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THE EVOLUTION OF 5G SPECTRUM

Contents

Executive Summary

5G revolutionized mobile broadband service by increasing the communications speeds and reducing air interface latency while simultaneously improving reliability. 5G-Advanced, currently standardized in 3GPP, will establish a foundation and direction for 6G by the end of this decade. As was the case for previous generations of mobile networks, successful deployment of 5G-Advanced and 6G will depend on the availability of new spectrum. It is critical to develop national strategy for new spectrum roadmap to ensure successful deployments of future mobile networks. However, new spectrum is increasingly difficult to find due to incumbencies, and this paper summarizes potential approaches for securing new spectrum for mobile networks.

The regulatory discussions currently taking place are relevant to new spectrum allocations that could be utilized to deploy new mobile networks by the end of this decade. Usage scenarios developed by the International Telecommunication Union (ITU) for International Mobile Telecommunications (IMT)-2030 form the basis for spectrum needs, estimates, and considerations on spectrum requirements. Use cases and applications, particularly those involving immersive experiences, rely on extremely high data rates, and require wide-area coverage to realize their full potential. This use case and others, such as joint communications and sensing, require large contiguous bandwidth, and potentially large coverage areas. It is important for U.S. regulators to consider the balance between licensed and unlicensed to make sure the mobile wireless industry has the appropriate amount of licensed spectrum to serve societies mobile communications needs.

Spectrum between 7.125 GHz and 15.35 GHz (preferably portion below 10 GHz) is suitable to satisfy the desirable capacity-coverage combination. The incumbencies in this frequency range require either relocations or the employment of sharing techniques. These could be existing techniques developed for other bands, or new sharing techniques that allow deployments of mobile networks. In addition to the 7.125-15.35 GHz range, mmWave bands continue to provide opportunities for mobile networks where high capacity is the primary deployment requirement. Sub-THz bands provide opportunities for next generation wireless technology to address new use cases with extremely high data rate requirements.

2023 ITU World Radiocommunication Conference (WRC)[1] adopted a new agenda item to identify a spectrum pipeline within the 4.4-15.5 GHz range for the next generation of wireless technology.

1. Introduction

It is clear that more capacity will be needed for the variety of potential use cases over the next decade as 5G continues to evolve beyond mobile broadband smartphone use cases into new use cases such as fixed wireless access, enterprise, and vertical industries. Spectrum is the “raw material” needed to support new services. It is important to create a runway of different spectrum types so spectrum can continue to fuel potential future use cases such as XR, connected cars, and the metaverse.

More spectrum will need to be identified in the spectrum pipeline to address new use cases toward 2030 and beyond. An important criteria when identifying new spectrum is that network operators can utilize the existing site grid infrastructure they have spent decades developing. With that goal in mind, the 7.125-15.35GHz range (the upper mid-band) appears the most promising candidate, because it is adjacent to the mid-band spectrum for which existing networks are designed. The prevalent view within the industry however, is that due to better propagation characteristics, the lower end of the upper mid-band range (spectrum below 10 GHz) is preferred. With the appropriate technical specifications, the upper mid-band should make it feasible to leverage the existing site grid in the dense portion of networks to provide additional capacity, and to complement the existing mid-band spectrum already in use in wireless networks. Additionally, in the U.S. it is imperative for technological and economic development and leadership that new spectrum ranges for the next generation of mobile networks are identified for a complete U.S. National Spectrum Strategy Pipeline so that the process of bringing the spectrum to commercial market in a timely fashion can be started. Upper mid-band spectrum is currently allocated to Federal and commercial incumbent users, and may be difficult to re-allocate. However, sharing techniques could critically enable identification of new spectrum in the 7.125-15.35 GHz range to address this challenge.

mmWave spectrum has been utilized for 5G networks in hot spot scenarios to support high capacity, and it is expected to be used for that purpose in the future. Support for even higher data rates requires expansion into new Sub-THz bands.

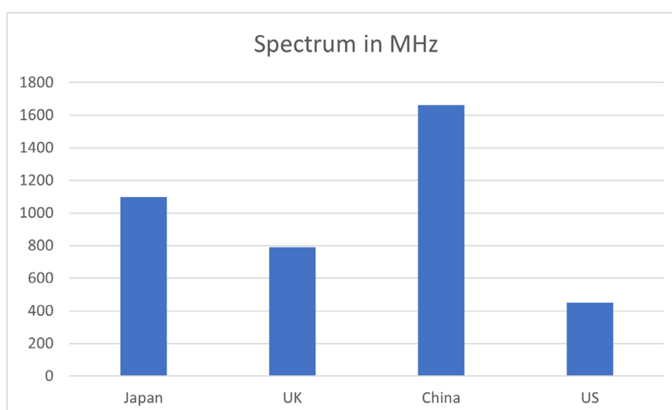
Several regional proposals calling for the identification of a spectrum pipeline for the next generation of wireless technology were considered at the 2023 ITU WRC.

2. U.S. spectrum position compared with other countries

According to 5G Americas’ white paper, Mid-band Spectrum Update, 5G networks require access to multiple ranges of frequency bands from low-band (below 1 GHz), mid-band (from 1 to 7 GHz), and high-band (mmWave bands above 24 GHz) spectrum. Access to all three frequency ranges is essential because they allow operators to optimize their networks based on environmental and network coverage, and capacity targets[2]. This section summarizes the U.S. spectrum position in low, mid, and high-bands in comparison to 15 leading markets that represent a global perspective published in a study by Analysis Mason[3].

