CmWave and Sub-THz: Key Radio Enablers and Complementary Spectrum for 6G

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***Abstract*—Sixth-generation (6G) networks are poised to revolutionize communication by exploring alternative spectrum options, aiming to capitalize on strengths while mitigating limitations in current fifth-generation (5G) spectrum. This paper explores the potential opportunities and emerging trends for cmWave and sub-THz spectra as key radio enablers. This paper poses and answers three key questions regarding motivation of additional spectrum to explore the strategic implementation and benefits of cmWave and sub-THz spectra. Also, we show using case studies how these complementary spectrum bands will enable new applications in 6G, such as integrated sensing and communication, holographic surfaces and space-air-ground integrated network. Numerical simulations reveal that the ISAC performance of cmWave and sub-THz spectra outperforms that of existing 5G spectrum, including sub-6 GHz and mmWave. Additionally, we discuss the importance of these complementary bands over conventional bands to enable extended ultra reliable and low-latency communications with better rate-latency-reliability trade-off. Finally, ongoing standardization endeavours, challenges and promising directions are elucidated for these complementary spectrum bands.**

***Index Terms*—Sixth-generation (6G) spectrum, centimeter wave (cmWave), sub-terahertz (sub-THz).**

I. Introduction

With 5G rolling out across sub-6 GHz and millimeter wave (mmWave) frequencies, sixth-generation (6G) networks will necessitate and unlock the new spectrum bands globally to accommodate and escalate International Mobile Telecommunications (IMT) 2030 requirements [1]. 6G aims to support millions of devices per square kilometer with individual throughputs exceeding 1 Gbps. Additionally, achieving near-instantaneous communication with exceptional network reliability (>99.99999%) is a key goal. In the foreseeable future,

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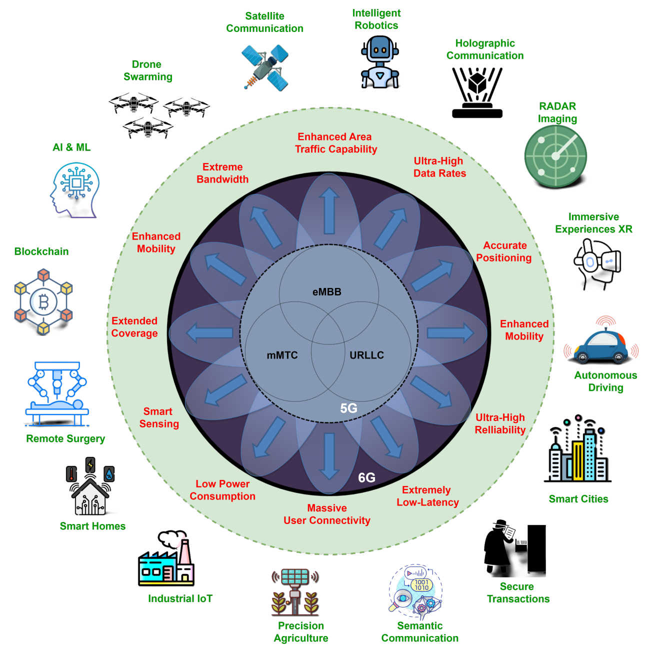


Fig. 1: 6G requirements, vision, and applications from WRC-2023, also see [2], [3].

more spectrum will need to be unlocked to serve the expansion of a myriad of applications, as shown in Fig. 1 [2], [3].

The International Telecommunication Union (ITU) World Radio-communication Conference 2023 (WRC-2023) convened administrations globally to discuss new spectrum bands and their allocation, including those for 5G Advanced and 6G. For instance, the 7 GHz to 24 GHz band, also called centimeter wave (cmWave) band or "frequency range 3 (FR3)", is a front-runner (particularly the 7-15 GHz segment) which offers a compelling combination of broad coverage for widespread connectivity and high data capacity for faster data transfer [4], [5]. Moreover, 5G millimeter wave (mmWave) spectrum can accommodate slightly higher spectrum deployments such as sub-terahertz (sub-THz) band, i.e., 90 Ghz-300 GHz, to offer ultra-fast speeds, low-latency, and enhanced user experiences, especially in dense urban environments. Propagation studies, such as [3], are crucial for pinpointing bands suitable for mobile and fixed service, a step vital for standardizing enabling technologies and facilitating widespread commercial deployment in a timely manner, while preserving a financially viable ecosystem to attract industry investments.

