COMMERCE SPECTRUM MANAGEMENT ADVISORY COMMITTEE (CSMAC)

Report of Subcommittee on 6G

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1. Mandate

The National Telecommunications and Information Administration (NTIA) provided the following background and question to the Commerce Spectrum Management Advisory (CSMAC) Subcommittee 2 on sixth-generation (6G) communications:

Background: Industry research and planning is well underway for 6G, expected to be the next major evolution of commercial wireless technology. The current interest and expectation for the U.S. to be a world leader in 5G will only increase for 6G, such that while deployment in earnest may be years out (2030 often cited as a target), the U.S. Government (USG) and the industry ecosystem must take steps now to lay the foundation for success.

Question: NTIA seeks input on what sort of use cases 6G may entail. Importantly, NTIA would like the CSMAC to consider use cases beyond traditional wireless communications including safety, sensor, radar, space, and other scientific applications and to address 6G's potential impact on federal government users. When considering spectrum bands that could be used to support 6G, NTIA observes that the terahertz (THz) bands have been identified for potential use; how would such use impact government users in that range and what recommendations could be made to help prepare for this? Are there other spectrum bands that may be appropriate for 6G and beyond use?

NTIA provided clarification that the scope of the subcommittee's work effort should concentrate on 6G services only. This effort should consider generally the benefits to federal government user, the positives for the federal government as a user of federal equities, and how federal agencies can benefit broadly from 6G.

2. Approach of the Subcommittee

To answer NTIA's questions, CSMAC initiated a multi-pronged approach. First, it scoped the work and developed a study plan and report outline. Second, the subcommittee collected key reference materials, including pertinent information on our topic. Third, to advance the body of knowledge and gain new information specific to NTIA's question, CSMAC conducted interviews with federal agencies, service providers, equipment manufacturers, and academia and other non-profit organizations. The subcommittee's interview questionnaire is included in Appendix A of this report. Each organization was given the option of providing written and/or verbal responses. All responses were compiled for further analysis and possible follow-up. Fourth, through ongoing CSMAC subcommittee cross-sectional analysis, inputs, and discussion, the subcommittee developed a 6G vision, observations, findings, considerations, and recommendations addressing the mandate given to the subcommittee by NTIA.

This subcommittee commenced work on August 22, 2022, and met on a recurring basis, held over 20 meetings, and conducted about 40 interviews (See Appendix B). Sections 4 through 12 summarize the CSMAC 6G Subcommittee findings and Sections 13 and 14 contain recommendations.

3. 6G Vision

CSMAC offers the following vision for 6G:

Dynamic connectivity across public and private digital and physical domains that enables intelligent communications while creating conditions for economic growth, enhanced national security, and societal well-being.

While 6G deployment may be years out (2030 often cited as a target), the U.S. must take steps now to better influence the complex process of technology development, standardization, and regulations, and lay the foundation for its success.

4. Overview of Organizations Involved in 6G Development

Domestic and international efforts to promote 6G began at the start of this decade and have continued accelerating. The current focus of most of these efforts is on research with an eye toward initiating standards processes, an important first step before equipment is manufactured. The principal efforts involve some level of partnership between government and industry to drive regional leadership in 6G research, development, and deployment. These "pre-standardization" efforts are critical to identifying technology and application priorities that will drive 6G development and timelines. Much of this work is well underway and includes significant government and industry financial commitments, reflecting a broader recognition of the importance of communications technology leadership to economic growth and national security. In short, there is already significant global competition to influence the evolution of 6G to reflect the social, economic, and security interests of the sponsoring regions.

4.1. North American Efforts

4.1.1. Next G Alliance

Established in 2021, ATIS Next G Alliance (NGA) is "an initiative to advance North American wireless technology leadership over the next decade through private sector-led efforts. With a strong emphasis on technology commercialization, the work will encompass the full lifecycle of research and development (R&D), manufacturing, standardization, and market readiness."[1] Notably, NGA has published several papers on its vision for a 6G roadmap for North America, aiming "to provide a foundational vision for 6G that addresses both North American needs and global alignment goals and to develop priorities and strategies for achieving North American leadership alongside other regions' leadership. This includes describing the key challenges across social and economic, technical, spectrum, applications, and sustainability (e.g., energy, environmental) considerations, and recommending governmental actions and standardization strategies."[2] NGA is contributing to developing the ITU-R's IMT-2030 6G framework.

NGA has explained that while previous generations of communications systems focused on densification and raising performance standards around network coverage and capacity, 6G will aim to shape a different dynamic around applications and use case diversity. The proliferation of use cases in smart homes, smart cities, and industrial environments, among others, will place new requirements on 6G, including those necessary to ensure trusted, secure, and resilient communications.[3]

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[1] Next G Alliance Report: *Roadmap to 6G*, https://www.nextgalliance.org/6g-library/.

[2] Next G Alliance Report: *Roadmap to 6G*, https://www.nextgalliance.org/6g-library/.

[3] https://usc-word-edit.officeapps.live.com/we/wordeditorframe.aspx?ui=en-US&rs=en-US&wopisrc=https://atisorg.sharepoint.com/sites/shared/_vti_bin/wopi.ashx/files/921747c3695f47a78c61508f5f71deee&wdlor=c8F28830A-3611-41B7-84FF-5A5DAFE44725&wdenableroaming=1&mscc=1&hid=B2CA8DD7-841E-4A40-85C1-EB7614544A71&wdorigin=Outlook-

The framework for NGA 6G vision adopts a layered approach from top down. The top layer, "national imperatives," is to look at the economic drivers, policies, societal needs etc., the middle layer will then look at the applications and markets that should be enabled by 6G, and the bottom layer is for technology development.[4]

To serve this vision, NGA organizes its work in multiple working groups (WGs):

- Application WG
- Green G WG
- National 6G Roadmap WG
- Societal and Economic Needs WG
- Spectrum WG
- Technology WG.

To move toward its goals, NGA has published numerous reports and white papers on various aspects of its vision for 6G.[5] These papers span a wide range of topics including technology elements, applications and use cases, green technologies and sustainability, security, and spectrum considerations.

4.1.2. USG Research Efforts

4.1.2.1. CHIPS and Science Act

On August 9, 2023, the president signed into law the CHIPS and Science Act, one of the most ambitious legislative efforts impacting the Information and Communication Technologies (ICT) sector in recent years, and one that is likely to guide U.S. investment in technology for the remainder of the decade. The headline provisions of the Act—the CHIPS portions—are appropriating $54 billion to fund previously authorized grant programs supporting onshore domestic manufacturing of semiconductors, and developing open-architecture wireless communications technologies. However, the "Science" half of this legislation includes provisions that, subject to funding, could be tremendously important to developing next-generation communications technologies.

The Act authorized $81 billion in funding over five years for the National Science Foundation, which is almost double its previous authorized budget of $36 billion. This includes $20 billion authorized for the first-of-its-kind Directorate for Technology, Innovation, and Partnership (TIP), which will focus on translational science to accelerate domestic development of national and economic-security critical technologies, specifically to include 6G communications.[6] The Act authorized nearly $3 billion in new funding for the National Institute of Standards and Technology (NIST) to support new R&D for critical and emerging technologies, including 6G.

Body.Sharing.ServerTransfer&wdhostclicktime=1689868148039&jsapi=1&jsapiver=v1&newsession=1&corrid=9d10bb4a-59cc-4f4d-ab73-bee2fc1d232f&usid=9d10bb4a-59cc-4f4d-ab73-bee2fc1d232f&sftc=1&cac=1&mtf=1&sfp=1&instantedit=1&wopicomplete=1&wdredirectionreason=Unified_SingleFlush&rct=Normal&ctp=LeastProtectedNext G Alliance Report, *6G Roadmap for Vertical Industries* (May 2023), https://www.nextgalliance.org/6g-library/.

[4] https://www.nextgalliance.org/wp-content/uploads/2022/02/NextGA-Roadmap.pdf.

[5] For a complete list, see https://www.nextgalliance.org/6g-library/.

[6] https://new.nsf.gov/chips.

For FY 2023, NSF received appropriations of about $9.9 billion—about $2 billion less than was authorized. On July 12, 2023, the Senate Appropriations Committee approved an FY 2024 Commerce, Justice, Science, and Related Agencies (CJS) appropriations bill that, consistent with the debt limit agreement, funds NSF at an amount equal to or slightly below its FY 2023 level. If passed by Congress, this would mean a total NSF budget of approximately $9.5 billion, in comparison to the approximately $15 billion authorized by the CHIPS and Science Act. These shortfalls have led to growing concerns in the research community and elsewhere about the ability to compete with other regions of the globe for leadership in critical and emerging technologies, including 6G.[7]

4.1.2.2. NSF Programs

NSF has been an important player in the development of each generation of communications technology. NSF is dedicated to driving research, innovation, and education through investment in a range of programs, including public and private partnerships, to advance the state of the art in advanced wireless research.

NSF's leadership of wireless research includes:

- Supporting fundamental research enabling advanced wireless technologies;
- Establishing and supporting experimentation on testbeds, including platforms for advanced wireless research, which are enabled by an industry consortium of private partners;
- Catalyzing academic, industry, and community leaders to work together to develop innovative wireless approaches to address societal challenges, and facilitate education and workforce development;
- Engaging in interagency research and development coordination through participation and leadership in the Networking and Information Technology Research and Development (NITRD), Wireless Spectrum Research and Development (WSRD), Interagency Working Group (IWG), and Advanced Wireless Test Platforms team.

As part of its leadership in advancing academic research, fostering collaboration, and promoting workforce development in wireless and spectrum domain, NSF invested in SpectrumX. This 5-year initiative with a $25 million grant from NSF is housed at the University of Notre Dame and brings together broad research capabilities from 27 universities, including 14 minority servicing institutions.[8]

The advanced wireless research portfolio within NSF covers a range of existing and emerging research areas including Massive MIMO, millimeter wave (MMW) technologies, beamforming, advanced low-power electronics, meta-materials and intelligent surfaces, free-space optics, and high-fidelity filter design.

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[7] https://fas.org/publication/chips-and-science-funding-update-fy-2023-omnibus-fy-2024-budget-both-short-by-billions/; https://www.nytimes.com/2023/05/30/us/politics/chips-act-science-funding.html; https://www.brookings.edu/articles/the-bold-vision-of-the-chips-and-science-act-isnt-getting-the-funding-it-needs/.
[8] https://www.spectrumx.org/about/.

4.1.2.2.1. Resilient and Intelligent Next G Systems

Announced by NSF in April 2021, Resilient and Intelligent Next G Systems (RINGS)[9] is a partnership[10] with federal agencies and private industry seeking to accelerate research in areas with potentially significant impact on next-generation (NextG) networking and computing systems. An emphasis of the program is on network resiliency and looks to advance network technologies to guarantee worldwide availability, security, and reliability of NextG systems.

4.1.2.2.2. Spectrum Innovation Initiative

NSF's Spectrum Innovation Initiative (SII)[11] presents a suite of opportunities to address the pressing challenges arising from the growing demand of electromagnetic spectrum use, including passive and active applications. Through this initiative, NSF focuses on cultivating research and innovation in spectrum use in the following ways: National Radio Dynamic Zones, National Center for Spectrum Innovation and Workforce Development, Spectrum Research Activities, and Education and Workforce Development.

4.1.2.2.3. Platform for Advanced Wireless Research

The Platform for Advanced Wireless Research (PAWR)[12] is a $100 million public-private partnership funded by NSF and a wireless industry consortium of 30 companies and associations, to deploy and manage up to four city-scale research testbeds. PAWR aims to support advanced wireless research platforms conceived by the U.S. academic and industrial wireless research communities. PAWR will enable experimental exploration of robust new wireless devices, communication techniques, networks, systems, and services that will revolutionize the nation's wireless ecosystem, thereby enhancing broadband connectivity, leveraging the emerging Internet of Things (IoT), and sustaining U.S. leadership and economic competitiveness for decades to come.

4.1.2.3. Other U.S. Government Programs

Other U.S. agencies have 6G efforts underway, including the White House National Security Council,[13] the Federal Communications Commission (FCC) Technological Advisory Council,[14] the Department of Defense,[15] and the Department of Homeland Security.[16]

4.1.3. Canadian Efforts

ENCQOR 5G[17] is a public-private partnership with Canada-Québec-Ontario focused on research and innovation in the fields of 5G disruptive technologies, adoption initiatives, and system uses. 5G efforts

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[9] https://new.nsf.gov/funding/opportunities/resilient-intelligent-nextg-systems-rings.

[10] https://www.nsf.gov/pubs/2021/nsf21581/nsf21581.htm#:~:text=The%20RINGS%20program%20seeks%20innovations,communications%2C%20networking%20and%20computing%20systems.

[11] https://www.nsf.gov/mps/oma/spectrum_innovation_initiative.jsp.

[12] https://advancedwireless.org/.

[13] "Principles for 6G: Open & Resilient by Design," White House National Security Council, April 21, 2023, shared online by the Open RAN Policy Coalition at https://www.openranpolicy.org/wp-content/uploads/2023/04/principles-for-6g.pdf.

[14] https://www.fcc.gov/sites/default/files/Consolidated_6G_Paper_FCCTAC23_Final_for_Web.pdf.

[15] https://www.defense.gov/News/Releases/Release/Article/3114220/three-new-projects-for-dods-innovate-beyond-5g-program/.

[16] https://www.dhs.gov/science-and-technology/5g6g.

[17] https://www.encqor.ca/.

were completed in early 2023 and the parties are working on plans to transition efforts toward ENCQOR+ focused on 6G.

4.2. Other Regional and International Efforts

Over the last few years, individual countries and regions have launched aggressive 6G research initiatives structured via public/private partnerships or government stimulus programs for early 6G development and proof of concepts. The European Union (EU), Finland, Germany, China, Japan, and South Korea are examples of regions and countries that have announced significant 6G R&D cooperative programs that will challenge North America's leadership in the future. These programs are targeted at advancing their respective domestic industries and taking the lead in 6G R&D (and beyond), manufacturing, and deployment. Some of the leading efforts are identified below but the number and scope of these initiatives is growing rapidly. In parallel to country-specific and regional research efforts, there were also efforts in the International Telecommunications Union Radiocommunications Sector (ITU-R) to define a basic framework, timeline, and spectrum needs for next generation of mobile networks.

4.2.1. ITU-R and IMT-2030

In 2022, the ITU-R adopted a Resolution on Further Developments of International Mobile Telecommunication (IMT) for 2030 and beyond (hereinafter referred to as IMT-2030). Subsequently, work started in ITU-R on developing an ITU-R Recommendation on framework and vision for major objectives of such future developments and adopted an overall timeline for IMT-2030 development. The ITU-R timeline envisions IMT-2030 standards development work to begin in 2027 to support initial 6G deployments beginning in 2030. This framework contains, among others, a description of envisioned IMT-2030 usage scenarios and major technical capabilities of IMT-2030, which will be further developed toward definition of technical performance requirements in the coming years.

In its July 2023 meeting, ITU-R Working Party 5D (WP5D) agreed to a Draft New Recommendation (DNR) on the IMT-2030 framework supporting enriched and immersive user experiences, enhanced ubiquitous coverage, and enabling new forms of collaboration.[18] IMT-2030 is envisaged to support expanded and new usage scenarios compared to those of IMT-2020, while providing enhanced and new capabilities. To support an inclusive information society and promote the UN's sustainable development goals, the development of IMT-2030 is expected to prioritize the following areas, among others: inclusivity; ubiquitous connectivity; sustainability; innovation; enhanced security, privacy, and resilience; standardization and interoperability; and interworking.[19]

The Recommendation on IMT-2030 framework is expected to be adopted by ITU-R Study Group 5 in September 2023 and published a few months after.

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[18] ITU-R Working Party 5D, *Framework and overall objectives of the future development of IMT for 2030 and beyond,* Draft New Recommendation (June 29, 2023). WP5D is responsible for the overall radio system aspects of the terrestrial component of International Mobile Telecommunications (IMT) systems, comprising the current IMT-2000, IMT-Advanced and IMT-2020 as well as IMT for 2030 and beyond. IMT is International Mobile Telecommunication, ITU-R's term for referring to various generations of cellular technologies. IMT-2030 is the name chosen to describe evolution of IMT for the year 2030 and beyond.
[19] Id.

Additionally, the ITU-R is looking at including satellite into IMT-2030. Work is underway in Working Party 4B on this important effort.

4.2.2. The European Union (EU)

The Council Regulation 2021/2085 established the Smart Networks and Services Joint Undertaking (SNS JU)[20] as a legal and funding entity. This is one of the European Partnerships which has the specific purpose to build research and innovation capacities for 6G systems and develop lead markets for 5G infrastructure as a basis for the digital and green transformation in Europe. The Partnership is jointly led by the European Commission (EC) and the 6G Smart Networks and Services Industry Association (6G-IA).

The SNS JU enables pooling EU and industry resources into Smart Networks and Services investment. It fosters alignment with Member States on 6G research and innovation, and deployment of advanced 5G networks. The SNS JU sets out an ambitious mission with an EU budget of EUR 900 million for the period 2021-2027. In December 2022, SNS JU launched the second phase of its program with earmarked public funding of EUR 132 million for 2023-24.

The 6G Smart Networks and Services Industry Association (6G-IA)[21] represents European Industry and Research for next generation networks and services. Its primary objective is to contribute to Europe's leadership on 5G, 5G evolution, and SNS/6G research. The 6G-IA represents the private side in both the 5G Public Private Partnership and the SNS JU. In the 5G Public Private Partnership and SNS JU, the European Commission represents the public side. The 6G-IA brings together a global industry community of telecoms and digital actors, such as operators, manufacturers, research institutes, universities, verticals, SMEs, and ICT associations. The 6G-IA carries out a wide range of activities in strategic areas including standardization, frequency spectrum, R&D projects, technology skills, collaboration with key vertical industry sectors (notably for the development of trials), and international cooperation. The U.S.-EU Technology and Trade Council at its May 2023 Ministerial meeting tasked 6G-IA and Next G Alliance to work together to develop an "interim, common, and aligned 6G industry roadmap by the end of 2023"[22] that would feed into a Trade and Technology Council 6G common vision established by the EU and U.S. governments. This document, in turn, would be used to scale up the existing R&D cooperation on 6G between the two countries.

6G Flagship,[23] housed at University of Oulu, is part of the Finnish government's national research spearhead program from 2018 to 2026. Its goal is to create the essential 6G technological components, the tools, and the equipment to build a 6G Test Network, develop chosen vertical applications for 6G to accelerate societal digitization, and be a recognized research partner in worldwide 6G research. Germany has also announced additional commitment of EUR 700 million between 2021-2025 to support 6G research.

In July 2023, the French government announced the launch of the France 6G Project, a new R&D program to be managed by the National Center for Scientific Research and the academic Institut Mines-Télécom.

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[20] https://smart-networks.europa.eu/.
[21] https://6g-ia.eu/.
[22] "6G Outlook," European Commission, https://digital-strategy.ec.europa.eu/en/library/6g-outlook.
[23] https://www.6gflagship.com/.

The European Space Agency (ESA) is looking at how 6G mobile communications technology will impact the world and what role satellites will play in providing 6G connectivity. Its Advanced Research in Telecommunications Program supports industrial partners with the development and application of 6G satellite technology. ESA's Space for 5G/6G and Sustainable Connectivity Strategic Program Line works with industrial partners to integrate satellite connectivity into telecommunications infrastructure. Its 6G laboratory in space supports test and experimentation to benefit European industry.[24]

4.2.3. Korea – 6G Forum

South Korea's Ministry of Science and ICT announced the intent[25] to commercialize an initial 6G network service in 2028, two years earlier than other international schedules. The aim is to boost private-public cooperation to develop 6G technologies, innovate around software-based next-generation mobile networks, and strengthen the network supply chain. The ministry has launched a feasibility study for R&D on core 6G technologies for a total of KRW 625.3 billion ($481.7 million) to locally produce materials, components, and equipment related to future 6G network.

South Korea's 6G Forum (formerly 5G Forum) aims to become the leading force in developing next-generation communications technology and contribute to the momentum of economic growth through developing the ICT industry in efforts to actualize the new administration's agenda of a creative economy.

4.2.4. Japan – Beyond 5G Promotional Consortium

Japan's Ministry of Internal Affairs and Communications has recently committed US$450 million to support 6G R&D to be established in the National Institute of Information and Communications Technology.[26]

Japan's Beyond 5G Promotion Consortium was established as a forum for industry, academia, and government to share information on the latest international trends related to specific initiatives and R&D to be implemented based on each strategy; to discuss how to promote initiatives for the early realization of Beyond 5G; and to disseminate the status of Japan's initiatives related to Beyond 5G internationally. The Beyond 5G Promotion Consortium aims to achieve the early and smooth introduction of Beyond 5G and strengthen the international competitiveness of Beyond 5G to realize the strong and vibrant society expected in the 2030s.

4.2.5. India – TIG 6G

On July 3, 2023, the Indian government formally announced the establishment of the Bharat 6G Alliance,[27] a collaborative effort consisting of public and private companies, academia, research institutions, and standards development organizations. The goal of the Bharat 6G Alliance is to accelerate and facilitate market access for Indian technology products and services, thereby enabling India to emerge as a global leader in 6G technology. By expediting the creation of standards-related patents within the country and actively contributing to standardization organizations such as 3rd Generation

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[24] ESA, *6G and Satellites, Intelligent Connectivity for a Sustainable Future,* https://connectivity.esa.int/sites/default/files/ESA_6G_White%20Paper_Dev_Proof_V14..pdf.
[25] http://www.5gforum.org/html/en/main.php.
[26] https://b5g.jp/en/.
[27] https://bharat6galliance.com/.

Partnership Project (3GPP) and ITU, Bharat 6G Alliance aspires to position India at the forefront of 6G innovation.

During a June 2023 visit to the White House by Indian Prime Minister Modi, President Biden and the Prime Minister acknowledged a shared communications technology vision focused on creating secure and trusted telecommunications, resilient supply chains, and enabling global digital inclusion. To fulfill this vision, the leaders announced efforts in developing 5G/6G technologies based on public-private cooperation led by India's Bharat 6G Alliance and the U.S. NGA.

4.2.6. China

Government activity is led by the Ministry of Science and Technology and Ministry of Industry and Information Technology. Government and industry coordination occurs through the IMT-2030 (6G) Promotion Group.[28] Reportedly there were 15 research projects launched by the Ministry of Science and Technology in December 2020 under the framework of "National Key R&D Project."