According to this CTIA-commissioned study[4], the U.S. is positioned 13th of 15 leading global markets regarding available, licensed mid-band spectrum. Mid-band spectrum is tailor-made for 5G deployments by offering a sweet spot between coverage and capacity. This lack of licensed mid-band spectrum is not expected to sufficiently improve in the next 5 years. For instance, the U.S. has made a total of 450 MHz available in the 3-7 GHz range[5,6]. In contrast, Japan’s current allocation is 1100 MHz, and the U.K.’s is 790 MHz. China has also currently allocated 460 MHz of mid-band spectrum; however, China also announced the identification of the upper 700 MHz of the 6 GHz band to IMT[7], and is considering the remaining 500 MHz for IMT. With the entire 1200 MHz in the 6 GHz band, there is a total of 1660 MHz of potential mid-band spectrum[8]. The mid-band spectrum allocation (current and planned) is illustrated in Figure 1.

Figure 1: Current and future mid-band spectrum allocation per country.



Meanwhile, the current U.S. allocation for both low-band and high-band are more favorable. High-band frequencies (mmWave) offer large bandwidths that can carry sizeable swaths of data with very low latency. As a tradeoff, high-band spectrum does not provide the coverage supported by mid- or low-band spectrum. The amount of currently allocated mmWave spectrum in the U.S. is reported by Analysys Mason as 4.95 GHz. Only Australia has more mmWave spectrum with a current allocation of 5.3 GHz. Unfortunately, in the next 5 years, the U.S. will sink to 6th as other countries have planned future allocations that will increase their current holdings above the United States'.

Low-band spectrum offers the best coverage and indoor penetration (when compared to higher-band spectrum), but it lacks the greater bandwidth available in mid- and high-band spectrum. According to the Analysys Mason report, the U.S. has the most allocated low-band spectrum in comparison to the other 15 global markets. Projections over 5 years forecast that the U.S. will be overtaken by several countries by an average of 70 MHz, absent of fresh U.S. efforts to open additional low-band spectrum.

3. Anticipated spectrum needs from 2027 to 2030

Global cellular data traffic has been increasing yearly and will continue to grow throughout the decade. According to Ericsson's June 2023 Mobility Report[9], the total monthly global mobile network data traffic has reached 126 EB in Q1 2023, having almost doubled in just 2 years. These numbers include fixed wireless access (FWA)—one of the drivers of long-term traffic growth—together with rising smartphone subscriptions and increasing average data volume per subscription. Total cellular data traffic is expected to reach 472 EB per month by the end of 2028—four times the data volume compared to end of 2022. This forecast may underestimate the data traffic by 2028 if the initial uptake of XR type services happens earlier than expected. Regardless of the level of conservatism in the assumptions for traffic demand forecast, additional spectrum will be required to support such growing cellular data traffic demand.

Spectrum in low, mid and high frequency ranges has been critical for cellular networks to adequately support different use cases and applications. A key learning from the introduction of the different mobile communications generations, including 5G, is that reusing the existing network site structure is essential for network planning and cost efficiency. Also, many 5G and beyond 5G use cases and applications, including those aimed to provide immersive experiences, such as eXtended Reality (XR), rely on both high data rates and wide-area coverage to realize their full potential. Therefore, additional mid-band spectrum that allows the combination of coverage and capacity, i.e., from sub-7GHz and in the 7.125-15.35 GHz range, will be needed.

Initial spectrum needs estimates for XR and holographic communications have been developed[10]. The minimum wide-area spectrum required is estimated to be roughly 1 GHz per network. The amount of additional spectrum needed would depend on the number of networks in a country or region, and the amount of existing spectrum being used for delivering these use cases. Assuming an existing licensing model with 3-4 independent nationwide network deployments, the estimated spectrum requirement is 3-4 GHz. Given that roughly 1 GHz of the existing mid-band spectrum could be utilized to enable the referred use cases, the estimated additional spectrum for wide-area deployments needed per network could be approximated to 500-750 MHz.

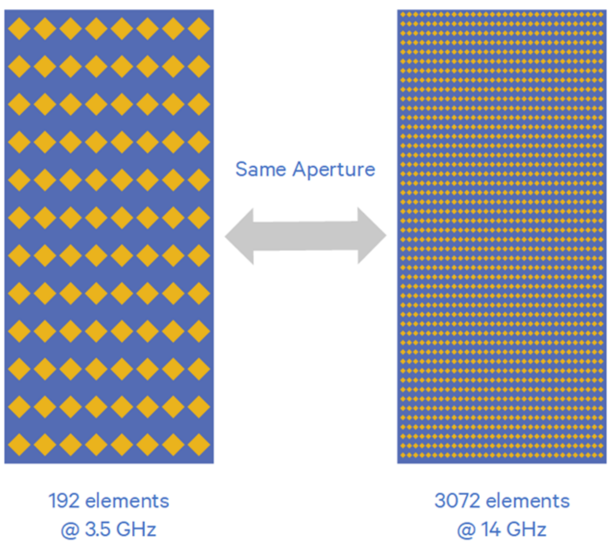
Joint Communications and Sensing (JCAS) is envisioned to be one of the main use cases for 6G in NextG Alliance Report on 6G Technologies[11], with the objective of communications aid sensing and sensing aids communications. It is also expected that JCAS will improve positioning accuracy. Sensing operation requires contiguous bandwidth, and the bandwidth is inversely proportional to resolution. Some use cases, such as smart transportation, will require contiguous bandwidth of 500 MHz.

4. Desired spectrum characteristics of target bands

The ability to reuse existing network site infrastructure is essential for the cost-efficient deployment of the new generation technology. While 5G NR technology was designed to operate in low, mid and high frequency bands, large-scale, wide-area coverage deployments largely utilize mid-band spectrum. The site planning that accounts for the existing 5G networks must be considered when selecting target bands for the new next generation technology. New applications and use cases will require even larger capacity, and new technology will need to meet new capacity demands while simultaneously ensuring the same coverage as existing 5G networks.

The most suitable spectrum to meet these requirements is upper mid-band spectrum (7.125-15.35 GHz range). Increased propagation losses observed in these bands compared to the mid-band are moderate. These additional losses can be addressed with advanced antenna technology, where more antenna elements are packed without increasing the antenna aperture size. The technique is illustrated in Figure 2 using 14 GHz carrier frequency as an example. Shorter wavelength at 14 GHz allows for packing 16x antenna elements within the same aperture size as in 3.5 GHz. For successful deployment of the technology, the regulation needs to allow for higher Equivalent Isotropic Radiated Power (EIRP) limits.