Regulatory bodies, mobile network operators (MNO), and the wireless research community are placing significant attention to these complementary frequency bands (cmWave and

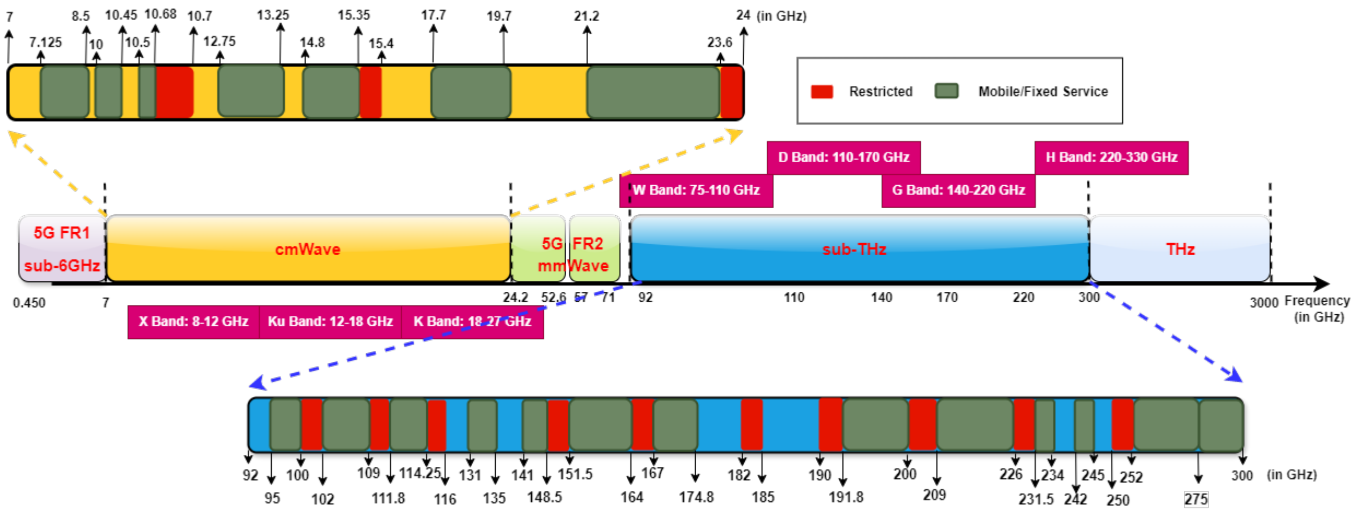


Fig. 2: CmWave and sub-THz Spectrum.

sub-THz) and working extensively on their development [3]–[7]. While some studies in [1], [8], [9] on the THz bands (0.1 THz-10THz) are recommendable, *a comprehensive exploration of complementary spectrum usage, including global regulatory coordination, standardization efforts, industry initiatives, numerical analyses of distinct spectra for key 6G scenarios, and the associated opportunities and challenges, is majorly missing. Furthermore, the potential of cmWave for coverage and bandwidth, as well as its synergy with higher-frequency bands, remains largely unexplored which constitute a prime motivation of this work.* This article offers a tutorial-style strong and comprehensive investigation of cmWave and sub-THz frequency bands, detailing their requirements and potential candidate bands for 6G networks (Sections II and III) and assessing their suitability for applications like integrated sensing and communication (ISAC), satellite-aerial-ground integrated networks (SAGIN), holographic surfaces (Section IV), etc. Additionally, it presents a numerical analysis of the impact of various bands on key metrics such as coverage, capacity, latency, and reliability, with a focus on sensing and communication (Section V). Finally, challenges and opportunities associated with these bands are discussed (Section VI).

