WHITE PAPER

Exploring the 6G Spectrum Landscape

An analysis of the spectrum potential for next-generation wireless systems

KEYSIGHT

Introduction

In each generation of cellular communications, new spectrum has been key to delivering more services, more capacity, and higher data throughput to end users. 5G benefited from large contiguous bandwidths of millimeter-wave (mmWave) spectrum, known as frequency range 2 (FR2). And 5G benefited from the reallocation and unlocking of midband spectrum (3.4 to 4.9 GHz) with its more favorable propagation characteristics. The spectrum that will be available for 6G is unclear, but three frequency ranges are under discussion, including the upper midband (sometimes called midband or, unofficially, FR3) from 7 to 24 GHz and sub-terahertz bands from roughly 90 to 300 GHz. The third range involves maximizing spectrum below 7 GHz through refarming, new band allocation, and increased spectral efficiency.

Each of the proposed bands has benefits and drawbacks. The bands below 7 GHz provide the best coverage. But the spectrum in this range is already allocated, and getting access to additional spectrum requires moving incumbents somewhere else or refarming. Research into ways to increase spectral efficiency and make the most of what is available must continue.

The bands between 7 and 24 GHz cannot provide the same coverage as those below 7 GHz. Still, this range is under significant research and is a useful and necessary candidate to expand capacity.

The millimeter bands between 24 and 90 GHz provide high capacity and low latency for local deployments. 5G introduced these bands, but they remain underused. These bands may not make headlines related to 6G, but they will likely be a part of the final makeup and will help deliver services when very high capacity is necessary in dense urban areas.

The sub-terahertz bands could meet extreme capacity needs in hyperlocal deployments. Figure 1 shows the relative bandwidth available in each of these areas. It is becoming clear that 7 to 24 GHz is the most popular target for new spectrum 6G deployments. While still of interest, the sub-terahertz bands are under scrutiny because of the challenges the industry faces with FR2. But they remain an option for the second phase or later rollouts.

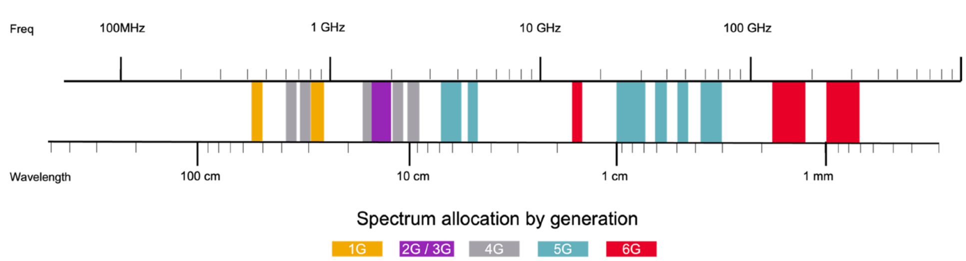

Figure 1. Frequency allocation and total aggregate bandwidth in each cellular generation

As with 5G, 6G will use multiple technologies. Specific frequency bands are suitable for different applications and technologies. Therefore, a combination of bands will likely deliver 6G services. Spectrum research is active on many specific bands. For example, the use case of coexistence with Wi-Fi and operating in unlicensed or industrial, scientific, and medical (ISM) bands is aiming below 8 GHz in the 2.4 GHz, 5.9 GHz, and now 6 GHz Wi-Fi bands as well as the 60 GHz (57 to 71 GHz) unlicensed band.

Other research areas, like power amplifiers and antennas, cover a broad range of frequency bands under consideration for 6G. Table 1 summarizes some 6G research topics and how they map to the different frequency bands considered for 6G. These bands do not require isolation, and some use cases will use multiple bands to complement one another and maximize performance. This table is not an exhaustive list of every use case, challenge, or in-depth regulatory situation, but it provides an overview of the current trends.

