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PATH TO SMART **6G SPECTRUM ACCESS**

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Introduction

The impact of sixth-generation (6G) communications is expected to be even more transformative than fifth-generation (5G) wireless technology. Although not yet fully defined, this advanced technology and its applications will likely follow the path of their predecessors, spurring economic growth and productivity, unlocking massive gross domestic product (GDP) growth and new industry verticals. With sound policy, 6G can also influence and enhance national and economic security, social equity, quality of life, and democratic values contributing to global peace and prosperity.

MITRE's vision for 6G is expansive: on-demand connectivity of every device, at any location and any time. To achieve this technological breakthrough, we must identify additional spectrum. This MITRE white paper identifies technical and spectrum requirements of 6G and proposes recommendations that provide a path toward ensuring sufficient spectrum for 6G while preserving other radio services vital to the U.S. economy and national security. Given the importance of these objectives, this paper calls for the earliest possible involvement of both technical and policy-oriented executives from government, while balancing the needs of evolving wireless technologies and standards.

US 6G LEADERSHIP NEEDS BOLD ACTION.

National-level Approach and Leadership –

From strengthening the spectrum regulatory structure to establishing shared goals and actions, our nation needs to unite industry, government, and academia in a concerted 6G approach.

Research and Development – America needs a whole-of-nation 6G R&D strategy that includes a community of interest, common research challenges, accountability for results, and the resources needed to sustain global 6G leadership.

Spectrum Reimagined – The time has come to question existing assumptions about spectrum allocation and use. Revolutionizing spectrum access will require breaking down barriers to identify what is in the art of the possible for spectrum use. We also need more efficient ways to use the spectrum, whether it's through AI, advanced spectrum sharing technologies, or even the use of quantum science.

This paper is organized as follows:

- Section 2 discusses performance requirements for 6G and the amount of spectrum required to support these requirements.
- Section 3 describes challenges associated with various spectrum components.
- Section 4 provides a summary and recommendations.
- Section 5 issues a call for action.

Vectors to 6G

This section describes expected requirements and key performance indicators (KPI) for 6G.

Requirements: KPIs

The standards and use cases for 6G are not yet fully defined^{1,2}. This paper extends previous studies and subject matter expert (SME) input and postulates a first-order approximation of spectrum requirements for 6G. Based on MITRE's interaction with the telecommunications industry, emerging technical characteristics of 6G currently include:

- A 100x increase in peak **data rates** from a per-device peak data rate of 10 gigabits per second (Gbps) for 5G to 1 terabit per second (Tbps) for 6G. Higher bandwidth methods are needed to facilitate these increased data rates.³
- A 10x decrease in **end-to-end latency** from 10 milliseconds (ms) for 5G to 1 ms in 6G.⁴ Lower latencies likely require extremely close computing and all-optical switching and routing at the towers.
- A 100x increase in the **density** of connected devices from 5G to 6G.⁵ This requires better spectrum efficiencies and adaptive routing protocols.

- The integration of **pervasive artificial intelligence (AI)** with 6G in contrast to the partial integration of AI for 5G. This integration requires cross-layer orchestration from waveform to application.

Requirements: Electromagnetic Spectrum

To meet the extraordinary vision and emergent requirements of this next generation of communications, additional spectrum will be needed. Spectrum requirements will differ by use case, and 6G use cases are under development and not yet defined. Spectrum requirements for 6G may follow trajectories of growth set by previous generations of technology or could expand beyond a linear extrapolation. Even assuming a linear extrapolation, 6G is expected to require large swaths of spectrum due to the massive data rates that will define the next phase of the cellular evolution.

Based upon historical trends, channel bandwidths need to expand 2.5-fold from 5G: from 100 megahertz (MHz) maximum to 250 MHz at mid-band, or Frequency Range 1 (FR1⁶), and from 400 MHz to 1 gigahertz (GHz) at high-band, or millimeter wave (mmW), (FR2).⁷ Additionally, it is expected that the FR2 range will need to be expanded into higher frequencies to accommodate expansion into terahertz ranges. This assumes four times as much traffic on high frequencies.

By some accounts, the amount of spectrum required for 6G may be greater than that predicted using linear extrapolation. Channel bandwidth has increased four times between generations, from 3G (5 MHz) to 4G (20 MHz) to 5G (100 MHz).⁸ Therefore, researchers from Nokia Bell Labs have predicted the need for a four-times (4x) increase in spectrum, which when multiplied by a five-times (5x) increase in spectral efficiency will provide a twenty-times improvement in capacity.⁹

Spectrum requirements for 6G are multi-faceted and depend on many investment and resource tradeoffs that can be optimized to increase spectrum efficiency and spectrum utilization efficiency. Some of the factors that must be balanced are identified in Table 1.

As described above, multiple factors affect spectrum requirements for 6G, and these factors cannot be fully assessed until 6G use cases are refined. Therefore, the exact amount of spectrum required for 6G is not yet possible to estimate.

Table 1. Considerations that will Influence 6G Spectrum Requirements

Characteristic	Consideration
Cell size	Small cell size enables greater reuse of the spectrum resources and therefore reduces spectrum requirements. However, smaller cells require an increased investment in infrastructure, including power, and could delay deployment due to construction, installation, and permitting processes.
Morphology	Use cases differ by urban, suburban, and rural areas. High-band and mid-band spectrum will likely be built out only selectively in rural areas. Given the relatively larger swaths of land and lower population densities, wide geographic coverage of mid- and high-band spectrum is not economically feasible in these areas without additional economic support.
User Equipment Density	The greater the population or user density, the more opportunities exist to generate revenue on a per person, per user, per household, or per account basis.
Temporal use	Sharing spectrum via time allotments may enable more efficient use of spectrum resources but adds to network complexity and reduces resilience to unusual demand cycles.
Power	Higher power limits enable more application options, whereas lower power limits increasingly constrain the viability of applications. Increased power limits are essential for coverage in low-population areas. However, higher power limits can make sharing spectrum more challenging.
Directionality	The greater the directionality of the signal transmission, the greater the level of possible spectrum reuse.
Spectrum Sharing and Aggregation	Smart spectrum sharing and spectrum awareness technologies can piece together spectrum from multiple bands. These technical methods include adaptations to the physical layer, such as subcarrier nulling, null steering, and compressive sensing. In situ sensing and orchestration is also a critical enabler to more advanced spectrum sharing. New business models for spectrum may emerge, and new policies may be required as well.

