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THE EVOLUTION OF 5G SPECTRUM

Purpose

The purpose of this briefing paper is to identify spectrum pipeline for the next generation of wireless technology. It is clear that more capacity will be needed for the variety of use cases that may emerge into the next decade as 5G continues to evolve beyond mobile broadband smartphone use cases and into new use cases like fixed wireless access, enterprise and vertical industries. Spectrum is the “raw material” that is needed to support new services, and it is important to create a runway of different spectrum types so spectrum can continue fueling potential future use cases such as eXtended Reality, connected cars, and the Metaverse.

Additional spectrum will need to be identified in the spectrum pipeline to address new use cases moving toward 2030 and beyond. The 3-15.35 GHz range (due to propagation characteristics, preferably below 10 GHz) is most suitable for next generation wireless technology requirements. 5G and 5G-Advanced standards currently support bands below 7.125 GHz and above 24 GHz. The next generation 6G standard is expected to operate in all bands that 5G and 5G-Advanced support, as well as support 7.125 GHz – 24 GHz bands. The 2023 International Telecommunications Union (ITU) World Radiocommunication Conference[1] adopted a new agenda item that identifies a spectrum pipeline within the 4.4-15.35 GHz range for the next generation of wireless technology.

Background

5G revolutionized mobile broadband service by increasing communications speeds and reducing air interface latency, while simultaneously improving reliability. 5G-Advanced, as currently standardized in 3GPP, is expected to establish a foundation for 6G (expected by 2030).

5G networks may be deployed from low-band (below 1 GHz), mid-band (from 1 to 7 GHz) to high-band (mmWave bands above 24 GHz). Mid-band spectrum is typically most desirable as it provides the most suitable capacity/coverage tradeoff for the enhanced mobile broadband (eMBB) mobile network service. The regulatory discussions taking place now 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 ITU for International Mobile Telecommunications 2030 (IMT-2030) form the basis for spectrum needs, estimates, and considerations on spectrum requirements. Use cases and applications, especially regarding 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.

Suitable spectrum that could be exclusively licensed was easier to identify in the past. This is due to significantly narrower bandwidth requirements than what is anticipated for the next generation 6G wireless technology. Historically, there is a bandwidth increase factor of 4-5x between subsequent generation of mobile networks and 6G bandwidth, after accounting for IMT-2030 requirements is expected to be 400-500 MHz.

Successful deployment of 5G-Advanced and 6G will depend on the availability of new spectrum, as was the case for previous generations. To ensure successful deployments of future mobile networks, it is critical to develop national strategy for new spectrum roadmap, considering the anticipated 400-500 MHz contiguous bandwidth requirement. However, due to incumbencies, it is difficult to find new spectrum suitable for next generation wireless technology. This paper summarizes the current status and potential approaches for securing new spectrum for mobile networks.

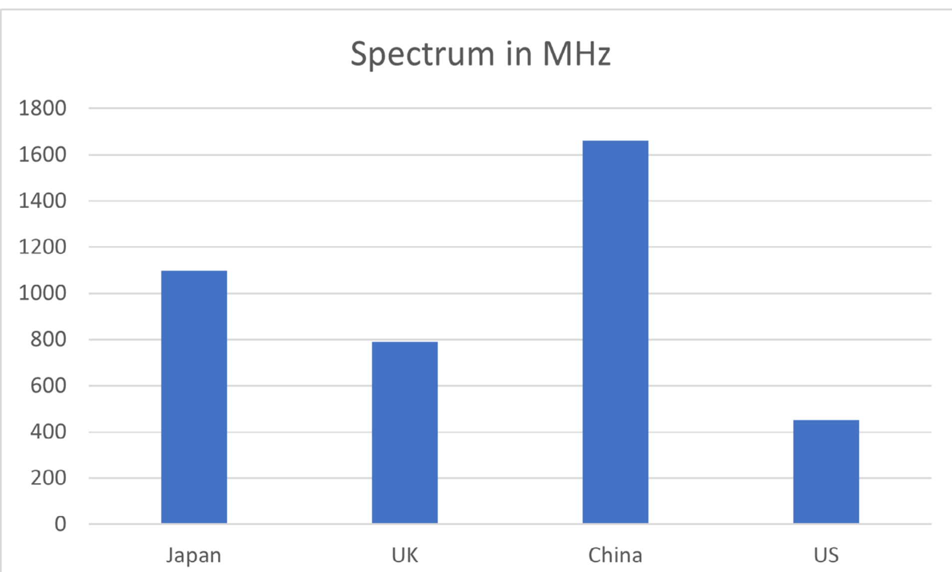
Current Status

According to the 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) to high-band (mmWave bands above 24 GHz). 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].

Mid-band spectrum

According to a Cellular Telephone Industry Association commissioned study[3], the U.S. is positioned 13th of 15 leading global markets when it comes to available licensed mid-band spectrum. Mid-band spectrum is tailor-made for 5G deployments by offering optimized coverage and capacity. The lack of licensed mid-band spectrum is not expected to sufficiently improve in the next five years. The U.S. has made available a total of 450 MHz in the 3-7 GHz range[4,5]. In contrast, Japan's current allocation is 1100 MHz, and the UK is 790 MHz. Additionally, China has 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[6], and is considering the remaining 500 MHz for IMT. With the entire 1200 MHz in the 6 GHz band, there is a potential for a total of 1660 MHz of mid-band spectrum[7]. The mid-band spectrum allocation (current and planned) is illustrated in Figure 1.