II. Complementary Spectrum: cmWave and sub-THz

As per third-generation partnership project (3GPP) Release (Rel.) 17, 5G FR2 has been allocated up to 71 GHz, spanning from 24.25 GHz to 71 GHz. This frequency region encompasses the 60 GHz unlicensed band, known as the E band (60 GHz to 90 GHz). Fig. 2 illustrates the potential bands for cmWave (FR3, highlighted in yellow) and sub-THz (highlighted in blue), as identified by the WRC and others. Below we detail the use of each of these bands:

A. Possible Candidate Bands

1) Lower cmWave band (7-15 GHz): WRC-2023 Resolution 256 along with WRC-2027 agenda Item 1.2 highlights potential IMT identification for bands such as 6.425 – 7.025 GHz in Region 1 (Europe), 7.025 – 7.125 GHz globally, and 10 – 10.5 GHz in Region 2 (North America). NATO bands encompass 7.25 – 8.4 GHz, 8.5 – 10.5 GHz, 13.4 – 14 GHz, 14.62 – 15.23 GHz, 15.7 – 17.7 GHz, and 20.2 – 21.2 GHz, among others:

- 7.125–8.5 GHz: This spectrum has gained significant interest for non-federal applications involving unlicensed ultra-wide band (UWB) devices for automotive radars, personal mobile, and tracking purposes; however, challenges with federal incumbents need to resolved.
- 10–10.5 GHz: This band is primarily used by earth exploration satellite system (EESS), radiolocation services (RLS), and amateur services. Similar to the 7.125–8.5 GHz range, low-power UWB devices are expected to utilize this spectrum. Active EESS and airborne/spaceborne radars operate here, but out-of-band emissions pose challenges due to the proximity of passive EESS systems in the adjacent 10.6–10.7 GHz band.
- 12.2–13.25 GHz: Part of this spectrum is under consideration by the FCC for flexible usage. Current services, such as direct broadcast satellite and multi-channel video and data distribution services, present promising sharing opportunities with future cellular infrastructures, leveraging adaptive architectures for integration.
- 18.8–20.2 GHz: Although this band has less favorable propagation characteristics than lower frequencies, it offers substantial bandwidth suitable for hotspots and wireless local area networks. These frequencies strike a balance by providing higher bandwidth similar to mmWave bands while maintaining satisfactory coverage levels (over 80%) [6].

2) Sub-THz Spectrum (90-300 GHz): Prospective frequency bands within the sub-THz spectrum, including the D band (110 GHz to 170 GHz), G band (140 GHz to 220 GHz), and the H/J band (220 GHz to 330 GHz), have been identified during WRC-2023. Resolutions 255,663,& 721 in WRC-2023 outline the necessity of specific spectrum ranges, such as 102-109.5 GHz, 151.5-164 GHz, 167-174.8 GHz, 209-226 GHz, and 252-275 GHz.

- W Band (75–110 GHz): Its consideration is underway for wireless backhaul and access applications along with the D band to meet 6G infrastructure requirements. A mix of licensed and unlicensed bands, including W and D bands, will cater to diverse 6G use cases and deployment types, as outlined in WRC-2023 resolutions.
- D Band (110–170 GHz): Identified as a key sub-THz band during WRC-2023, with specific ranges like 151.5–164 GHz and 167–174.8 GHz prioritized for 6G mobile communication. Active development is underway for wireless backhaul and access, particularly by base station (BS) infrastructure vendors.
- G Band (140–220 GHz): Highlighted during WRC-2023 for its potential in 6G communication systems, including prioritized sub-ranges such as 209–226 GHz.
- H/J Band (220–330 GHz): Emerging as a focus for 6G research, especially around 300 GHz. Includes the 252–275 GHz range identified for mobile communication and the 275–296 GHz spectrum allocated with conditions to protect EESS passive applications.

B. Qualitative Requirement

Below, three key concerns are discussed to explore the requirement of cmWave and sub-THz spectra, shedding light on their motivations, challenges, and advantages.