Figure 2: Comparison of antenna arrays for the same aperture size (3.5 GHz vs 14 GHz).



As carrier frequency increases, losses through building materials (like concrete) increase. They become too large at a certain threshold, and it is difficult to maintain satisfactory coverage in a cost-efficient manner. 15.35 GHz is seen as the upper end of the spectrum that could be considered for wide-area coverage. The lower end of the upper mid-band range remains the preferred choice for new data rate demanding applications, because maintaining good coverage in a cost-efficient manner is critical. The upper portion offers even larger capacity, but maintaining the same coverage could be challenging in some cases.

In addition to the carrier frequency requirement, another important characteristic for the target bands is the available contiguous bandwidth. Integrated communications and sensing may require relatively large contiguous bandwidth to meet target accuracy requirements. In many cases, the target range for these applications coincides with a typical macro cell radius, implying that the bandwidth requirement for sensing applies to the upper mid-band range.

Contiguous bandwidth requirement is also important from the cost and relative power consumption perspective. It is possible to support high data rate requirements associated for XR type services utilizing aggregation of non-contiguous bands, but it is cheaper and more power-efficient to support the same data rates utilizing contiguous bandwidth. Historically, each new generation of mobile technology has resulted in increased contiguous bandwidth by a factor of 4 or 5. Preliminary industry discussions also suggest that the next 6G mobile network standard may be designed with a target of 400-500 MHz.

5. Techniques to enable use of cellular systems in new bands

New, potential spectrum bands for mobile terrestrial use have a combination of Federal and non-Federal incumbents. Considering the characteristics of the incumbents' systems in the target bands is of primary concern for the introduction of mobile services. Aspects to be considered are the type of incumbent services, geographic location of the incumbent, how often the spectrum is used by the incumbent, and other factors.

For example, microwave services will require different considerations than satellite services or radio astronomy. Radio astronomy systems are generally located in remote areas that are naturally separated from the population centers where mobile service is most densely deployed. In some cases, incumbent services do not fully utilize the existing spectrum, or the existing uses can be transitioned to a more spectrally efficient technology. In some cases, relocating, transitioning, and repacking spectrum are not suitable mechanisms for spectrum access. In these cases, spectrum sharing can be the preferred means for the introduction of mobile services.

For example, the Federal Communications Commission (FCC) established a regulatory framework in the 28 GHz band that allowed the deployment of terrestrial mobile service while supporting existing and future satellite gateways in the band. In this case, sharing was possible by restricting the conditions by which satellite gateways could be deployed. In another example, the FCC established the Citizens Broadband Radio Service (CBRS) in the 3.55-3.70 GHz band for wireless broadband service. The incumbent in the band of primary consideration are government radars, specifically the high-powered, shipborne naval radars. In this case, it was not deemed optimal to clear the spectrum. Ultimately, the FCC established a spectrum sharing framework that serves to support incumbent use of the band while allowing some limited access for mobile services.

5.1 Clearing of spectrum

There are many models that can be collectively considered for clearing spectrum for mobile licensed use. The following sections cover models for relocation, transition, and repacking.

5.1.1 Relocation

There are two main approaches that could be considered for relocating incumbents. The first approach is through government requirements, and the second is market-based. The first approach would utilize regulations to mandate that incumbents are required to relocate to another band. This approach is also applicable for satellite incumbents with equipment capable of operation in multiple bands. Incumbents of the mandatory relocation could be compensated through a license auction of the licenses.

A second approach for relocating incumbents is a more market-based approach where relocation would be voluntary for the incumbent to move their operations to other frequencies or other locations. Incumbents could also decide to terminate their operations instead of relocating. There are several ways that a market-based approach could be conducted. For instance, it is possible that this type of relocation could be executed through a direct engagement by the incumbent with a new entrant to clear spectrum for the introduction of new services.

Another market-based approach is where the regulator provides incentives for the incumbent(s) to relocate their services/traffic to new frequencies. Incentives could include the ability for the incumbent to take part in an auction and benefit from the sale of its license as was done in the U.S. in the 600 MHz Incentive Auction. In this case the FCC conducted a first-of-its-kind auction that compensated TV broadcasters that relinquished their licenses.

The benefit of these market-based approaches is the voluntary nature of cooperation between the incumbents and the new entrant, which could mean less industry opposition and delays as FCC decisions are appealed, and the expectation that spectrum access is expedited. However, there is also a level of uncertainty that is avoided when relocation is mandated; specifically, the uncertainty of when the spectrum would be made available, what spectrum is available and under what terms. In some cases, there may need to be widespread agreement among the incumbent community to ensure that spectrum access, sufficient to supports competition among service providers with sufficient bandwidth.

5.1.2 Transition

This model focuses on how alternative transmission platforms can be used to clear spectrum for mobile licensed use. For example, a 5G network has the capability of delivering high-definition video in real-time. The very high uplink and downlink speeds of 5G provide an alternative to services currently allocated in bands for electronic news gathering and similar applications.

5.1.3 Repacking

Repacking is the process by which existing services are required to relocate their operations to another portion of the same frequency band. The relocated operations will have to modify their existing facilities (for example, antennas) to transmit on a different frequency. The benefit of repacking is that fragmented spectrum can be cleared by moving operations to another portion of the spectrum. Ideally, contiguous spectrum remains, and incumbents operate in adjacent frequencies which provides cost-savings. For example, the 600 MHz incentive auction mandated a 39-month period during which time TV stations were required to transition to new channel assignments. The repacking process allowed the introduction of mobile services in vacated spectrum. Another example is the repacking of Fixed Satellite Service (FSS) in the C-Band (3.70-4.20 GHz). In this case, FSS was re-packed to the upper 200 MHz of C-Band and the lower 280 MHz of this spectrum was auctioned for mobile broadband services.

