popular form of shared spectrum, unlicensed spectrum is already vital to our nation's interests. As noted previously, unlicensed spectrum carries the great majority of smartphone wireless data traffic over a Wi-Fi airlink. Unlicensed wireless technologies can also share spectrum resources with protected incumbent services such as the protection of radar systems in the 5 GHz U-NII 2A and U-NII 2C bands via Dynamic Frequency Selection (DFS) mechanisms, or the protection of incumbents via an Automated Frequency Coordination (AFC) function that has been proposed for unlicensed operation in the 5925 to 7125 MHz (i.e. 6 GHz) band.

Wi-Fi Alliance. To assess this threat, Wi-Fi Alliance commissioned a Spectrum Needs Study that analyzed current and future Wi-Fi spectrum requirements. Based on projected growth in demand for use of spectrum on which Wi-F devices operate, by 2025, up to 1500 megahertz of additional mid-band spectrum may be needed to sustain the Wi-Fi ecosystem.

Prioritize sharing

Dynamic Spectrum Alliance. [FCC and NTIA] should consider the costs and benefits of shared access over cleared and licensed access. This has two results: (1) sharing becomes a primary instead of secondary part of the strategic policy discussion; and (2) it will potentially uncover bands that would not be available (either for non-Federal or Federal) without shared access.

Facilitate sharing via data and automation

Alion. Dynamic coordination, or dynamic spectrum access, will require automation … [and] will need a much larger range of data inputs and will dispense with the current deliberative administrative processes and their associated fixed frequency assignment databases.

Comsearch. In recent years Federal and non-Federal interests have been able to employ new technology and/or carefully manage the introduction of new services while ensuring the satisfaction of both parties…. The use of SAS/ESC technology in the CBRS represents one success story…. The 1695-1710 MHz Advanced Wireless Service 3 ("AWS-3") band represents another success story…. To facilitate shared use of the band, NTIA and private industry developed a "customized web-based database storage software solution that … facilitates careful coordination around Federal earth stations before an AWS-3 licensee deploys network infrastructure.

Facebook. Moreover, an ongoing sustainable spectrum strategy will require spectrum sharing, the use of automated sharing technologies, and possibly the use of additional buildout requirements to ensure that spectrum is used efficiently.

Federated Wireless. [D]ynamic sharing technologies are significantly better suited to enabling 5G operations in the near term than lengthy clear-and-auction approaches. In light of its clear advantages over traditional management paradigms and ability to both preserve spectrum access to meet Federal mission requirements and facilitate near-term access to the spectrum needed to maintain U.S. global leadership in the race to 5G, this SAS-enabled sharing model can and should be replicated in other frequency band**s** as part of an effort to develop and execute a sustainable National Spectrum Strategy.

LS Telecom. To support the increased efficiency, which also must incorporate legacy systems, it is imperative that the Spectrum Management system in place provides the foundation for the evolution of spectrum allocation into dynamic environments, shared usage, and increasingly tighter tolerances. A continued operation with disparate databases and varied processes can produce inconsistencies in Spectrum Management lead to interference, lack of coverage and ultimately unpredictable disruption in services. To prepare for the next 15–20 years the proper foundation must be established including consistency in data and process automation.

National Association of Broadcasters. In this case, shared use between DoD and broadcaster systems is challenging because it requires the exchange of information involving sensitive (in some cases classified) DOD uses as well as broadcast uses that change dynamically in real-time (e.g., electronic news gathering equipment on moving vehicles). Such challenges can frustrate the transparency that would support independent analysis by either party…. Based on this experience, NAB suggests that widespread successful spectrum sharing involving sensitive information is likely to require a third party, trusted by all involved spectrum users, to act as a frequency coordinator.

Shared Spectrum Communications. Local distributed systems that can react to the spectrum environment encountered by the radio(s) offers more efficient spectrum sharing. To achieve increased spectrum sharing over time, the rules should support and encourage the development of local distributed spectrum sharing solutions.

Share, but test first, to protect incumbents

Aerospace Industries Association (AIA). As the Administration looks to continue to develop a "National Spectrum Strategy," it is critical that it establish sharing regimes that ensure adequate testing is completed beforehand, take into account safety over speed of introducing new allocations, and add more transparency to the process.

Association of Public-Safety Communications Officials-International, Inc. (APCO). Any spectrum strategies or policies must respect the life-or-death nature of these communications and preserve public safety's need for reliable, interference-free access to spectrum… [A]ny sharing techniques must be tested and proven to be effective at protecting public safety's use of the band before being put to use….