1) Despite the opportunity for wider IMT identification in the upper 6GHz band and the substantial contiguous spectrum in mmWave, what motivates the push for additional spectrum?: Reusing existing frequencies for 6G may seem appealing, but achieving IMT-2030 goals is challenging due to regulatory and compatibility constraints. Temporary spectrum sharing is technically feasible but often economically inefficient. The upper 6 GHz band (6425–7125 MHz) offers only 700 MHz of bandwidth, insufficient for the data growth expected by 2030. While mmWave enables high data rates, its limited range due to building penetration losses makes it less practical for widespread deployment [3]. Insights from the Millimeter Wave Coalition reveal that mmWave is increasingly used for fixed wireless access (FWA), backhaul, and high-density venues. With real-time data generation accelerating exponentially—doubling the world's knowledge every 12 hours—the bandwidth demand on communication networks is expanding astronomically. According to GSMA's 2023 report on 5G mmWave, a 35% annual increase in demand translates to a 2000% growth in capacity over a decade. As highlighted in [4], *cmWave provides a balanced trade-off between capacity and coverage*, emerging as a promising alternative. Nonetheless, cmWave spectrum remains highly congested, often allocated to military or satellite applications, making large contiguous bandwidths rare [7]. Emerging applications like immersive digital experiences, 3D digital twinning, and fiber-like fixed wireless access will require unprecedented capacity. 6G must deliver at least 20 times more wide-area capacity than 5G, as per IMT 2030 requirements. Sub-THz frequencies, with their wider bandwidths, promise significantly higher capacities and data rates. These bands also share similar propagation characteristics with mmWave, making them ideal for next-generation networks like immersive AR/VR, 3D digital twinning, and fiber-like FWA requiring unprecedented capacity and low-latency connectivity.

2) Does network densification necessitate a shift from omnidirectonal antenna and sub-6Ghz spectrum to high-gain directional antenna and high-carrier frequency spectrum? : Indeed, small cells offer much better power efficiency than larger cells when considering energy per bit [10]. However, the increased deployment of small cells, essential for densification, raises concerns for power consumption and environmental sustainability. Finding suitable locations for numerous small cells complicates network planning and deployment, and achieving high user experience through extreme densification increases the utility bill and negatively impacts the carbon footprint. Small cells require specific separation distances to prevent interference and ensure seamless user experiences during handovers, which can be facilitated by tighter adaptive beam technology in mmWave and sub-THz frequencies. Countries like UK, China, Japan and others are rapidly adopting mmWave based fixed wireless access, with over 1 billion users, replacing traditional fiber and copper infrastructure. Nevertheless, increasing BS density at higher frequencies improves communication efficiency, but benefits plateau beyond a certain point [10]. Directional antennas mitigate free space losses in higher-frequency networks but escalate power consumption with more BSs. To boost network efficiency without sacrificing throughput, transitioning to higher carrier frequencies with high-gain antennas is recommended [10].

3) Why cmWave spectrum should be complemented with sub-THz spectrum and not with mmWave and higher THz frquencies?: The aggregate available spectrum is immensely greater at the sub-THz and terahertz (THz) range [7], yet cmWave spectrum, when augmented with sub-THz spectrum is advantageous because sub-THz offers both outdoor, outdoor-to-indoor penetration, and indoor and short-range urban deployments, unlike the very short range of higher THz frequencies alone. Sub-THz provides superior sensing and communication capabilities that will become part of all multiple-input multiple-output (MIMO) system in the coming decade [3]. Additionally, cmWave can leverage existing infrastructure given similar propagation properties to sub-6 GHz deployments [5], thereby reducing deployment costs and providing better coverage and penetration, making it a practical and cost-effective choice for widespread 6G roll-out. For instance, cmWave can be used for fronthaul and sub-THz can be preferred for backhual links between cell sites, as well as for mobile access (e.g., integrated access and backhaul, a new feature in the 5G Standard).