Bands Under Consideration

Identifying sufficient additional spectrum for 6G is challenging. The electromagnetic spectrum is congested. Demand and requirements are increasing, while supply is practically limited. Because spectrum is a critical national resource, we must find a way to meet requirements for this next generation of communications while balancing the needs of previous generations and incumbent spectrum users, as well as a diverse ecosystem of non-cellular wireless technologies. This paper considers low-, mid-, and high-band spectrum options for meeting 6G spectrum requirements. Higher-band spectrum may facilitate greater bandwidth with less propagation. Combining different bands and regulatory structures could provide a solution to this spectrum challenge.

We expect the spectrum utilized by 6G to include an increasing number of bands already in use for prior generations of cellular technology, as well as new bands. This section provides an overview of band challenges and opportunities, currently available bands, and those that are under consideration for repurposing or sharing with radio access networks that may support 6G. Following recent National Telecommunications and Information Administration (NTIA) practice,¹⁰ we use the following terminology: low-band (below 1 GHz), mid-band (1–10 GHz), and high-band (above 10 GHz).

Band Challenges and Opportunities

Low-band spectrum enables signals to travel relatively far distances and penetrate buildings, foliage, and other obstructions. Low-band spectrum can play an important role in building out network coverage, particularly in large geographic areas with relatively few users. By implementing carrier aggregation, a technique that

assigns multiple blocks of spectrum to the same user, data rates can be increased. Multi-radio dual connectivity could also increase user throughput by allowing simultaneous transmission and receipt of data by using two distinct schedulers. Mobile Network Operators (MNO) may continue to leverage low-band spectrum for long-range and/or exclusive uses, such as rural broadband coverage and closing the digital divide as well as public safety cases.

Mid-band spectrum provides a balance between coverage and capacity. As defined above, mid-band encompasses nine times more spectrum than low-band (9 GHz vs. 1 GHz), and larger channel bandwidths are available for mobile broadband networks. Not all mid-band spectrum, however, is available for mobile telephony. Mid-band spectrum in the United States (and globally) has many incumbent users, particularly federal radar systems. Subsets of mid-band spectrum could be pieced together and utilized for 6G through the implementation of smart sharing techniques. U.S. leadership could take an early lead in establishing its plans for 6G spectrum and proposing harmonization to facilitate global convergence, particularly with mid-band spectrum.

Signals operating in high-band (including terahertz), or millimeter wave (mmW), spectrum travel shorter distances and may not penetrate buildings. High-band spectrum is less congested and contains fewer incumbent users. Current use includes federal point-to-point microwave systems and satellite services. This spectrum is most ripe for identifying “greenfield” spectrum for up- and down-links. High-band spectrum could also be used to provide line-of-sight backhaul communication links for 6G. The Federal Communications Commission’s (FCC) Spectrum Horizon First Report and Order opened experimental 6G spectrum licenses in the 95

GHz to 3 terahertz (THz) range. Referred to as tremendously high frequency (THF), these signals are millimeter waves in the 95 GHz to 300 GHz range and at or under 1 millimeter (“submillimeter waves”) from 300 GHz to 3 THz.

Currently Allocated Bands

Licensed Spectrum

Table 2 identifies the licensed bands that are currently used in the United States for 3G, 4G, and 5G mobile broadband networks.

In addition to the bands listed in the table, the FCC has authorized licensed mobile broadband operations in bands not yet fully in use:

- 1526–1536, 1627.5–1637.5, and 1646.5–1656.5 MHz – This spectrum can be used by Ligado Networks for a 5G network, per an FCC April 2020 Order¹¹. To protect the Global Positioning System (GPS) and other adjacent satellite navigation and satellite communication networks, the FCC limits the effective isotropic radiated power (EIRP) of base station emissions in 1526–1536

Table 2. Licensed 3G/4G/5G Bands in the United States in Current Use⁶²

Band	Uplink (MHz)	Downlink (MHz)	Total MHz	Notes
600 MHz	663–698	617–652	70	LTE Band 71, 5G Band n71
700 MHz	698–716	728–746	70	LTE Bands 12, 13, 29; 5G Bands n12, n13, n29
	746–757	776–787		
800 MHz ESMR	817–824	862–869	14	LTE Band 26, 5G Band n26
850 MHz	824–849	869–894	50	LTE Band 5, 5G Band n5
AWS (paired)	1710–1780	2110–2180	190	Bands 66, n66
	2000–2025	2175–2200		
PCS	1850–1915	1930–1995	130	Bands 2, 25, n2, n25
WCS	2305–2315	2350–2360	20	Bands 30, n30
BRS/EBS	2496–2690		194	Bands 41, n41
CBRS	3550–3700		150	Band 48, n48
24 GHz	24,250–24,450		700	Band n258
	24,750–25,250			
28 GHz	27,500–28,350		850	Band n261
37, 39, and 47 GHz	37,600–38,600		3,400	Band n260, n262
	38,600–40,000			
	47,200–48,200			

MHz to under 10 watts and places other constraints on the network. NTIA has filed a Petition for Reconsideration to the FCC regarding this order, on which the FCC has not yet acted. Further, the National Defense Authorization Act (NDAA) of 2021 has mandated an independent study of the FCC order and placed constraints on the DoD regarding compliance with it. Although Ligado has not yet built out a network, this spectrum is included in the Third Generation Partnership Project (3GPP) 4G and 5G standards (Band 24/n24).