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



mmW spectrum

Currently, the U.S.'s allocated high-band is more favorable. High-band frequencies (mmWave) offer large bandwidths that can carry sizeable swaths of data with very low latency. 5G mmWave service is now available in scores of U.S. cities, more than 160 areas in Japan, and is rapidly expanding globally to multiple countries in Europe, Asia, and South America. Global support for 5G mmWave technology continues to grow, with Global System for Mobile Communications Association announcing the formation of the global accelerator initiative. It aims at building upon the existing momentum behind 5G mmWave mobile connectivity while also providing reliable connectivity to many more users in dense settings, and supporting 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 using low-band and mid-band spectrum bands to offer massive capacity and low latency connectivity. Indeed, a Global System for Mobile Communications Association Intelligence study 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.

Low-band

Low-band spectrum offers the best coverage and indoor penetration (when compared to higher-band spectrum), but it lacks the greater bandwidth available in the 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 the next five 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.

Spectrum needs

Global cellular data traffic has been growing yearly and will continue to grow throughout the decade. According to studies[8], 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. This characteristic will remain. A key learning from the introduction of the different mobile communications generations, including 5G, is that re-using 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, 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 (preferably below 10 GHz) range, will be needed. For successful deployment in new bands, the regulation needs to allow for higher Equivalent Isotropic Radiated Power (EIRP) limits. Higher EIRP limits compensate higher propagation losses in new bands and allow operators to reuse of the existing 5G sites, which is critical for the economic deployment of new technology.

Initial spectrum needs estimates for XR and holographic communications have been developed[9]. 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 is envisioned to be one of the main use cases for 6G in NextG Alliance Report on 6G Technologies[10]. The goal is that communications aid sensing and sensing aids communications. It is also expected that joint communications and sensing 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.

Sub-THz spectrum

Sub-THz commonly refers to the spectrum above 90 GHz and up to 300GHz and it is currently being considered for 6G technology. 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 mmWave spectrum. The reflection and absorption losses are also generally higher, while atmosphere absorption can be significantly larger, for some narrow frequency ranges.

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 141-148.5 GHz band is roughly 2mm. 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. In addition to communications, positioning and sensing applications can benefit from the use of sub-THz. Due to availability of larger bandwidths in the sub-THz band, resolution issues associated with the low and midbands can be addressed and enable new use cases for RF sensing.

World Radiocommunications Conference 2023 decisions

At ITU World Radiocommunication Conference 2023, several proposals have been adopted across various regional groups to recommend either identification or the inclusion of a future agenda item to identify 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 IMT Region 3 Brazil, Mexico Cambodia, Laos, and the Maldives have also identified the 6.425-7.125 GHz band for IMT. Indonesia, Thailand, Vietnam, China, Philippines, Bangladesh, Myanmar, and Sri Lanka 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 a portion, in Region 1
- 14.8-15.35 GHz

On an individual country level, and as indicated in Section 4, 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 U.S. national spectrum strategy on November 12, 2023[11] which includes 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.

Techniques to enable cellular use 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.

Clearing of spectrum

There are many models that can be collectively considered in the clearing of spectrum for mobile licensed use. In the following sections, models for relocation, transition and re-packing are explained.

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.

A second approach for relocating incumbents is more market-based, where incumbent relocation to other frequencies or locations would be voluntary. 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 the spectrum for the introduction of new services.

The transition 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.

Re-packing 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 re-packing 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.

Mechanisms for spectrum sharing

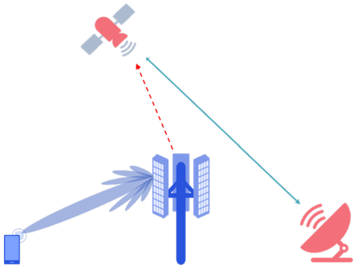
Spectrum sharing can be considered when clearing spectrum is not feasible. Spectrum sharing typically involves co-frequency coordination between services with similar access rights, and can facilitate access to spectrum that is underutilized.

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. An extension of the exclusion zone concept is the protection zone. 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. 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.

Massive-Multi Input Multi Output (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 2, several antenna elements allow terrestrial networks to create beams that limit emissions in the direction of the satellite receivers.

Figure 2: 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 definition of new network interfaces so that information about incumbent use can be handled by 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.

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 3 to 4 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 Federal Communications Commission[12], the following upper mid-band ranges are recommended to be considered for the evolution of 5G spectrum pipeline:

- 3.1-3.3 GHz: Recommended in the U.S. as 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 and 7.75 - 8.4 GHz, is recommended to study for IMT in Region 1. Most suitable to provide desired capacity/coverage trade off.
- 12.7 GHz - 13.25 GHz: Recommended for mobile service in the U.S. This is 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 globally, across all 3 ITU Regions. This is 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.

Conclusion

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. 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.

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 (preferably below 10 GHz) frequency range, 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 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.

Acronyms

EIRP: Equivalent Isotropic Radiated Power

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.

M-MIMO: Massive-Multi Input Multi Output

References

1 https://www.itu.int/wrc-23/

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

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

4 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.

5 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.

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

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

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

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