4.3. Standards Development Organizations

4.3.1. ITU – IMT-2030

As mentioned in Section 4.2.1, ITU-R is undertaking the effort of defining the international standardization process for IMT-2030.[29] Figure 1 shows the timeline.

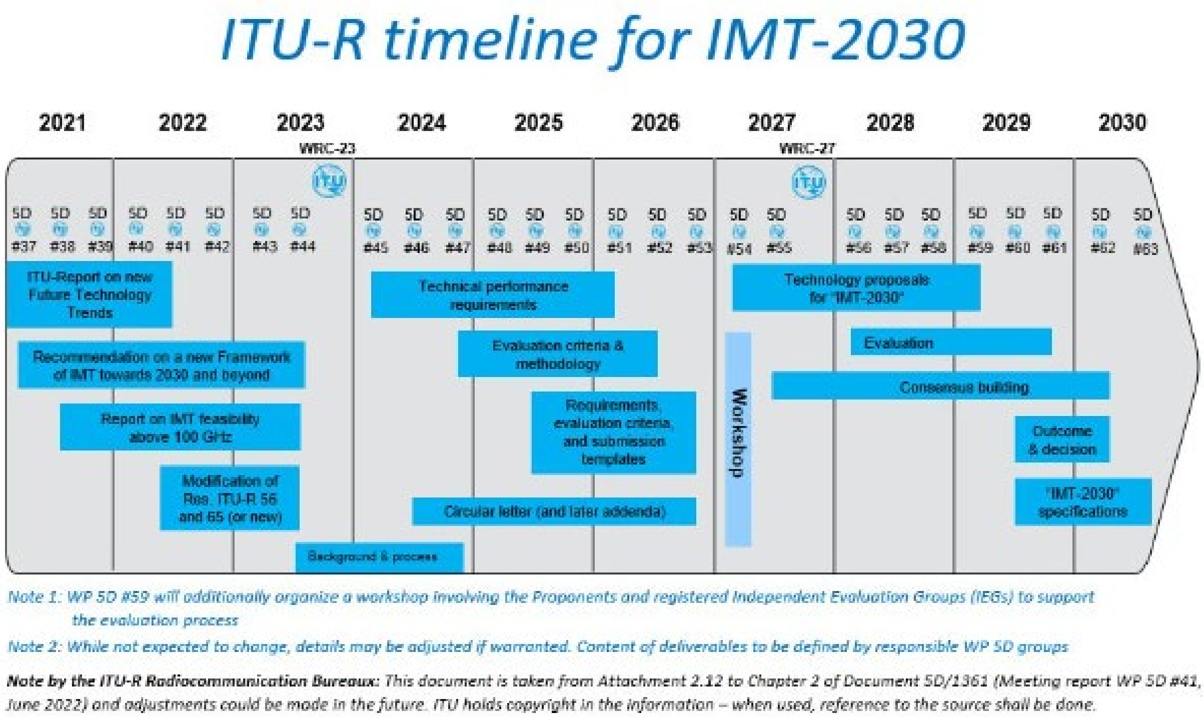

Figure 1 ITU-R WP5D Timeline for Standardization of IMT-2030[30]

[28] https://www.chinadaily.com.cn/a/202304/29/WS644c5c9fa310b6054fad0706.html.
[29] This is for the terrestrial component. Work has just started on the satellite component.
[30] https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx.

In this process, starting next year (in 2024), ITU-R will start discussions on Technical Performance Requirements (TPRs) for IMT-2030 from 2024 to 2026. These TPRs include Key Performance Indicators (KPIs) of 6G and will have a defining effect on capabilities and functions of 6G standards. They will include technical capability elements listed in IMT-2030 framework recommendation such as supported data rates and target spectral efficiency, latency, device density, reliability, etc. Developing TPRs is then followed by defining how to evaluate them in forthcoming proposals. Next, various standard organizations are expected to submit their proposals for radio interface technologies of IMT-2030 to ITU-R starting around 2027. These proposals are then discussed and evaluated against the agreed TPRs, using evaluation criteria and methodology agreed upon in previous stages of the process. After a consensus building phase, differences, if any, among the proposals would be sorted out. The final set of specifications for IMT-2030 radio interface is scheduled to be adopted by ITU-R administrations at the end of year 2030.

4.3.2. 3rd Generation Partnership Project

The 3GPP has been the principal standards-setting organization for the past several generations of mobile communications. 3GPP unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as Organizational Partners, or OPs. 3GPP specifications cover cellular and non-terrestrial wireless telecommunications technologies, including radio access and core network and service capabilities, which provide a complete system description for mobile telecommunications. 3GPP specifications also provide hooks for non-radio access to the core network, and for interworking with non-3GPP networks. Once the specifications have been submitted and have completed the ITU-R consensus process as part of ongoing IMT standardization in WP5D, those specifications are adopted by OPs as national standards.

3GPP is currently working on Release 18 and finalizing the priorities for Release 19 work, supporting both 5G and 5G Advanced. It is anticipated that standards development for 6G will also be led by 3GPP, although no formal announcements have been made at this time.

The process described in Section 4.3.1 is closely followed by 3GPP, which has been a major contributor to the ITU-R processes for previous IMT generations. 3GPP and its membership are expected to take a similar approach toward IMT-2030 and be closely engaged in every step of the process starting in 2024 with definition of TPRs. A statement of intent on 3GPP’s role in 6G is anticipated in Q4 2023.

5. Key Application Drivers

6G is expected to be a general-purpose technology that provides pervasive and seamless connectivity across public and private digital and physical domains. New and emerging applications will be enabled by 6G, while previous generation use cases such as enhanced mobile broadband, massive machine-type communications, and ultra-reliable, low-latency communications must continue to be supported.

Drivers of innovative 6G applications include pursuing solutions to the biggest challenges and opportunities for improvement. Key application drivers can optimize the benefits of 6G and contribute toward achieving societal and economic goals. These can include national goals of public safety, security, economic competitiveness, and digital equity; international goals such as the United Nations’ Sustainable Development Goals and environmental goals; and enterprise goals like productivity, cost savings, quality, and time-to-market.

The ATIS Next G Alliance categorized drivers of 6G applications into four foundational areas of innovation: enhancing the quality of everyday living, improving customer experiences and technology interfaces, advancing critical functions in multiple industry sectors, and attaining societal goals and increasing public safety.[31] It identified four categories of 6G use cases:[32]

- Network-enabled robotics and autonomous systems
    - Use of sensors to perceive the environment
    - More integrated human interaction with robots and autonomous systems
- Multi-sensory extended reality
    - Immersive technologies
    - Includes AR and VR
- Distributed sensing and communications
    - Sensors tightly coupled with communications enable autonomous systems
    - Ubiquitous connectivity, massive throughput, and ultra-low power operations
    - Massive sensor and data collection
- Personalized user experiences
    - Real-time, fully automated personalized devices, networks, products, and services
    - Based on personal profile and contextual information.

While these application drivers are initially developed by and geared toward industry, CSMAC believes they are also applicable to federal agency users. Further, federal agencies will have specific other uses of 6G required to achieve their missions that extend those of the consumer. Federal agency engagement early on will help shape these 6G use cases, their associated target KPIs for any envisaged federal applications, and ensure their eventual support by forthcoming industry standards.

6. 6G Use Cases

A major differentiating factor of 5G with previous generations of wireless—among faster and better performance—has been the support for new use cases beyond enhanced mobile broadband (eMBB). These new use cases, generally categorized under the two usage scenarios of Massive Machine Type Communications (mMTC) and Ultra-Reliable and Low Latency Communications (URLLC), have stark differences with traditional usages in characteristics and performance indicators. In some cases, these new use cases even introduce KPIs not applicable to previous generations.

A usage scenario is a set of use cases enabled by a common set of technical capabilities in support of certain applications. Usage scenarios have expanded through generations from cellular service with voice and data (3G), through broadband data services for high mobility as well as nomadic/local access (4G) to the three usage scenarios eMBB, URLLC, and mMTC (5G). These usage scenarios, as depicted in **Error! Reference source not found.** (from ITU-R), encompass applications in various types of environments, e.g., dense urban, suburban, rural, indoor, high-speed, etc.

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[31] Next G Alliance, *6G Market Development*, July 2022, https://www.nextgalliance.org/wp-content/uploads/dlm_uploads/2022/07/NGA-Perspective-Brochure-V6.pdf?utm_source=yxnews&utm_medium=desktop.

[32] Next G Alliance, Report on 6G Applications and Use Cases.

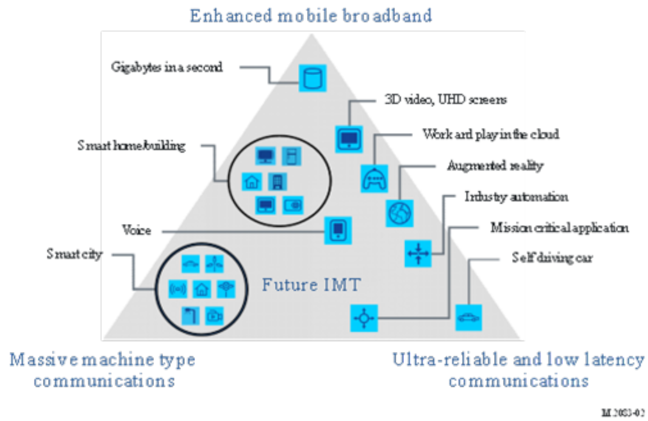

Figure 2 Usage Scenarios of IMT-2020 (5G) from Recommendation ITU-R M.2083

Usage scenarios of 6G are still under discussion in various 6G related R&D projects around the world, including in ITU-R. At its June 2023 meeting, ITU-R WP5D agreed to a new draft recommendation for the IMT-2030 Framework, which brings the usage scenarios for 6G closer to formal adoption. ITU-R Working Party 4B is working on the definitions for the satellite component of IMT-2030.

Based on the current draft IMT-2030 Framework agreed upon by ITU-R WP 5G, enhancing the three main usage scenarios of 5G (which are all communication-based usage scenarios) is envisioned. The future generation is also envisaged to include new usage scenarios going beyond pure communication by combining communication-based usages with new non-communication techniques. Specifically, new usage scenarios will arise from integrated artificial intelligence (AI) as well as joint communication and sensing, which previous generation networks were not designed to support. Table 1 presents a summary of IMT-2030 usage scenario categorization. Figure 3 depicts these usage scenarios, as agreed upon by ITU-R, in a graphical format, including relationship with usage scenarios of IMT-2020 (5G).

Table 1 Categorization of IMT-2030 Usage Scenarios

Usage Scenario Category	Usage Scenario	Notes
Evolved (Communication-based)	Immersive Communication	Evolution of eMBB
	Massive Communication	Evolution of mMTC
	Hyper Reliable and Low Latency Communication	Evolution of URLLC
	Ubiquitous Connectivity	New
New (Beyond Communication)	Integrated AI and Communication	New
	Integrated Sensing & Communication	New

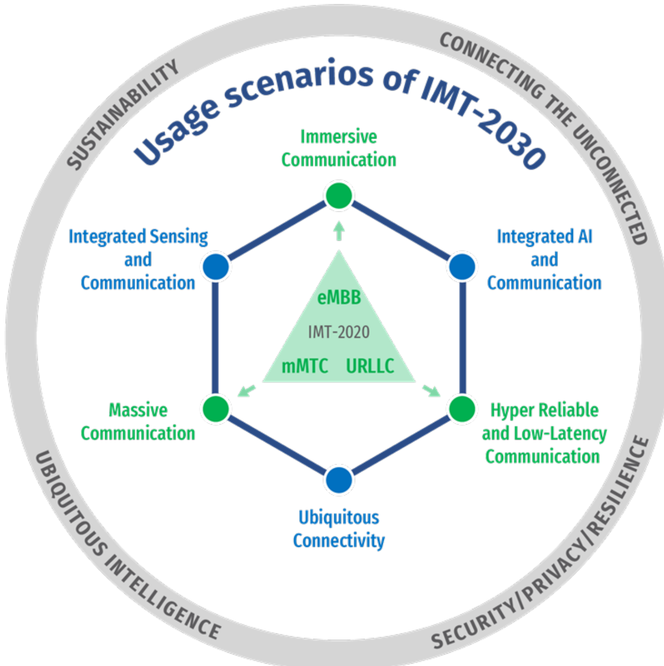

Figure 3 Usage Scenarios of IMT-2030[33]

Usage scenarios of 6G support a variety of use cases and applications. These use cases and applications consist of those evolved from traditional use cases of previous generations as well as emerging ones. In addition, some of these use cases lend themselves better to certain regulatory regimes. Table 2 lists 6G use cases and applications envisioned today for each of the 6G usage scenarios and separates them by category and anticipated licensing regime.

*Table 2 Summary of 6G Use Cases**

Contributing Use Case	Usage Scenario	Wireless Communications Category		Anticipated Licensing Regime		
		Traditional	Non-Traditional	Unlicensed	Shared License	Exclusive License
AR/VR/XR (Augmented Reality, Virtual Reality, and Extended Reality)	Immersive Communication	✓		✓	✓	✓
Telepresence	Immersive Communication	✓		✓	✓	✓
Holographic interactions	Immersive Communication	✓		✓	✓	✓
Gaming	Immersive Communication	✓		✓	✓	✓

33 https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx.

Contributing Use Case	Usage Scenario	Wireless Communications Category		Anticipated Licensing Regime		
		Traditional	Non-Traditional	Unlicensed	Shared License	Exclusive License
Entertainment	Immersive Communication	✓		✓	✓	✓
Streaming	Immersive Communication	✓		✓	✓	✓
Large venue networking	Massive Communication	✓		✓	✓	✓
Backhaul	Ubiquitous Connectivity	✓		✓		
Mesh networking/inter-node links	Ubiquitous Connectivity	✓		✓	✓	✓
Terrestrial & non-terrestrial integrated connectivity	Ubiquitous Connectivity		✓			✓
Public safety	Ubiquitous Connectivity	✓			✓	✓
High speed mobility	Ubiquitous Connectivity	✓			✓	✓
Environmental sensing & mapping	Integrated Sensing & Communication		✓	✓	✓	✓
High resolution mapping: digital twins & virtual worlds	Integrated Sensing & Communication		✓	✓	✓	✓
Human digital twins	Integrated Sensing & Communication		✓	✓	✓	✓
Gesture & activity detection	Integrated Sensing & Communication		✓	✓	✓	✓
Digital healthcare	Integrated Sensing & Communication, Immersive Communication	✓		✓	✓	✓
Smart industry	Massive Communication, Hyper Reliable and Low-Latency Communication	✓		✓	✓	✓
Smart cities	Massive Communication	✓		✓	✓	✓

Contributing Use Case	Usage Scenario	Wireless Communications Category		Anticipated Licensing Regime		
		Traditional	Non-Traditional	Unlicensed	Shared License	Exclusive License
Robots & cobots (collaborative robots)	Integrated AI and Communication, Hyper Reliable and Low-Latency Communication		✓	✓	✓	✓
Transportation safety – vehicle-to-everything (V2X)	Integrated AI and Communication, Hyper Reliable and Low-Latency Communication	✓	✓			✓
Autonomous vehicles	Integrated AI and Communication, Hyper Reliable and Low-Latency Communication	✓				✓
Security as a service	Integrated AI and Communication		✓	✓	✓	✓
Road traffic management & monitoring	Integrated AI and Communication		✓			✓
UAV inspection	Integrated AI and Communication		✓	✓	✓	✓

* Note the use cases listed in Table 2 and their associated usage scenarios and anticipated licensing regime are based on current thinking in academia and industry. As 6G use cases and applications develop, some use cases could become applicable to other usage scenarios or licensing regimes as well.

The remainder of Section 6 describes 6G traditional and non-traditional wireless communications use cases.

6.1. Traditional Wireless Communications

Traditional wireless communications use cases extend the evolution of 5G eMBB to 6G, to include even faster data rates, lower latency, and the integration of pervasive AI. These networks will require even greater coverage and resilience, which non-terrestrial networks will be able to provide. Networks can be more interconnected and seamless. These advancements are expected to provide operational impacts of improved reliability and availability of wireless cellular communication even across multiple communications links, as well as platforms, and in densely populated areas, moving vehicles, and indoor settings.

6.1.1. Use Cases for Immersive Communications

Immersive Communications extends the enhanced Mobile Broadband usage scenario from 5G to include use cases providing rich and interactive video experience to users.[34] Typical use cases for Immersive Communications include "communication for immersive XR, remote multi-sensory telepresence, and holographic communications. Supporting mixed traffic of video, audio, and other environment data in a time-synchronized manner is an integral part of immersive communications, including also stand-alone support of voice."[35] This type of time-synchronized or real-time mixed traffic is essential for gaming, entertainment, and live video streaming use cases.

6.1.2. Use Cases for Ubiquitous Connectivity

Ubiquitous Connectivity is intended to "enhance connectivity to bridge the digital divide."[36] Enhancements envisioned for 6G are expected to bring coverage and services to the presently unconnected or sparsely connected and includes network interworking. As 6G evolves, satellite and terrestrial operations are expected to share common technology and user equipment. A universal standard and common technology will increase seamless interoperability across terrestrial and satellite networks. The current conventional terrestrial cellular networks are expected to evolve into hybrid terrestrial, space, aerial, and underwater networks.

Use cases for Ubiquitous Connectivity include:

- Evolution of eMBB in 6G, including high speed mobility (airplanes, high speed trains, automobiles)
- IoT
- Public safety and priority users
- Device-to-device communications
- Inter-node links, such as for terrestrial and non-terrestrial mesh networking
- Backhaul connections.

6.1.3. Use Cases for Massive Communication

Massive Communication in 6G extends the massive Machine Type Communication (mMTC) usage scenarios from 5G to involve an even greater number of devices and sensors over a wide range of use cases.[37] An exemplary use case where IoT and massive communication in 6G are foundational, is the smart city. 6G enables the ability to connect IoT devices and sensors, data, analytics, computing, and intelligence, empowering cities to transform into efficient, sustainable, and highly resilient spaces.

Transportation and logistics use cases are also inclusive with massive communications. Connecting devices and sensors to support public and private transportation infrastructure, as well as enabling a variety of logistics applications and scenarios, are expected with next generation networks. Use cases for large venues and networks benefit from 6G enabled massive communication to support the extremely

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[34] ITU-R Working Party 5D, *Framework and overall objectives of the future development of IMT for 2030 and beyond,* Draft New Recommendation (June 29, 2023).
[35] Id.
[36] Id.
[37] Id.

dense population of devices and connections, with varying service requirements. Additional use cases for massive communications include health, energy, environmental monitoring, and agriculture.[38]

6.1.4. Use Cases for Integrated AI and Communication

The vision of future 6G wireless communication and its network architecture is an Intelligent Communication Ecosystem combining several emerging technologies to fulfill growing demands of connectivity and data resources.[39] AI and machine learning (ML) will be integrated in the whole 6G architecture and is fused inside every protocol layer as well as computation architecture including virtual functions, network slices, edge/cloud, and network orchestration and management. Inherent AI within and across the next generation network enables real-time optimizations of network resources and services. Use cases include:

- Spectrum management to dynamically allocate and adapt frequencies and resources
- Intelligent beamforming
- Predictive maintenance
- Quality of Service improvements
- Optimization of edge computing
- Traffic predictions to intelligently adapt network resources
- Network security continual learning to detect and mitigate new threats

Beyond using AI for improving the underlying network operation and performance, next generation networks will support a wider array of integrated AI and communication use cases for:

- Control and collaboration with robots/cobots
- Collaboration between devices, e.g., with medical assistance applications
- Improved transportation safety
- Support for autonomous vehicles
- Security as a service
- UAV inspections, such as for network infrastructure maintenance, first responders, public and private security, border protection, etc.

6.1.5. Use Cases for Hyper Reliable and Low Latency Communication

Next generation use cases for hyper reliable and low latency communication extend URLLC capabilities from 5G and are expected to have even more stringent latency and reliability requirements. Typical uses involve time-synchronized operations where “failure to meet these requirements could lead to severe consequences for the applications.”[40] Examples of traditional wireless use cases include smart industry (e.g., manufacturing, logistics), where extreme reliability and low latency communication are essential for full automation, control, and operation. Transportation safety and V2X, particularly with control and

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[38] ITU-R Working Party 5D, Framework and overall objectives of the future development of IMT for 2030 and beyond, Draft New Recommendation (June 29, 2023).
[39] M. Z. Chowdhury, M. Shahjalal, S. Ahmed and Y. M. Jang, "6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions," IEEE Open Journal of the Communications Society, pp. 957-975, 2020.
[40] ITU-R WP5D draft “Framework and overall objectives of the future development of IMT for 2030 and beyond.”

coordination of autonomous vehicles, are additional examples of hyper reliable and low latency communication uses cases.

6.1.6. Anticipated Spectrum Licensing Regime for Traditional Use Cases

Historically, terrestrial mobile broadband networks primarily relied on licensed, exclusive spectrum. That has evolved over time as mobile, unlicensed, and shared access networking technologies began to converge. The growing need for more bandwidth and higher data rates to support performance intensive immersive communications (e.g., telepresence, holographic communications, etc.) highlights the need for more spectrum. Using unlicensed and shared licensed spectrum will play an important role, alongside exclusively licensed spectrum, to enable these use cases. Additionally, with NTN networks being a critical component of 6G, preserving current and making available future allocations in the low-, mid-, and high bands is critical to meet demand.

6.2. Non-traditional Wireless Communications

5G was the first cellular radio technology designed with business and IoT applications in mind, which has fueled the inclusion of non-traditional wireless use cases. 6G will continue this trend into vertical markets that have not been traditionally supported with previous generations of non-terrestrial wireless and cellular communications. This section describes non-traditional wireless communications use cases.