Perform compatibility studies to protect incumbents

American Radio Relay League (ARRL). However, the key elements of any successful spectrum management plan going forward must include technical compatibility studies and increased transparency and partnership between and among NTIA, FCC telecommunications manufacturers, their customers and the public.

Echostar. [U]sing automation to facilitate assessments of spectrum and the coordination of shared access is particularly important in bands where aggregate interference is a potential issue. For example, in the 27.5–28.35 GHz band (the 28 GHz band) the FCC has authorized the use of the band for both UMFUS and satellite gateways, with FSS space station receivers also operating in the band. While potential of interference from an individual UMFUS station into a satellite space station receiver is minimal, the aggregate interference impact must be assessed as UMFUS deployments are made. The potential for aggregate interference can be minimized by terrestrial operators' adherence to reasonable total radiated power and base station antenna down tilt standards. With the advent of terrestrial 5G, it is important that such protections must be adopted to ensure that all communications are protected from harmful interference.

GPS Innovation Alliance. In particular, spectrum management must consider that systems that support navigation functions are sensitive to adjacent-band operations in different ways than systems that operate communications services – particularly when services in adjacent spectrum bands operate with very different power levels. A "zoning" approach to spectrum management that groups similar services together can generally protect navigation services by ensuring that high-powered communications services are separated from services like GPS that require a "quiet neighborhood." That approach allows a broad range of spectrum-based services to co-exist in adjacent bands while ensuring that devices that are vulnerable to interference, such as GPS and GNSS receivers, can still function in other bands.

Support flexible use

Apple. Apple suggests that the National Spectrum Strategy support the adoption of flexible technical rules in commercial bands whenever possible. Prescriptive technical rules, for example those that mandate, or that lock in the details of interference-reduction mechanisms, are necessarily based on assumptions built on today's technologies. This approach handcuffs future advances.

DISH. The FCC's flexible use spectrum policies have encouraged the deployment of innovative new services…. The NTIA should maintain this flexible use approach.

Small UAV. [P]olicymakers …must focus on mid-band spectrum, [whose] characteristics will be important in many UAS applications such as search and rescue, real-time inspections, natural resource management, and more…. UAS technology is developing quickly and there is a need to adopt flexible allocation and, ultimately, flexible service rules that allow the market and advances in technology to dictate the best uses of the spectrum over time.

Recognize the special needs of public safety and critical infrastructure

Edison Electric Institute. These communications needs [coordinating with first responders and day-to-day operations of electric companies] cannot be met effectively by commercial service providers, which is why many critical-infrastructure industries including electric utilities operate their own private wireless networks.

New York City Department of Information Technology and Telecommunications. Public safety use of spectrum is paramount, and sometimes sharing is not possible or advisable.

Balance the needs of *all* industries (e.g., aerospace, satellite, stratospheric based communications, broadcasters)

Aviation Spectrum Resources, Inc. ("ASRI"), the Air Line Pilots Association ("ALPA"), and the Aircraft Owners and Pilots Association ("AOPA"). ASRI, ALPA, and AOPA strongly recommend that the [National Spectrum Strategy] should account for all industry sectors contributing to the US economy through effective use of spectrum….. In North America alone, the aviation industry supports $844 billion of GDP and 7.3 million jobs….. Therefore, a singular policy focus on the headline growth industries that use radio spectrum, i.e., the commercial mobile broadband industry, would overlook large areas of economic development that should benefit from sound spectrum strategy…. ASRI, ALPA, and AOPA would also note that demands for additional spectrum should be rationalized and deliberately reviewed rather than simply presumed…. Any attempts by the mobile industry to acquire additional spectrum from other services while not using the existing spectrum already allocated for such a purpose only increases tension and the protective nature of affected industries.

Boeing. This said, the spectrum management challenge is far more complicated than the view expressed by those who claim the U.S. is in a race with other countries over which country allocates the most spectrum as rapidly as possible to still-aspirational 5G wireless services. Instead, countless U.S. industries and public interests depend on access to spectrum resources to develop, test and operate industrial, transportation, and aerospace systems that contribute greatly to U.S. foreign trade and the quality of life for U.S. citizens. Therefore, the spectrum management policies of the United States must entail a careful balancing of the needs of different spectrum uses, ensuring that no particular interest is permitted to employ unproven and potentially inflated estimates of economic benefits at the expense of access to sufficient spectrum resources used for industry, transportation, science, government, public safety, and other important uses….