III. CmWave and sub-THz: Applications and Synergies with 6G Usage Scenarios

The potential synergy between cmWave and sub-THz spectra paves the way for highly interconnected mobile networks that can deliver smart sensing, high mobility and tracking support, gigantic user connectivity, ultra-high bandwidth, ultra-high data rates, exceptional reliability, and ultra-low latency.

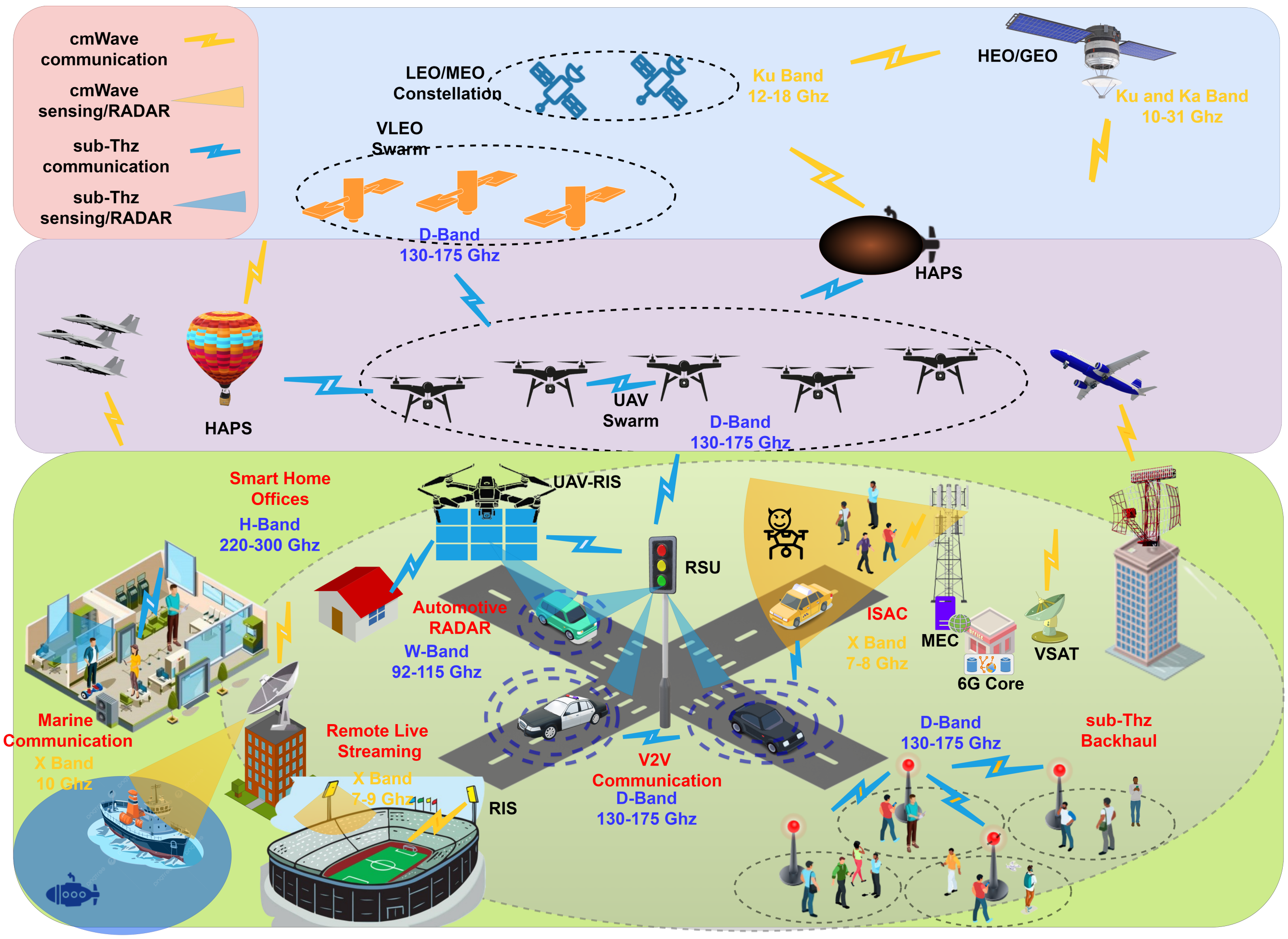


Fig. 3: Potential usage scenarios for cmWave and sub-THz spectrum for mobile access.