6.2.1. Use Cases for Hyper Reliable and Low Latency Communication

6G will evolve and enhance URLLC features from 5G to support hyper reliable and low latency use cases. Non-traditional wireless use cases are expected to include communications in an industrial environment for full automation, control, and operation. These types of communications can help in realizing various applications such as robotic interactions, emergency services, telemedicine, and monitoring for electrical power transmission and distribution.[41]

6.2.2. Use Cases for Integrated Sensing and Communication

While location-based services and support for active positioning have evolved with 4G and 5G, there has not been a significant drive to extend the scope and purpose of the network beyond communication. This view is changing with 6G, whereby a common theme has emerged to design a system that jointly supports sensing and communication. Network sensing "refers to the detection of the presence of objects, their shape, location, and speed of movement using radio signals transmitted and received by network elements."[42] A growing number of potential use cases and network services are envisioned that can reap the benefits of integrated sensing and communication in a 6G system. Not only could this be used to improve the performance of the network itself, but spatial sensing by the network can spawn new innovations for services and applications external to the network. The following four broad categories[43] provide a solid starting point for identifying potential new uses cases for integrated sensing and communication in 6G:

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[41] ITU-R WP5D draft "Framework and overall objectives of the future development of IMT for 2030 and beyond."
[42] T. Wild, V. Braun and H. Viswanathan, "Joint Design of Communication and Sensing for Beyond 5G and 6G Systems," *IEEE Access,* vol. 9, pp. 30845-30857, 2021.
[43] D. K. Pin Tan et al., "Integrated Sensing and Communication in 6G: Motivations, Use Cases, Requirements, Challenges and Future Directions," in *2021 1st IEEE International Online Symposium on Joint Communications & Sensing (JC&S)*, 2021.

High-Accuracy Localization and Tracking

With an increased level of accuracy beyond previous generations, 6G will enable additional services such as cobots,[44] particularly where these types of robots are assisting humans in daily life. High precision intelligent factories or manufacturing with cobots is further realized, with the move toward more autonomous systems. Localization extends beyond just having specific target coordinates for autonomous systems to perform certain tasks. It includes an awareness of the environment in which it is performing that task, along with the intelligence and communication to interpret the dynamic information.

Simultaneous Localization and Mapping

Simultaneous Localization and Mapping (SLAM) has been a topic of research for many years and is largely a computational problem to create or update a map of an unknown environment while keeping track of the device/agent in that environment. In the context of 6G, network sensing information from the network and devices can expand the use and services even further. Integrated sensing and communication enable SLAM services without needing external cameras or sensors. The creation and support of high-resolution mapping and digital twins are key use cases.

Augmented Human Sense

Precise imaging and detection open the door for numerous applications that can be delivered over the 6G network. A number of medical use cases and applications can benefit from integrated sensing and communication, which further enhance remote telehealth checks (e.g., heartbeat monitoring, respiratory monitoring, physiotherapy exercise monitoring, etc.) minimizing the need for other sensing devices. Gesture recognition is also possible, which can further enhance communication and controls.

Safety and Security

A variety of safety and security use cases are possible due to integrated sensing and communication in 6G. For example, network sensing can be used to detect intruders or unaccounted for objects. Assisted living centers could benefit from notifications via network sensing and intelligence if a resident falls or becomes incapacitated. Non-intrusive inspections are possible to detect hidden or banned objects (e.g., weapons, contraband) at certain events or locations.

6.2.3. Safety-related Use Cases

Safety use cases center around reducing risk and improving situations for people, equipment, or data. They can be nominally grouped into public safety, health safety, and transportation safety. 6G will support these classes of use cases via the forecasted network connectivity improvements. Support capabilities, such as localization services, will become more precise and ubiquitous (and lead to a host of other use cases leveraging location such as personalized shopping, personalized hotel experiences, and other traveler's help ideas).

Public Safety

Use cases related to public safety include security screening (i.e., airport security check point) and disaster detection. Using the expansion of AI into the network, use cases such as automatic detection, recognition, and inspection of things at venues such as airport security or a concert will become realistic.

[44] A. Behravan et al, "IdPositioning and Sensing in 6G: Gaps, Challenges, and Opportunities," November 2022.

Leveraging multiple sensor modalities merged with historical information would allow for screening to be moved from security lines to screening naturally throughout the activity, maybe detecting certain substances.

Another public safety use case leverages the ubiquitous sensor coverage for disaster detection. Using historical data and trending techniques, AI based algorithms could detect weather events or other natural disasters earlier, giving valuable evacuation time. These tools could also be used in planning- or tracking-type applications with a goal of saving lives or property.

Health Safety

Health Monitoring

Current medical care is centered around averages that drive diagnosis, prevention, and treatment. As the next generation network evolves, numerous sensors (wearable and environmental) will collect individual variations in lifestyle, genes, and environment to aid and inform medical professionals and algorithms related to various conditions. An example use case is seen in the Precision Medicine Initiative, where 24/7 monitoring of various sensors for the basis for treatment, prevention, or diagnosis helps improve the condition of patients.

Elder care

Leveraging the projected ubiquitous sensor coverage, elder care monitoring use cases will become more realistic. Things like fall detection, sleep monitoring, and others will potentially use AI services to support our aging population to live more independently longer. Combining living independently with self-driving transportation use cases and 6G stands to lengthen quality of life for many.

Transportation Safety

Transportation use cases will support the automation of transportation functionality leveraging self-driving tools and techniques (i.e., V2X to connect nodes and vehicles) to control traffic flow, congestion, break downs (via vehicle monitoring), and inefficiency in wrong turns. This should allow AI based algorithms to perform trip planning and resource allocation more reliably.

Security as a Service

The need to have trusted data exchanges between local nodes and end-to-end connections in various conditions will prove to be important. Capabilities such as on-demand deployment of security functions or assets will support communication, transportation, and sensing use cases. This framework will also support enhanced network segmentation as the network changes with the dynamic environment.

Other new advances will allow for security to be considered a service. Network understanding, outline responses, and a strong communication back plan could support a transition to security as a service, where defense can be changed dynamically given the equipment or current environment.

6.2.4. Sensor-related Use Cases

Many emerging use cases taking advantage of various sensing mechanisms are under discussion and, in some cases, are already being implemented. These use cases reflect an array of applications ranging from IoT sensor networks for environmental, industrial, and other uses, to applications involving sensing the presence of moving or stationary objects and people.

In previous generations, we saw the advent of numerous varieties of sensors. 6G will be no different, as efforts are undertaken to produce biofriendly, zero/low energy sensors. This would allow for broad distribution of these sensors without as much concern about support infrastructure, tracking, or disposal. These sensors will produce large amounts of data, targeting the monitoring of things such as climate statistics, weather, or some other feature of interest. Using this data the system can update system models, monitor environmental status, or predict future system conditions. Uses such as traffic avoidance, medical monitoring, VR/XR, and digital twinning will become more realizable. Another new advent will be using Joint Communication and Sensing (JCAS). In this use case the communication links between nodes will serve two purposes, the first surrounding communications and the other focused on sensing. Leveraging aspects of signal processing and AI/ML things like range, velocity, and orientation will be sensible and stored for other use cases supporting safety, understanding, and prediction. Integrated sensing and communication will enhance performance of communication itself.

6.2.5. Radar-Related Use Cases

Some of the sensing applications discussed in Section 6.2.2 go beyond pure passive sensing of various factors in the environment, and deal with obtaining location and movement information. For instance, human gesture recognition and touchless control of data can be implemented in the same way a radar operates. Most of these applications are short range interactions between a human and a machine or between two nearby machines, and because of the short range, only require low power transmissions. An array of such applications has been designed and implemented already using unlicensed bands such as 60 gigahertz (GHz).[45]

Implementing these radar-type applications can be done either directly as standalone radars or by using communication system radio interface resources such as beacons or other periodically transmitted control information. The latter case is what led to the emerging usage scenario of Integrated Sensing and Communication as included in ITU-R framework for IMT-2030 (see Table 1 in Section 5).

The amount of bandwidth required for these sensing operations depends on the detection and range resolution required by the applications. Table 3 presents the required bandwidth for a sample of applications and their range resolution targets.

Table 3 Examples of Required Bandwidth for a Set of Integrated Sensing and Communication Applications[46]

Application	Range Resolution (m)	Required Bandwidth (megahertz, MHz)
Road Traffic Management and Monitoring	Relaxed, e.g., >10	Up to 15
UAV Inspection	Moderate, e.g., 1-10	150
Autonomous Vehicles	Stringent, e.g., 0.1-1	1500
Gaming/XR	Very Stringent, e.g., 0.01-0.1	15000

[45] https://docs.fcc.gov/public/attachments/DOC-393502A1.pdf.
[46] R. Arefi, et. al. "Spectrum Needs of 6G," TPRC51, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4523991, (Sep. 2023).

6.2.6. Space-Related Use Cases

As 6G is expected to move to a ubiquitous connectivity model, space interaction becomes more important as it holds the key to broader coverage options. In this model space assets will be integrated together with existing terrestrial networks building a composite network, often termed Space-Air-Ground-Sea Integrated Network or 3D networks. This will be an overarching 3D network architecture with connection among terrestrial (ground and sea) and non-terrestrial (air and space) domains. A great variety of satellites in Low Earth Orbit, Medium Earth Orbit, and Geosynchronous Equatorial Orbit comprise the space domain, with the space industry continually adding services. This means tremendous possibilities for use cases requiring massive connections such as environmental monitoring, forest fire prevention, drone inspection, ocean-going container information collection, the Internet of Vehicles business and many more. Other use cases include high-speed internet coverage, enhanced cellular coverage and connectivity, and core network support in underdeveloped areas.

Satellites are envisioned to play an important role in 6G next-generation networking. The European Space Agency says, satellites "offer unique advantages in terms of security, resilience, coverage, and mobility; they remain the only way to make 5G and 6G available everywhere."[47] If 6G is a true "network of networks," then including space-based assets as an integral part of network standardization and planning will enable more integrated and robust 6G use cases. For example, the ETRI journal notes "6G is expected to support non-terrestrial coverage using unmanned aerial vehicles and Low Earth Orbit satellites to serve the three-dimensional spatial coverage, such as high-rise buildings, aerial places, and seas."[48] 3GPP began working on integrating satellite communications with 5G, and it is anticipated 6G NTN will be included as part of Release 20. Including non-terrestrial technologies in next-generation networking standards will foster the expansion of satellite communications, including for direct to device, cellular backhaul, IoT, and other widespread uses.[49]

Next-generation satellite connectivity is anticipated to support a host of use cases. For example, commercial satellite broadband and narrowband services are already being used to address the digital divide so all users have access to service.[50] Satellite supports communications services on the move, including in the air and on water.[51] Satellite technology is expected to scale the performance of smart industrial applications and IoT, as a result of its global coverage area, resilience, and low infrastructure requirements.[52]

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[47] European Space Agency, Connectivity and Secure Communications, Space for 5G & 6G, https://connectivity.esa.int/space-5g-6g.

[48] Taesoo Kwon, et al., Guest Editorial: Special Issue on 6G and Satellite Communications, ETRI Journal Vol 44, Issue 6 (Dec. 2022), https://onlinelibrary.wiley.com/doi/epdf/10.4218/etr2.12551.

[49] See, e.g., Caio Castro, Satellites Will Complement Current Networks in 6G – But How?, 6G World (June 14, 2022), https://www.6gworld.com/exclusives/satellites-will-complement-current-networks-in-6g-but-how.

[50] Ken Peterman, The Answer to Solving the Digital Divide is Hybrid Connectivity Infrastructures, Space News (May 11, 2023), https://spacenews.com/the-answer-to-solving-the-digital-divide-is-hybrid-connectivity-infrastructures; Bridging the Broadband Gap, Society of Satellite Professionals International, Podcast (2023), https://www.sspi.org/cpages/bridging-the-broadband-gap.

[51] See Blane Boynton, "The Promise of the Next Generation Network," Intelsat (Aug. 18, 2023), https://www.intelsat.com/2023/08/18/the-promise-of-the-next-generation-network-antenna-technology.

[52] See Estefania Quiroz, Key Advantages of Satellite IoT Deployments (Aug. 2, 2023), https://www.iotforall.com/key-advantages-of-satellite-iot-deployments.

Next-generation satellite technology will continue contributing to the growth of telemedicine and digital health services, including supporting wearables for remote monitoring, telediagnosis, remote tele-medical assistance, tele-rehabilitation, and digital clinical trials.[53] Modern satellite technologies can also assist in studying the environmental factors that can lead to vector-borne diseases, in monitoring air quality, traffic, and other factors affecting human health.[54]

Satellite services could also enable environmental monitoring including climate change surveillance, energy and emissions management, and monitoring animal populations. Leveraging satellite technology facilitates a broader understanding of our planet, supports sustainable practices, and aids in the conservation of biodiversity.[55] Satellite connectivity and service offerings will continue to support increasingly advanced disaster prevention and response, and direct to device connectivity will add to its utility. Satellites' "wide coverage, infrastructure resilience, availability, and ease of deployment"[56] make them essential in disaster management. IoT sensors can be deployed to monitor for natural disasters in remote areas and small aperture earth stations can be deployed to quickly restore communications to an area affected by an emergency. Meteorological and Earth observation satellites can likewise enable monitoring and early warning of natural disasters such as wildfires, hurricanes, and other storms, and aid in recovery efforts such as mapping feasible evacuation routes.[57]

Satellites also have a role to play for next-generation space-based connectivity. For example, satellites orbiting the moon are planned to provide consistent connectivity to Earth and also facilitate connectivity of lunar equipment such as handheld devices, landers and rovers, and habitations, taking into consideration communications technologies and standards available on Earth today.[58] In fact, lunar positioning, navigation, and timing (PNT) and comms systems are seeking to leverage commercial 5/6G next generation technology for some lunar surface elements. Next-generation satellites will increasingly be equipped with intersatellite links to reduce latency and provide ubiquitous connectivity for satellite services. Intersatellite links will allow satellites to communicate amongst themselves, including to relay data when a particular satellite is out of range of an Earth station.[59] Intersatellite links are a focus of World Radiocommunications Conference 2023 in Agenda Item 1.17.[60]

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[53] See Marcin Frackiewicz, The Advantages of Satellites for Telemedicine and Healthcare, Ts2 (March 24, 2023), https://ts2.space/en/the-advantages-of-satellites-for-telemedicine-and-healthcare.
[54] United Nations Office for Outer Space Affairs, Sustainable Development Goal 3: Good Health and Well-Being (2023), https://www.unoosa.org/oosa/en/ourwork/space4sdgs/sdg3.html.
[55] United Nations, Office for Outer Space Affairs, Space Supporting the Sustainable Development Goals (2023), https://www.unoosa.org/oosa/en/ourwork/space4sdgs/index.html.
[56] Fair Tech Institute, The Role of Satellite Communications in Disaster Management, 24 (2022), https://accesspartnership.com/wp-content/uploads/2022/03/The-Role-of-Satellite-Communications-in-Disaster-Management.pdf.
[57] Id.
[58] See, e.g., Lunar Satellites, European Space Agency (Nov. 16, 2020), https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Lunar_satellites.
[59] National Aeronautics and Space Admin., Communications Services Project (CSP) (2023), https://www1.grc.nasa.gov/space/scan/communications-services-program.
[60] Transfinite Systems, WRC 2023 Agenda Item Details, https://www.transfinite.com/content/wrc2023list (see entry for Agenda Item 1.17).

7. Potential Use of 6G by Federal Government Users

This section discusses the potential use of 6G by federal government users, including traditional, emerging, and unlicensed use cases. Federal agencies will likely focus on service level agreements, quality of service, and quality of experience metrics. Federal agency use cases may have additional security requirements. Some of these use cases will evolve to meet the unique needs of government or industry users. Others will involve dual use, where the use case applies similarly to both government and industry users. Traditional and non-traditional use cases may blend; moreover, there is expected to be cross-pollination between industrial and federal agency use cases.

7.1. Traditional (Mobile Broadband) Use Cases

Federal agencies are expected to broadly benefit from traditional (NTN, mobile broadband and unlicensed) 6G use cases. Traditional use cases will evolve to more advanced human-to-human, human-to-machine, and machine-to-machine communications, providing improved performance and quality of service. Operational benefits to federal agencies include increased speed; lower latency; improved reliability, resiliency, redundancy, service continuity, ubiquity, and scalability; higher density; more precise timing; and improved network services. These advancements will support new and innovative federal agency mobile broadband applications, such as enabling autonomous systems.

Traditional 6G use cases are expected to benefit federal agencies in areas such as public safety and law enforcement, disaster recovery and operations, robotics, etc. with enhanced performance over 5G.

7.1.1. Terrestrial and Non-Terrestrial Integrated Connectivity

Current conventional terrestrial cellular networks relying on both licensed and unlicensed spectrum technologies are already evolving into hybrid terrestrial, space, aerial, and underwater networks. Further, 6G is expected to support self-organizing, mobile, and ad-hoc networks to provide advanced communications and seamless roaming across networks in environments with limited infrastructure. This will improve global communications coverage regardless of the time or the location of federal government users. It will also provide resiliency during extreme conditions, such as those caused by climate change, natural disasters, or other emergency crises.

Federal agencies can use the link best suited for their given application, and 6G will act as the glue to enable seamless and ubiquitous connectivity. This seamless and ubiquitous connectivity is valuable to federal agencies in multiple ways; for instance, it can support edge computing and real-time information sharing; a space or other network to move large sets of data around the globe for access when and where needed; and an international handset providing wireless communications coverage, seamless handoffs across services, and compatibility anywhere in the world. Terrestrial and non-terrestrial integrated connectivity will increase broadband coverage in rural and/or under-served areas to help close the digital divide and provide increased connectivity solutions in general. This improves digital equity, affordability, access to government and community services, and social, business, and economic opportunities. 6G can improve radio/signal-interference/coexistence and broadband maps.

7.1.2. Private 6G Network

This non-public network is not mobile network operator (MNO)-dependent and can include micro-networks of potentially different owners and/or shared infrastructure. Federal agencies can use a private 6G network to rapidly create a mobile connection for fixed and nomadic transport. The government can differentiate on top of the commercial verticals to leverage the best of both standardization, which generally provides economies of scale and interoperability, and a specialized product. External security management and trusted policy may be integrated into the network. Note that smart government facilities, smart grid, and smart warehouses are all potential use cases for private networks, which may rely on exclusively licensed, shared licensed, or unlicensed spectrum.

7.1.3. Autonomous Systems and IoT

Federal agencies can benefit from more autonomous systems including service or network-enabled robotics, connected intelligent machines, industrial automation, and AI/ML to optimize operations. AI of things, which combines AI with IoT, provides enhanced machine-to-machine communications that leverage data, including data processed at the edge. Multiple independent signals can be processed akin to massive multiple-input multiple-output (mMIMO) transceivers. Long-range radio for Machine-to-Machine (M2M) and IoT communications and connections from sensor networks to the cloud, for real-time communication of data and analytics, can be supported by both licensed and unlicensed spectrum access regimes.

These systems can increase data availability across connected devices, which can contribute to additional cost and operational efficiency and effectiveness. Autonomous systems provide the opportunity for federal agencies to reduce human labor requirements, allowing agencies to reassign labor to less mundane and higher value responsibilities.

7.1.4. Transportation

Intelligent transportation system applications include vehicle-to-vehicle (V2V), vehicle-to-infrastructure, and vehicle-to-pedestrian communications, as well as communications with vulnerable road users and with cloud networks that encompass V2X.

6G is expected to provide wireless communications that function well in non-networked (ad hoc) rapidly moving, continuously changing, dynamic, and highly variable environments when users are not subscribers to a centrally managed service. 6G is expected to increasingly rely on integrated communications and computation at the edge, including enabling 360-degree sensors effective in non-line-of-sight conditions, and can include video, security, and surveillance capabilities.

The capabilities of 6G will improve road and aviation safety, as well as crash prevention and management of complex traffic conditions. The low latency of 6G could allow enough time to issue warning and take action to prevent or mitigate crashes. Secure communication can be interoperable across makes and models of devices and modes of transportation. A virtualized model and real-time representation of the transportation system can integrate advanced analytics and modeling to improve transportation management. Depending on the accuracy and localized PNT, 6G might also offer cooperative perception and maneuvering and automated fleet movement. Transportation will benefit from 6G’s improved energy efficiency and sustainability.

7.1.5. Public Safety (Including Robots and Cobots)

6G is expected to increase interoperability of law enforcement operations and public safety. This will improve coordination and robustness for first responders, emergency services, and disaster recovery and operations. Advancements in radio over IP technologies will provide a faster network with reduced latency between cellular and land mobile radio networks. Reconfigurable and self-optimizing networks can support unexpected and ad-hoc communications, as well as rapid organic network recovery following an event. Detection of objects can mitigate privacy concerns. More advanced robotics can be used for hazardous environments. A network of sensors and assimilation of data will provide improved situational awareness. Public safety will benefit from increased fault-tolerance and awareness of threats.

7.1.6. Augmented Reality, Virtual Reality, and Extended Reality

Immersive communications deliver heightened experiences and remove distance as a barrier to communications. Commercial development of the AR/VR/XR use case has been slow, but federal agencies could benefit from AR/VR headsets. Soldiers can use augmented reality headsets to improve defense capabilities, such as an application of the integrated Visual Augmentation System. Telemedicine and real-time remote support could be provided with guaranteed high-bandwidth and low latency connectivity. Extended reality may include human sensory feedback. These high bandwidth, indoor applications are well-suited for unlicensed 6G networks.

7.1.7. Digital Health

6G communications will strengthen electronic health systems by utilizing body and health sensors and digital twinning. Body and health sensors could provide miniature nodes that measure bodily functions. Health could be continuously monitored with adjustments made as needed, such as devices dispensing medicine or providing physical assistance. Digital twinning could provide continuous analysis, incorporating advanced analytics and modeling to enable precision healthcare, personalized medical treatment, and improved health outcomes.

7.2. Non-Traditional Use Cases

Federal users can leverage the emerging vertical use case services.

7.2.1. National Security

National security will benefit from guaranteed data rates and improved security, fault-tolerance, and awareness of threats. Merged cyber and physical worlds will enable mixed reality to optimize decision making to reduce risk and increase mission success. The Internet of Senses will improve context-aware applications. Remote operations as well as live, virtual, and constructive training, including with joint forces, and logistics and maintenance will benefit from 6G. 6G is expected to protect privacy data via joint communications and sensing that detects objects to alleviate privacy concerns.

7.2.2. Intelligent Sensors and Systems

Emerging 6G use cases include massive growth of connected sensors and cameras. Federal agencies will benefit from multi-sensory, including haptics, applications, and Internet of Senses to provide greater context awareness and interaction.

7.2.3. Environmental Sensing

6G is expected to improve weather and environmental micro-forecasting, increasing the detail of map and terrain information, and strengthening situational awareness via better detail, accuracy, and real-time information. Federal agencies can benefit from data collected by sensor systems along with network-enabled edge computing and advanced analytics to inform decisions. A real-time digital replica can help optimize federal agency mission operations.