5.2 Mechanisms for spectrum sharing

Spectrum sharing can be considered when clearing spectrum is not feasible. Spectrum sharing typically involves co-frequency coordination between services with similar access rights and can facilitate access to spectrum that is underutilized. Spectrum sharing can also facilitate access to spectrum in cases where spectrum clearing is not possible in a timely manner or when the incumbents are not planning to relocate. Spectrum sharing to allow the introduction of licensed mobile service on a primary basis, in some cases, can be facilitated by designating the incumbent services on a secondary basis. This option is best considered when the incumbent has limited operations and therefore interference would likely be minimal to begin with.

5.2.1 Exclusion zones

Exclusion zones are based on interference protection of a specific geographical area. Exclusion zones are useful if the incumbent operation is unlikely to receive harmful interference from the introduction of other spectrum uses, or if the number and scope of incumbent operations to protect is limited. For instance, when the operation of the incumbent is in a remote area and relocation does not make sense, interference protection is possible using a defined geographical exclusion zone. Another example is within the CBRS band where defined exclusion zones preclude operation of CBRS radio service within those zones. In this case, exclusion zones are enforced and maintained by the spectrum database manager or SAS. An extension of the exclusion zone concept is the protection zone. A protection zone defines coordination requirements. An example of that are Cooperative Planning Areas (CPAs) and Periodic Use Areas (PUAs) in the 3.45 GHz (3.45-3.55 GHz) band.

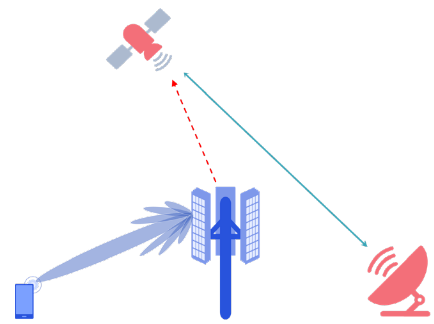
CPAs are geographic locations in which non-Federal operations shall coordinate with Federal systems in the band to deploy non-Federal operations in a manner that shall not cause harmful interference to Federal systems operating in the band. Operators of non-Federal stations may be required to modify their operations to protect Federal operations against harmful interference and, where possible, to avoid interference and potential damage to the non-Federal operators' system. Non-Federal operations may not claim interference protection from Federal systems.

PUAs are geographic locations in which non-Federal operations in the band shall not cause harmful interference to Federal systems operating in the band for episodic periods. During these times and in these areas, Federal users will require interference protection from non-Federal operations. PUAs are required to provide quiet environments to test and calibrate radar equipment to support large-scale military exercises or for short-duration, high-power, radar operations.

5.2.2 Spatial sharing

Massive MIMO (M-MIMO) systems exploit large number of antenna elements to improve coverage and capacity of the cellular networks. The ability to create 3-dimentional (3D) narrow beams combined with improved area capacity, M-MIMO systems can also be exploited for improved coexistence with incumbents. For example, 3D spatial techniques can enable spectrum sharing between cellular terrestrial networks and satellite incumbents, particularly in the portion of 7.125-15.35 GHz band that is utilized for Earth to Space communication links. As shown in Figure 3, several antenna elements allow terrestrial networks to create beams that limit emissions in the direction of the satellite receivers.

Figure 3: Massive MIMO systems can protect incumbent satellite users.



Depending on the spectrum being utilized, and the number of available antenna elements, spatial techniques may also be utilized in other scenarios. For example, M-MIMO systems could improve coexistence with radars, terrestrial incumbents and other existing spectrum users, thus potentially creating new opportunities for spectrum for cellular networks.

Dynamic spectrum sharing refers to a set of techniques where available spectrum varies in time. A database-driven spectrum sharing approach could be used to manage exclusion zones and protection requirements and facilitate access to spectrum when the nature of incumbents and new entrants justify such an approach. Under this framework, the database is responsible for determining the available spectrum, depending on the location of the user and the proximity of the user to other uses in the band. The data-based driven approach results in a relatively slow change in the available spectrum, suitable for scenarios such as sharing with Federal shipborne radars in 3.55 GHz to 3.7 GHz band, where rate of adaptation is on the order of minutes or hours. More agile adaptation is necessary to share spectrum with the incumbents with faster mobility, such as Federal airborne radars. Techniques that facilitate faster adaptation require new, defined network interfaces so that information about incumbent use can be handled by the radio resource management function of the terrestrial mobile network.

Bi-directional sharing has recently received attention as an emerging new technique that may be suitable for sharing of spectrum between Federal users and commercial mobile networks. Bi-directional sharing refers to cooperative procedures between two services to manage access to spectrum and mitigate interference. Bi-directional sharing is not suitable for sharing with legacy systems, but it could be a promising technique for sharing if Federal users are equipped with such capability.

In addition to relying on the network interfaces to enable sharing, sensing techniques can be utilized to detect presence of incumbents, and dynamically share spectrum when interference conditions permit. These techniques are suitable when incumbents' signals are strong enough to be detected before the signals transmitted by the cellular network can cause harmful interference to incumbents.

6. Current and future use of mmWave

5G is the first mobile technology generation that uses mmWave spectrum bands to provide mobile connectivity. After more than a decade of advanced R&D and ecosystem trials, 5G mmWave service is now available in scores of U.S. cities and more than 160 areas in Japan, and is rapidly expanding globally to multiple countries in Europe, Asia, and South America as shown on the map in Figure 4.

Global support for 5G mmWave technology continues to grow, with GSMA having announced the formation of the global accelerator initiative, which aims to build on existing momentum behind 5G mmWave mobile connectivity. 5G mmWave provides reliable connectivity to many more users in dense settings and supports massive increases in user mobile data demand. 5G mmWave also is expanding the core role of mobile communication across various industries.