Table 1. Overview of 6G research topics and spectrum

	6G research topics										**Mobile regulatory situation**	**Technical challenges**
	NOMA	Waveforms	Channel coding	Unlicensed / WiFi	Advanced MIMO	Satellite	Mobility / coverage	Radar / JACAS	PA and LNA	Antennae		
< 8 GHz	x	x	x	x	x	x			x	x	Continued changes 4 – 8 GHz 6 GHz: Unlicensed / licensed global variances	Coverage spectral efficiency
8 – 15 GHz		x	x		x	x	x	x	x	x	Co-primary use regulation for most of the band Heavy DOD allocation passive (EES) satellite / radio astronomy coexistence	Coexistence / sharing coverage and cell density
15 – 24 GHz						x			x			“FR2-like” (more than < 16 GHz)
24 – 71 GHz			x	x			x	x	x	x	57 – 71: Unlicensed 24 – 52: Allocated or will be allocated to mobile use 52 – 57: Still unclear	Coverage Energy efficiency Mobility
71 – 110 GHz		x	x					x	x	x	PTP and automotive radar (71 – 86) Inadequate contiguous sub-bands Heavy constraints 90 – 110	Coverage Energy efficiency Noise BW Mobility
110 – 170 GHz		x	x		x	x	x	x	x	x	Lightly regulated so far RR5.340 constraints: radio astronomy / EES Early discussion: WRC-23 (almost none) Most decisions: WRC-27	Coverage Energy efficiency Link budget Noise BW Mobility
> 170 GHz		x					x	x	x	x	Lightly regulated so far RR5.340 constraints: radio astronomy / EES ITU decisions post WRC-27	

Frequency Bands

Here is a closer look at the upper midband, the sub-terahertz bands, and the lower bands.

The upper midband (7 to 24 GHz)

The spectrum from 7 to 24 GHz is the most appealing for early 6G systems. The 7 to 15 GHz range is attractive for its propagation characteristics, which are similar to the bands immediately below 7 GHz. At these frequencies, signals have less propagation loss than with FR2 and stand a better chance of penetrating buildings and other structures, allowing for indoor coverage. This would enable operators to increase network capacity without adding significant cell-site density, as would be required to expand mmWave FR2 coverage.

While this band faces technical issues, the main challenge for using this spectrum in 6G is regulatory. The spectrum is fraught with civilian and government incumbents, and applications other than fixed and mobile wireless access use it. These applications include satellite communications, meteorology, radio astronomy, radio navigation, radiolocation, maritime radio navigation, and space research. Many of the incumbents will be challenging to relocate. Satellite communications, for example, are difficult, if not impossible, to change once a satellite is in orbit. If regulators can agree on spectrum availability and licensing schemes, perhaps the most challenging technical aspect to overcome will be how to share the spectrum without disrupting other users.

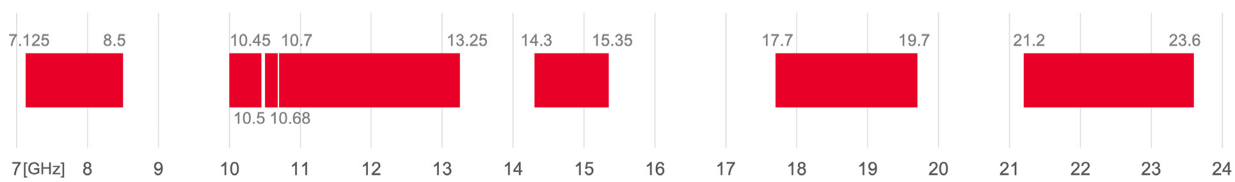

Figure 2. Simplified global allocation mobile / fixed frequency allocation, 7 to 24 GHz

Finding a single-frequency band for global coverage will be difficult. International harmonization of frequencies for communications occurs once every four years at the World Radio Conference (WRC), hosted by the International Telecommunication Union (ITU). WRC-23 will focus on additional spectrum for 5G-Advanced. The agenda includes discussion of 10.0 to 10.5 GHz for mobile use, but this is just for Region 2 (North and South America). Toward the end of the month-long WRC-23 meeting, attendees will set the preliminary agenda for WRC-27. The frequencies that make it into that agenda will be the most promising candidates for early 6G deployments. To help free up potential spectrum in the United States, the US Federal Communications Commission is considering repurposing up to 550 MHz of spectrum between 12.7 and 13.25 GHz for 6G. This is good news for the United States, but whether other countries will follow suit is unknown.