These bands present unique opportunities for advanced applications and key 6G use cases, as illustrated in Fig. 3.

A. *Integrated Sensing and Communications (ISAC)*

The extensive bandwidth and large antenna arrays available in complementary bands elevate ISAC to new heights, enabling high-speed, reliable connectivity along with advanced tracking, positioning, and activity recognition, gesture detection, and environmental monitoring capabilities. This advancement drives innovation across diverse applications, including vehicle-to-everything communication, cellular offloading, RADAR, WiFi sensing, connected robotics and autonomous systems (CRAS), extended reality (XR), digital twin (DT), emergency response, underwater and maritime navigation, healthcare and medical imaging, and smart city monitoring. Most current commercial automotive radars operate within the industrial, scientific and medical (ISM) 77 GHz band, and more recently, the 76-81 GHz band. However, in the automotive context, the current resolution and information provided by mm-wave radar may not suffice for many applications, like CRAS, DT and XR [1]. Additionally, the Rayleigh criterion dictates that at such high frequencies, many common surfaces appear rough to low-THz radar, leading to diffuse surface scattering. This allows reflections from the same radar target area to be intercepted from various positions with different aspect angles, making sub-THz radar more sensitive to surface textures of road objects and enabling finer resolution radar images. With a per-operator contiguous bandwidth of 200 MHz in the cmWave band and 2 GHz in sub-THz band, sensing and time-of-flight measurements can achieve a range resolution of less than a meter and millimeter, respectively [3]. Specifically, X-band (8-12 GHz) radars, widely used for weather monitoring, air traffic control, and maritime security, can share the same frequency band for both sensing and communication using specially designed waveforms. IEEE Std. 802.15.3d, the first IEEE standard with sub-THz band (253–322 GHz) [11], can enable advanced Wi-Fi sensing for short-range communication. However, several key questions remain to be addressed including spectrum policy, architectures, topologies hardware model, modulation, reference signals and frame structure.

B. *Space-Aerial-Ground Integrated Network (SAGIN)*

The cmWave spectrum has traditionally been utilized extensively for satellite services. Currently, low earth orbit (LEO) satellites operate in Ku-band, Ka-band, and Q-/V-bands. The interplay of mega LEO constellations with aerial nodes, such as high-altitude platform systems (HAPS) and unmanned aerial vehicles (UAVs), and ground users will prompt effective SAGIN architecture. To enable higher data rates reaching multi-gigabits per second (MGbps) and lower latency, SAGIN are expected to utilize higher frequencies, like W-band. At these frequencies, antennas can achieve high directional gain with narrow beams, supporting high-capacity systems and secure communications with reduced risk of eavesdropping. However, operating at these high frequencies cause significant frequency-selective molecular absorption losses and signal attenuation due to atmospheric gases, primarily water vapor and oxygen, at sub-THz frequencies. Molecular absorption by atmospheric gases also introduces noise by re-radiating absorbed power back into the communication channel.Mitigating these challenges requires highly directional antennas with low beam divergence, smaller size, and massive antenna arrays for effective communication. Phased array technology can enable electronic beam steering to maintain line-of-sight with moving satellites. Furthermore, spectrum sharing strategies can optimize communication by dynamically allocating spectral resources based on the application and environment [1]. Sub-THz bands can be utilized for aerial-aerial links, where high-capacity and short-range communication are critical, while cmWave bands can be leveraged for broader coverage and robust connectivity to ground users. Nevertheless, the network/topoplogy management and optimization with prior testing of space-qualified radios front-ends are crucial aspects.