5G mmWave mobile deployments complement 5G deployments by using low-band and mid-band spectrum bands to offer massive capacity and low latency connectivity. The use cases for mmWave connectivity are vast and growing rapidly: from providing fixed wireless broadband to homes in rural locations and in cities, to delivering reliable, high-speed connectivity to mobile users in densely populated urban cores and transportation hubs, shopping malls and stadiums, in all types of settings. A GSMA Intelligence study[12] found the large spectral bandwidth available in the mmWave bands can meet high mobile traffic demand while maintaining the performance and quality requirements of 5G services. The study also found that 5G network deployments using both mid-band and mmWave bands can provide the same or better level of service and at lower cost to carriers when compared to 5G network deployments using only mid-band spectrum.

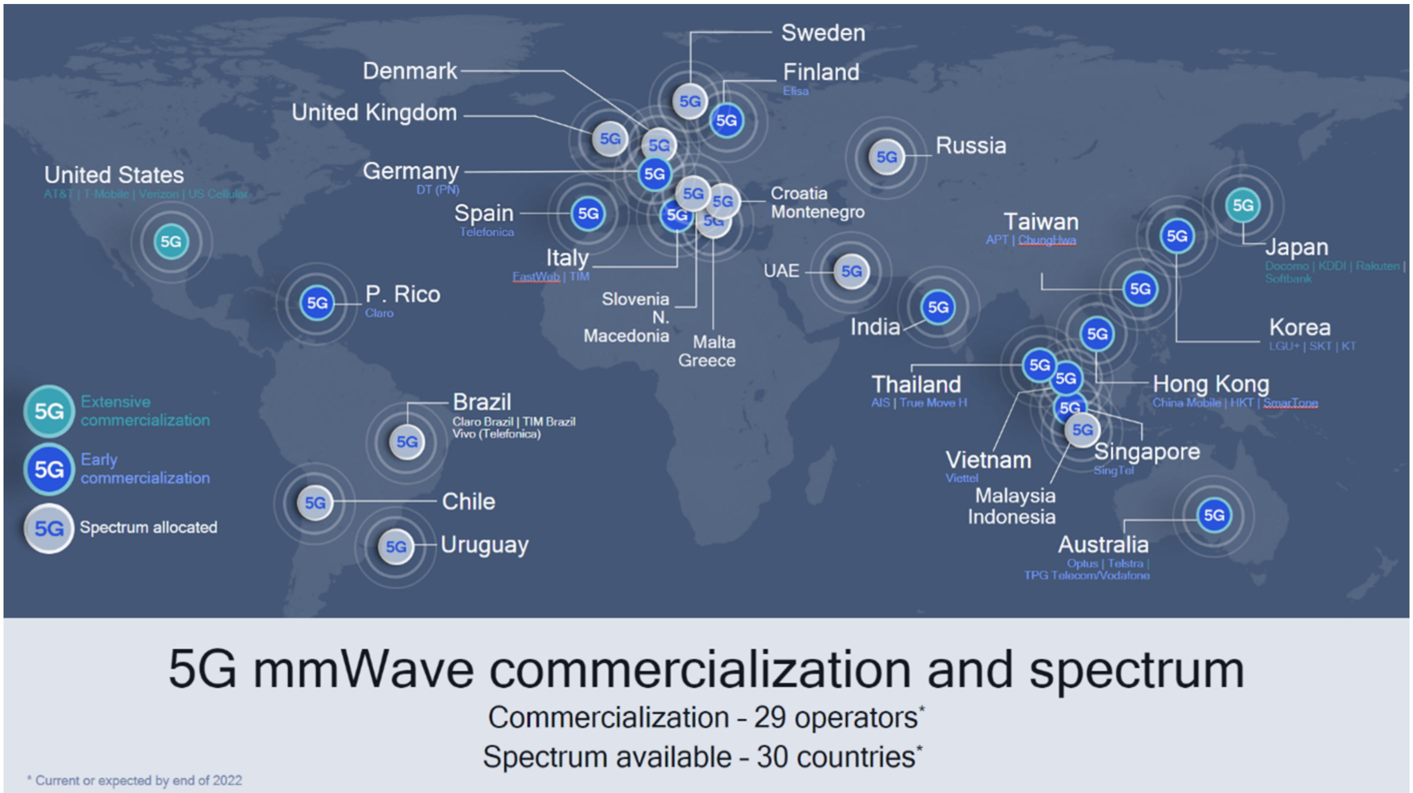
5G mmWave is successfully deployed in multiple markets, and provides vast benefits to consumers. More than 65 vendors have developed over 170 devices[13] equipped with mmWave connectivity collectively, including smart phones, customer premises equipment, IOT devices, wireless hotspots, and laptops. Today's 5G mmWave capabilities are just the tip of the iceberg and will form the foundation to enable use cases that need extreme throughput and single-digit millisecond latency that are not presently feasible. Many entertainment venues and sports stadiums are equipped with mmWave connectivity, allowing tens of thousands of fans to receive high-quality 5G connectivity. Innovative AR/VR applications that mmWave connectivity will support could allow baseball fans to enjoy the real-time visual and audio experience of the home plate umpire, or shortstop during a major league baseball game. Public safety is another important use case where high-capacity, 5G mmWave connectivity can address traffic demand during an emergency.

In addition to delivering service directly to end users, mmWave bands can simultaneously be used for backhauling connections. 5G-based Integrated Access and Backhaul (IAB) deployments—a key wireless backhaul innovation that was first standardized in 3GPP Release 16—allows the same spectrum band to be used for both access and backhaul connections. 5G IAB allows use of the access link for backhaul connections by efficiently multiplexing access and backhaul in the frequency, time, and space domains.

The beam steering capability in high-band massive MIMO solutions provides spatial separation between backhaul and access links, greatly increasing spectrum efficiency. IAB also allows a service provider to improve coverage by installing denser networks, without having to lay fiber to all nodes—or at least not requiring the major investment of laying fiber for all backhaul needs at initial deployment stages. This facilitates rapid, lower cost dense deployments that improve coverage and user services.