7.2.4. Education

Mixed reality and holographic telepresence will enable a more immersive experience and improve remote education and accessibility to experts, increase teacher-student interactions, and improve knowledge capture, retention, and use. It will also enable realistic simulation of complete scenarios.

7.2.5. Logistics and Tracking

A virtual representation of the end-to-end system can incorporate advanced analytics and modeling to improve logistics and tracking. Automating movements, predicting supplies, and inventory tracking will be improved. 6G will enable remote inspection, assembly, and data logging and situational awareness. Consequently, this can improve allocating resources, including during abnormal times caused, for instance, by weather, hazards, health crises, or disasters.

7.2.6. Positioning, Navigation, and Timing

6G will enable high accuracy PNT to provide high accuracy location and spatial mapping. This can enable indoor location mapping, robotic navigation, and extended reality technology.

7.2.7. Testing

Use of augmented reality, holographic technologies, and digital replicas can improve extreme communication performance and testing.

7.2.8. Sustainability

6G can enable a connected, sustainable world. It is being designed to optimize energy consumption and efficiency. 6G could minimize energy consumption with smart communication adapted based on environmental sensing. AI/ML could be used to improve resource efficiency and utilization. Although AI is complex and requires additional energy, AI/ML could be used to optimize energy and power consumption. 6G could utilize bio-friendly, energy-harvesting sensors. It can perform surveillance and monitoring of environmental status and provide micro-weather forecasting and improved earth observation, space sustainability, earth monitoring, and smart agriculture.

Digital twinning of the physical environment can be used to analyze and experiment with actions. Energy efficient technology can reduce greenhouse gas emissions and address climate change, biodiversity loss, and pollution while improving resource efficiency.

7.2.9. Economic Value and Growth

6G can improve the U.S. economy by driving greater productivity and economic value and growth. Expected to be a general-purpose technology, 6G will likely make all industries in the economy more efficient. However, telecommunications companies are often international, and investment is needed to advance markets and devices for 6G. Different verticals require different approaches. There are costs to develop a prototype for an application, and then to productize it. Innovators can experiment via digital twinning.

8. Technologies and Technical Capabilities of 6G

Technologies that form major elements of 6G and the type of technical capabilities they bring about are still under development and investigation by academia, industry, and various government funded projects around the world. In North America, NGA has been actively working to identify major technical elements of 6G and their associated performance requirements from radio interface technologies to access and network aspects. In other parts of the world, e.g., in Europe, similar efforts are underway. Last year, ITU-R published a report[61] describing major technology trends for future development of next generation mobile systems.

8.1. 6G Enabling Technologies

This section provides a high-level summary of 6G's enabling technologies, as perceived today. For a more detailed description of 6G enabling technologies see, for instance, Next G Alliance's Report on "6G Technologies," June 2022.[62]

8.1.1. Radio Interface Technologies

Generally, technologies under consideration that enhance radio interface technologies include the following:

- Advanced modulation, coding, and waveforms
- Advanced multiple access techniques, including orthogonal multiple access and non-orthogonal multiple access
- Beyond mMIMO, including distributed mMIMO, advancements for sub-6GHz support, and expansion to THz, etc.
- Reconfigurable Intelligent Surfaces (RIS)
- In-band full-duplex communications
- Holographic beamforming
- Orbital angular momentum
- THz/sub-THz communications
- Ultra-high accuracy positioning
- AI-native radio interface.

8.1.2. Radio Access Network Technologies

Technologies under consideration that enhance the radio network include the following:

- Adaptive radio access network (RAN) slicing
- Software defined networks
- New RAN architectures (e.g., cell-free, mesh, service-based, etc.)
- Next generation open architecture and interfaces
- Technologies to support digital twin network
- Support for ultra-dense deployments
- Technologies to enhance RAN infrastructure sharing
- Dynamic spectrum sharing and co-existence techniques.

8.1.3. System and Network Technologies

Technologies under consideration that enhance the system and network include the following:

- Integrated terrestrial and non-terrestrial network segments
- Network disaggregation

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[61] Report ITU-R M.2516, *Future technology trends of terrestrial International Mobile Telecommunications systems towards 2030 and beyond*, December 2022.

[62] https://www.nextgalliance.org/6g-library/.

- User-centric network architectures (distributed intelligence at endpoints)
- Distributed cloud platform
- Energy harvesting, near-zero power communications
- Post-quantum cryptographic techniques
- Evolved sidelink (device-to-device) communications.

8.2. 6G Key Technical Capabilities

This section provides a high-level view of 6G's technical performance requirements of major 6G enabling technologies as characterized by their key performance indicators.

ITU-R WP5D has been collecting information from administrations and industry on key technical capabilities of the next generation of IMT. These capabilities are contained in "ITU-R Recommendation on overall framework of IMT for 2030 and beyond."[63] Figure 4 depicts major 6G technical capabilities envisioned by ITU-R for IMT-2030, which will be supplemented by the work done in ITU-R WP4B on the satellite component of IMT-2030.

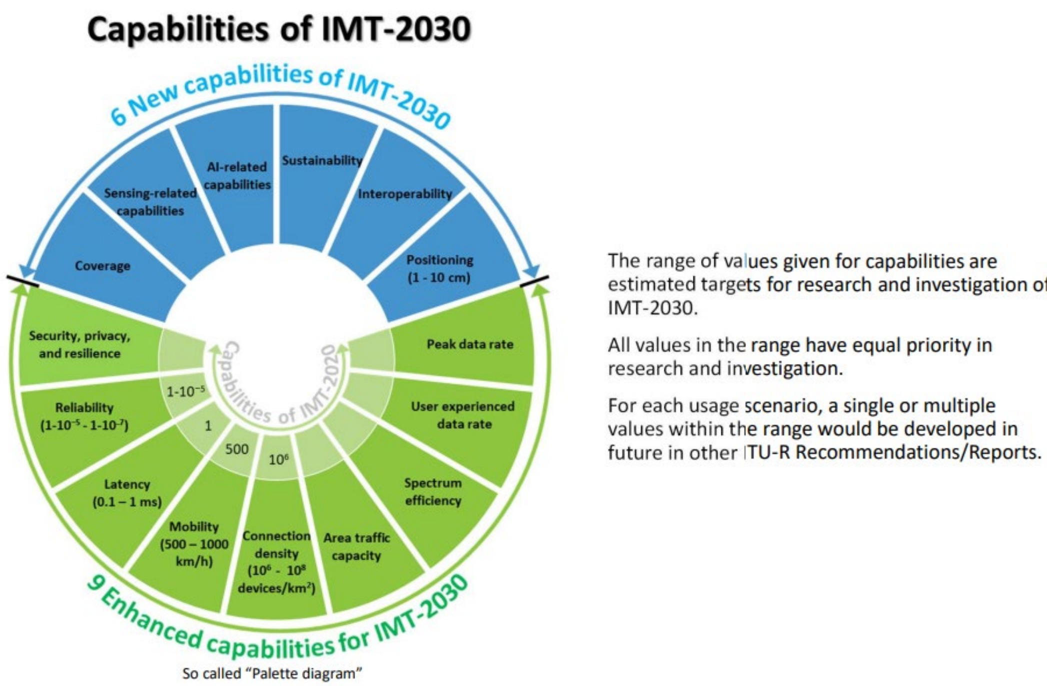

Figure 4 Capabilities of IMT-2030[64] (6G)

8.2.1. Immersive Communications

Key technical capabilities of immersive communication techniques include various types of data rate (e.g., peak, average, user-experienced), and their associated spectral efficiency values. According to ITU-R, "capabilities that aim for enhanced spectrum efficiency and consistent service experiences along with leveraging the balance between higher data rates and increased mobility in various environments are

[63] ITU-R Working Party 5D, *Framework and overall objectives of the future development of IMT for 2030 and beyond,* Draft New Recommendation (June 29, 2023).
[64] https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx.

essential. Certain immersive communication use cases may also require support of high reliability and low latency for responsive and accurate interaction with real and virtual objects, as well as larger system capacity for simultaneously connecting numerous devices."[65]

8.2.2. Critical/Hyper Reliable and Low Latency Communications

Key capabilities of critical communications include factors such as availability and reliability. According to ITU-R, "this usage scenario would require support of enhanced reliability and low latency, and depending on the use case, precise positioning, and connection density."[66]

8.2.3. Massive Communications

Key capabilities of massive communications include factors such as number of users/devices per unit area. According to ITU-R, "this usage scenario would require support of high connection density, and depending on use cases, different data rates, low power consumption, mobility, extended coverage, and high security and reliability."[67]

8.2.4. Joint Communication and Sensing

Key capabilities of joint communication and sensing technologies include factors such as range resolution, range accuracy, maximum unambiguous velocity, and velocity resolution. According to ITU-R, "this usage scenario requires support of high-precision positioning and sensing-related capabilities, including range/velocity/angle estimation, object and presence detection, localization, imaging and mapping.[68]"

8.2.5. Ubiquitous Intelligence and Compute

According to ITU-R, "This usage scenario would require support of high area traffic capacity and user experienced data rates, as well as low latency and high reliability, depending on the specific use case. Besides communication aspects, this usage scenario is expected to include a set of new capabilities related to the integration of AI and compute functionalities into IMT-2030, including data acquisition, preparation, and processing from different sources; distributed AI model training; model sharing and distributed inference across IMT systems; and computing resource orchestration and chaining.[69]"

8.2.6. Ubiquitous Connectivity

The focus of ubiquitous connectivity according to ITU-R is "to enhance connectivity with the aim to bridge the digital divide." As a result, its key capabilities are related to coverage, which, as a capability, is defined by ITU-R as "the ability to provide access to communication services for users in a desired service area. In the context of this capability, coverage is defined as the cell edge distance of a single cell through link budget analysis.[70]"

8.3. Security

There are many aspects to the security of radiocommunication networks. The focus of this section is on technologies enabling more secure communication networks in the run up to 6G.

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[65] https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx.
[66] Id.
[67] Id.
[68] Id.
[69] Id.
[70] Id.

8.3.1. Background

The inherent openness of wireless networks means they are subject to physical layer security attacks including jamming, spoofing, and sniffing/unauthorized interception/eavesdropping. These vulnerabilities are inherent in current 5G networks and will be present in future 6G networks as well. Moreover, as recently stated by the National Institute of Health (NIH):[71]

> "Due to the high communication requirements and needs of the 6G applications, many applications and services have very demanding performance and extraordinarily stringent security requirements. The interaction between general performance expectations and security needs to become increasingly more complex as highly competent, ubiquitous attackers and malicious activity become more prevalent."

Because of the above and the results of the interviews this subcommittee has conducted, it is established that security must be foundational in the design of 6G. Herein, the focus is physical layer security attacks, rather than attacks higher in the protocol stack. This is because attacks at the higher layers are common to all networks—wired and wireless—and therefore attract commensurate research and other attention. Some observers would argue physical layer attacks are often under-appreciated in policy discussions.

8.3.2. Jamming, Spoofing and Sniffing/Unauthorized Interception/Eavesdropping

Radio jamming is defined as deliberately jamming, blocking, or otherwise interfering with wireless communications. Jamming disrupts information flows in wireless networks. One way jamming can be accomplished is by transmitting an interfering signal, powerful enough to overwhelm the victim receiver by decreasing the received signal-to-noise ratio available at its input. Note, when the receiver is jammed, functions carried out higher in the protocol stack under normal conditions (e.g., authentication) cannot be performed in the receiver. Jamming is a form of a denial-of-service attack and is sometimes referred to as a denial-of-spectrum attack. The attacks described can be refined by not transmitting the deliberate interference continuously, but, instead, at critical times based upon the specifics of the protocol being used, thus maximizing the impact and/or reducing the amount of power required (i.e., frequently referred to as smart jamming).

Radio spoofing is defined as the deliberate transmission of fake signals (disguised as friendly, legitimate ones) containing false, corrupt, harmful, or duplicate data to the victim receiver.[72] An example is global positioning system (GPS) spoofing in which a transmitting device is used to make a GPS receiver calculate a false time or position.[73] Another example is a replay attack in which a transmitting device records a legitimate wireless message and retransmits it in a different context to accomplish a nefarious result such as unlocking a vehicle door.

Sniffing, unauthorized interception, and eavesdropping are closely related terms associated with capturing the content or meta-data associated with transmitting a wireless message, thus invoking privacy and secrecy concerns about the technical characteristics of a target to enable crafting and launching tailored jamming and spoofing attacks with more efficiency or greater impact.

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[71] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8914636/.
[72] [https://rbcsignals.com/blog/electronic-warfare-jamming-spoofing-and-ground-stations/].
[73] [https://www.everythingrf.com/community/what-is-gps-spoofing].

8.3.3. Distinguishing Between Mischievous, Non-Malicious, and Malicious Jamming

The motivation for jamming, as defined above, is often divided into three categories: mischievous, non-malicious, and malicious. An example of mischievous jamming is a technically savvy student or hacker doing it for bragging rights. Examples of non-malicious jamming include a teacher preventing students from using cellphones during a class, a truck driver preventing their employers from using GPS to track them, or an operator of a gravel pit preventing employees from using their cellphones because of legitimate safety concerns. The motivation for malicious jamming includes attacks for profit, out of grudges, or for political or military advantage.

8.3.4. Potential Perpetrators of Malicious Interference

Potential perpetrators of deliberate, malicious interference include individual criminals, organized crime groups, foreign powers, non-state actors, disgruntled employees, and activists.

8.3.5. Before the Fact (Ex Ante) and After the Fact (Ex Post) Activities for Dealing With Jamming

Ex ante enforcement activities are grounded on the statutory prohibitions against the operation, manufacture, importation, marketing, and sale of equipment designed to jam or otherwise interfere with authorized communications such as radar, GPS, and cellphone communication. Despite the statutory prohibitions, jamming devices range from inexpensive but less effective products to more expensive but sophisticated devices and systems that are widely available.

Ex post enforcement activities for dealing with malicious jamming include (1) detecting, (2) classifying/identifying, (3) locating, (4) reporting, (5) mitigating, (6) remediating, and (7) recording the incident future analysis and action.

The first four steps (e.g., detecting, classifying/identifying, locating, and reporting the jamming source), must occur before it can be mitigated or stopped. Likewise, remediation, the successful prosecution of the perpetrator or perpetrators of the illegal jamming signal, cannot be accomplished until the first five steps are completed. In the ex ante mitigation step, it is essential to consider the time scale involved. In industrial, medical, public safety, and critical infrastructure applications, 6G must support ultra-reliable, low-latency communications applications. That requirement dictates that outages and delays associated with the steps leading up to mitigation must be minimized.

9. Potential Spectrum Bands to Support 6G and Potential Implications to Government Users

Usage scenarios of 6G are still under discussion in various R&D projects around the world. The envisaged usage scenarios, from what can be gleaned, are diverse and span a large set of potential deployment environments and models, from wide area to local area to very short-range scenarios. The great diversity of use cases and applications envisaged for 6G (see Sections 5 and 6) emphasizes the fact that other than having access to sufficient spectrum, it is essential for the spectrum to have characteristics, mostly related but not limited to propagation, that optimally match the applications and the environment they operate in (i.e., there is also need for the right type of spectrum). Both of these conditions are influenced by the technical capabilities of 6G, and band-specific regulatory conditions of operation. These are further discussed in the following sections.

9.1. Technical Suitability

Technical capabilities and performance of any radio interface are generally characterized by a few KPIs. Peak data rate, spectral efficiency, target range resolution, over-the-air latency, supported number of users per unit area, and minimum SINR are a few of the KPIs applicable to a variety of radio interfaces. Some of these KPIs have direct or indirect, impact on the amount of spectrum and/or the type of spectrum. For instance, peak data rate is an example of a KPI directly affecting the amount of spectrum, while radar angular resolution indirectly relates to spectrum through antenna effects. Analytical methods as well as simulations could be performed to derive the amount of spectrum needed as a function of various KPIs.

The amount of spectrum is generally impacted by capacity and interference environment considerations and characterized by certain KPIs including, but not limited to:

- Peak, average, or minimum (e.g., fifth-percentile) data rates
- Peak, average, or minimum spectral efficiency (including effect of multi-antenna techniques)
- Over-the-air packet/burst latency
- Target range resolution
- Number of simultaneous users per unit area requiring same KPI values.

The type of spectrum is generally impacted by the deployment model in conjunction with propagation and wireless channel model considerations and characterized by certain KPIs including, but not limited to:

- Wide-area outdoor and outdoor-to-indoor acceptable coverage levels
- Short range LOS/near-LOS requirements
- Target velocity detection
- Operation in cluttered environment
- Degree of mobility.

Consideration of the above would guide toward determining suitability from a technical point of view.

9.2. Regulatory Suitability

In addition to technical suitability, there are regulatory considerations that must be taken into account to have a better understanding of the overall suitability. Deploying 6G in bands other than traditional cellular bands (5G and earlier generations, assuming migration to later generations are allowed under tech neutral regulations) through sharing requires adequate service rules be put in place. These service rules act as the basis for sharing mechanisms that could enable protection of incumbents in-band and in adjacent bands.

Incumbent services come with a variety of operational and deployment characteristics, leading to different necessary conditions for protection against harmful interference. These conditions play a major role in determining suitability for sharing.

In general, there are multiple techniques that can be used for sharing, affecting regulatory suitability in various ways.

9.2.1. Suitability of Time-based Sharing

The intermittent nature of some operations could, in some cases, present an opportunity for spectral resources to be shared by other applications when not actively used in a given geographical area. This kind of sharing requires adequate coordination among the systems involved (e.g., through the Incumbent Informing Capability under development by NTIA). The complexity of implementing a secure and effective time-based sharing mechanism increases with the level of dynamism required. Specifically, especially with a near-real time or real-time level of dynamism, this type of sharing could require high speed and secure exchange of a large amount of data among the parties involved with ultra-low latency.

One important feature envisaged for 6G, which could help with real-time or near-real-time exchange of information, is ubiquitous computing (i.e., the proliferation of compute resources throughout the network). Ubiquitous computing, also referred to as communication and computing convergence, is the trend by which computing services and data services are expected to become an integral component of future terrestrial mobile broadband systems. Emerging technology trends include expanding data processing from the core toward the device, including at the network edge closer to the origination of information. The distribution of compute resources allows for improvements for real-time responses, low data transport costs, energy efficiency and security/privacy protection, as well as scaling device computing capability for advanced application computing workloads such as dynamic sharing.

It should be noted that with regards to sharing with wide-area terrestrial licensed services, the duration and predictability of unavailability periods play a key role in suitability of this sharing model. Suitability is also related to the availability of other licensed spectral resources by the same network operator in the same area during the unavailability periods.

9.2.2. Suitability of Location-Based Sharing

This type of sharing has been extensively used in the past through creating exclusion, or coordination zones around certain locations that need to be protected. The protection could also be time-based, such as in the case of certain radio astronomy sites during observation periods. Some of the provisions in the 3.45-3.55 GHz spectrum band are examples of this type of sharing mechanism. Coordination contours are usually derived based on required protection levels (e.g., maximum tolerable Interference to Noise Ratio (I/N), expressed in terms of power flux density (pfd), or field strength).

It should be noted that with respect to sharing with wide-area terrestrial licensed operations, the suitability of this sharing model is related to the availability of other licensed spectral resources by the same network operator in the same area at the same time.

9.2.3. Suitability of Frequency-Based Sharing

This is also not a new concept and has been tried in the past, e.g., Dynamic Frequency Sharing, or DFS, in the 5 GHz spectrum band. It is not clear, however, whether this scheme would be suitable for sharing involving licensed operations, which require QoS-bounded scheduling of services to users. It should be noted that the suitability of this sharing model is related to the availability of other licensed spectral resources by the same network operator, in the same area, at the same time.

9.2.4. Suitability of Time/Location/Frequency-Based Sharing (Toolbox Approach)

Intelligent sharing techniques are likely to be incorporated into 6G, which can enable spectrum to be shared at a more granular level and in more flexible ways. Such techniques could help select the best approach for particular bands/use cases. It can be argued there is no single universal sharing scheme that can address all sharing concerns. Instead, sharing can be facilitated through a “toolbox approach.” This approach would have various sharing tools available to the parties involved, which can then (through either a distributed or centralized decision-making process) be adapted to optimally solve the problem at hand. KPI-based analytics[74] can be used that relies on the envisaged ubiquitous intelligence and computing power present throughout the networks extending from devices/users to the cloud. An example of the KPI-based analytics would be choosing a mechanism, from among various sharing options, that maintains a minimum user data rate over a specified time interval at a given location. Another example would be choosing a mechanism from among various sharing options that minimizes latency for a given application at a specified time and location. The suitability of this sharing model depends on the availability of well-defined KPIs and computing resources for performing the analytics needed to find optimum solutions.

9.2.5. Suitability of Power Restrictions

This method provides for operating terrestrial services under a capped transmit power, TRP or EIRP, which curtails interference to federal incumbents at an acceptable level, but at a level still suitable to provide meaningful connectivity to enable sharing the spectrum band. This sharing solution is most suitable for sharing between federal incumbents and local-area networks and other short-range communication services.

9.2.6. Suitability of Indoor Restrictions

In some cases, sharing between federal incumbents and certain terrestrial services can be facilitated through imposing an indoor restriction on the terrestrial service. While this restriction might not be appropriate for some terrestrial services (e.g., wide-area connectivity), it might be a good solution for other services, such as private networks operating inside enterprises, factories, or other enclosed structures. The increasing trend in using energy-efficient building materials, such as metal-coated glass, could facilitate this type of sharing in some cases.

Suitability of this sharing mechanism depends on the deployment model of the new entrant and whether it can operate indoors and maintain a maximum pfd level just outside of the service area, e.g., a factory boundary that protects the incumbents, while still at a level that provides meaningful connectivity for the indoor operation.

9.3. Spectrum Below 3 GHz

Smaller bandwidths are available below 3 GHz. There are rising ambient noise levels in lower frequency bands, further eroding usability of this spectrum.

However, under-utilized spectrum, particularly in large geographic areas with relatively few users, could potentially be pieced together via carrier aggregation and multi-radio dual connectivity to leverage for 6G network coverage. This is a focus area for NTN networks, that could be facilitated by access to additional low band spectrum for applications such as direct handset connectivity through NTN.