On the technical side, coexistence and smart spectrum sharing are two major research areas. For the higher frequencies in this band, density and deployment must also be addressed as the electromagnetic waves begin to behave more like FR2. 5G has proven to require higher-density deployments in strategic locations rather than the blanket coverage we are all used to. Interference is another concern in the bands of operation and with / from adjacent bands. These are all areas of active research. Channel measurements and more detailed channel models under development will provide a better understanding of communications scenarios for these bands, including the novel discipline of joint communications and sensing.

The sub-terahertz bands (90 to 300 GHz)

Sub-terahertz frequencies offer large, contiguous chunks of spectrum that could be suitable for 6G. With bandwidths up to 20 GHz, they must be part of the discussion for 6G, even if they present profound technical challenges. It is not difficult to envision applications that require very high data throughput, perhaps greater than 100 Gbps. Given the state of the art in spectral efficiency, these will require larger contiguous bandwidths than those available in lower-frequency bands. Despite the associated technical challenges, the potential to solve difficult problems, like space-to-Earth links, multidimensional visual and audio communications, and advanced communications and sensing applications, makes these bands worth further research.

Which frequencies sub-terahertz bands will use remains an open question. The 90 to 110 GHz range (W-band) has multiple segments with reasonable contiguous bandwidth allocated for mobile or fixed wireless. Larger contiguous bandwidths are available in the 110 to 170 GHz D-band.

Figure 3. Simplified global allocation mobile / fixed frequency allocation, 92 to 175 GHz

There are other bands allocated for mobile and fixed services above 200 GHz in the G-band and H-band, but the use of these frequencies for commercial communications will be further in the future than in the W-band or D-band.

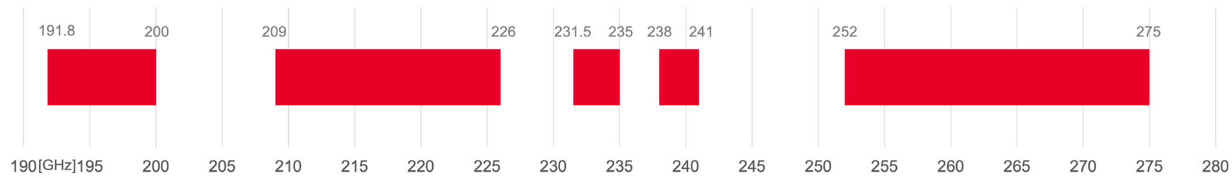

Figure 4. Simplified global allocation for mobile / fixed frequency allocation, 92 to 175 GHz

To deploy 6G at sub-terahertz frequencies, equipment must be available to operate at those frequencies. Building new semiconductors and antennas at mmWave frequencies for 5G was a challenge, but the industry developed and built them quickly by leveraging the foundation for consumer-grade technology developed for 60 GHz WiGig applications. Thus, much of the underlying technology already existed.

The same is not true for sub-terahertz. Limited components are available off the shelf to build prototypes, and even fewer integrated circuits (ICs) are available. Creating ICs at these frequencies will require more exotic materials because CMOS cannot deliver the power levels needed at a reasonable efficiency. Compound semiconductor technologies based on silicon germanium, gallium nitride, and indium phosphide, or a combination of those with CMOS, will aid in creating the new generation of components needed to establish the sub-terahertz ecosystem. Research is underway, and early prototypes show up in many technology symposia demonstrating capabilities in W-band and D-band with the occasional demonstration at or higher than 300 GHz.

The W-band and D-band are the most likely sub-terahertz bands for initial use because of the relative maturity of the ecosystem at those frequencies and their more favorable propagation characteristics. The higher the frequency, the greater the attenuation in free space. Molecular absorption peaks in our atmosphere aggravate this situation, as shown in Figure 5. Technologies like beam steering, reconfigurable intelligent surfaces, and novel antennas could help to overcome the path loss in sub-terahertz. Even with these technologies and techniques, the propagation loss is enough that it will be some time before sub-terahertz will be available for traditional mobile applications.