Smart repeaters are another mmWave innovation that can improve outdoor coverage and enable mmWave signals to be brought indoors from a gNodeB or small cell, and then spread to enhance coverage indoors. Smart repeaters can support dense indoor mesh networks, enabling traffic to be dynamically routed based on signal quality, bandwidth, latency and network congestion.

Figure 4: 5G mmWave commercialization.



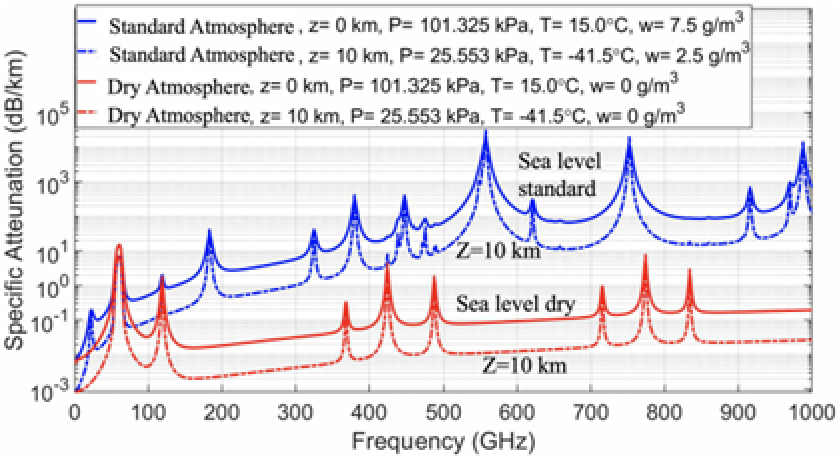
7. Sub-THz spectrum for new 6G use cases

Sub-THz commonly refers to the spectrum above 90 GHz and up to 300GHz. Due to technology maturity challenges for higher bands, it is expected that initial interest will be in the lower portion of the band. The main advantage of Sub-THz band is potentially large available bandwidth that can offer significantly higher data rates compared to all other bands considered for 6G. However, the path loss can be substantially higher than in mid-band and mmW spectrum. The free space propagation losses increase by 6 dB as the frequency doubles. The reflection and absorption losses are also generally higher, while atmosphere absorption can be significantly larger for some narrow frequency ranges.

Atmospheric attenuation as a function of carrier frequency is illustrated in Figure 5. Frequencies with low atmosphere attenuation and weather impact are more desirable for the link budget limited deployment scenarios. High atmospheric absorption may be more desirable for the short-range communications because high losses can isolate different deployments, and ultimately simplify sharing scenarios (including sharing with incumbents).

Power efficiency for Sub-THz systems is a crucial parameter. Power efficiency at high-bands is generally poorer compared to lower bands, so implementation of a power-efficient Radio Frequency (RF) architecture is critical for the success of Sub-THz systems. For example, a carrier wavelength of 141-148.5GHz band is roughly 2 mm. Such a small wavelength lends itself to a power-efficient RF architecture, where low-power amplifier efficiency is compensated with a small aperture antenna array and passive beamformers, like a lens or dish antenna. The lens solution can be practical for semi-static communication links because it allows creation of a narrow beam to the desired location, while simultaneously reducing interference to the unintended receivers, and maximizing spatial multiplexing.

Figure 5: Specific atmospheric attenuation in dB/km as a function of carrier frequency, and altitude (z), atmospheric pressure (P), temperature (T), and water content (w) as a parameter.[14]



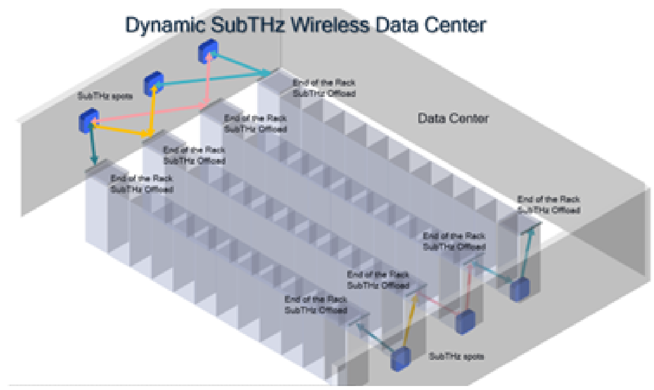
Accounting for the previously discussed constraints, the most promising use cases for high data rate communications utilizing Sub-THz bands are:

- **Wireless fronthaul:** Sub-THz bands can enable new cells deployments when optical fiber is unavailable and the cost of deploying new fiber is prohibitively high. Increase in the throughput demands requires a low-cost, high-throughput, and a low latency solution that can replace the high cost of optical fiber deployments. The capability to deliver up to 300 Gbps in point-to-point links with less than 100 microseconds latency have been demonstrated by Qualcomm's prototype system shown in Figure 6.

Figure 6: Lens antenna prototype solution capable of delivery 300 Gbps with 100 us latency

- **Wireless data center:** The data traffic demand in wireless data centers is high, and peak to average ratio of traffic in wireless data centers can cause system overload. Today's solution is to multiply the infrastructure requirements and hardware to reduce the probability of overload, but this results in poor utilization and high cost (typically, half of the components are for Backup). This approach is not scalable going forward because the traffic in the data centers is expected to increase exponentially. The number of fiber links that connect N racks with the other N racks in the cluster is N^2. The squared relationship is unfavorable compared to the linear scaling in the case of wireless transmitters and receivers that Sub-THz solution can offer, in conjunction with a lower cost. A wireless data center utilizing dynamic configuration can handle peak traffic demands by tuning the beam steering to the required direction such that it will offload the bottleneck path. The wireless data center solution is illustrated in Figure 7. The Sub-THz solution can operate in a low power and a high throughput manner utilizing lens RF beamformer which is those low distances can achieve a massive number of streams on the same direction with a good spatial separation.