9.4. Mid-Bands and Extended Mid-Bands

There is general consensus among mobile industry and academia on the continued use of mid-bands and possible expansion into extended mid-bands for evolution of 5G and emergence of 6G applications. The

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[74] Optimally, the KPIs guiding the analytics are those of 6G services as well as the incumbent systems.

satellite community also has significant needs for spectrum in the mid-bands. In this context, the term "mid-bands" generally refers to spectrum between around 3 to around 7 GHz, a range within which currently a majority of mobile broadband deployments reside, whereas the term "extended mid-bands" is predominantly thought of as frequencies up to around 15 GHz beyond which propagation, deployment models, and component technologies begin to resemble those of MMW.

Appendix D contains an analysis of spectrum allocations and use of mid-bands and extended mid-bands domestically and internationally. These bands are characterized by extensive and diverse use by several terrestrial and space services inclusive of commercial and federal deployments.

Mid-bands are also home to the bulk of cellular bands developed in recent years by 3GPP for introduction of 5G NR. Table 4 lists 3GPP bands in frequency range (FR)1 above 3 GHz. FR2 NR bands are also included for the sake of completion.

Table 4 – 3GPP NR Bands above 3 GHz

NR Band	FR	Common Name	From		To	NR Release
n46	FR1	LAA 5GHz	5150	-	5925	Rel-16
n47	FR1	V2V 5GHz	5855	-	5925	Rel-16
n48	FR1	US CBRS 3500	3550	-	3700	Rel-16
n77	FR1	3.7GHz	3300	-	4200	Rel-15
n78	FR1	3.5GHz	3300	-	3800	Rel-15
n79	FR1	4.5GHz	4400	-	5000	Rel-15
n96	FR1	6GHz unlicensed (U.S.)	5925	-	7125	Rel-16
n257	FR2	28GHz / LMDS	26500	-	29500	Rel-15
n258	FR2	26GHz / K-band	24250	-	27500	Rel-15
n259	FR2	V-band	39500	-	43500	Rel-16
n260	FR2	39GHz / Ka-band	37000	-	40000	Rel-15
n261	FR2	28GHz USA / Ka-band	27500	-	28350	Rel-15
n262	FR2	47GHz USA / V-band	47200	-	48200	Rel-16
n263	FR2	60GHz / V-band	57000	-	71000	Rel-17

FR1: 450MHz - 7125MHz

FR2-1: 24250MHz – 52600MHz

FR2-2: 52600MHz - 71000MHz

9.4.1. Information on Specific Spectrum Bands in Mid-Bands and Extended Mid-Bands

There are a variety of factors influencing the consideration of bands for 6G, including technical and regulatory suitability, coexistence with incumbents, and economical aspects. Some of these aspects are described in Sections 9.1and 9.2. However, a few high-level criteria can be gleaned from experience with previous generations.

- Sufficient bandwidth – Bands which do not offer enough bandwidth commensurate with typical channel bandwidths of a given generation are generally not as attractive.[75] While the typical channel bandwidth for 4G was 20 MHz, a 100 MHz bandwidth became the norm for typical 5G deployments. Typical channel bandwidths for 6G are expected to be in the order of 200 to 400 MHz.[76] Having said this, bands with smaller bandwidths can still be used through carrier aggregation, but carrier aggregation comes at a certain performance cost, which makes it a suboptimal solution.
- Ubiquitous incumbent deployment – Differences in incumbent systems and deployment models play a role. Ubiquitous distribution of terminals of an incumbent system can create prohibitively difficult sharing conditions with wide area deployments of 6G. Coexistence of cellular and FSS DL in the 4 GHz band has been an example for the past decades, in many cases only made possible through band segmentation.[77]
- Space services – Coexistence between terrestrial and space services is generally conditioned on the amount of energy radiated above horizon or some other elevation angle. As a result, for bands shared by space and terrestrial services, means to curb such radiation, for instance through appropriate effective isotopically radiated power (e.i.r.p.) masks, is critical.

NGA published a white paper[78] on 6G terrestrial spectrum considerations in which it “assesses potential 6G suitable spectrum bands based on applications and technology requirements, including required bandwidth/amount of spectrum.” In this paper, which will be followed by another paper focused on the methodology and derivation of spectrum needs of 6G, NGA analyzed spectrum bands in various ranges from low to very high with the goal of informing the process of finding suitable spectrum for 6G. The paper recommends the following set of bands to be prioritized for further study with the goal of making additional spectrum available for mobile services.

> 3.1–3.45 GHz*

> 4.4–5.0 GHz*

> 7.125–9.3 GHz

> 10–10.5 GHz*

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[75] Another important factor here is the number of mobile operators in any given market.
[76] Future developments in standard setting organization and ITU-R activities during 2024 on development of IMT-2030 Technical Performance Requirements (TPR) will include indications on typical channel bandwidths for various applications/environments.
[77] For instance, C-band in the U.S. (Auction 107).
[78] https://www.nextgalliance.org/white_papers/6g-spectrum-considerations/.

> 12.7–13.25 GHz

> 25.25–27.5 GHz

> 37.0–37.6 GHz

> 42–42.5 GHz

> 42.5–43.5 GHz.

The ranges marked with an asterisk (*) are those for which "international decisions regarding the addition of mobile allocations in these bands or a portion of these bands and their identification for International Mobile Telecommunications (IMT) will be made at the upcoming 2023 ITU World Radiocommunication Conference (WRC-2023)."[79]

This is generally consistent with comments to the NTIA National Spectrum Strategy regarding the question related to which spectrum bands should be studied for potential repurposing as shown in Figure 5 below.[80] The bands depicted in orange below indicate those that are consistent with the NGA recommendations.

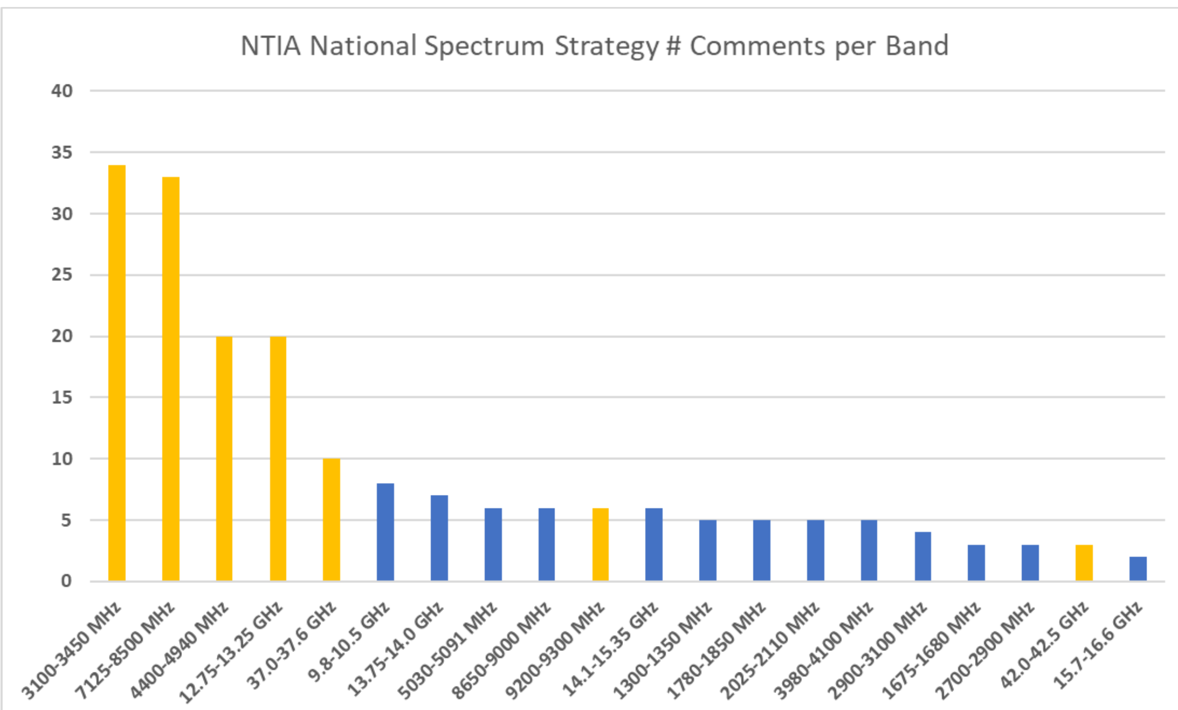

Figure 5: Tabulation of Comments to NTIA National Spectrum Strategy Regarding Spectrum Bands that Should be Studied

CSMAC considered the NGA recommendations and the National Spectrum Strategy comments, albeit with a focus on major elements to be considered for suitability of various frequency ranges. The following

[79] https://www.nextgalliance.org/white_papers/6g-spectrum-considerations/, page 19.
[80] *Development of a National Spectrum Strategy, Request for Comments*, 88 Fed. Reg. 16,244 (March 16, 2023) Pillar 1, Question #3, " What spectrum bands should be studied for potential repurposing for the services or missions of interest or concern to you over the short, medium, and long term?"

subsections (9.3.1.1-7) contain detailed descriptions of major elements to be considered for suitability of various frequency ranges analyzed.

9.4.1.1. 3100-5000 MHz

As shown in Table 4, this is 1900 MHz of spectrum and contains 16 band segments allocated to 12 services. The allocations range from 10 MHz wide to 300 MHz wide. The average allocation is close to 120 MHz.

Most of the primary allocations in this band are for Fixed for International (3400-4200 MHz and 4400-5000 MHz) and Non-Federal (3450-4200 MHz and 4940-4990 MHz). There are a few Fixed Federal allocations (4400-4990 MHz).

There are also a substantial number of primary international allocations for Fixed Satellite downlink (3400-4200 MHz and 4500-4800 MHz), plus a few Non-Federal allocations (3600-3650 MHz, 3700-4200 MHz and 4500-4800 MHz).

There are several primary International Mobile allocations (3400-4200 MHz and 4400-5000 MHz). There are some secondary allocations depending on ITU region. There are a few primary Federal allocations (4400-4940 MHz). There are several primary Non-Federal allocations (3450-4000 MHz and 4940-4990 MHz).

There are primary international allocations for Radiolocation (3100-3400 MHz) and secondary international allocations for Radiolocation (3400-3700 MHz). There are also primary Federal allocations for Radiolocation (3100-3650 MHz).

There is a primary international allocation for Aeronautical Mobile (4200-4400 MHz).

There is a primary international, Federal, and Non-Federal allocation for Aeronautical Radionavigation (4200-4400 MHz).

Finally, there are secondary allocations for Amateur (3300-3500 MHz), Earth Exploration Satellite (3100-3300 MHz), and Active and Passive Space Research (3100-3300 MHz and 4990-5000 MHz respectively).

Many portions of the 3100-5000 MHz band have already been opened for commercial use:

- 3450-3550 MHz (3.45 GHz Service, 10 x 10 MHz channels)
- 3550-3700 MHz (CBRS, 15 x 10 MHz channels)
- 3700-3980 MHz (3.7 GHz Service, 14 x 20 MHz channels)
- 4940-4990 MHz (4.9 GHz Service, 1, 5, 10, 15, 20, 30, 40 & 50 MHz channels).

The 3100-3450 MHz portion is currently being studied on the feasibility of making the band available for shared Federal and Non-Federal commercial licensed use under the National Spectrum Consortium Partnering to Advance Trusted and Holistic Spectrum Solutions (PATHSS). The final report is due by the end of 2023.

Note there is also commercial interest in opening the 4400-4940 MHz band for commercial use as noted in Figure 5 above.

The propagation characteristics of these bands are favorable for large-scale deployments, but are subject to ducting, which may complicate interference management. In addition, signals in this band are subject to impacts from clutter and buildings.

Considering that 580 MHz of the 3100-5000 MHz bands have already been allocated for commercial use, with a possible additional 750 MHz in the spectrum pipeline, a total of 1330 MHz of the 1900 MHz available in these bands may ultimately be available for commercial use.

9.4.1.2. 5000-5925 MHz

As shown in Table 5, this is 925 MHz of spectrum and contains 16 band segments allocated to 18 services. The allocations range from 5 MHz wide to 110 MHz wide. The average allocation is close to 60 MHz.

Most of the band is allocated on a primary basis for international and Federal Radiolocation (5250-5850 MHz). There is also both a secondary Non-Federal allocation (5250-5470 MHz) and a primary Non-Federal allocation (5470-6560 MHz).

Aeronautical Radionavigation has primary allocations for international, Federal, and Non-Federal (5000-5250 MHz and 5350-5460 MHz).

Aeronautical Mobile Satellite (Route) also has primary allocations for international, Federal, and Non-Federal (5000-5150 MHz).

Aeronautical Mobile (Route) has primary allocations for Federal and Non-Federal (5000-5010 MHz and 5030-5150 MHz) and primary international allocations (5030-5091 MHz).

Earth Exploration Satellite has primary allocations for international and Federal (5250-5570 MHz) and secondary Non-Federal allocations (5250-5570 MHz).

Mobile has primary international allocations (5150-5350 MHz, 5470-5725 MHz, and 5850-5925 MHz). There is also a primary Non-Federal allocation (5850-5925 MHz).

Space Research has a primary international and Federal allocations (5250-5570 MHz) and a secondary Non-Federal allocation (5250-5570 MHz).

Fixed Satellite uplink has primary international allocations (5091-5250 MHz and 5725-5925 MHz). There are also primary Non-Federal allocations (5150-5250 MHz and 5850-5925 MHz).

Fixed has an international primary allocation (5850-5925 MHz).

Radionavigation Satellite uplink has a primary international, Federal, and Non-Federal allocation (5000-5010 MHz).

Radionavigation Satellite downlink and space-to-space has a primary international, Federal, and Non-Federal allocation (5010-5030 MHz).

Finally, unlicensed Part 15 uses of the band are permitted for the Unlicensed National Information Infrastructure (5150-5350 MHz and 5470-5895 MHz).

Propagation characteristics for this band are slightly worse considering free space loss (~2.7 dB) than for the 3100-5000 MHz band. Signals are still subject to ducting and are more susceptible to effects of clutter and buildings.

The 5000-5925 MHz band is heavily used by radar and unlicensed Wi-Fi. The radar uses tend to be for high-powered weather radar (e.g., 100 GW), Terminal Doppler Weather Radar, and numerous airborne weather radars. As noted, unlicensed uses are part of the Unlicensed National Information Infrastructure (U-NII). The Wi-Fi Alliance reports that there are 19.5 billion Wi-Fi devices in use worldwide, in three bands: 2.4 GHz, 5 GHz, and 6 GHz.[81] In addition, the FCC's Equipment Authorization System shows over 88,000 devices that are certified to operate in the 5000-5925 MHz band.

9.4.1.3. 5925-7145 MHz

As shown in able 6, this is 1220 MHz of spectrum and contains eight band segments allocated to five services. The allocations range from 20 MHz wide to 500 MHz wide. The average allocation is a little more than 150 MHz.

The entire band is allocated on a primary basis to Fixed for international. Portions of the band are also allocated on a primary basis for Non-Federal (5925-6425 MHz and 6525-7125 MHz).

The entire band is also allocated on a primary basis to Mobile for international. Portions of the band are also allocated on a primary basis for Non-Federal (6425-6525 MHz and 6875-7125 MHz).

Fixed Satellite uplink has a primary allocation for international (5925-6700 MHz) and Non-Federal (5925-6700 MHz and 7025-7075 MHz).

Fixed Satellite downlink (and uplink) has a primary international allocation (6700-7025 MHz) and a Non-Federal allocation (6700-7025 MHz).

Finally, unlicensed Pt. 15 uses of the band are permitted for the Unlicensed National Information Infrastructure across most of the band (5925-7125 MHz).

The 5925-7145 MHz band is heavily used for point-to-point microwave. The FCC recently indicated there are almost 47,000 unique microwave call signs in the band.[82] The band is also used for Fixed Satellite. The FCC has indicated there are almost 1500 satellite call signs in the band.[83] The band has recently been opened for unlicensed use as part of the Unlicensed National Information Infrastructure (U-NII-5 to U-NII-8). Unlicensed use can be low power (at or below 30 dBm) or higher power (at or below 36 dBm). In addition, unlicensed point-to-point and fixed wireless access operation is permitted using directional antennas.

The majority of licensed systems (and some unlicensed systems as noted above) use highly directional antennas to focus energy in the direction of their associated receivers, which also use directional antennas. This is generally to overcome propagation loss, but also helps to mitigate interference. Propagation characteristics in this band will be slightly worse considering free space loss (~1.5 dB) than the 5000-5925 MHz band and are more susceptible to atmospheric refraction effects and diffraction over objects and terrain. Systems tend to operate more as line-of-sight.

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[81] https://www.wi-fi.org/beacon/the-beacon/wi-fi-by-the-numbers-technology-momentum-in-2023.
[82] See *Unlicensed Use of the 6 GHz Band*, Notice of Proposed Rulemaking, 33 FCC Rcd 10496, 10499-501 at ¶8.
[83] Id. at Appendix A.

9.4.1.4. 7145-8500 MHz

As shown in Table 7, this is 1355 MHz of spectrum and contains 15 band segments allocated to 15 services. The allocations range from 15 MHz wide to 200 MHz wide. The average allocation is a little more than 90 MHz.

Mobile has primary international allocations across the entire band. There is also a single primary Federal allocation (7375-7450 MHz).

Fixed has primary international allocations across the entire band. There are also primary Federal allocations across most of the band (7145-7250 MHz, 7300-7900 MHz, and 8025-8500 MHz) and two secondary Federal allocations (7250-7300 MHz and 7900-8025 MHz).

Fixed Satellite downlink has primary international and Federal allocations (7250-7750 MHz).

Fixed Satellite uplink has primary international and Federal allocations (7900-8400 MHz).

Earth Exploration Satellite uplink has primary international and Federal allocations (7190-7250 MHz).

Earth Exploration Satellite downlink has primary international and Federal allocations (8025-8400 MHz).

Maritime Mobile Satellite downlink has primary international and Federal allocations (7375-7750 MHz).

Meteorological Satellite downlink has primary international and Federal allocations (7450-7550 MHz and 7750-7900 MHz).

Meteorological Satellite uplink has a primary international and Federal allocation (8175-8215 MHz).

Mobile Satellite downlink has a primary Federal allocation (7250-7300 MHz) and secondary Federal allocations (7300-7750 MHz).

Mobile Satellite uplink has a primary Federal allocation (7900-8025 MHz) and secondary Federal allocations (8025-8400 MHz).

Space Research uplink has a primary international and Federal allocation (7190-7235 MHz).

Space Research downlink has a primary international allocation (8400-8500 MHz) and a primary Federal and Non-Federal allocation (8450-8500 MHz). Note, this is the only Non-Federal allocation in the 7125-8500 MHz band.

Finally, unlicensed use is permitted (7145-7250 MHz).

While most of this range is allocated exclusively for Federal for Fixed point-to-point microwave and Fixed Satellite uplink and downlink, there is substantial commercial interest in gaining access to all or portions of this band.[84]

Propagation in these bands is slightly worse considering free space loss (~1.6 dB) than the 5925-7145 MHz band, but more susceptible to atmospheric refraction and diffraction over objects and terrain. Systems tend to operate more as line-of-sight.

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[84] See, Accenture, “Spectrum Allocation in the United States,” Commissioned by CTIA, Sep. 2022 (https://api.ctia.org/wp-content/uploads/2022/09/Spectrum-Allocation-in-the-United-States-2022.09.pdf).

9.4.1.5. 8.5-10.0 GHz

As shown in Table 8, this is 1500 MHz of spectrum and contains 11 band segments allocated to eight services. The allocations range from 50 MHz wide to 200 MHz wide. The average allocation is a little over 135 MHz.

Radiolocation has a primary international allocation across the entire band and a primary Federal allocation across two portions (8.5-9.2 GHz and 9.3-10.0 GHz) plus a secondary Federal allocation (9.2-9.3 GHz). There is a secondary Non-Federal allocation across the entire band.

Earth Exploration Satellite (active) has a primary international and Federal and a secondary Non-Federal allocation (8.55-8.65 GHz). There is also a primary international allocation (9.2-9.8 and 9.9-10.0 GHz) and a secondary international allocation (9.8-9.9 GHz). There is a primary Federal allocation (9.3-9.8 GHz) and a secondary Federal allocation (9.8-9.9 GHz). There is a secondary Non-Federal allocation (9.3-9.9 GHz).

Aeronautical Radionavigation has primary international allocations (8.75-8.85 GHz and 9.0-9.2 GHz) and a primary Federal and Non-Federal allocation (9.0-9.2 GHz).

Fixed has a secondary international allocation (9.8-10.0 GHz).

Maritime Radionavigation has primary international allocations (8.85-9.0 GHz and 9.2-9.3 GHz) and a primary Federal and Non-Federal allocation (9.2-9.3 GHz).

Meteorological Aids has a secondary Federal and Non-Federal allocation (9.3-9.5 GHz).

Radionavigation has a primary international allocation (9.3-9.9 GHz). There are also primary Federal and Non-Federal allocations (9.3-9.5 GHz) and a primary Federal allocation (9.8-9.9 GHz).

Space Research (active) has primary international and Federal allocations (8.55-8.65 GHz and 9.3-9.8 GHz). There is a secondary international and Federal allocation (9.8-9.9 GHz) and secondary Non-Federal allocations (8.55-8.65 MHz and 9.3-9.9 GHz).

Commercial use of this band includes radiolocation, maritime radiolocation, and aeronautical radiolocation, mostly on a secondary basis.[85] As noted in Figure 5, several comments to the NSS suggested opening portions of this band to broader commercial use.

Propagation in these bands is slightly worse considering free space loss (~1.5 dB) than the 7145-8500 MHz band, but more susceptible to atmospheric refraction and diffraction over objects and terrain. Systems tend to operate more as line-of-sight.

9.4.1.6. 10.0-13.25 GHz

As shown in Table 9, this is 3250 MHz of spectrum and contains 17 band segments allocated to 14 services. The allocations range from 20 MHz wide to 500 MHz wide. The average allocation is close to 190 MHz.

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[85] See 47 CFR §90.103.

Fixed has primary international allocations (10.0-10.45 GHz, 10.5-10.68 GHz, and 10.7-13.25 GHz). There are also primary Non-Federal allocations (10.55-10.68 GHz, 10.7-11.7 GHz, and 12.2-13.25 GHz).

Mobile has primary international allocations (10.0-10.45 GHz, 10.5-10.68 GHz, and 10.7-13.25 GHz). There are also primary Non-Federal allocations (12.7-13.25 GHz).

Fixed Satellite downlink has primary international allocations (10.7-12.75 GHz). There are also primary Non-Federal allocations (10.7-12.2 GHz).