Coalition of Aviation, SATCOM, and Weather Information Users (General Aviation Manufacturers Association, Iridium Communications, Inc., Narayan Strategy). [I]t is critical that U.S. policy continue to value and enhance the stability of L-band satellite spectrum allocations [specifically, 1525-1695 MHz], protect those investments from harmful interference, and robustly advocate for these principles in international fora. These principles create the solid foundation America's space industry needs to continue to succeed.

Echostar. [I]t is important to remember, that as opposed to terrestrial communications, a fair amount of satellite and satellite equipment manufacturing occurs in the United States. This is complemented by a very robust launch industry with the addition of a new US launch providers in the past few years, including SpaceX. If spectrum policies fail to provide sufficient access to spectrum to support the commercial satellite industry, it is possible that these industries will fail.

Satellite Industries Association. Satellite operators have already invested billions of dollars in dozens of satellite networks that provide coverage of the United States and provide important services to consumers across the country, including the government, both directly or indirectly. Due to the long lead time to design, construct, and deploy satellite networks, satellite operators must obtain funding and spectrum rights years in advance of launch. Furthermore, geostationary satellite orbit networks, for instance, generally remain in operation for at least 15 years once on orbit and cannot be reconfigured to operate on different spectrum channels following launch. The Federal Communications Commission maintains space station and earth station approval lists, which detail frequencies utilized by these satellite systems. It is for these reasons, among others, that long-term certainty for satellite spectrum access is a necessity that should be included in any U.S. spectrum strategy.

SES Americom. The predictability of spectrum access is critical for the efficient deployment of satellite services…. Additionally, these systems are designed to cover wide geographic areas, and a single system will typically cover multiple countries, if not continents. Satellite operators must be able to rely on stable and internationally-harmonized spectrum policies to use satellite capacity efficiently, deliver affordable and innovative services, and ensure that these long-term investments are successful…. When spectrum policy is subject to changes, the upheaval experienced by satellite operators affects their customer bases as well, impacting U.S. consumers as well as USG users.

SpaceX. While spectrum policy has properly migrated towards emphasizing flexible use of spectrum, too often the technical rules governing these licenses effectively restrict use to specific technologies or use cases…. [Inter Satellite Links (ISLs)] are being developed today to operate using either optical or RF technology. Yet, despite the benefits of ISLs and the development of cutting-edge Non-Geostationary Orbit (NGSO) satellite systems, few spectrum bands are available for RF-based NGSO ISLs… Once again, a National Spectrum Strategy could avoid the limitations of centrally planned zero-sum allocations by making more room for RF-based ISLs. Making more frequencies available for NGSO ISLs could allow NGSO networks to offload traffic from heavily congested terrestrial networks, thereby resulting in more spectrum available for terrestrial use.

Spire. [Commercial Smallsat Spectrum Management Association (CSSMA)] notes that these discussions involving such shared bands ignores the reality that all of the shared bands under discussion are also allocated, on the same primary basis, by all other administrations of the world. The length of the NTIA coordination process and the effect of a non-concurrence by NTIA in precluding an ITU filing both can have the effect of prejudicing a United States company's ability to establish international spectrum rights.

Viasat. However, a potential looming satellite spectrum crunch threatens to impede progress…. Indeed, even though technical studies from both 5G and satellite interests show that the 5G terrestrial access being proposed is incompatible with existing satellite operations in the 28 GHz band, terrestrial wireless network manufacturers and carriers still have suggested reopening the debate and repurposing the 28 GHz band for 5G terrestrial access. Rather than impairing the continued deployment of these essential satellite services, the U.S., led by NTIA, should be confident that 5G can be accommodated, … without revisiting the 28 GHz band, or otherwise impeding satellite broadband capabilities and the ability of satellite to close the digital divide and offer true global connectivity.

Elefante Group. Elefante Group is concerned, as explained herein, that the apparent rush to free up and make these large amounts of spectrum available to the land-based commercial mobile industry without due consideration of need or the potential preclusive impacts on other spectrum users, emerging technologies, and innovative applications, both Federal and non-Federal, leaves this country's spectrum policy headed toward a near-sighted future. In particular, Elefante Group is concerned that the trajectory of the current spectrum decisions is providing much more spectrum to commercial mobile than needed for America to become the leader in 5G, while at the same time squandering opportunities for the United States to be in the front of the pack globally in other emerging technologies, such as Stratospheric Based Communications Services ("SBCS"). The United States can be a leader in both ways, and it should.