Figure 7: Sub-THz application to data centers



- Wireless "fiber" to the home - 5G is utilized today to enable high date rate internet connectivity to homes that do not have a fiber deployment as illustrated in Figure 8. mmWave bands have good potential to satisfy today's data rate requirements. However, as the data rate requirements increase, the bandwidth requirements also rise. There is plenty of available spectrum in the Sub-THz bands that can be utilized to support multiple users simultaneously, due to the narrow beams that the Sub-THz bands enable.

Figure 8: Wireless fiber to home

- Relays – Large available Sub-THz bandwidth can be exploited to carry the data over a gNB to relay links, and then forwarded to the end users manner utilizing low carrier frequencies, such as mmWave or mid-band spectrum.

In addition to communications, positioning and sensing applications can utilize Sub-THz bands and offer some advantages over lower frequency bands. To achieve centimeter-level positioning in the current mmWave bands, advanced techniques, like bandwidth aggregation or real-time kinematics, are required because sufficiently large contiguous bandwidth is not available. Sub-THz offers bands with sufficiently large contiguous bandwidths where centimeter-level accuracy can readily be attained without such complex techniques. For some sensing applications, such as human-machine interface and health care, high resolution sensing is necessary. For example, today's RF sensing solutions for gesture recognition are largely restricted to presence, motion, and posture recognition due to the limited resolution and accuracy. Fine-grained gesture recognition (i.e., finger gesture recognition) is gaining popularity in emerging AR/VR applications, and mostly relies on camera or wearable sensor-based solutions. Some applications in health care (i.e., heartbeat and respiration monitoring) also require very high sensing resolution and accuracy, which is not feasible with current mmWave sensing. Greater Sub-THz bandwidth availability could overcome these issues and enable new use cases for RF sensing.

8. WRC Decisions

International Telecommunications Union World Radio Conference (ITU WRC 2023), several proposals have been adopted across various regional groups to recommend for either identification or inclusion in a future agenda item that identifies a spectrum pipeline for the next generation of wireless technology. In particular, the following bands were identified for IMT:

- 3.3 – 3.4 GHz. Identified for IMT in Region 1 and are across Africa and Asia Pacific
- 3.6 – 3.8 GHz. The band 3.6-3.7 GHz was identified for IMT in Region 2
- 6.425 -7.125 GHz. The band 6.425-7.125 GHz was identified for IMT in Region 1 and 7.025-7.125 in Region 3
  - » Brazil, Mexico Cambodia, Laos, and the Maldives have also identified the 6.425-7.125 GHz band for IMT in Indonesia, Thailand, Vietnam, China, Philippines, Bangladesh, Myanmar, and Sri Lanka in Region 3 indicated their intent to join in 2027, making the band suitable for 6G/IMT-2030. The IMT recognize that the frequency bands are also used for Wireless Access System including Radio Local Area Networks.
- 10 - 10.5 GHz. IMT identification in Region 2. The maximum EIRP of the base station is limited to 30 dB (W/100 MHz) to protect radio location and Earth Exploration Satellite Services, which may restrict the deployment to hotspots only.

The following bands were identified for study for IMT under WRC-27 Agenda Item 1.7:

- 4.4 – 4.8 GHz, or parts thereof, in Regions 1 and 3
- 7.125 -8.4 GHz, or part thereof, in Regions 2 and 3
- 7.125 – 7.25 GHz and 7.75 – 8.4 GHz, or portion, in Region 1
- 14.8-15.35 GHz

On an individual country level, and as indicated previously, China has already announced its support for IMT identifications in the 6.425 GHz to 7.125 GHz band. In the U.S., Chairwoman Rosenworcel has identified the 7-15 GHz range for studies for the next generation wireless technology. NTIA published a U.S. national spectrum strategy on November 13, 2023 (https://www.ntia.gov/sites/default/files/publications/national_spectrum_strategy_final.pdf) which included identifying spectrum for key stakeholders. To date, the U.S. has only included the 3.1-3.3 GHz and 12.7-13.25 GHz bands for study.

Recommendations

Economical deployment over the wide-area utilizing existing 5G sites optimized for mid-band spectrum is critical for the success of 6G. It is necessary that new 6G spectrum is available in bands as close as possible to the mid-band spectrum so that adequate coverage can be provided with new 6G technology. Upper mid-band spectrum is identified as the prime candidate for spectrum suitable for economic wide-area deployments.

The existing licensing model assumes that three to four independent operators deploy a mobile network nationwide. Utilizing this model, it is estimated that at least 2 GHz of spectrum is needed in upper mid-band to cover new 6G applications and use cases. Upper mid-band spectrum covers more than 8 GHz range, and the propagation characteristics differ. There is approximately 6 dB difference accounting for the free space propagation losses between the lower and upper end of the range. Providing adequate coverage is critical for the success of any network deployment, so it is recommended that at least part of the newly available upper mid-band spectrum is in the lower part of the range. When accounting for the outcome of the Word Radio Conference 2023 across regions, and current Notices by FCC[15], the following upper mid-band ranges are recommended to be considered for 6G spectrum pipeline:

- 3.1-3.3 GHz: Recommended in the U.S. suitable to provide desired coverage and capacity.
- 4.4 - 4.8 GHz: Recommended to study for IMT in Regions 1 and 3 as suitable to provide desired capacity/coverage trade off.
- 7.125 GHz - 8.5 GHz: Recommended to study for IMT in Regions 2 and 3. 7.125 - 7.25 GHz.
    - » 7.75 - 8.4 GHz, is recommended to study for IMT in Region 1. It would seem most suitable to provide desired capacity/coverage trade off.
- 12.7 GHz - 13.25 GHz: Recommended for mobile service in the U.S. This seems more challenging to ensure coverage than in the lower end of the upper mid-band.
- 14.75 GHz - 15.35 GHz: Recommended to study for IMT. This seems more challenging to ensure coverage than in the lower end of the upper mid-band.