- 1695–1710; 1755–1780; 2155–2180 MHz – The FCC auctioned licenses for these bands in their 2015 Advanced Wireless Service (AWS)-3 auction. This spectrum is currently used for some mobile broadband services. However, constraints are in place until most federal systems are moved out of the band. This transition is expected to be completed in 2025¹².
- 2483.5–2495 MHz – The FCC issued a Report and Order¹³ in December 2016 modifying its rules for an ancillary terrestrial component (ATC) of the sole mobile-satellite service (MSS) operating in the 1.6/2.4 GHz bands, i.e., Globalstar. Globalstar announced in August 2017 that the FCC issued licenses authorizing a terrestrial mobile service in the 2483.5–2495 MHz band¹⁴. Although Globalstar ATC services are not yet operational, this band is included in 3GPP 4G and 5G standards (Band 53/n53) and this band was introduced into Qualcomm modems for mobile devices as of February 2021¹⁵.
- 3.7–3.98 GHz – Licenses for use of this spectrum by 5G networks were auctioned by the FCC. The auction, completed in February 2021, raised over \$81 billion in gross proceeds. 5G operations in this band could not begin until incumbent satellite service providers migrated out of the band. 5G licensees that bid on the A Block licenses in 46 of the 50 top U.S. markets (auctioned in 20-MHz blocks within 3.7–3.8 GHz) were obligated to make additional payments to the incumbent satellite service providers who met an accelerated relocation deadline of December 5, 2021. The remaining licenses will allow 5G services to begin in December 2023. Due to concerns of interference to aircraft radio altimeters, A Block licensees AT&T and Verizon announced a one-month delay in rolling out initial services in this band from December 5, 2021, to January 5, 2022.¹⁶ This delay was later extended by two weeks. AT&T and Verizon also committed to voluntarily adopting “additional precautionary measures” for the initial six months of network operation.¹⁷
- 3.45 GHz band (3.45–3.55 GHz) – The FCC auctioned 4,060 licenses for this 100 MHz of spectrum on an unpaired basis divided into 10 MHz blocks in partial economic areas (PEA) located in the contiguous 48 states and Washington, D.C. The auction (FCC Auction 110) concluded on January 4, 2022. Gross bids exceeded \$22 billion.

Many of the licensed bands identified above are likely to be “refarmed” (representing the use of some or all portions vacated by earlier-generation cellular technology) or shared (e.g., with techniques akin to 5G’s Dynamic Spectrum Sharing [DSS]) with 6G as capable networks are deployed. Refarming and DSS have limitations. For instance, the characteristics of many of the licensed bands identified above are not well-suited even for 5G, for which unpaired channel bandwidths of 80–100 MHz are preferred.¹⁸ Even larger channel bandwidths would be preferred

for 6G. Also, carriers are expected to continue to provide prior-generation services for extended periods after a new generation is deployed. This requirement limits the amount of spectrum that can be refarmed or shared to allow the deployment of the next-generation technology. For instance, at present the major U.S. MNOs are carrying most traffic over 4G networks while deploying initial 5G services; they are continuing at the same time to provide 3G services until sometime in 2022¹⁹.

In a June 2020 study²⁰ conducted for CTIA, Analysys Mason concluded that the United States was well-positioned with respect to other countries with allocating licensed spectrum for 5G in bands below 2.6 GHz and above 7 GHz. However, they

noted that the United States was lagging in 5G spectrum within the range of 2.6 to 7 GHz. At the time, there was no U.S.-allocated spectrum within this range. As summarized above, great progress has been made toward freeing mid-band spectrum in the United States over the past couple of years.

Unlicensed Spectrum

Table 3 identifies unlicensed spectrum within the United States that may be used for 6G, either through WiFi offloading (i.e., off-loading traffic to unlicensed WiFi spectrum) or other unlicensed 6G services (e.g., extensions of 5G New Radio Unlicensed (NR-U)). Many of the bands listed are considered by the FCC to be part of the Unlicensed National Information Infrastructure (U-NII).

Table 3. Unlicensed Spectrum in the United States

Band	Frequencies (MHz)	Total MHz	Notes
915 MHz	902–928	26	WiFi HaLow, IEEE 802.11ah
2.4 GHz	2400–2483.5	83.5	IEEE 802.11b and 802.11g
U-NII-1	5150–5250	100	IEEE 802.11a/n/ax
U-NII-2a	5250–5350	100	
U-NII-2c	5470–5725	255	
U-NII-3	5725–5850	125	
U-NII-4	5850–5895	45	
U-NII-5	5925–6425	500	Established by FCC rulemaking in 2020 ²¹ . WiFi 6E.
U-NII-6	6425–6525	100	
U-NII-7	6525–6875	350	
U-NII-8	6875–7125	250	
60 GHz	57000–71000	1400	WiGig, IEEE 802.11ad and 802.11ay
Spectrum Frontiers	116000–122250	21200	
	112250–1230000		
	174800–182000		
	185000–190000		
	241000–248000		

As noted in the table, the FCC introduced 1,200 MHz of unlicensed mid-band spectrum in 2020 through their 6 GHz (5925–7125 MHz) rulemaking. This rulemaking hasn't been universally embraced. AT&T opposed the FCC's 6 GHz band decision due to concerns of interference to point-to-point microwave links. They noted that there are approximately 100,000 microwave links in the 6 GHz band, they hold more than 8,000 licenses for such links, and these links support critical applications like cellular backhaul²³. Shortly after the FCC's April 2020 order, AT&T filed a lawsuit against the FCC with the U.S. Court of Appeals to have the rulemaking reversed²⁴. GSMA provided a very different perspective after the FCC's April 2020 order was released; in May 2020, they issued a press statement warning that the "global future of 5G is at risk if governments fail to align on licensing 6 GHz spectrum"²⁵. GSMA's statement notes that some countries are permitting 5G licensees to utilize the band, whereas others (such as the United States) "have declared that none of this valuable resource will be made available for 5G, but rather will be offered to Wi-Fi and other unlicensed technologies."

The FCC's 5.9 GHz rulemaking that permitted unlicensed devices in 5850–5925 MHz has also met opposition. Three automotive associations or advocates filed Petitions for Reconsideration, noting that the entire 5.9 GHz band (5850–5925 MHz) has historically been set aside for Intelligent Transportation Systems (ITS) and that ITS has a greater need for this band than WiFi²⁶.

Candidate Future Bands

This section summarizes bands that are under consideration for spectrum repurposing or sharing by the FCC and NTIA, as identified in NTIA's December 2020 report on spectrum repurposing.²⁷

Low-band (< 1 GHz) spectrum

Only three bands under 1 GHz are identified in NTIA's December 2020 report on recent and future spectrum repurposing:

- 512–698 MHz
- 809–817; 854–862 MHz
- 896–901; 935–940 MHz.

All three of these bands have already been repurposed, and Table 2 includes the 70 MHz portion of the 600 MHz band that was freed from 512–698 MHz upon completion of the U.S. digital television transition and completion of the FCC's TV incentive auction. The 809–817/854–862 MHz and 896–901/935–940 MHz bands are divided into 12.5 kilohertz (kHz) channels for public safety and public land mobile radio (PLMR) services²⁸ and are not of interest for 6G. No other bands below 1 GHz have been publicly identified for potential repurposing by the U.S. spectrum regulators.