Telecommunications Industry Association (TIA). [T]here is clearly a need for more mid-band spectrum…. Moreover, TIA believes in technology neutrality and that several different wireless solutions, including 5G, other terrestrial applications, and various space-based applications, can play a role in meeting future service needs. For example, satellite operators are now offering broadband service…. TIA has also recently noted that the FCC could consider creating reasonable spectrum opportunities for upper airspace-based technologies such as stratospheric platform stations ("STRAPS").

National Association of Broadcasters. NAB respectfully submits that no party is in a position to offer a responsible answer to this question [question #7], especially while 5G services remain largely speculative. The past several years have seen major spectrum policy decisions turn on hyperbolic claims of an impending "spectrum crunch" or a "spectrum crisis," that proved overblown. NAB urges that a national spectrum strategy be based on facts, not marketing campaigns.

Consider licensing of small geographic areas

National Spectrum Consortium (NSC). However, long-term micro licensing could provide a means to commoditize remote areas and place fallow spectrum into use. Long-term use must be supported to allow this to be economically viable to the license holder and to the micro licensee.

WISPA. [L]icensed spectrum should be accessible to small broadband providers through various means such as small geographic license areas and build-out rules that incentivize deployment to rural areas or leasing of spectrum in rural areas.

Increase commercial access to Federal spectrum

Consumer Technology Association (CTA). Specifically, [the National Spectrum Strategy] should seek to increase transparency regarding how Federal spectrum is used and what Federal spectrum could be made available for commercial use…. The FCC and NTIA continue to explore innovative ways to maximize sharing opportunities between Federal and commercial users.

Ericsson. Ericsson supports the Spectrum PM's directive that executive departments and agencies report on their anticipated future spectrum requirements…. Through this process, the U.S. government should identify opportunities for commercial operations while maintaining Federal use – be it, for example, where Federal spectrum is unused, or where multiple Federal spectrum systems can be combined (e.g., multifunction radars), or where Federal needs can be met by using commercial services (including 5G), or where Federal spectrum use can be accommodated via other technologies (e.g., fiber connections). The U.S. government should conduct spectrum reviews on a recurring basis to make sure that all information about Federal use of spectrum is as current as possible.

Free State Foundation. In the past, it is well known that the decision to repurpose government spectrum for commercial use is an extremely lengthy process…. Providing greater transparency into the process, -- what proposals are being considered, by what agencies, on what timeframe, how to submit further information to aid in those decisions – would substantially improve these processes.

Frontier Communications. In other words, it is not just mobility driving significant demand for wireless spectrum, and NTIA should not only maximize the spectrum available but also consider where fixed wireless deployments would be uniquely suited for sharing bandwidth with Federal users….Indeed, incorporating fixed wireless into long-term spectrum planning can help the Administration accelerate achieving its goal of closing the urban-rural digital divide…. While sharing is certainly feasible regardless of the use case, fixed wireless is particularly well-suited for facilitating sharing; by design the transmitters and receivers are set at fixed points…. Frontier and Windstream would be eager to explore leasing spectrum from Federal users, including in rural areas. On the one hand, imposing spectrum fees on government users could be a good "stick" to incentivize sharing by agencies and should be fully explored. On the other hand, allowing government spectrum holders to uncover value through a leasing (or potentially, reverse auction) method could be a good "carrot."

Mercatus Center. An alternative proposal for spectrum reform (resembling Commissioner Rosenworcel's proposal) is to auction overlay licenses which permit the commercial use of spectrum currently encumbered by Federal users. These licenses are called *overlays* because they geographically surround an existing spectrum assignment. Overlays have enabled the relocation and clearing of state government systems and public safety systems from a few hundred MHz of spectrum. Overlays have not been used for Federal spectrum because agencies cannot directly receive consideration from commercial users…

mmWave Coalition. The mmWave Coalition submits these comments to urge NTIA to facilitate greater access to spectrum above 95 GHz for non-Federal use…. The spectrum in the 95-275 GHz region is very promising for both communications and noncommunications uses due to the wide bandwidths that are available and the opportunities for very intensive spectrum reuse because of the unusual nature of radio propagation here and the new antenna techniques enabled by the very small wavelengths involved.

Nokia. An additional model for unlocking greater value from Federal spectrum, public private partnerships (PPP) should be considered. For example, FirstNet's partnership with AT&T, allows commercial access to 20 MHz of low-band spectrum allocated to Public Safety in return for substantial value. That PPP will allow FirstNet to achieve its public safety mission more efficiently and more rapidly than it could ever do on its own.