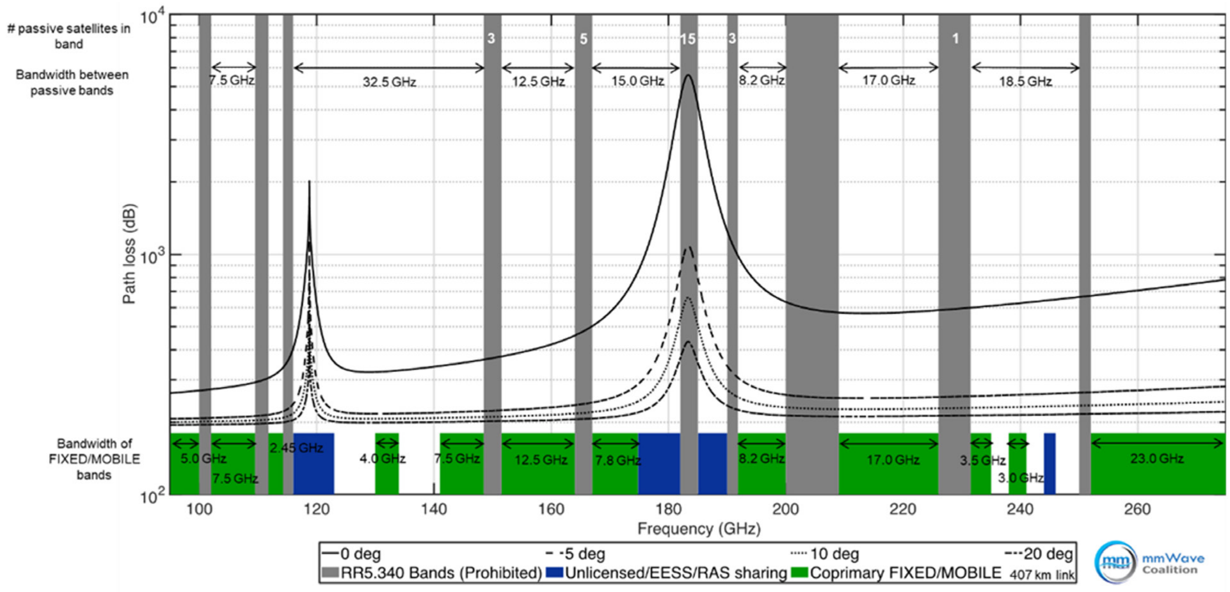

Figure 5. Atmospheric attenuation by frequency, courtesy of the mmWave Coalition

The high attenuation of sub-terahertz waves makes it suboptimal for mobile use cases but well suited for other use cases that lower frequencies are not. For example, the inherent electromagnetic properties of these frequencies make them good for sensing applications. Airport scanners leverage this today, operating in the high-centimeter-wave and low-mmWave range. The way different materials absorb and reflect the shorter wavelengths at these frequencies creates a unique signature that can help identify materials and create virtual maps of environments. Also, non-terrestrial networks will leverage sub-terahertz frequencies. Transmitting signals between satellites is challenging today because of the increasing bandwidth requirements. Sub-terahertz frequencies could provide a potential solution.

The lower bands (below 7 GHz)

The 600 MHz through 900 MHz bands will continue to be the mainstays of wide area coverage. These frequencies cover the most distance and have high outdoor-indoor penetration. They will continue to be important in rural deployments and for best reaching the cell edge. Wider bandwidths in these bands are not feasible, even if national regulators allocate more adjacent spectrum. Even without new spectrum in this band for 6G, these low bands will continue to play an important role.