Mid-band (1–10 GHz) spectrum

The December 2020 NTIA repurposing report identifies the following portions of mid-band spectrum as candidates for future repurposing²⁹:

- 1300–1350 MHz – This band³⁰ is used primarily for many federal long-range radars, including Air Route Surveillance Radars (ARSR-4), Common Air Route Surveillance Radars (CARSR), the Tethered Aerostat Radar System (TARS)³¹, and the North Warning System (NWS). These radars are used for air traffic control, drug interdiction, border surveillance, and early missile warning detection. A cross-agency program referred to as the Spectrum Efficient National Surveillance Radar (SENSR),³² with participation by the Federal Aviation

Administration (FAA), DoD, and Department of Homeland Security (DHS), is currently investigating whether a 30-MHz portion of 1300–1350 MHz can be freed by a retuning of the long-range radars to support an FCC auction in 2024. These studies will examine whether the radars can be packed within the remaining subset of the 1240–1390 MHz radiolocation band considering each radar type's tuning range, other incumbent federal systems within the band, and the need to avoid mutual interference. Also, there is an international allocation for radionavigation satellite services (RNSS) in the 1164–1300 MHz bands. Although the United States does not have an RNSS allocation for 1240–1300 MHz, some high-precision GPS receivers in use in the United States have the capability to process foreign RNSS signals in this band, which include Galileo and Quasi-Zenith Satellite System (QZSS) signals centered at 1278.75 MHz and BeiDou signals centered at 1268.52 MHz. These receivers may be susceptible to adjacent band interference from mobile broadband networks operating in 1300–1350 MHz³³.

- 1675–1680 MHz – In May 2019, the FCC proposed repurposing this band for flexible wireless use³⁴. The band is currently allocated for meteorological aids (e.g., radiosondes) and meteorological satellite services including the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellites (GOES). Ligado Networks petitioned the FCC to initiate rulemaking to consider repurposing this band since they have a lease agreement to utilize the adjacent 1670–1675 MHz band for terrestrial mobile services. The weather community and mobile wireless

advocates have filed opposing views to the FCC as to whether 1675–1680 MHz can be repurposed³⁵. Ligado and mobile wireless advocates assert that the band can be repurposed through a relocation of radiosondes to another band (401–403 MHz), the establishment of protection/coordination zones to protect reception of GOES weather downlinks by the 14 FCC-authorized Earth stations, and the creation of an internet service to provide GOES weather data to other end users. Many weather organizations assert that internet delivery of GOES data is not a sufficiently reliable replacement for their current direct reception of GOES downlinked data considering that their services are most critical during natural disasters, when the internet may not be accessible.

- 3100–3450 MHz – As required by the MOBILE NOW Act of 2018, NTIA studied the feasibility of allowing commercial wireless services to share 3100–3550 MHz with federal users. NTIA determined that 3450–3,550 MHz was most promising for near-term sharing, and subsequently the FCC auctioned commercial licenses for this band segment (see Section 3.2.1.). NTIA determined that “although sharing of spectrum below 3450 MHz may be possible as well, additional analysis of the entire band should be conducted”³⁶. They note that there are classified and unclassified federal operations that “could be problematic for sharing with a commercial wireless system.” Unclassified federal systems within 3100–3450 MHz include DoD and DHS fixed, airborne, and shipborne radars for national defense and domestic security. Radio astronomy is authorized to use 3260–3267 MHz, 3332–3339 MHz, and 3345.8–

3352.5 MHz. Federal and non-federal Earth-exploration satellite services and space research services are also authorized to use portions of this band, as are non-federal radiolocation and amateur services. The FCC imposed a freeze on applications for non-federal radiolocation services in 3.1–3.55 GHz in February 2019 and proposed removing non-federal allocations for 3.3–3.55 GHz and relocating non-federal users out of this band³⁷.

- 4940–4990 MHz – The FCC designated this band for public safety use in 2002. Noting that the band is under-utilized, the FCC in October 2020 released an order allowing states to either continue to use this band for public safety purposes or to lease the spectrum for non-public-safety use. Public safety organizations filed petitions for reconsideration due to concerns that the FCC order would preclude nationwide interoperability of public safety users. The FCC agreed and issued a new order in October 2021³⁸ disallowing the state-by-state lease provisions of the October 2020 order while seeking public input on how use of the band for public safety services could be increased. In the October 2021 order, the FCC notes that this band is currently used by 3541 public safety licensees and that they are committed to protect the significant investments they represent. The licenses are for a wide variety of systems, including bomb robots, security cameras, land mobile radio backhaul, and various other fixed and mobile communication links.

Not mentioned in their December 2020 report, but included in earlier NTIA repurposing reports,^{39,40} are the following bands:

- 2700–2900 MHz – This band⁴¹ is used by federal agencies for air traffic control and weather radars, including FAA and DoD Airport Surveillance Radars (ASR) and the Next Generation Weather Radars (NEXRAD) operated by the National Weather Service (NWS), FAA, and DoD. ASRs are located at major civilian and military airports, some of which are in major U.S. population centers. By design, the NEXRAD network provides coverage of most of the United States to provide real-time weather data.
- 2900–3100 MHz – This band is also mostly used by federal and non-federal radars. NEXRAD uses frequencies from 2700–3000 MHz. Footnote US316 within the United States. Table of Frequency Allocations stipulates that NEXRAD use of 2900–3000 MHz is limited to cases “where accommodation in the band 2700–2900 MHz is not technically practical.” Other radars in the 2900–3100 MHz band are for DoD radionavigation and radiolocation systems and federal and non-federal maritime radionavigation. Within the maritime community, 2900–3100 MHz is referred to as the “3 GHz” band that is used for “S-band” radars⁴². Although most marine radars operate in X-band, S-band is favored for specialized applications such as seeing through heavy weather or precipitation⁴³.

These bands were presumably found to be much more difficult to share or repurpose than the bands discussed above that NTIA and FCC are currently focusing on.