Technology Policy Institute. [Government Spectrum Ownership Corporation, or] GSOC could also help implement a version of "overlay" licenses for government-occupied bands…. Secondary rights to unused spectrum in the band could be auctioned to commercial users through overlay licenses issued by the Federal government. This would open the opportunity for bargaining between those users and the incumbent.

T-Mobile. While sharing along the time dimension may be challenging, industry has a successful record of sharing spectrum geographically where its use is not required for Federal operations…. Any

Federal/non-Federal sharing should focus on geographic sharing where spectrum cannot be reallocated on a nationwide basis for commercial operations.

Enable bi-directional sharing (Federal use of commercial spectrum)

Oceus Networks. To enable use of commercial wireless-based solutions, the U.S. must make real progress on establishing a bi-directional sharing framework… Access to commercial spectrum by the Federal government also has other benefits. [Following some recent natural disasters], [a] private cellular LTE network could have provided immediate communications for safety and continuity of operations. However, existing spectrum policies do not allow spectrum managers to operate private communication as a bridge to commercial service.

Appendix D. 3GPP 5G Operating Bands as of December 2018

3GPP Technical Specification TS 38.104, V15.4.0, *Base Station (BS) radio transmission and reception (Release 15),* specifies operating bands for 5G NR in two ranges (3GPP 2018):

- Frequency Range 1 (FR1) – 450 MHz – 6 GHz (sub 6 GHz range)
- Frequency Range 2 (FR2) - 24.25 GHz – 52.6 GHz (millimeter range)

This is because requirements throughout the RF specifications are, in many cases, defined separately for FR1 and FR2 (3GPP 2018).

Tables D-1 and D-2 list the operating bands specified for FR1 and FR2, respectively, as of December 2018.

The bands highlighted in green are bands that are new to cellular telephony, chosen specifically for 5G NR. The others are LTE bands that are being repurposed for 5G NR. Where there is recent or ongoing FCC or NTIA activity in a band, or a portion of a band, the band is named and highlighted in the right-most column.

Table D-1. 3GPP Operating Bands in Frequency Range 1 (450 MHz–6 GHz)

Band	Uplink (UL)	Downlink (DL)	Duplex Mode	Subject of FCC Rulemaking or NTIA Study?
n5	824 MHz–849 MHz	869 MHz–894 MHz	FDD	
n8	880 MHz–915 MHz	925 MHz–960 MHz	FDD	
n12	699 MHz–716 MHz	729 MHz–746 MHz	FDD	
n20	832 MHz–862 MHz	791 MHz–821 MHz	FDD	
n28	703 MHz–748 MHz	758 MHz–803 MHz	FDD	
n71	663 MHz–698 MHz	617 MHz–652 MHz	FDD	600 MHz
n81	880 MHz–915 MHz	N/A	SUL	
n82	832 MHz–862 MHz	N/A	SUL	
n83	703 MHz–748 MHz	N/A	SUL	
n1	1920 MHz–1980 MHz	2110 MHz–2170 MHz	FDD	
n2	1850 MHz–1910 MHz	1930 MHz–1990 MHz	FDD	
n3	1710 MHz–1785 MHz	1805 MHz–1880 MHz	FDD	
n7	2500 MHz–2570 MHz	2620 MHz–2690 MHz	FDD	
n25	1850 MHz–1915 MHz	1930 MHz–1995 MHz	FDD	
n28	703 MHz–748 MHz	758 MHz–803 MHz	FDD	
n34	2010 MHz–2025 MHz	2010 MHz–2025 MHz	TDD	
n38	2570 MHz–2620 MHz	2570 MHz–2620 MHz	TDD	
n39	1880 MHz–1920 MHz	1880 MHz–1920 MHz	TDD	
n40	2300 MHz–2400 MHz	2300 MHz–2400 MHz	TDD	