Obtaining new spectrum between 1 and 7 GHz for mobile and fixed wireless will happen over the next five to 10 years to meet the throughput demands of 5G. 6G will leverage any new spectrum allocated in this lower midband. Participants at WRC-23 will consider several new bands in this range: 3.3 to 3.4 GHz, 3.6 to 3.8 GHz, 6.425 to 7.025 GHz, and 7.025 to 7.125 GHz. The 7.025 to 7.125 GHz band is the only band identified for use globally. Reexamining the use of spectrum in this band and refarming it out for new generations, as seen for the C band in 5G, is one way to obtain wider bandwidths below 7 GHz. Spectrum in this frequency range is a finite and scarce resource that must be used in the smartest and most efficient ways possible. Research to improve spectral efficiency in this valuable space will continue for the foreseeable future.

Spectrum Timeline

The exact frequencies 6G will use are unknown. As noted, the ITU allocates spectrum for international mobile telecommunications (IMT) at WRC. WRC attendees work together to identify frequency bands that IMT could use internationally to harmonize global spectrum while balancing the need to protect incumbents in any bands of interest. Global spectrum harmonization is desirable because it enables an economy of scale for components and limits the number of bands that user equipment must support.

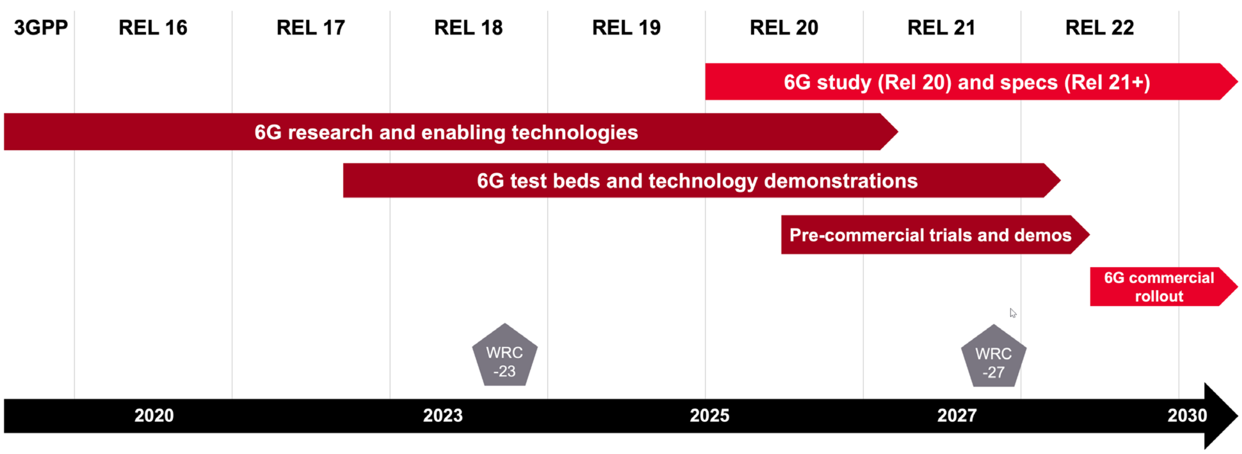

Figure 6. Timeline of 6G rollout

After the WRC identifies IMT bands, national regulators must allocate them for mobile service in their regions. This may require specific bands to be reserved or reallocated. Auctions, bidding, and direct licenses as some ways of assigning bands.

At the end of each WRC, attendees set the agenda for the next conference, including the list of frequencies for potential allocation. The agenda for WRC-27 will provide more clarity but no guarantees that the proposed bands will be implemented when 6G rolls out. Based on industry trends, 6G will leverage many different bands. The 7 to 15 GHz band is the most likely candidate for initial 6G deployments, but 6G must leverage the already-allocated spectrum below 7 GHz.

Improvements in smart and dynamic spectrum sharing are necessary to leverage all bands with the highest efficiency. While not a target for 2030 deployments, the sub-terahertz bands still hold promise. These bands are a target for a later phase of 6G in the 2035-to-2040 timeframe. Their wide bandwidths are necessary to enable some of the new applications and use cases targeted for 6G.

Conclusion

6G will use multiple frequency bands, from the lower bands all the way up to the sub-terahertz bands. They will be used smartly, with different bands used for different applications to complement one another and provide the best all-round user experience. By leveraging different spectra to provide different kinds of performance, 6G will be able to meet the ever-growing demands and expectations for cellular communications.

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