High-band (> 10 GHz) spectrum

The December 2020 NTIA repurposing report identifies the following portions of high-band spectrum as candidates for future repurposing⁴⁴:

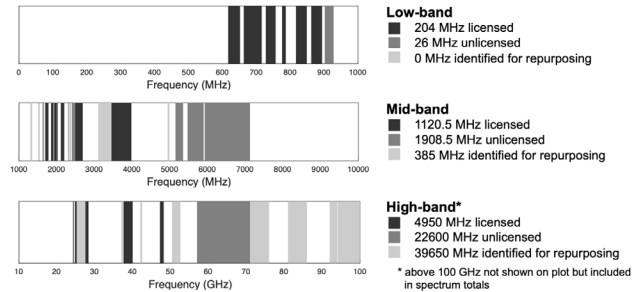
- 25.25–27.5 GHz
- 37–37.6 GHz
- 42–42.5 GHz
- 50.4–52.6 GHz
- 71–76; 81–86; 92–94; 94.1–95 GHz
- 95–3000 GHz (aligned with the FCC’s Spectrum Horizons Proceeding)
- 116–123; 174.8–182; 185–190; 244–246 GHz

Rather than provide a detailed description of each of these bands, we note that there is already 4.95 GHz of high-band spectrum available for licensed mobile broadband use and 22.6 GHz for unlicensed mobile broadband use. There are also many candidate bands above 10 GHz for additional mobile broadband spectrum that are less encumbered with incumbent users than sub-10 GHz spectrum, and we conclude that the supply of high-band spectrum is not likely to be a constraint for 6G.

Spectrum Summary and Observations

Figure 1 provides a summary of the low-, mid-, and high-band spectrum currently available in the United States for mobile broadband services as well as the spectrum that has been publicly identified by NTIA and FCC as candidates for future repurposing or sharing by mobile broadband.

Figure 1. Summary of Candidate Spectrum for 6G in the United States



The spectrum totals compare favorably between the United States and other developed nations, and many of the bands are harmonized across a sufficient number of nations to create economies of scale within the mobile broadband equipment ecosystem.⁴⁵

As can be seen in Figure 1, there are some notable gaps in mobile broadband spectrum. There is very little interest in pursuing spectrum below 600 MHz because of the required large antenna sizes for efficient transmission/reception and the large number of legacy systems. Two large gaps occur in mid-band spectrum. The first occurs from 3980 MHz to 4940 MHz, which among other reasons is to protect aircraft radio altimeters that operate in the 4200–4400 MHz band. As noted earlier, there have already been concerns raised with the United States repurposing of the 3700–3980 MHz band due to potential impacts to radio altimeters. The second large mid-band spectrum gap occurs between 7.125 GHz and 10 GHz and continues into the high-band until 24.25 GHz. This second gap is occupied by many legacy systems, including fixed point-to-point microwave and satellite up- and down-links^{46,47}.

Summary and Recommendations

Summary

Although not yet fully defined, 6G is expected to provide a significant increase in performance over 5G, including:

- A 100x increase in peak data rates (from 10 Gbps to 1 Tbps)
- A 10x decrease in end-to-end latency (from 10 ms to 1 ms)
- A 100x increase in device density.

A large amount of spectrum currently supports 3G–5G networks in the United States and, by some estimates, four times this amount will be required in at least some geographic areas to support 6G.

As identified in this paper, the spectrum needed to support 6G is expected to come from: (1) refarming or sharing of spectrum currently available for earlier-generation (3G–5G) networks, or (2) new bands that may be repurposed from or shared with incumbent radio services. Spectrum currently available for earlier-generation networks within the United States includes:

- Low-band (under 1 GHz) spectrum – 204 MHz licensed, 26 MHz unlicensed
- Mid-band (1–10 GHz) spectrum – 1120.5 MHz licensed, 1908.5 MHz unlicensed
- High-band (above 10 GHz) spectrum – 4940 MHz licensed, 22600 MHz unlicensed.

NTIA and FCC have publicly identified an additional 385 MHz of mid-band spectrum and 39650 MHz of high-band spectrum to be studied for repurposing or sharing. No spectrum has been identified publicly by NTIA and FCC as a candidate

for repurposing or sharing below 1 GHz.

Recommendations to Accelerate and Improve 6G Deployment

A national spectrum strategy, roadmap, and research agenda will accelerate and improve the deployment of 6G. For the United States to achieve and sustain global leadership in 6G, these must be developed by following a whole-of-nation approach that integrates industry, government, academia, and other resources to address 6G in a strong, innovative, and coordinated manner. Advanced and aligned goals and plans for research and development (R&D), stakeholder roles, and standardization can propel the acceleration and improve the transition to 6G.

Spectrum will likely be the largest hurdle to overcome to realize the benefits of 6G. While concrete use cases and detailed spectrum requirements to support those use cases will take time to emerge, we know that there is no other way to achieve the huge performance leaps that define 6G capabilities without additional spectrum. Since there is not fallow spectrum, the spectrum resources targeted for 6G must be supported by deliberate research and development, data-driven market needs, partnerships, and enabling economic and policy mechanisms.

National goals for 6G must be established, with a roadmap to achieving those goals. While the details of our National 6G goals are being developed, we know that these goals will require spectrum access and the United States should move out proactively to identify the means by which sufficient spectrum will be made available for 6G. There are three lines of effort that work toward a coordinated, whole-of-nation roadmap to make spectrum available to meet spectrum requirements for 6G and pave the way to U.S. leadership in 6G. Some of these areas are underway as the community is leaning forward

into the 6G revolution, while other areas need to be initiated. The lines of effort include:

1. National-level approach and leadership
2. Coordinated R&D activities
3. Spectrum use reimaged.

The remainder of this section details these lines of effort and identifies a transition path for accomplishing the actions and establishing the support structures needed to accelerate and improve the transition to 6G.

National-level Approach and Leadership

The U.S. government plays a vital role in the development of 6G by establishing national goals, objectives, policies, regulations, and funding research. MITRE recommends the early development of a national plan establishing U.S. goals, objectives, policies, and a transition path toward 6G that includes R&D priorities and funding.