Band	Uplink (UL)	Downlink (DL)	Duplex Mode	Subject of FCC Rulemaking or NTIA Study?
n41	2496 MHz–2690 MHz	2496 MHz–2690 MHz	TDD	2.5 GHz (EBS)
n50	1432 MHz–1517 MHz	1432 MHz–1517 MHz	TDD	
n51	1427 MHz–1432 MHz	1427 MHz–1432 MHz	TDD	
n65	1920 MHz–2010 MHz	2110 MHz–2200 MHz	FDD	
n66	1710 MHz–1780 MHz	2110 MHz–2200 MHz	FDD	
n70	1695 MHz–1710 MHz	1995 MHz–2020 MHz	FDD	
n74	1427 MHz–1470 MHz	1475 MHz–1518 MHz	FDD	
n75	N/A	1432 MHz–1517 MHz	SDL	
n76	N/A	1427 MHz–1432 MHz	SDL	
n77	3300 MHz–4200 MHz	3300 MHz–4200 MHz	TDD	3.7–4.2 GHz (C Band)
n78	3300 MHz–3800 MHz	3300 MHz–3800 MHz	TDD	3.1–3.55 GHz 3.45–3.55 GHz 3.5 GHz (CBRS)
n79	4400 MHz–5000 MHz	4400 MHz–5000 MHz	TDD	4.9 GHz (public safety)
n80	1710 MHz–1785 MHz	N/A	SUL	
n84	1920 MHz–1980 MHz	N/A	SUL	
n86	1710 MHz–1780 MHz	N/A	SUL	

Notes: (1) The bands highlighted in green are new 5G NR bands; the other bands are repurposed from LTE; (2) FDD=Frequency Division Duplex; (3) TDD=Time Division Duplex; (4) SDL=Supplementary Downlink; (5) SUL=Supplementary Uplink.

Source: Adapted from 3GPP 2018 and Keysight Technologies 2019

Table D-2. 3GPP Operating Bands in Frequency Range 2 (24.25 GHz–52.6 GHz)

Band	Uplink (UL) and Downlink (DL)	Duplex Mode	Subject of FCC Rulemaking
n257	26500 MHz–29500 MHz	TDD	28 GHz
n258	24250 MHz–27500 MHz	TDD	24 GHz and 26GHz
n260	37000 MHz–40000 MHz	TDD	37 GHz and 39 GHz
n261	27500 MHz–28350 MHz	TDD	subset of n257

Notes: (1) The bands are all new 5G NR bands, highlighted in green for emphasis; (2) TDD=Time Division Duplex.

Source: Adapted from 3GPP 2018 and Keysight Technologies 2019

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FCC 17-27. *Second Report and Order and Second Further Notice of Proposed Rulemaking – - Amendment of Parts 1 and 22 of the Commission's Rules with Regard to the Cellular Service, Including Changes in Licensing of Unserved Area* (24 March). https://docs.fcc.gov/public/attachments/FCC-17-27A1.pdf.

FCC 17-104*. Notice of Inquiry –Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz* (3 August). https://docs.fcc.gov/public/attachments/FCC-17-104A1.pdf.

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FCC 17-134. *Notice of Proposed Rulemaking and Order Terminating Petitions – Promoting Investment in the 3550-3700 MHz Band; Petitions for Rulemaking Regarding the Citizens Broadband Radio Service* (24 October). https://docs.fcc.gov/public/attachments/FCC-17-134A1.pdf.

FCC 17-152. *Second Report and Order, Second Further Notice of Proposed Rulemaking, Order on Reconsideration, and Memorandum Opinion and Order – Use of Spectrum Bands Above 24 GHz For Mobile Radio Services* (22 November). https://docs.fcc.gov/public/attachments/FCC-17-152A1.pdf.

FCC 18-17. *Notice of Proposed Rulemaking and Order – Spectrum Horizons, Battelle Memorial Institute Petition for Rulemaking to Adopt Fixed Service Rules in the 102-109.5 GHz Band* (28 February). https://docs.fcc.gov/public/attachments/FCC-18-17A1.pdf.

FCC 18-33. *Sixth Further Notice of Proposed Rulemaking – Amendment of Part 90 of the Commission's Rules* (23 March). https://docs.fcc.gov/public/attachments/FCC-18-33A1.pdf.

FCC 18-59. *Notice of Proposed Rulemaking – Amendment of Parts 1, 21, 73, 74 and 101 of the Commission's Rules to Facilitate the Provision of Fixed and Mobile Broadband Access* (10 May). https://docs.fcc.gov/public/attachments/FCC-18-59A1.pdf.

FCC 18-73. *Third Report and Order, Memorandum Opinion and Order, and Third Further Notice of Proposed Rulemaking – Use of Spectrum Bands Above 24 GHz For Mobile Radio Services and Amendment of Parts 1, 22, 24, 27, 74, 80, 90, 95, and 101 To Establish Uniform License Renewal* (8 June). https://docs.fcc.gov/public/attachments/FCC-18-73A1.pdf.