C. Holographic MIMO Surfaces

Indeed, higher frequency bands increase path-loss, which can be mitigated with massive MIMO arrays; however, deploying active antennas or relays at these frequencies requires high power and complex, costly hardware. Leveraging intelligent control algorithms, beamforming can be achieved using the holographic principle. Specifically,holographic MIMO surfaces (HMIMOs) aim to surpass traditional mMIMO by utilizing cost-effective, compact, lightweight, and low-power hardware architectures [12]. These surfaces enable a revolutionary approach by transforming the wireless environment into a programmable, intelligent system. Deployed at BSs or as aerial nodes , they act as smart repeaters. HMIMOs include various reconfigurable intelligent surfaces (RIS) topologies, such as continuous, discrete, active, passive, stacked, and unstacked designs [12]. They recycle ambient electromagnetic (EM) waves, directing them toward target users by adjusting their unit elements. In these setups, these surfaces function as relays, enhancing beamforming, compensating for signal attenuation, and reducing co-channel interference from nearby BSs. Mainly, the integration of very large numbers of tiny and inexpensive antennas or reconfigurable elements into a compact space is employed to realize a holographic array with a spatially continuous aperture. This holographic architecture is easier to realize in the sub-THz band thanks to the miniaturization of THz electronic components. For example, the size of each graphene-based reflecting element is 200 μm × 190 μm at a carrier frequency of 0.22 THz that corresponds to a wavelength $\lambda \approx 1360$ μm. Therefore, the reflecting elements can be spaced more densely than $\lambda/2$ so as to form a spatially continuous surface, since the resulting surface is homogenizable [13]. However, the successful implementation of HMIMOS requires addressing several challenges and opportunities, including rigorous prototyping at multi-band and higher spectrum, backward compatibility, channel-dependent beamforming, configuration selection, and their effective regulation and control.

D. Others

Investing in the synergy between the THz band and lower frequency bands enables future wireless systems to achieve universal coverage and scalable solutions. This integration leverages the benefits of THz communications and sensing, especially for outdoor environments and highly mobile user equipment , despite THz's short communication range due to power and propagation limitations. For instance, CRAS applications such as autonomous vehicles or drones require the rapid download of high-quality 3D maps. Another technical motivation for their synergy is the need for wireless backhaul/fronthaul that can provide very high throughput, catering to both mobile and fixed or nomadic scenarios. Together, the three radio access network (RAN) links−backhaul (core and the central unit), midhaul (between distributed units), and fronthaul (between central and distributed unit) is referred to as X-haul. A dense deployment of X-haul cannot rely solely on optical fiber; it requires the flexibility and cost-efficiency provided by wireless links.Achieving data rate in tens of Gb/s wirelessly requires very wide frequency channels in previously untapped bands at the mmWave spectrum and above, such as the E-band (10 GHz over 71-76 GHz and 81-86 GHz) and the sub-THz spectrum (over 100 GHz in the range of 110-310 GHz). Moreover, sub-THz bands are crucial for mobile edge computing and cell-free communication applications as they enable ultra-high capacity, low-latency communication, and seamless connectivity with immersive experiencess.

IV. Numerical Analysis for Various Case Studies

Next, we describe case studies of this complementary spectrum which offer insights into the diverse applications and their prospects for 6G networks.

A. ISAC with cmWave and sub-THz

First, we analyze the performance of ISAC framework across various spectra, encompassing sub-6 GHz, cmWave, mmWave, sub-THz and THz operating within distinct geographical deployment (areas). As shown in Fig. 4, the sensing power and spectral performance is assessed under a varying free-space path loss model for different carrier frequencies. In Area-1, sub-THz frequencies outperform mmWave in both sensing and spectral efficiency, primarily due to the advantages of massive antenna arrays enabled by their shorter wavelengths. Notably, while the number of antennas for THz is higher than sub-THz, the performance improvement of THz over sub-THz is not significant in the given network scenario.