As indicated previously, identifying the spectrum to support 6G while preserving other radio services vital to the U.S. economy and national security is a tremendous challenge. Unlike many other nations, the United States has a bifurcated spectrum management regulatory structure, with NTIA managing federal spectrum use and the FCC managing non-federal spectrum use. Recently, as demand for spectrum continues to increase, there have been a growing number of coordination issues that have resulted in White House and Congressional intervention⁴⁸. We recommend that U.S. spectrum governance and leadership be revisited to ensure a whole-of-nation approach including shared goals and alignment of diverse stakeholders and resources. In particular, two

potential options have been discussed amongst the spectrum policy community:

1. Improve collaboration within the current spectrum regulatory structure – The FCC and NTIA are taking steps to improve coordination. The Department of Commerce Spectrum Management Advisory Committee (CSMAC) proposed revisions to the memorandum of understanding (MOU) between the FCC and NTIA in January 2021.⁴⁹ In June 2021, the Government Accounting Office (GAO) recommended that the FCC and NTIA take steps to strengthen their collaboration,⁵⁰ and Congress has drafted a Spectrum Coordination Act (H.R.2501) that would require that the FCC and NTIA update their 2003 MOU to: (1) improve the process for resolving frequency allocation disputes in shared or adjacent bands to ensure that such disputes are resolved expeditiously and efficiently; and (2) ensure that spectrum is used or shared efficiently⁵¹. The FCC and NTIA most recently announced a new initiative to improve spectrum coordination and management.⁵²
2. Establish a new spectrum regulatory structure – More than 20 years ago, the Defense Science Board (DSB) recommended that the United States re-establish a White House-level office for telecommunication policy “...that can develop and administer a national spectrum policy that comprehends the full scope of U.S. spectrum needs”⁵³. Although the DSB envisioned this new office to be on a parallel level with

the National Security Council (NSC), National Economic Council (NEC), and the Office of Science and Technology Policy (OSTP) within the Executive Office of the President (EOP), it could alternatively be established as a subordinate entity to another office (e.g., OSTP). More recently, the CSMAC developed options for reforming spectrum governance in July 2020.⁵⁴

A national 6G plan with technical foundations and supported by objective engineering analysis is needed to underpin a whole-of-nation spectrum approach and align our national stakeholders and resources toward a unified path to smart 6G spectrum access. The national plan for 6G should include shared goals and a roadmap toward identifying sufficient spectrum, which may include the following elements:

1. Implement smart sharing techniques, including spectrum situational awareness and in situ sensing and orchestration. The flexibility of the 6G network is a critical enabler to incorporate features that can be used to share spectrum at a more granular level. The introduction of Open Radio Access Networks (ORAN) into the commercial cellular ecosystem shows promise to enable flexibility in the mobile network side that has not been possible before 5G.⁵⁵
2. Piece together low-band spectrum for greater utilization, public safety applications, and to help close the digital divide.
 - a. Use low-band spectrum for network coverage, particularly for devices requiring throughputs that are achievable with the smaller bandwidths available below 1 GHz.
3. Continue to explore repurposing or sharing large portions of mid-band spectrum for 6G, including spectrum in the 3.1–3.45 GHz range.
 - a. Utilize mid-band spectrum for a balance between coverage and capacity.
 - b. Facilitate global harmonization of mid-band spectrum for 6G.
 - c. Implement smart sharing techniques, including with federal radar systems.⁵⁶
4. Leverage the 4.95 GHz of high-band spectrum already available for licensed mobile broadband use and 22.6 GHz for unlicensed 6G use, and continue to explore repurposing or sharing of the nearly 40 GHz of additional high-band spectrum identified by NTIA and FCC.
 - a. Employ high-band spectrum to achieve capacity in areas with high device densities.
 - b. Deliver greenfield up- and down-links and line-of-sight backhaul communication.
 - c. Identify opportunities to leverage

THz frequencies and enabling technologies for even greater capacity, potentially enabling new and innovative applications demanding enormous amounts of bandwidth within a very short range.

Additional objectives of a national plan should be the establishment of U.S. leadership in 6G standards development and R&D. While impressive work has been done in standards, allowing for an ever-growing range of devices to be connected to new telecommunication networks, more work is needed to address standards challenges for 6G. The ability of 6G networks to connect billions of Internet of Things (IoT) devices will require standards ranging from interfaces to device spectrum usage. For that reason, the involvement of standards development organizations (SDO) as early as possible will help identify and address standards issues in a way that will strengthen the efficiency and usability of 6G networks. Other standards issues will likely include those for data and propagation. Overall, an aggressive standards approach will help the United States and its partners shape a global 6G ecosystem that is both open and efficient, helping us avoid a situation in which that ecosystem is dominated by authoritarian international competitors.

R&D priorities and funding are addressed in the subsequent section.

R&D

As an element within a national plan for 6G, MITRE recommends a national R&D strategy to support whole-of-nation objectives. Identifying gaps, clearly communicating targeted R&D needs, and managing the R&D investments as a portfolio will focus national R&D investment priorities. Vital to such a strategy is the creation of a whole-of-

nation 6G R&D community that encompasses the government, private sector, academia, and other contributors. Such a community would take responsibility for identifying key 6G spectrum (and other) R&D challenges, allocating those challenges to community members, providing resources, and tracking results.

Employing this community, the United States must continue national-scale investments, including strategic investment in R&D to develop technologies foundational to 6G. The United States must stimulate a pipeline of advanced technologies to influence future standards and intellectual property rights. Such an approach harkens back to the success our nation achieved in mastering nuclear energy, aerospace technology, and key biomedical advances.

Developing, maintaining, and evolving the testing and experimentation facilities, infrastructure, and networks is critical to advance R&D by demonstrating the operations necessary to gain confidence in new approaches to spectrum access. The National Science Foundation (NSF) National Radio Dynamic Zones (NRDZ)—part of the Spectrum Innovation Initiative (SII)—will establish new test ranges focused on enabling research and development of dynamic spectrum sharing for both passive and active users.⁵⁷ This initiative is critical to ensure that testing facilities and infrastructure are prioritized when determining how to use spectrum more effectively while protecting critical passive systems. The NRDZ program, coupled with existing testing network efforts such as the NSF Platforms for Advanced Wireless Research (PAWR) program⁵⁸ and the National Advanced Spectrum and Communications Test Network (NASCTN)⁵⁹, need to continue to be evolved to meet the needs of the U.S. 6G R&D priorities.