FCC 18-91. *Order and Notice of Proposed Rulemaking – Expanding Flexible Use of the 3.7 to 4.2 GHz Band, Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz* (13 July). https://docs.fcc.gov/public/attachments/FCC-18-91A1.pdf.

FCC 18-110. *Fourth Further Notice of Proposed Rulemaking – Use of Spectrum Bands Above 24 GHz for Mobile Radio Services* (3 August). https://docs.fcc.gov/public/attachments/FCC-18-110A1.pdf.

FCC 18-147. *Notice of Proposed Rulemaking—Unlicensed Use of the 6 GHz Band and Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz* (24 October). https://docs.fcc.gov/public/attachments/FCC-18-147A1.pdf.

FCC 18-180. *Fourth Report and Order – Use of Spectrum Above 24 GHz For Mobile Radio Services* (12 December). https://docs.fcc.gov/public/attachments/FCC-18-180A1.pdf.

FCC 18-181. *Communications Marketplace Report* (26 December). https://docs.fcc.gov/public/attachments/FCC-18-181A1.pdf.

List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G IA	5G Infrastructure Association
5GPPP	5G Infrastructure Public Private Partnership
ADC	Analog-to-Digital Converter
AFC	Automated Frequency Coordination
AIA	Aerospace Industries Association
ALPA	Air Line Pilots Association
AMT	Aeronautical Mobile Telemetry
ANPRM	Advance Notice of Proposed Rulemaking
AOPA	Aircraft Owners and Pilots Association
APCO	Association of Public-Safety Communications Officials
API	Application Programming Interface
AR	Augmented Reality
ARIB	Association of Radio Industries and Businesses, Japan
ARRL	American Radio Relay League
ASRI	Aviation Spectrum Resources, Inc
ATIS	Alliance for Telecommunications Industry Solutions, North America
AWS	Advanced Wireless Services
BAS	Broadcast Auxiliary Service
BBU	Baseband Unit
BRAS	Broadband Remote Access Server
BS	Base Station
C-RAN	Cloud-Radio Access Network
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
CB	Citizens Band
CBRS	Citizens Broadband Radio Service
CCSA	China Communications Standards Association
CDMA	Code Division Multiple Access
CFR	Code of Federal Regulations
CGNAT	Carrier Grade Network Address Translator
CGSN	Combined GPRS Support Node
CMA	Cellular Market Area
CoMP	Coordinated Multipoint
CPRI	Common Public Radio Interface
CR	Cognitive Radio
CriC	Critical Communications
CSMAC	Commerce Spectrum Management Advisory Committee
CSSMA	Commercial Smallsat Spectrum Management Association
CTA	Consumer Technology Association
CTIA	Cellular Telecommunications and Internet Association
DARS	Digital Audio Radio Service
DBS	Direct Broadcast System
DFS	Dynamic Frequency Selection
D2D	Device-to-Device
DAC	Digital-to-Analog Converter
DFT-S-OFDM	Discrete Fourier Transform-Spread-OFDM
DHS	Department of Homeland Security
DOD	Department of Defense
DPI	Deep Packet Inspection
DSA	Dynamic Spectrum Access
DSRC	Dedicated Short-Range Communications
DSSS	Direct Sequence Spread Spectrum
EBS	Education Broadband Service
ECC	Electronic Communications Committee
EC-GSM	Extended Range GSM
EDGE	Enhanced Data Rates for GSM Evolution
eMBB	Enhanced Mobile Broadband
EMS	Element Management System
ENG	Electronic News Gathering
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FPGA	Field-Programmable Gate Array
FR	Frequency Range
FS	Fixed Service
FSS	Fixed Satellite Service
FNPRM	Further Notice of Proposed Rulemaking
FWA	Fixed Wireless Access
GAA	General Authorized Access
GAO	Government Accountability Office