Radiolocation has primary international allocations (10.0-10.55 GHz) and secondary international allocations (10.55-10.68 GHz). There are also primary Federal allocations (10.0-10.55 GHz). There is a primary Non-Federal allocation (10.5-10.55 GHz) and secondary Non-Federal allocations (10.0-10.5 GHz).

Fixed Satellite uplink has primary international allocations (10.7-11.7 GHz and 12.5-13.25 GHz).

Broadcasting has primary international allocations (11.7-12.7 GHz).

Broadcasting Satellite has primary international allocations (11.7-12.75 GHz) and primary Non-Federal allocations (12.2-12.7 GHz).

Earth Exploration Satellite (active) has a primary international allocation (10.0-10.4 GHz).

Earth Exploration Satellite (passive) has primary international, Federal, and Non-Federal allocations (10.6-10.7 GHz).

Radio Astronomy has primary international allocations (10.6-10.7 GHz) and primary Federal and Non-Federal allocations (10.68-10.7 GHz).

Space Research (passive) has primary international, Federal, and Non-Federal allocations (10.6-10.7 GHz).

The 12.2-13.25 GHz portions of this spectrum are the subject of FCC rulemakings seeking to open these to flexible use. The 10.0-10.55 GHz portions are heavily used for commercial radiolocation and the 10.7-11.7 GHz and 12.2-13.25 GHz portions are heavily used for point-to-point microwave. The only Federal allocations are for radiolocation in the 10.0-10.55 GHz portion and Space Research (passive) in the 10.6-10.7 GHz portion.

Propagation in these bands is slightly worse considering free space loss (~2.0 dB) than the 10.0-13.25 GHz band, but more susceptible to atmospheric refraction and diffraction over objects and terrain. Systems tend to operate more as line-of-sight.

9.4.1.7. 13.25-15.7 GHz

As shown in Table 10, this is 2450 MHz of spectrum and contains 19 band segments allocated to 16 services. The allocations range from 30 MHz wide to 336.5 MHz wide. The average allocation is about 130 MHz.

Fixed has primary international allocations (14.3-15.35 GHz) and primary Federal allocations (14.5-14.7145 GHz and 15.1365-15.35 GHz). There are also secondary Federal allocations (14.4-14.5 GHz and 14.7145-15.1635 GHz).

Fixed Satellite uplink has primary international allocations (13.75-14.8 GHz and 15.43-15.63 GHz). There are also primary Non-Federal allocations (13.75-14.5 GHz and 15.43-15.63 GHz). In addition, portions of these frequency bands are part of the ITU's Planned Bands for developing countries.

Mobile has a primary international allocation (14.3-15.35 GHz). There are primary Federal allocations (14.7145-15.1365 GHz). There are also secondary Federal allocations (14.4-14.7145 GHz and 15.1365-15.35 GHz).

Radiolocation has primary international and Federal allocations (13.4-14.0 GHz, 14.2-14.25 GHz, and 15.4-15.7 GHz). There is a secondary Non-Federal allocation (13.4-14.0 GHz).

Aeronautical Radionavigation has primary international, Federal, and Non-Federal allocations (13.25-13.4 GHz and 15.4-15.7 GHz).

Earth Exploration Satellite (active) has primary international allocations (13.25-14.0 GHz) and primary Federal allocations (13.25-13.75 GHz). There is a secondary Non-Federal allocation (13.25-13.75 GHz).

Earth Exploration Satellite (passive) has a primary international, Federal, and Non-Federal allocation (15.35-15.4 GHz).

Space Research has primary international and Federal allocations (13.4-13.75 GHz) and secondary international allocations (13.75-14.3 GHz, 14.4-14.47 GHz and 14.5-15.1365 GHz). There are also additional primary Federal allocations (14.8-15.35 GHz). There are additional secondary Federal allocations (13.75-14.2 GHz and 14.5-14.8 GHz). There are secondary Non-Federal allocations (13.4-14.2 GHz).

Radio Astronomy has a primary international, Federal, and Non-Federal allocations (15.35-15.4 GHz).

Radionavigation has a primary international allocation (14.0-14.3 GHz).

Mobile Satellite uplink has secondary international and Non-Federal allocations (14.0-14.5 GHz).

Radionavigation Satellite has a secondary international allocation (14.3-14.4 GHz).

Space Research (active) has a primary international and Federal allocation, and a secondary Non-Federal allocation (13.25-13.4 GHz).

Space Research (passive) has a primary international, Federal, and Non-Federal allocation (15.35-15.4 GHz).

Finally, Standard Frequency and Time Signal Satellite uplink has secondary international, Federal, and Non-Federal allocations (13.4-14.0 GHz).

The 13.75-14.5 GHz bands are heavily used for commercial satellite uplink. The 14.5-14.7145 GHz and 15.1365-15.35 GHz bands are used for Federal point-to-point microwave systems.

Propagation in these bands is slightly worse considering free space loss (~1.9 dB) than the 8.5-10.0 GHz band, but more susceptible to atmospheric refraction and diffraction over objects and terrain. Systems tend to operate more as line-of-sight.

9.5. Millimeter Wave Frequencies

MMW frequencies were considered a new frontier in the run up to the development of 5G systems as a means to access large bandwidths in support of new use cases and aggressive KPI targets. WRC-19 identified more than fifteen GHz of spectrum between 24 and 71 GHz for IMT and 3GPP specifications including support for operation in several bands above 24 GHz (See table X earlier in this section). However, due to multiple factors including equipment complexity, propagation conditions, and economical aspects, deployments in these so-called "high bands," or "FR2" in 3GPP terms, have seen a much slower growth compared to lower frequencies.

In preparation for 6G, some research efforts have been made on the possibility of removing certain obstacles to utilization of MMW frequencies.[86] These efforts include the following areas:

- Improving coverage and moving toward a more uniform performance throughout the cell by using frequency selective and Reconfigurable Intelligent Surfaces (RIS).
- Improving range and going beyond "hot-spot" deployment model through the use of advanced beamforming and massive multi-antenna techniques.

It should be noted, currently most use of these frequencies by 5G systems is for Fixed Wireless Access deployments. Portions of these bands remain critical for satellite communications to support 6G as these are the key bands for broadband services.

9.6. Sub-THz and THz Frequencies

Appendix E contains an analysis of spectrum allocations and use of sub-THz spectrum domestically and internationally from 95 GHz to 275 GHz.[87] These bands are characterized by wider allocations to radiocommunication services and numerous bands allocated to scientific and space applications. In addition to increasing basic propagation losses due to increasing frequency, there are also unique propagation phenomena occurring in this range of frequencies due to atmospheric absorption effects, which impact the way these frequencies could be utilized (See Appendix E).

9.6.1. Information on Specific Spectrum Bands in the THz and Sub-THz Ranges

As can be seen in Appendix E, spectrum above 95 GHz contains many allocations to science services including Earth Exploration Satellite Service and Radioastronomy Service (RAS). Technical and operational characteristics of the systems operating in those allocations are contained in various ITU-R Recommendations and Reports. Not all bands allocated to these services in frequencies above 95 GHz are home to operational systems. However, these allocations are generally selected for specific bands due to scientific reasons mostly involving resonance frequencies of various molecules. Therefore, both current and future use of the bands with up-to-date operational parameters of the incumbent services should be considered.

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[86] Next G Alliance, *6G Technologies*, June 2022.

[87] ITU-R Radio Regulations lists allocations to radiocommunication services only up to 275 GHz. According to ITU-R definition, THz frequencies, or THF, is referring to the range of frequencies between 300 GHz and 3 THz. Therefore, in this report we refer to spectrum in the upper part of mm-wave (95 GHz to 275 GHz) as sub-THz. It should be noted that even though there are no allocations above 275 GHz, ITU-R Radio Regulations include designations to various radiocommunication services between 275 GHz and 1 THz through footnotes. Frequencies between 1 THz and 3 THz can be used by all services.

Earth Exploration Satellite Service applications up to 110 GHz include passive measurements of snow, sea ice, precipitation, and clouds as well as atmospheric temperatures. Above 110 GHz, in addition to precipitation and clouds, applications include water vapor and atmospheric chemistry measurements.[88]

The International Astronomical Union maintains and updates the list of spectral lines important to RAS. These spectral lines are specified both in bands allocated to RAS, as well as outside the allocated bands. Observations at rest frequencies and Doppler-shifted frequencies of the astrophysical important spectral lines as well as continuum observations spectral lines are specified up to 1 THz. See Figure E-2 in Appendix E for a depiction of these spectral lines up to 600 GHz.

Radiolocation service also has several relatively large allocations in frequencies above 95 GHz. However, the extent of current use of those bands, especially above 140 GHz, is not clear. The large allocations to radiolocation service in those frequencies renders itself to applications involving precision tracking. Based on some discussions in automotive radar communities, the possibility of a future move to radiolocation service bands above 95 GHz for automotive radars, due to congestion of current bands, has surfaced.

9.6.1.1. 95.0-174.5 GHz

As shown in Table 11, this is 79.5 GHz of spectrum and contains 21 band segments allocated to 14 services. The allocations range from 750 MHz wide to 7500 MHz wide. The average allocation is close to 3785 MHz.

Earth Exploration Satellite (active) has primary international, Federal and non-Federal allocations (100-102 GHz, 109.5-111.8 GHz, 114.5-122.5 GHz, 148.5-151.5 GHz, and 164-167 GHz). There is a primary international allocation (155.5-158.5 GHz).

Earth Exploration Satellite (passive) has a single primary international, Federal and non-Federal allocation (130-134 GHz).

Fixed has several primary international, Federal and Non-federal allocations (95-100 GHz, 102.109.5 GHz, 111.8-114.25 GHz, 122.25-123 GHz, 130-134 GHz, 141-148.5 GHz, 151.5-164 GHz and 167-174.5 GHz)

Fixed Satellite downlink has primary international, Federal and non-Federal allocations (123-130 GHz, 158.5-164 GHz and 167-174.5 GHz)

Inter-Satellite has primary international, Federal and non-Federal allocations (116-123 GHz, 130-134 GHz, and 167-174.5 GHz).

Mobile has several primary international, Federal and non-Federal allocations (95-100 GHz, 102-109.5 GHz, 111.8-114.25 GHz, 122.25-123 GHz, 130-134 GHz, 141-148.5 GHz, 151.5-164 GHz and 167-174.5 GHz).

Mobile Satellite downlink has a couple of primary international, Federal and non-Federal allocations (123-130 GHz and 158.5-164 GHz).

[88] Recommendation ITU-R RS.1861.

Radio Astronomy is very prominent in this band with several primary international, Federal and non-Federal allocations (95-116 GHz, 130-134 GHz, 136-158.5 GHz and 164-167 GHz). There are also two secondary international allocations, Federal and non-Federal allocations (123-130 GHz and 134-136 GHz).

Radiolocation has primary international, Federal and non-Federal allocations (95-100 GHz, 136-148.5 GHz and 151.5-155.5 GHz)

Radionavigation and Radionavigation Satellite have a couple of primary international, Federal and non-Federal allocations (95-100 GHz and 123-130 GHz).

Space Research (passive) has primary international, Federal and non-Federal allocations (100-102 GHz, 105-122.5 GHz, 148.5-151.5 GHz, and 164-167 GHz). There is also a primary international allocation (155.5-158.5 GHz).

Finally, unlicensed use is permitted (116-123 GHz).

Propagation in these bands is substantially affected by free space loss compared to the 13.25-15.7 GHz bands (~ 19.3 dB). However, as shown in Figure 6, propagation in these bands is affected more by oxygen and water resonance. For example, there are notable peaks at 118.75 GHz and 183.31 GHz where the attenuation is close to 100 dB. The nature of propagation in these bands may make them more useful for localized operation such as body area networks.

9.6.1.2. 174.5-3000 GHz

As shown in Table 12, this is 100.5 GHz of spectrum and contains 21 band segments allocated to 15 services. The allocations range from 300 MHz wide to 13000 MHz wide. The average allocation is over 5000 MHz. The spectrum above 275 MHz to 3000 GHz is not allocated.

Amateur and Amateur Satellite have a rare primary international and non-Federal allocation (248-250 GHz) and a secondary international and non-Federal allocation (241-248 GHz).

Earth Exploration Satellite (passive) has a primary international, Federal and Non-Federal allocation (174.8-191.8 GHz, 200—209 GHz, 226-231.5 GHz, 235-238 GHz, and 250-252 GHz).

Fixed has primary international, Federal and non-Federal allocations (174.5-174.8 GHz, 191.8-200 GHz, 209-226 GHz, 231.5-235 GHz, 238-241 GHz and 252-275 GHz).

Fixed Satellite downlink has primary international, Federal and non-Federal allocations (232-240 GHz).

Fixed Satellite uplink has primary international, Federal and non-Federal allocations (209-226 GHz and 265-275 GHz).

Inter-Satellite has primary international, Federal and non-Federal allocations (174.5-182 GHz, 185-190 GHz and 191.8-200 GHz).

Mobile has primary international, Federal and non-Federal allocations (174.5-174.8 GHz, 191.8-200 GHz, 209-226 GHz, 231.5-235 GHz, 238-241 GHz and 252-275 GHz).

Mobile Satellite downlink has a primary international, Federal and non-Federal allocation (191.8-200 GHz)

Mobile Satellite uplink has a primary international, Federal and non-Federal allocation (252-265 GHz).

Radio Astronomy has primary international, Federal and non-Federal allocations (182-185 GHz, 200-231.5 GHz, 241-248 GHz, and 250-275 GHz). There is also a secondary international, Federal and non-Federal allocation (248-250 GHz).

Radiolocation has primary international, Federal and non-Federal allocations (238-248 GHz) and secondary international, Federal and non-Federal allocations (231.5-235 GHz).

Radionavigation and Radionavigation Satellite have primary international, Federal and non-Federal allocations (191.8-200 GHz, 238-240 GHz and 252-265 GHz).

Space Research (passive) has primary international, Federal and non-Federal allocations (174.8-191.8 GHz, 200-209 GHz, 217-231.5 GHz, 235-238 GHz and 250-252 GHz).

Finally, unlicensed use is permitted (248-250 GHz).

Propagation in these bands is substantially affected by free space loss compared to the 13.25-15.7 GHz bands (~ 23.8 dB). However, as shown in Figure 6, propagation in these bands is affected more by oxygen and water resonance. For example, there are several peaks across the band where the attenuation is over 100 dB and a few where the attenuation is even greater. As noted above, the nature of propagation in these bands may make them more useful for localized operation such as body area networks.

9.7. Licensed and Unlicensed

Terrestrial licensed and unlicensed spectrum can support both commercial and federal agency 6G use cases. Licensed spectrum is typically used to achieve wide-area coverage, critical performance, and/or security requirements. In general, unlicensed spectrum can support wireless backhaul; localized terrestrial use cases complemented by other services such as satellite or fiber connectivity; and low-power uses such as picocell and indoor enterprise or residential use. Unlicensed 6G use cases are particularly relevant within dense urban environments and indoor settings.

As witnessed in the case of 6 GHz in the U.S. and elsewhere, protecting incumbents has been accommodated through varying regulatory conditions; where outdoor, high-power ubiquitous operation of new entrants is expected to create undue interference to incumbents, only low power indoor or very low power transmissions are allowed. Given that most of such low power applications operate under an unlicensed regime, the regulatory approach in 6 GHz has allowed sharing the band between licensed fixed links and unlicensed mobile systems.
This approach can be adopted for other bands, provided feasibility of sharing can be demonstrated, especially for higher frequencies in the sub-THz range where propagation losses, including building losses, are much more helpful in enabling sharing than in the 6 GHz band. Figure 5 from Recommendation ITU-R P.2109 depicts the median building loss for traditional buildings and thermally efficient buildings at frequencies up to 100 GHz. The building loss, especially for the case of thermally efficient buildings, which is the trend in most new constructions, is evident and can be taken advantage of for certain types of sharing, especially at higher frequencies (~55 dB at 100 GHz).

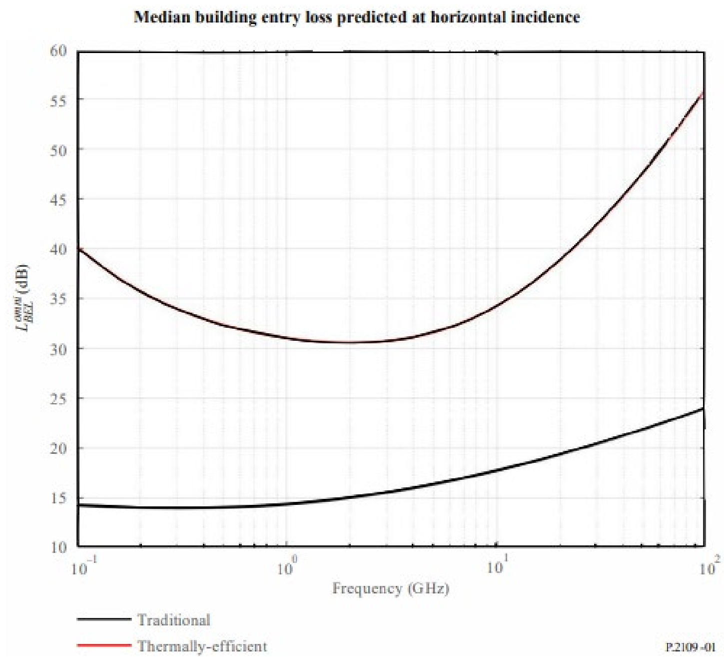

Figure 5 Median Building Entry Loss

In addition, in cases where operation of incumbent systems occur only in limited time or geography (e.g., in the 3.45-3.55 GHz), new entrants might be allowed even with high-power outdoor operation, common with licensed mobile systems. In general, a "toolbox" approach to spectrum sharing discussed earlier in this section can be adopted to best match sharing approaches to the specific conditions of each band.

10. International Considerations

6G technology is expected to improve global communications coverage, compatibility of handsets, and security and privacy concerns. Cloud solutions, for example, enable the RAN in one country and the base station in another country. The CSMAC considered it worthwhile to mention a few international considerations that can affect the viability of 6G use cases, given their potential global applicability. Those considerations include global standardization, global spectrum availability, and global manufacturing economies of scale. These are not unique considerations for the 6G ecosystem, but are equally applicable and important to a range of manufacturing sectors in the U.S. economy (e.g., aviation, defense). Despite the potential global applicability, there can be national differences in approach to 6G services, whether regulatory schemes, licensing obligations, security requirements, or spectrum availability, that could impact the future direction of 6G use cases and technology. In the context of standardization, it is important that the U.S. government implement the National Standards Strategy in collaboration with industry stakeholders, in a way that minimizes the risk of fragmentation in the development of standards. Security considerations could be advanced by the U.S. continuing to identify policies that foster the development of U.S.-based manufacturing in the 6G ecosystem, which will bring both economic and security benefits to the U.S. It would advance security objectives for the U.S. to continue to work with its allies and partners to support trusted suppliers in the interim.

Finally, while global harmonization of spectrum has traditionally been an objective, it is unclear whether harmonization of the bands remains as critical with the evolution of chipsets for terrestrial networks. However, for satellite networks, it remains an important consideration because of cost and weight considerations of including multiple bands on space craft. However, it is increasingly complex to achieve global harmonization of spectrum bands, should standards bodies continue to target heavily incumbered, national security spectrum bands. Nonetheless, the harmonization of bandwidth continues to be important, irrespective of the bands, for both terrestrial and non-terrestrial services.

11. Findings

The subcommittee has observed that carriers are still focused on deploying 5G and moving on to 5G-Advanced, which will take a few years. On the other hand, RAN and device vendors are aggressively defining 6G technology elements and spectrum for 6G.

Carriers and network infrastructure vendors see open networks and Open Radio Access Network (ORAN) as dominant in the 6G era.

This section presents the subcommittee's overall findings on use cases and spectrum.

11.1. Use Cases

The subcommittee contends that, given the early stage of its development, the state of 6G is currently enduring a clash between visionary ideas and practical realism. The subcommittee observed that currently equipment providers and researchers are driving the development of 6G visionary ideas on evolution of legacy as well as newly defined use cases, until service providers complement the process by providing operational and business requirements for their choice of use cases commensurate with their business objectives and plans.

There is a need to address the challenges of 6G, which include filling the gaps of 5G by properly addressing usage scenarios and applications that have not been widely developed and deployed yet. Challenges include making the business case and achieving the expected return on investment, the need for convergence of vision and the path forward, the risk of fragmentation, and regional divergence.

There are always tradeoffs between economies of scale, economies of specialization, and economies of scope as well as between open architectures and diverse specialized systems. These tradeoffs are expected to impact both the business case and the market for 6G. The subcommittee suggests that indicators of use case viability and eventual adoption by users should include several factors including R&D investment by both public and private sources, technology readiness level progression, convergence, low barriers to entry, and demonstrated societal and economic impact.

11.2. Spectrum

Most focus for terrestrial use is now on mid-bands and extending them up to around 15 GHz (in contrast to MMW or THz).[89] Other bands are being considered for non-terrestrial use. Interest in sub-THz spectrum is limited to research areas for mostly short-range communications and have a longer associated timeframe for commercial use.

[89] For instance, see *6G Spectrum Considerations*, NGA, August 2023, https://www.nextgalliance.org/white_papers/6g-spectrum-considerations/.

There is lack of suitable dedicated or shared spectrum for 6G. The subcommittee considered various frequency ranges for potential 6G use, including both terrestrial and non-terrestrial services, described below.

- Low-band spectrum has not been a focus for terrestrial 6G. This spectrum is generally congested. However, spectrum that is under-utilized, particularly in large geographic areas with relatively few users, could be pieced together via carrier aggregation and multi-radio connectivity for increased coverage. There are also recent activities around the world for augmenting terrestrial coverage through space (MSS) by utilizing some low-band spectrum to provide connectivity directly to user devices.
- Mid-band—considered the sweet spot between coverage, capacity, and contiguity—is of widespread interest for supporting terrestrial 6G applications and use cases. Most, if not all, of IMT spectrum proposals under consideration in ITU-R Regions for study toward WRC-27 are in mid-bands.
- MMW is valuable spectrum for enabling "information showers" via wireless local and personal area networks for home, office, transportation center, and city hotspot access. Portions of these bands remain critical for satellite communications, including to support 6G.
- The sub-THz and THz bands are suited for fixed wireless and backhaul, high bandwidth applications if feasible, and passive services.