To support these actions, R&D should focus on key spectrum challenges, specifically:

- Sharing methods and techniques applicable to radars and other incumbent systems. These may include in situ sensing and orchestration as well as more advanced techniques, including schedulers that enable increased density of use via more precise timing information.
- Measurement campaigns of out-of-band sensitivities of incumbent systems in bands adjacent to all mobile broadband candidate bands. The objective would be to determine and characterize the potential for adjacent-band interference far in advance of band repurposing to avoid problems such as the ongoing issue with the 3.7–3.98 GHz band (see Section 3.2.1).
- Use of tremendously high frequency spectrum
- Spectrum for IoT connectivity
 - Any regulatory changes needed to support IoT uses
 - Role of unlicensed operations and licensed spectrum in the growth of IoT
- Testing equipment and facilities to accommodate technology innovation
- Economic and policy mechanisms to support increased spectrum sharing.

Further, R&D should also be conducted to address broader, related gaps and challenges, including in areas identified by the ATIS Next G Alliance: component technologies; network operations, administration, and management (OA&M) and service enablement; radio technologies, system, and network architectures; and trustworthiness.⁶⁰

Spectrum Use Reimagined

In the development of a national plan for 6G,

the United States should consider the following methods for reducing the amount of spectrum that may be required to meet 6G performance requirements:

- Spectrum management and allocation changes to increase efficiency. Our current approach to spectrum policy and spectrum access is to wedge new uses into a structure that was established many years ago, when the electromagnetic environment was much less congested. The principles and structures established in the early stages of wireless access were not created to address the challenges that we currently face today in our exploding wireless ecosystem. U.S. government regulators, and the processes they are bound by, have little flexibility to rethink spectrum policy, and no room to take a completely greenfield approach. Innovative means to policy and spectrum access are encouraged and needed, but if innovation is constrained to the core structures that are currently in place, we are not reaping the full benefits of the art of the possible.

To accommodate 6G and beyond, we recommend that the spectrum regulatory structures and allocation schemes in the United States be looked at in a greenfield manner, removing all barriers. It is recommended that a comprehensive framework for spectrum access—including a completely greenfield spectrum allocation scheme which foundationally changes and revolutionizes spectrum access in the United States—be developed. The foundational impetus is to spark ideas that will add efficiency to all generations of commercial cellular deployments and create the electromagnetic environment necessary such that spectrum access is not a barrier to harnessing the potential of 6G and xG

technologies. The intent is not for this framework to be implemented in full, but rather to provide the canvas on which ideas can be explored to provide a vision of what the future could look like to accommodate all spectrum uses in a more efficient manner.

- Use of fiber and free space optics in lieu of radio spectrum for 6G backhaul or fixed services.
- Developments in quantum communications—such as systems that exploit orbital angular momentum—that may someday practically enable higher-capacity services within existing spectrum⁶¹.

for any errors or omissions

A Call to Action

Bold and forward-leaning action is needed to establish U.S. leadership in 6G, including action to make the best possible use of spectrum, a vital national resource. This paper provides a summary of the current spectrum situation as it relates to 6G. More important, it conveys clear recommendations to advance U.S. 6G leadership. Those recommendations, a national-level approach and strategy, whole-of-nation 6G research and development, and a new way to imagine the use of spectrum, comprise the core of what our nation must do to employ spectrum resources effectively.

MITRE's technology professionals are ready to help advance this conversation and work with leaders in government and industry to establish and sustain American 6G leadership.

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Endnotes

1. H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland and F. Tufvesson, “6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities,” in Proceedings of the IEEE, vol. 109, no. 7, pp. 1166-1199, July 2021, doi: 10.1109/JPROC.2021.3061701.
2. M. Z. Chowdhury, M. Shahjalal, S. Ahmed and Y. M. Jang, “6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions,” in IEEE Open Journal of the Communications Society, vol. 1, pp. 957-975, 2020, doi: 10.1109/OJCOMS.2020.3010270.
3. “NIST and University Researchers Offer Future 6G Network Concept,” NIST, December 29, 2021. Available: <https://www.nist.gov/news-events/news/2021/12/nist-and-university-researchers-offer-future-6g-network-concept#:~:text=Compared%20to%205G%2C%20the%206G,edge%20intelligent%20devices%20and%20computing>.
4. Kranz, Garry and Gerry Christensen, “What is 6G?” Available: <https://www.techtarget.com/searchnetworking/definition/6G>.
5. Alraih, Saddam, Ibraheem Shayea, Mehran Behjati, Rosdiadee Nordin, Nor Fadzilah Abdullah, Asmá Abu-Samah, and Dalia Nandi, “Revolution or Evolution?” MDPI, Sensors 2022. Available: <https://www.mdpi.com/1424-8220/22/3/762/pdf>
6. Frequency Range (FR) 1 includes all existing and new bands below 7.125 GHz; FR2 includes new bands from 24.25-52.6 GHz
7. Clancy, T. Charles, “6G Spectrum and PHY,” The MITRE Corporation, March 29, 2021.
8. Holma Harri, Harish Viswanathan, and Preben Mogensen, “The 6G Era’s Enormous Capacity Demands Will Require New Spectrum and Extreme Massive MIMO,” Nokia Bell Labs, October 1, 2021. Available: <https://www.bell-labs.com/institute/white-papers/extreme-massive-mimo-for-macro-cell-capacity-boost-in-5g-advanced-and-6g/>
9. Holma, Harri and Harish Viswanathan, “The 6G Era’s Enormous Capacity Demands Will Require New Spectrum and Extreme Massive MIMO,” Nokia Bell Labs, 6 October 2021. Available: <https://www.bell-labs.com/institute/blog/6g-eras-enormous-capacity-demands-will-require-new-spectrum-and-extreme-massive-mimo/#gref>.
10. https://www.ntia.doc.gov/files/ntia/publications/second_annual_ntia_spectrum_repurposing_report.pdf.
11. <https://www.fcc.gov/document/fcc-approves-ligado-l-band-application-facilitate-5g-iot>.
12. <https://www.ntia.doc.gov/category/aws-3-transition>.
13. <https://docs.fcc.gov/public/attachments/DA-03-3926A1.doc>.
14. https://www.globalstar.com/Globalstar/media/Globalstar/Downloads/Spectrum/Globalstar_Statement_Re_Issuance_of_Terrestrial_Licenses.pdf.
15. <https://investors.globalstar.com/news-releases/news-release-details/globalstars-band-n53-qualcomms-x65-modem>.
16. <https://www.wsj.com/articles/at-t-verizon-to-delay-5g-rollout-over-faas-airplane-safety-concerns-11636039555>.
17. <https://ecfsapi.fcc.gov/file/11241848723664/2021-11-24%20ATT%20Verizon%20Letter%20FINAL.pdf>.
18. <https://ecfsapi.fcc.gov/file/10901090717973/Spectrum%20Agg%20Pet%20final.pdf>.
19. <https://www.fcc.gov/consumers/guides/plan-ahead-phase-out-3g-cellular-networks-and-service>.
20. <https://api.ctia.org/wp-content/uploads/2020/06/Comparison-of-Total-Mobile-Spectrum-in-Different-Markets-Final-Report-290620.pdf>.
21. <https://docs.fcc.gov/public/attachments/FCC-20-164A1.pdf>.
22. <https://ecfsapi.fcc.gov/file/0424167164769/FCC-20-51A1.pdf>
23. https://ecfsapi.fcc.gov/file/10319087261781/OETMtgMidBand_Final.pdf