Gbps Gigabits per second
GDP Gross Domestic Product
GGSN Gateway GPRS Support Node
GHz Gigahertz
GOES Geostationary Operational Environmental Satellites
GPRS Generalized Packet Radio Service
GPU Graphics Processing Unit
GSA Global mobile Suppliers Association
GSM Global System for Mobile Communication
GSMA Global Scheduling Multiple Access
HAPS High Altitude Platform Systems
HetNet Heterogeneous Networks
HSPA High-Speed Packet Access
IBFD In-Band Full Duplex
ICT Information and Communications Technology
IDA Institute for Defense Analyses
IEEE Institute of Electrical and Electronics Engineers
IMT International Mobile Telecommunication
IMT-2020 International Mobile Telecommunication-2020
IoT Internet of Things
IP Internet Protocol
IRAC Interdepartment Radio Advisory Committee
ISL Inter Switch Link
ISM Industrial, Scientific, and Medical
ITS Institute for Telecommunication Sciences
ITS Intelligent Transportation System
ITU International Telecommunication Union
ITU-R International Telecommunication Union-Radiocommunication
IVDS Interactive Video and Data Services
kHz Kilohertz
km Kilometer
LAA Licensed Assisted Access
LMDS Local Multipoint Distribution System
LMS Location and Monitoring Services
LPWA Low-Power Wide Area
LP-WAN Low-Power Wide Area Networking
LTE Long Term Evolution
LTE-A LTE Advanced
LTE-U LTE-Unlicensed
LWA LTE/Wi-Fi Aggregation
LWIP LTE WAN Integration with IPSec
m meter
M2M Machine-to-Machine
MAC Medium Access Control
Mbps Megabits per second
MEC Multiaccess Edge Computing
MedRadio Medical Device Radiocommunication Service
METIS Mobile and wireless communications Enablers for the Twenty twenty Information Society
MHz Megahertz
MICS Medical Implant Communications Service
MIMO Multiple Input Multiple Output
MIoT Massive Internet of Things
MME Mobility Management Entity
mMTC massive Machine Type Communications
mmWave Millimeter Wave
MS Mobile Service
MSA Metropolitan Service Area
MSS Mobile Satellite Service
MU-MIMO Multiple User-Multiple Input Multiple Output
MVDDS Multichannel Video Distribution & Data Service
NAB National Association of Broadcasters
NB-IoT Narrow Band-Internet of Things
NCTA National Cable & Telecommunications Association
NEO Network Operation
NFV Network Functional Virtualization
NGNM Next Generation Network Management
NGSO Non-Geostationary Orbit
NOI Notice of Inquiry
NOOA National Oceanic and Atmospheric Administration
NOMA Non-Orthogonal Multiple Access
NPRM Notice of Proposed Rulemaking
NR New Radio
NSC National Spectrum Consortium
NTIA National Telecommunications and Information Administration

OFDMA	Orthogonal Frequency Division Multiple Access
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PAL	Priority Access License
PCAST	President's Council of Advisors on Science and Technology
PCS	Personal Communications Service
PE	Provider Edge
PEA	Partial Economic Area
PGW	Packet Data Network Gateway
PMP	Point-to-MultiPoint
POES	Polar Operational Environmental Satellites
PPP	Public Private Partnerships
PSK	Phase Shift Keying
ProSe	Proximity Service
PWB	Provisionally Winning Bids
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RFC	Request for Comments
RGW	Residential Gateway
RNC	Radio Network Controller
RRH	Remote Radio Head
RSA	Rural Service Area
SAS	Spectrum Access System
SATCOM	Satellite Communications
SDL	Satellite Data Link
SDN	Software Defined Networking
SDR	Software Defined Radio
SGSN	Serving GPRS Support Node
SGW	Serving Gateway
SON	Self-Organizing Network
SPS	Semi-Persistent Scheduling
SRF	Spectrum Relocation Fund
STA	Special Temporary Authority
STPI	Science and Technology Policy Institute
STRAPS	Stratospheric Platform Stations
SU-MIMO	Single User-Multiple Input Multiple Output
SUL	Saturated Unilateral Link
TAS	Telecom Advisory Services
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TIA	Telecommunications Industry Association
TSDSI	Telecommunications Standards Development Society, India
TTA	Telecommunications Technology Association, Korea
TTC	Telecommunication Technology Committee, Japan
U-NII	Unlicensed National Information Infrastructure
UAS	User Agent Server
UAV	Unmanned Aerial Vehicle
UHD	Ultra High Definition
UNB	Ultra Narrow Band
UMFUS	Upper Microwave Flexible Use Service
URLLC	Ultra Reliable Low Latency Communications
V2X	Vehicle-to-Everything
VHF	Very High Frequency
VNI	Visual Networking Index
VR	Virtual Reality
WCA	Wireless Communications Alliance
WCS	Wireless Communications Service
WISP	Wireless Internet Service Provider
WLAN	Wireless Local Area Network
WMTS	Wireless Medical Telemetry Service
WPAN	Wireless Personal Area Networks
WRC	World Radiocommunication Conferences
WSBD	White Space Band Devices
WSDMA	Wideband Space Division Multiple Access