Sub-THz frequency ranges (90 GHz to 300 GHz) need further study. Due to the technological maturity challenges, most of the initial interest is focused on the lower portion of the band.

Conclusions

By 2028, the traffic over cellular networks is expected to grow four times compared to 2022. The introduction of new use cases and deployment scenarios envisioned for 6G will likely increase traffic even further in the future. New spectrum needs to be allocated to the mobile networks to support such an increase in traffic. Due to the propagation characteristics differences, not all spectrum is equal. Higher frequency spectrum is more abundant, and while it offers potential for high capacity, it is also associated with higher propagation losses. The propagation losses characteristics make higher frequency bands unsuitable for economical deployments over large areas. It is crucial to account for the optimized capacity and coverage tradeoff that the spectrum provides when identifying new spectrum for 6G networks.

Upper mid-band, associated with the 7.125-15.35 GHz frequency range (preferably portion below 10 GHz), is best suited to provide a desired capacity/coverage tradeoff for the future mobile networks. This range has enough spectrum to accommodate increases in traffic demand, and new use cases. It is also suitable for economic deployment over wide areas. With the advancements in antenna technology, upper mid-band can be utilized to provide the same coverage as the current 5G networks that are deployed in 3-4 GHz range without increasing antenna aperture size. For successful deployment of the technology, however, the regulation needs to allow for higher EIRP limits.

The ability to relocate incumbents or coexist with incumbent users will be a deciding factor in which part of the upper mid-band is suitable for use by mobile networks. From the capacity/coverage tradeoff perspective, the lower end of the upper mid-band range is the preferred choice for new data rate demanding applications, because it is critical to maintain good coverage in a cost-efficient. The upper portion offers even larger capacity, but maintaining the same coverage is more challenging.

mmWave spectrum will continue to be used to provide high-capacity mobile communications in hotspot scenarios. Expansion to Sub-THz bands may be needed to support even higher data rates, such as fixed links, wireless data centers, and new use cases associated with positioning and sensing.

Appendix

Acronyms

APT: Asia Pacific Telecommunity

ATU: African Telecommunications Union

ASMG: Arab Spectrum Management Group

CBRS: Citizens Broadband Radio Service

CEPT: European Conference of Postal and Telecommunications Administrations

CITEL: Inter-American Telecommunication Commission

CPA: Cooperative Planning Areas

CTIA: Cellular Telephone Industry Association

FCC: Federal Communications Commission

EIRP: Equivalent Isotropic Radiated Power

FSS: Fixed Satellite Service

FWA: Fixed Wireless Access

GSMA: Global System for Mobile Communications Association

IAB: Integrated Access and Backhaul

IMT: International Mobile Telecommunications

ITU: International Telecommunications Union

ITU Region 1: Region 1 comprises Europe, Africa, the Commonwealth of Independent States, Mongolia, and the Middle East west of the Persian Gulf, including Iraq.

ITU Region 2: Region 2 covers the Americas including Greenland, and some of the eastern Pacific Islands.

ITU Region 3: Region 3 contains most of Asia's Post Soviet States east of and including Iran, and most of Oceania.

JCAS: Joint Communications and Sensing

MIMO: Multi Input Multi Output

PUA: Periodic Use Areas

RCC: Regional Commonwealth in the field of Communication

RF: Radio Frequency

SAS: Spectrum Access Server

XR: eXtended Reality

WRC: World Radiocommunications Conference

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2 https://www.5gamericas.org/wp-content/uploads/2023/03/Mid-Band-Spectrum-Update-2023-Id.pdf

3 https://www.analysysmason.com/

4 https://api.ctia.org/wp-content/uploads/2022/09/Comparison-of-total-mobile-spectrum-28-09-22.pdf

5 In this global perspective, Analysis Mason recognized that there is a lack of definition when it comes to low, mid and high band frequency ranges. The decision to use 3-7 GHz as midband spectrum was based on the actions by the global markets recent and planned assignment decisions for 5G deployments. In the US, the 2.5 GHz band was allocated many years ago and is also being used for 5G in the US and has many of the propagation characteristics associated with midband spectrum; however, the focus of the Mason report, and the frequency range that is defined here for midband, reflects comparison of the most recent decisions of the global market when deploying 5G.

6 Consideration for spectrum in the 3.1-3.45 GHz range is subject to further study. At this stage of the study, the timeframe, amount and suitability of spectrum in the lower 3 GHz band has not been determined.

7 GSMA | MWC Shanghai: 6 GHz takes big steps towards commercial 5G ecosystem - Spectrum

8 The status of whether this spectrum will be licensed has not been set.

9 https://www.ericsson.com/49dd9d/assets/local/reports-papers/mobility-report/documents/2023/ericsson-mobility-report-june-2023.pdf

10 Doc. PTA(23)047, "IMT-2030 (6G) Spectrum needs and candidate bands", Annex 1.

11 See section 3.5.1 in https://www.nextgalliance.org/wp-content/uploads/dlm_uploads/2022/07/TWG-report-6G-technologies.pdf

12 https://data.gsmaintelligence.com/api-web/v2/research-file-download?id=59768858&file=210121-Economics-of-mmWave.pdf

13 GSA report, December 2023

14 Y. Xing and T. S. Rappaport, "Terahertz Wireless Communications: Co-sharing for Terrestrial and Satellite Systems above 100 GHz (Invited Paper)," submitted to 2021 IEEE Communications Letters, May 2021, pp. 1-5.

15 REPORT AND ORDER AND FURTHER NOTICE OF PROPOSED RULEMAKING AND NOTICE OF PROPOSED RULEMAKING AND ORDER, available at: https://docs.fcc.gov/public/attachments/FCC-23-36A1.pdf

Acknowledgments

5G Americas' Mission Statement: 5G Americas facilitates and advocates for the advancement of 5G and beyond throughout the Americas.

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