24. The U.S. Court of Appeals for the District of Columbia Circuit ruled in favor of the FCC in a December 28, 2021 decision. See, e.g., <https://www.fiercewireless.com/wireless/fcc-prevails-6-ghz-court-challenge-led-att>.
25. <https://www.gsma.com/newsroom/press-release/gsma-calls-on-governments-to-license-6-ghz-to-power-5g/>
26. https://www.fcc.gov/ecfs/search/filings?proceedings_name=19-138&sort=date_disseminated,DESC&submissiontype_description=PETITION%20FOR%20RECONSIDERATION
27. We omit mention here of spectrum that has already been repurposed and discussed earlier in Sections 3.1 and 3.2.
28. <https://docs.fcc.gov/public/attachments/FCC-20-62A1.pdf>
28. We omit mention here of spectrum that has already been repurposed and discussed earlier in Sections 3.1 and 3.2.
29. https://www.ntia.doc.gov/files/ntia/publications/compendium/1300.00-1350.00_01MAR14-1.pdf.
30. https://www.cbp.gov/sites/default/files/assets/documents/2021-Aug/TARS_508%20compliant.pdf.
31. https://www.faa.gov/air_traffic/technology/sensr/.
32. See, e.g., the measured frequency responses of active antennas used for high precision GPS receivers within Section 6.2 of <https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1952.pdf>
33. <https://ecfsapi.fcc.gov/file/05132467403342/FCC-19-43A1.pdf>
34. https://www.fcc.gov/ecfs/search/filings?proceedings_name=19-116&sort=date_disseminated,DESC
35. https://www.ntia.doc.gov/files/ntia/publications/ntia_3100-3550_mhz_mobile_now_report_to_congress.pdf
36. <https://ecfsapi.fcc.gov/file/121661888341/FCC-19-130A1.pdf>
37. <https://docs.fcc.gov/public/attachments/FCC-21-106A1.pdf>
38. https://www.ntia.doc.gov/files/ntia/publications/tenyearplan_11152010.pdf
39. https://www.ntia.doc.gov/files/ntia/publications/ntia_6th_interim_progress_report_on_ten-year_timetable_june_2016.pdf
40. <https://www.ntia.doc.gov/files/ntia/publications/compendium/2700.00-2900.00-02092021.pdf>
41. https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1313-0-199710-S!!PDF-E.pdf
42. https://www.furunousa.com/en/knowledge_base/general/x-band_versus_s-band_radars
43. We again omit mention of spectrum that has already been repurposed and discussed earlier in Sections 3.1 and 3.2.
44. Damjanovic, A., “Spectrum Working Group – Upper Midband for 6G Wide Area Coverage,” presentation to ATIS Next G Alliance, December 9, 2021.
45. <https://www.ntia.doc.gov/legacy/osmhome/reports/NTIA84-159.pdf>.
46. https://www.ntia.doc.gov/files/ntia/publications/guidance_to_agencies_on_current_spectrum_usage_final_08-01-2019.pdf.
47. Some of these issues were discussed earlier in this document within Section 3.2.1.
48. https://www.ntia.doc.gov/files/ntia/publications/csmac_subcommittee_1_mou_01142021.pdf.
49. <https://www.gao.gov/assets/gao-21-474.pdf>.
50. <https://www.congress.gov/bill/117th-congress/house-bill/2501/text>.
51. <https://www.ntia.doc.gov/press-release/2022/fcc-ntia-establish-spectrum-coordination-initiative#:~:text=The%20Spectrum%20Coordination%20Initiative%20will,to%20resolve%20spectrum%20policy%20issues.&text=The%20Initiative%20will%20improve%20the,address%20gaps%20in%20governmental%20coordination>.

52. <https://dsb.cto.mil/reports/2000s/a386136.pdf>. Note that this November 2000 report states that “The United States lacks a national spectrum policy/strategy. The multiplicity of organizations charged, by the Communications Act of 1934, with spectrum management responsibilities in the United States each have different goals, objectives, and constituencies. There is no effective mechanism to resolve conflicts, such as those that arise from pressures for spectrum for burgeoning civilian wireless services and military necessity.”
53. https://www.ntia.doc.gov/files/ntia/publications/csmac_sc1_report_july_2020_r1.pdf.
54. Smith, Rob, Connor Freeberg, Travis Machacek, and Venkatesh Ramaswamy, “An O-RAN Approach to Spectrum Sharing Between Commercial 5G and Government Satellite Systems,” The MITRE Corporation, 2021.
55. Based on the overview of band considerations in Section 3, the most promising mid-band spectrum for repurposing is currently used by radars.
56. https://nsf.gov/mps/oma/spectrum_innovation_initiative.jsp.
57. <https://advancedwireless.org/>.
58. <https://www.nist.gov/ctl/nasctn>.
59. “Next G Alliance Report: Roadmap to 6G,” https://nextgalliance.org/white_papers/roadmap-to-6g/, February 2022.
60. S. M. Mohammadi et al., “Orbital Angular Momentum in Radio—A System Study,” in *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 2, pp. 565-572, Feb. 2010, doi: 10.1109/TAP.2009.2037701.
61. Table 2 acronyms: Enhanced Specialized Mobile Radio (ESMR); Advanced Wireless Services (AWS); Personal Communications Service (PCS); Wireless Communications Service (WCS); Broadband Radio Service (BRS); Education Broadband Service (EBS); Citizens Broadband Radio Service (CBRS);