12. Recommendations to Help Prepare for Impact to Government Users

The CSMAC 6G subcommittee offers recommendations to help prepare for 6G's impact to government users. An important caveat, and in line with the mandate from NTIA, is that this report does not include operational impacts to federal government users. CSMAC was directed that the effort should consider generally the benefits to federal government user, the positives for the federal government as a user of federal equities, and how federal agencies can benefit broadly from 6G.

Therefore, CSMAC recommends the following:

1. NTIA should work with the FCC and federal agencies to develop more spectrum sharing-friendly plans and designs across government and commercial systems.
    a. NTIA should engage early with federal incumbents with assignments in bands of particular interest for 6G, including mid-bands and above 95 GHz, to understand the type and degree of use and ability to share.
    b. NTIA should work with FCC to leverage more data-driven, automated, and dynamic methods into its plans, such as the incumbent informing capability vision and use of schedulers.
2. NTIA should work with the FCC, federal agencies, the White House, and Congress to consider acquisition reform and incentives for federal agencies and commercial industry to use spectrum as efficiently and effectively as possible to increase spectrum sharing and/or facilitate relocation, as appropriate.

13. CSMAC Recommendations

CSMAC's recommendations to NTIA are as follows:

Use Case Recommendations:

1. NTIA should work with federal agencies to identify, if and when, commercial 6G services would benefit their missions, characterize any expected differentiated requirements (such as related to standards, security, and technical performance criteria) in alignment with the ITU-R timeline, and coordinate with industry to address federal agencies requirements.

Spectrum Recommendations:

2. NTIA should work with the FCC, federal agencies, the White House, and Congress to proactively help prepare for the impact of 6G to government users, as described in Section 12 above.
3. NTIA should work with federal agencies to update the spectrum compendium more frequently, adding additional, more detailed and granular data, e.g., location and time of use, describing federal spectrum uses and extending its compendium above 7.125 GHz to at least the THz range.
4. NTIA should adopt a "toolbox" approach to spectrum sharing (see Section 9) to best match sharing approaches to specific conditions by customizing sharing techniques to frequency band and range of incumbent systems (including commercial incumbents) and consider the requirements of commercial services in the process of devising and implementing new sharing methods. Also, less management may be required in the sub-THz or THz ranges where propagation, including building losses, are helpful in enabling sharing.
5. NTIA should collaborate with the FCC to facilitate innovation in THz spectrum for 6G on an exploratory basis (e.g., waivers, possible additional unlicensed spectrum), considering that operations tend to be localized based on the propagation characteristics of this range.

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Appendix A Interview Questionnaire

Background and Question from NTIA:

The National Telecommunications and Information Administration (NTIA) provided the following background and question to the Commerce Spectrum Management Advisory (CSMAC) Subcommittee 2:

Background: Industry research and planning is well underway for 6G, expected to be the next major evolution of commercial wireless technology. The current interest and expectation for the U.S. to be a world leader in 5G will only increase for 6G, such that while deployment in earnest may be years out (2030 often cited as a target), the USG and the industry ecosystem must take steps now to lay the foundation for success.

Question: NTIA seeks input on what sort of use cases 6G may entail. Importantly, NTIA would like the CSMAC to consider use cases beyond traditional wireless communications including safety, sensor, radar, space and other scientific applications and address 6G's potential impact on federal government users. When considering spectrum bands that could be used to support 6G, NTIA observes that the THz bands have been identified for potential use; how would such use impact government users in that range and what recommendations could be made to help prepare for this. Are there other spectrum bands that may be appropriate for 6G and beyond use?

NTIA provided clarification that the scope of the subcommittee's work effort should concentrate on 6G services only. This effort should consider generally the benefits to federal government user, the positives for the federal government as a user or federal equities, and how federal agencies can benefit broadly from 6G.

Introduction

1. What is your organization's involvement in 6G development?

6G Use Cases

2. What traditional wireless 6G use cases do you expect?
    a. Do you expect federal government users to benefit from these?
    b. If so, how?
    c. If not, why?
3. What 6G use cases do you expect beyond traditional wireless communications including safety, sensor, radar, space and other scientific applications, and any emerging/new use cases?
    a. Do you expect federal government users to benefit from these?
    b. If so, how?
    c. If not, why?
4. What unlicensed 6G use cases do you expect?
    a. Do you expect federal government users to benefit from these?
    b. If so, how?
    c. If not, why?
5. Are there any differences across domestic and international use cases and, if so, what?
6. Do you have any other thoughts or suggestions on how federal government users can benefit from 6G?

Spectrum Considerations

7. How would use of mid-band spectrum for 6G impact government users in that range?
    a. If additional spectrum sharing is required for 6G services, would this be feasible, and why or why not?
    b. If so, in broad terms, what are your thoughts on how this spectrum could be shared?
    c. If not, what are the pertinent obstacles?
    d. What could help prepare for use of mid-band spectrum for 6G?
8. How would use of THz bands (with specific interest above 95 GHz) impact government users in that range?
    a. If additional spectrum sharing is required for 6G services, would this be feasible, and why or why not?
    b. If so, in broad terms, what are your thoughts on how this spectrum could be shared?
    c. If not, what are the pertinent obstacles?
    d. What could help prepare for use of THz bands for 6G?
9. Do you expect open networks and virtual networks to impact government users and, if so, how?
10. Do you have any other thoughts or suggestions on how to help prepare for impacts to government users?
11. What international spectrum considerations are important?

Other

12. What other national or international considerations are important?
13. What are the most important steps or research needed to make sure your organization's requirements are met?
14. Are there any other thoughts you would like to provide?

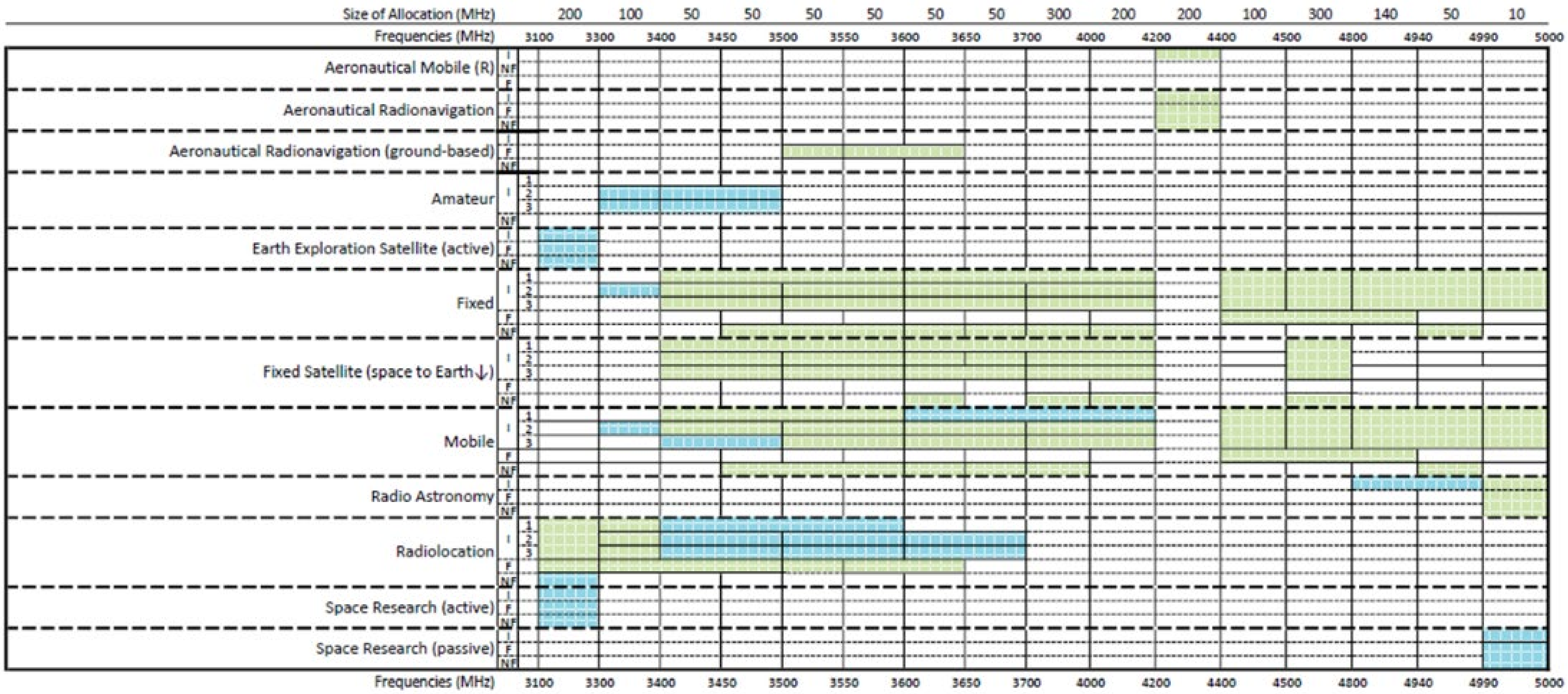
Appendix B Interviews Conducted

This appendix lists the surveys and interviews conducted by CSMAC. Thank you to these organizations for their responses!

Organization
6G Flagship
Amazon - AWS
Broadcom
CableLabs
Cisco
CTIA
Department of Defense – DISA DSO
Department of Defense – OUSD (R&E)
Department of Homeland Security – Science & Technology
Department of Energy – Idaho National Laboratory
Department of Energy – Pacific Northwest Laboratory
Department of Interior
Department of Justice
Department of State
Department of Transportation - PNT
Department of Treasury
EchoStar
Ericsson
Google
Hexa-X and 6G-IA
Intel
Intelsat
Japan 6GPG
Microsoft
Networld Europe
Next G Alliance
Nokia
NTIA - ITS
ORAN Policy Alliance
Qualcomm
Samsung
SES
SpaceX
SpectrumX
USAGM
VMware
White House - National Security Council

Appendix C Spectrum Allocations in the 3-15 GHz Range

Table 5 Spectrum Allocations in 3100-5000 MHz



Legend
Primary
Secondary
Unlicensed/ISM
I - International
(1,2,3 - ITU Region)
F - Federal
NF- Non-Federal

Statistics	
1900	MHz Total Spectrum
16	Band Segments
12	Allocations

Table 6 Spectrum Allocations in 5000-5925 MHz

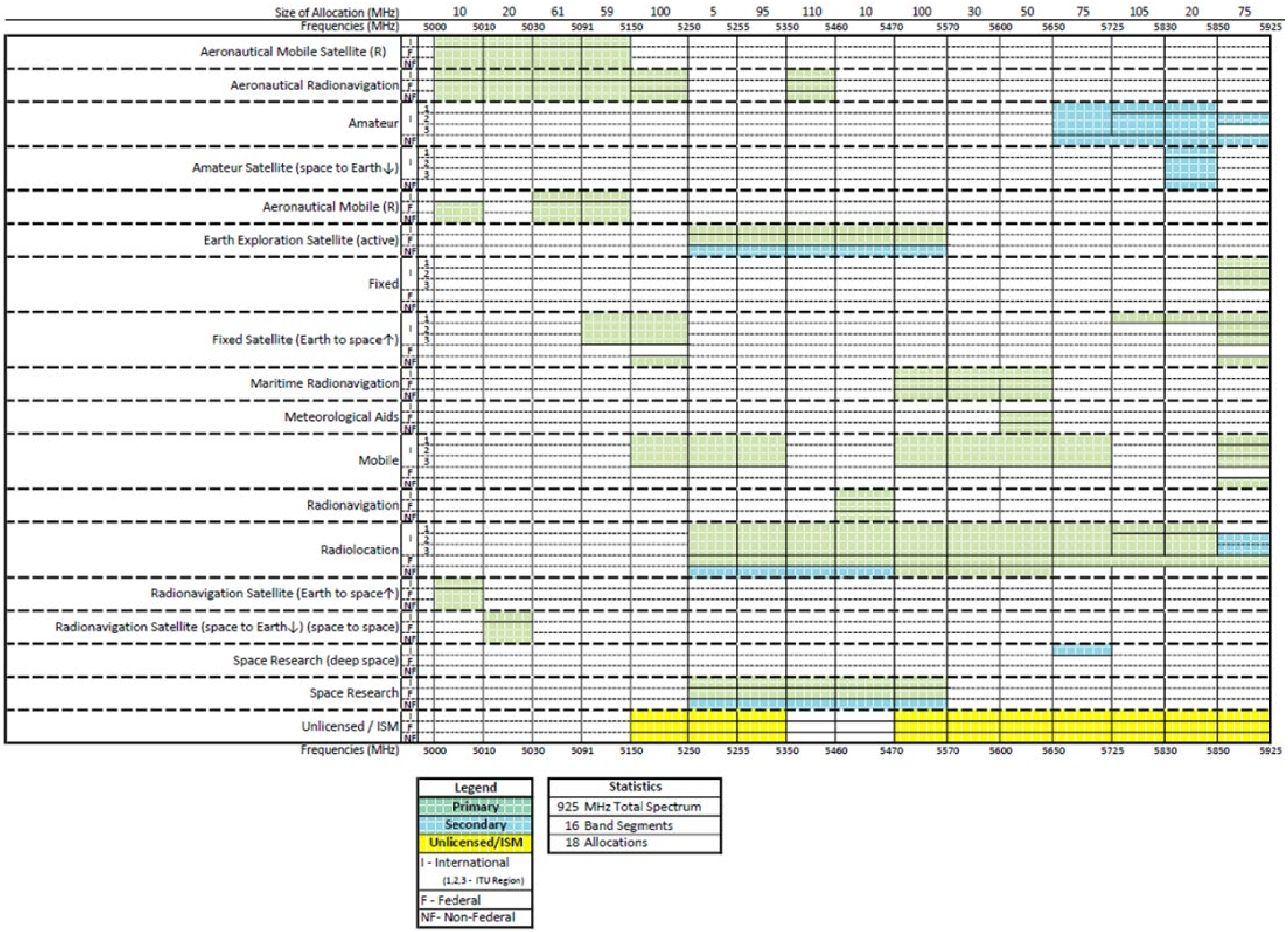


Table 7 Spectrum Allocations in 5925 MHz-7145 MHz

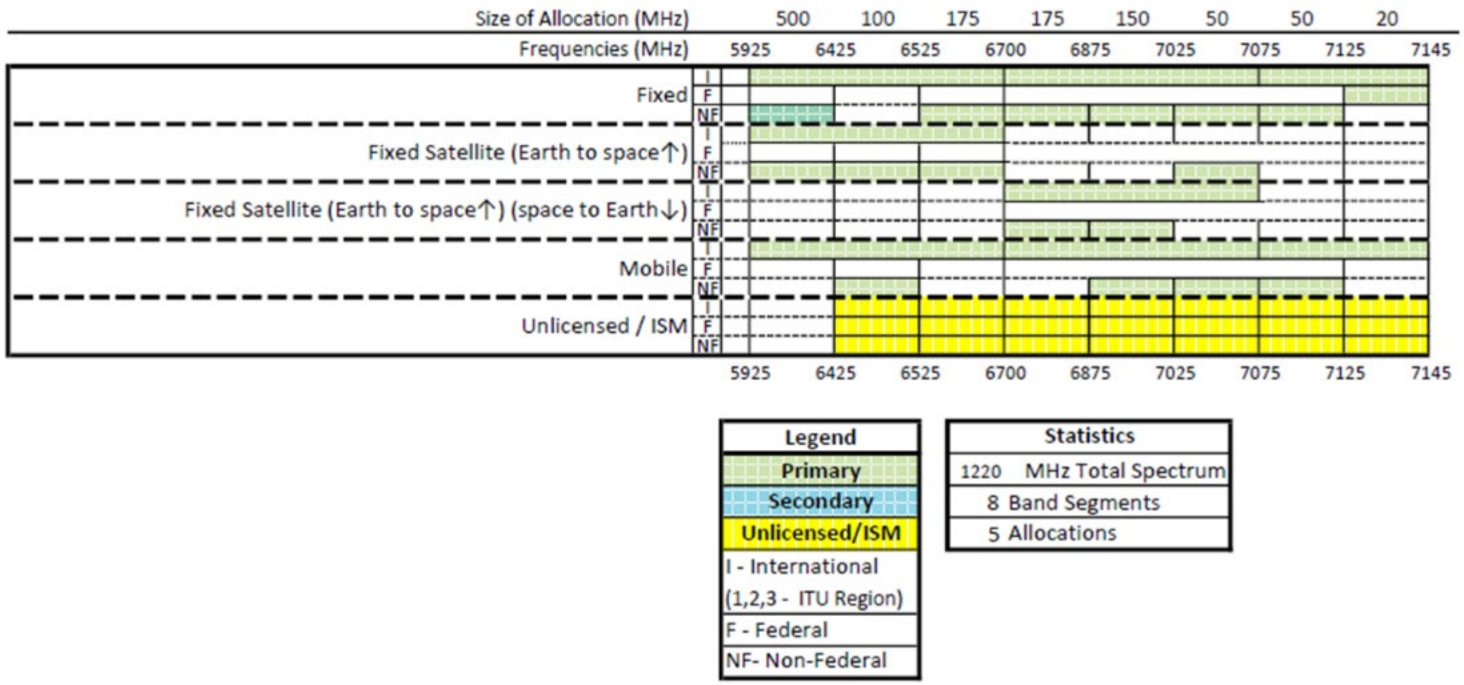


Table 8 Spectrum Allocations in 7145 MHz-8500 MHz

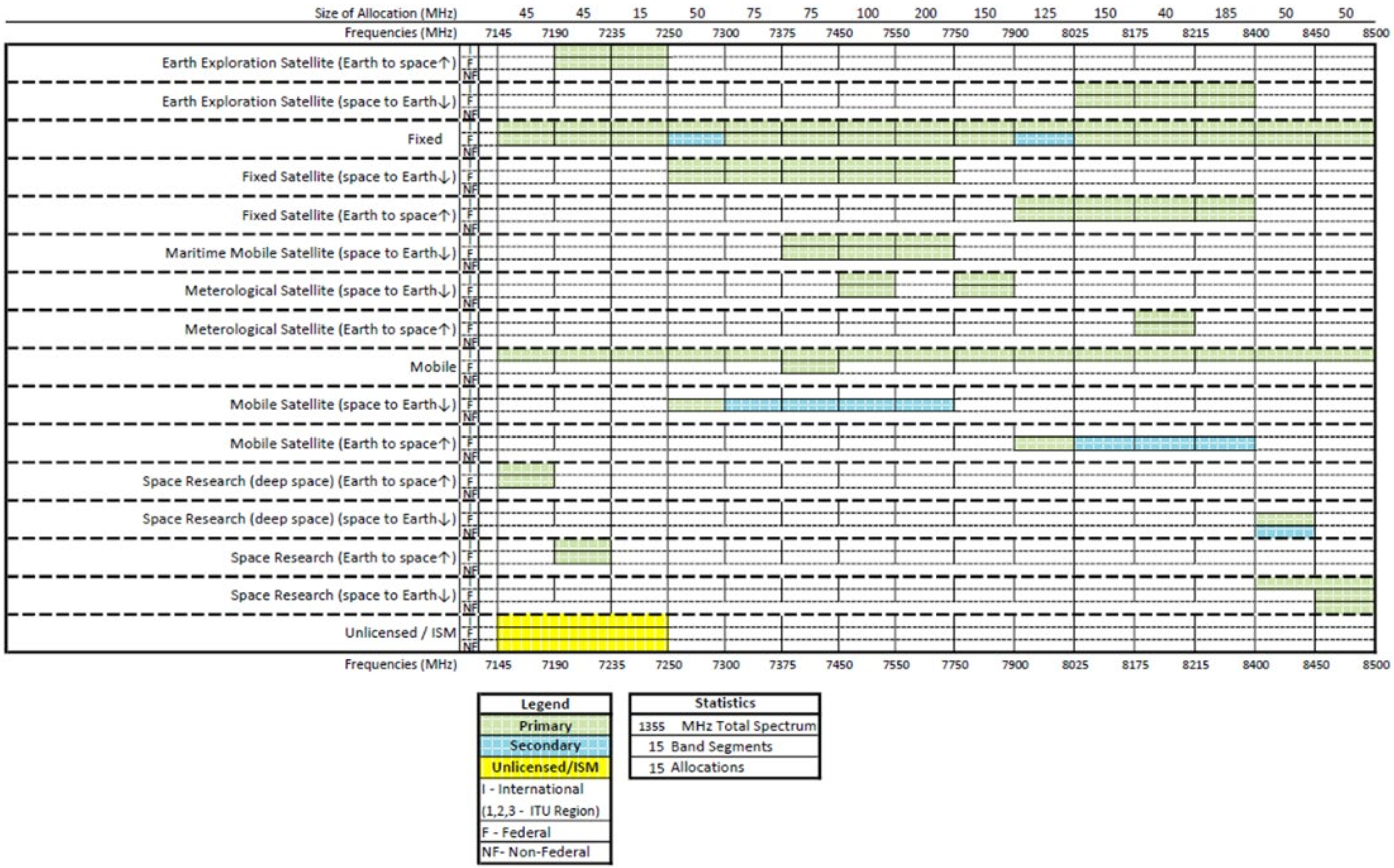


Table 9 Spectrum Allocations in 8.5-10.0 GHz

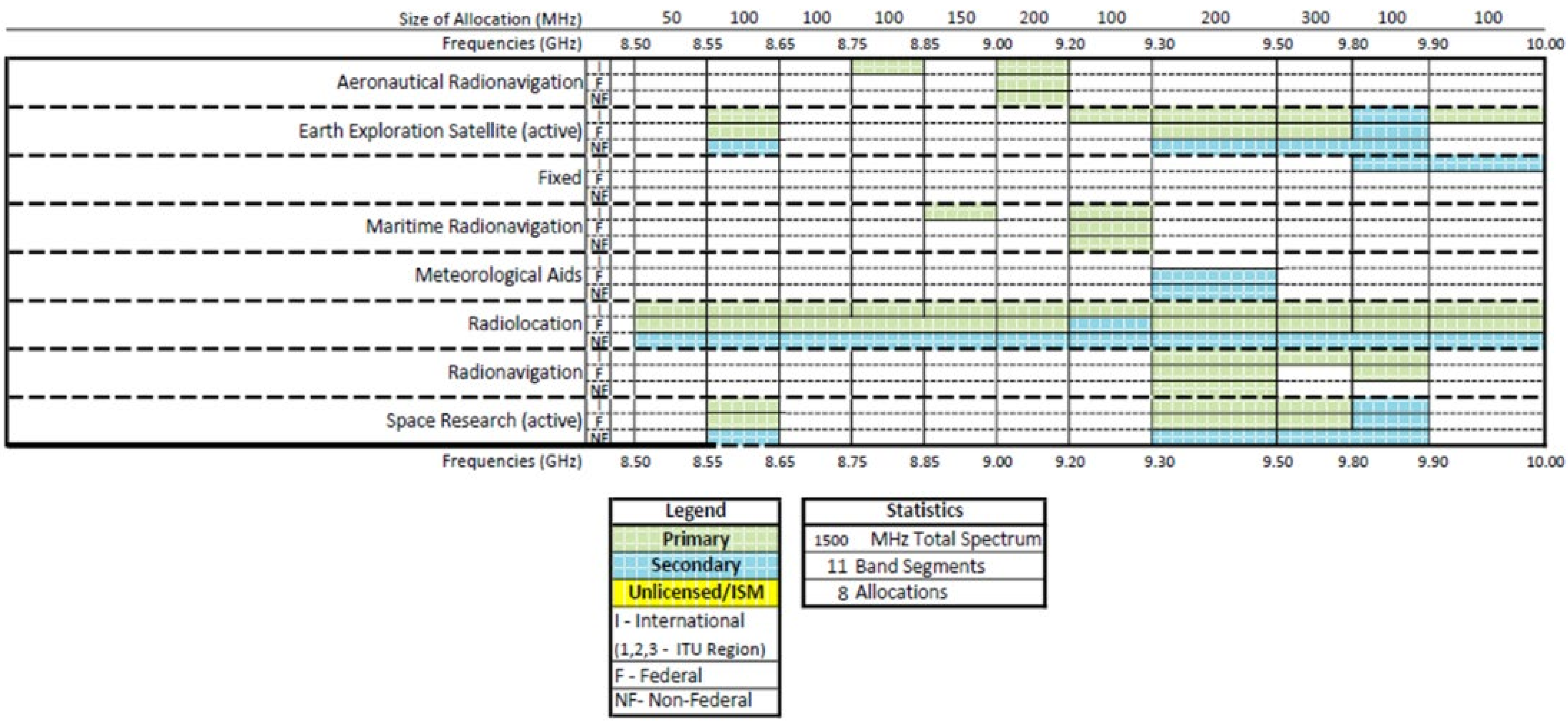


Table 10 Spectrum Allocations in 10.0-13.25 GHz

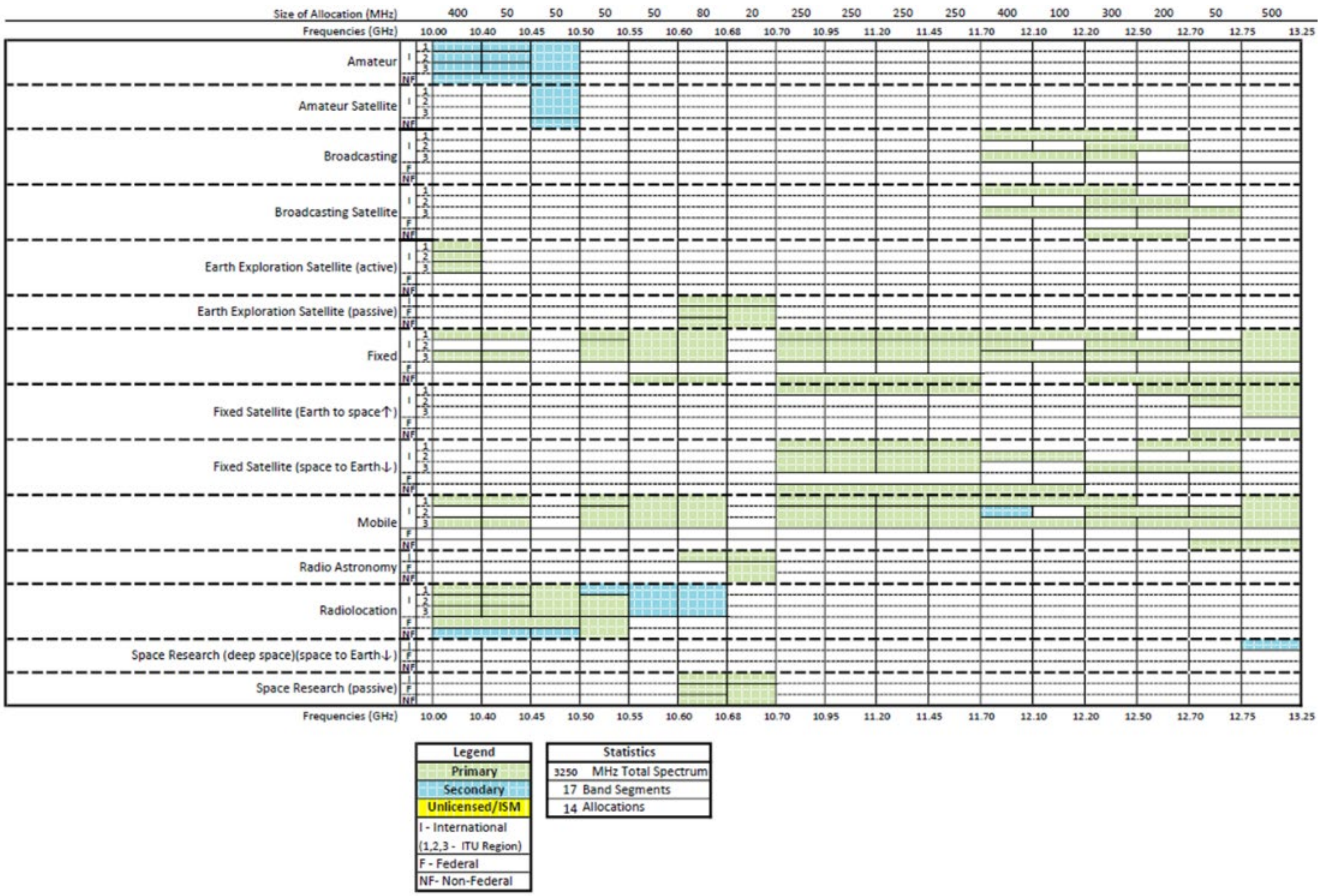
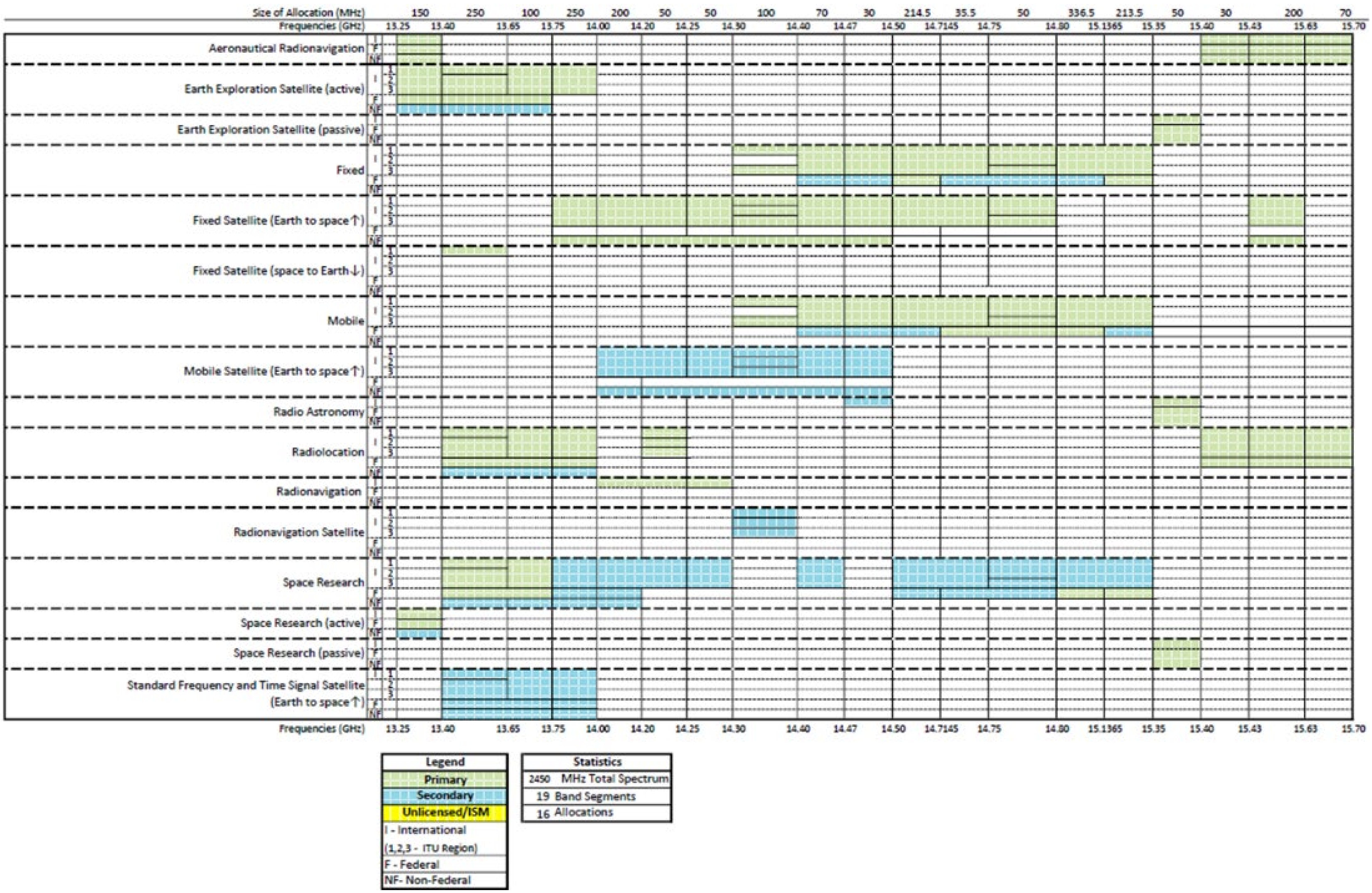


Table 11 Spectrum Allocations in 13.25-15.7 GHz



Appendix D Spectrum Allocations in the 95-3000 GHz Range

Table 12 Spectrum Allocations in 95.1-174.5 GHz

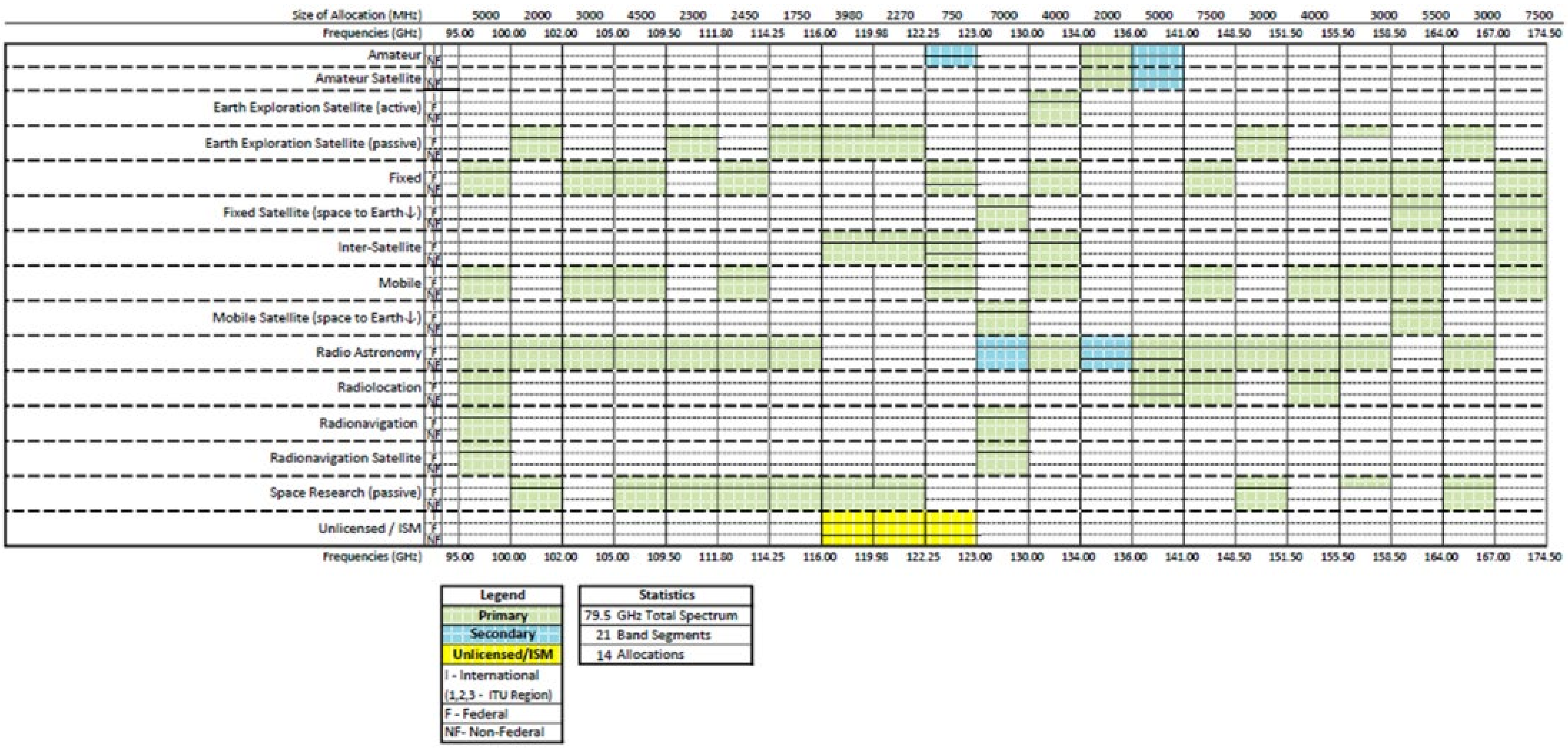


Table 13 Spectrum Allocations in 174.5-3000 GHz

Legend
Primary
Secondary
Unlicensed/ISM
I - International
(1,2,3 - ITU Region)
F - Federal
NF- Non-Federal

Statistics
100.5 GHz Total Spectrum
21 Band Segments
15 Allocations

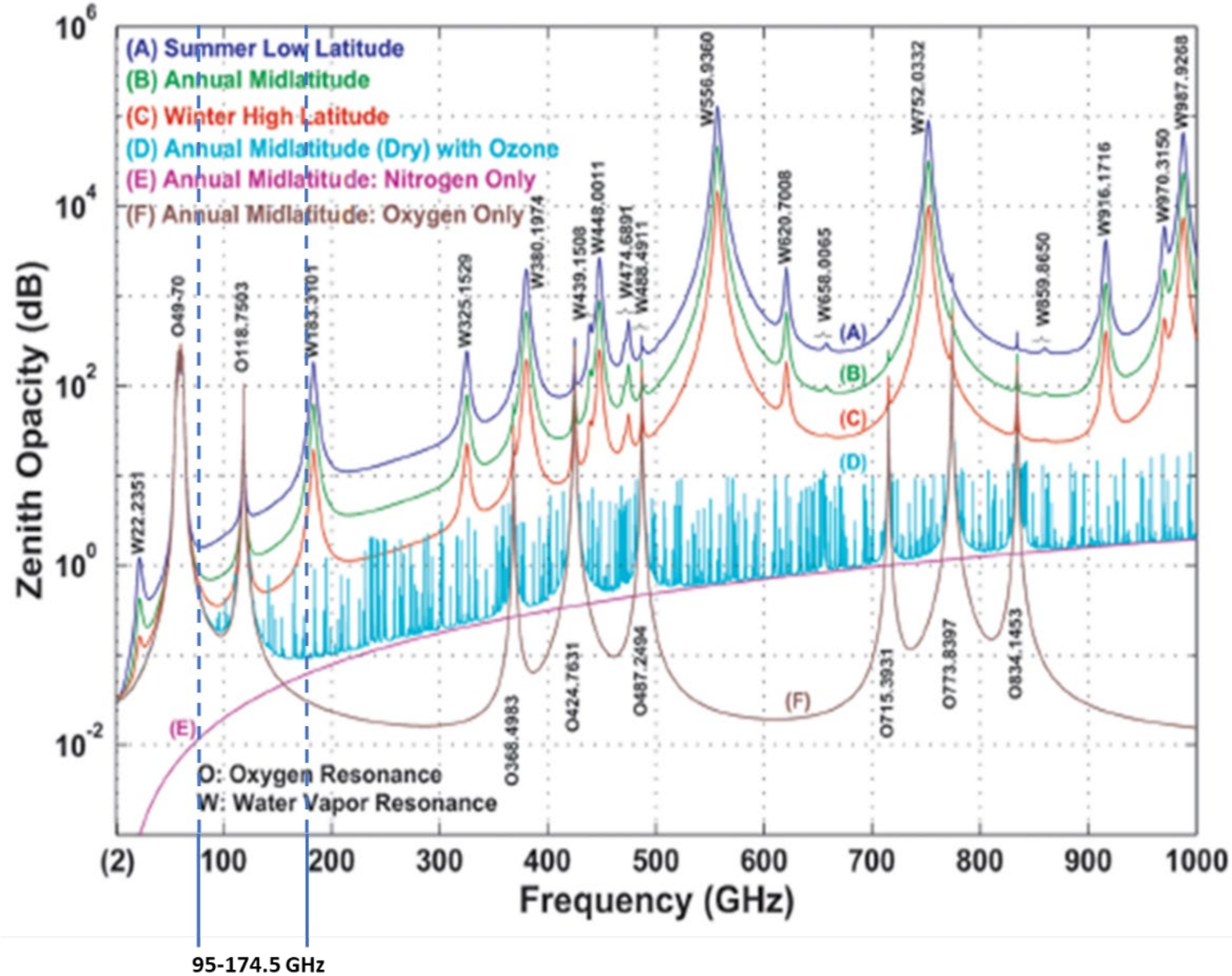
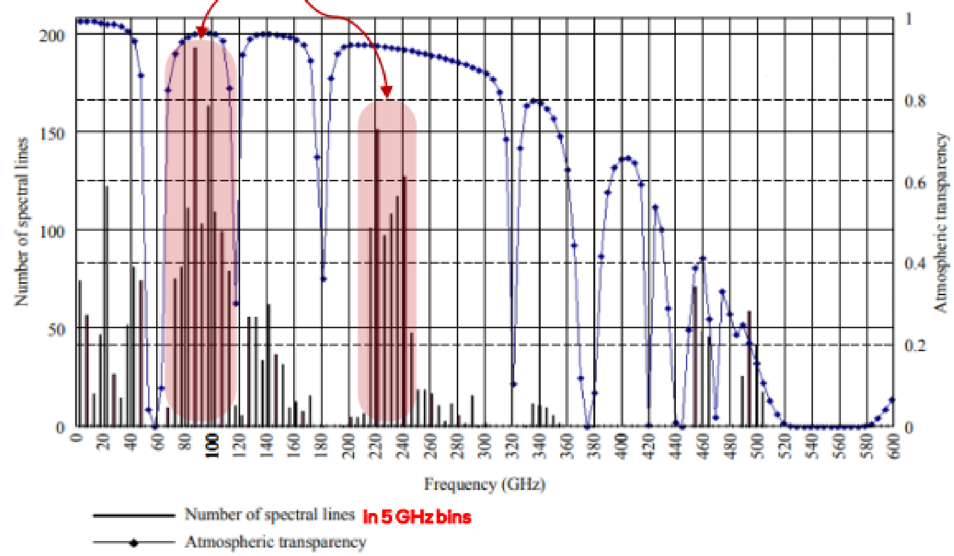


Figure 6 Atmospheric Absorption Effects (The zenith opacity is the vertically integrated absorption coefficient [Recommendation ITU-R P.676-13 (08/2022) Attenuation by atmospheric gases and related effects]

Very high concentration of spectral lines

FIGURE 1

Frequency distribution of spectral lines detected by radio astronomical observations and atmospheric transparency below 600 GHz



Note – Histogram shows the number of currently detected spectral lines, in 5 GHz bins. Several lines have been detected above 600-625.9 GHz (HCl), 691.5 GHz (CO), 806.9 GHz (CO) and 809.3 GHz (C). The US standard atmosphere model was used for the calculation of atmospheric transparency. The transparency was calculated in every 5 GHz bin for: altitude = 4.2 km, H_2O pressure = 1 mm precipitation, and pressure = 640 hPa. Atmospheric transparency is the fraction of energy from outside of the atmosphere, that reaches the surface of the Earth. It can be related with the atmospheric attenuation by attenuation (dB) = –10 log (transparency).

Figure 7 Frequency Distribution of Spectral Lines Used by RAS up to 600 GHz

Appendix E Acronyms

Acronym	Definition
3GPP	3rd Generation Partnership Project
6G	Sixth-generation
6G-IA	6G Smart Networks and Services Industry Association
AI	Artificial Intelligence
AR	Augmented Reality
CJS	Commerce, Justice, Science, and Related Agencies
Cobots	Collaborative Robots
CSMAC	Commerce Spectrum Management Advisory
DNR	Draft New Recommendation
eMBB	Enhanced Mobile Broadband
ESA	European Space Agency
EU	European Union
FCC	Federal Communications Commission
FR	Frequency Range
FY	Fiscal Year
GHz	Gigahertz
GPS	Global Positioning System
ICT	Information Communications Technology
IMT	International Mobile Telecommunication
IoT	Internet of Things
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union Radiocommunications Sector
KPI	Key Performance Indicators
MHz	Megahertz
ML	Machine Learning
mMIMO	Massive Multiple-Input Multiple-Output
mMTC	Massive Machine Type Communications
MMW	Millimeter Wave
NGA	Next G Alliance
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development
NR	New Radio
NTIA	National Telecommunications and Information Administration
NTN	Non-Terrestrial Networks
Ops	Organizational Partners
PATHSS	Partnering to Advance Trusted and Holistic Spectrum Solutions
PNT	Positioning, Navigation, and Timing
R&D	Research and Development
RAN	Radio Access Network
RAS	Radioastronomy Service

SNS JU	Smart Networks and Services Joint Undertaking
THz	Terahertz
TIP	Technology, Innovation, and Partnership
TN	Terrestrial Networks
TPRs	Technical Performance Requirements
U.S.	United States
URLLC	Ultra-Reliable and Low Latency Communications
USG	United States Government
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VR	Virtual Reality
WG	Working Group
WP5D	Working Party 5D
WSRD	Wireless Spectrum Research and Development
WRC	World Radiocommunication Conference
XR	Extended Reality