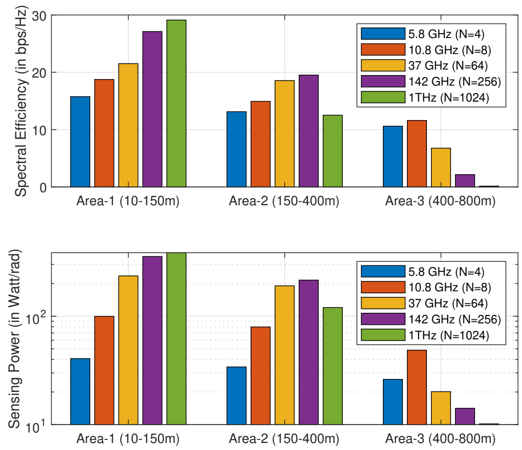


Fig. 4: ISAC performance for various spectra when 2 targets and 3 single-antenna users are in line-of-sight with uniform-linear array of length 0.25m with adaptive beamforming design (N = number of antenna).

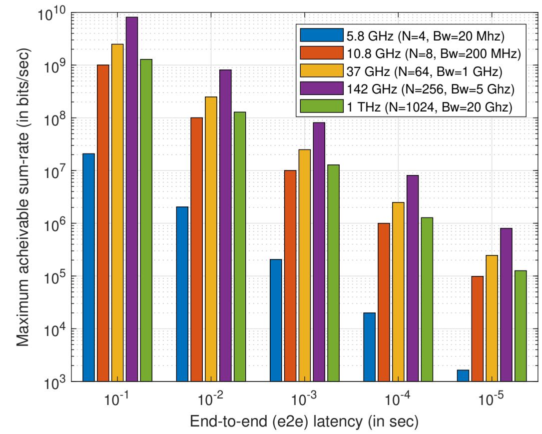


Fig. 5: Theoretical achievable rate throughput with mBURLLC for various spectra when packet-error probability = 10^{-6} and 5 users randomly deployed in 100 x 100m^2 region (Bw = total bandwidth support)

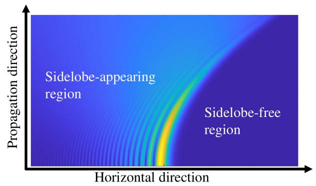
As the antenna count increases from sub-THz to THz, the selection degree of freedom initially grows but eventually saturates. Furthermore, sub-THz antennas achieve comparable performance to THz with significantly reduced signal attenuation. However, as the deployment area expands to Area-3, all bands—THz, sub-THz, and mmWave—experience substantial performance degradation due to rapid signal attenuation, with THz showing the most significant losses. In Area-2, the advantage of sub-THz over mmWave narrows, with sub-THz offering only marginal gains while remaining vulnerable to rapid attenuation. In Area-3, the cmWave band demonstrates moderate improvements in spectral efficiency and significant gains in sensing capability compared to sub-6 GHz. This advantage arises from the larger effective antenna size at cmWave, despite sub-6 GHz benefiting from lower attenuation. Additionally, cmWave experiences less attenuation than higher bands like sub-THz and mmWave. Across all deployment areas, cmWave consistently outperforms sub-6 GHz, striking an optimal balance between carrier frequency attenuation and the benefits of larger antenna arrays. Moreover, it can be observed that the synergy between sub-THz and cmWave can be highly effective for dynamic network configurations, offering enhanced ISAC performance.

B. Mobile broadband reliable low latency communication (mBRLLC)

6G applications will demand extended ultra-reliable low-latency communications (URLLC) which will not require only high reliability and low latency but also data rates comparable to 5G enhanced mobile broadband (eMBB) service. Consequently, a new service class, mobile broadband reliable low-latency communication (mBRLLC), is expected to emerge, enabling 6G systems to deliver performance across the rate-reliability-latency spectrum [2]. Fig. 5 discusses the importance of high spectra bands over conventional FR1 and FR2 bands for mBRLLC systems. Undoubtedly, the increase in operating frequency inherently enhances the maximum bandwidth support and shorter wavelength inherently allows for a higher number of antennas. This enables the deployment of more compact antenna arrays, facilitating advanced techniques like mMIMO and effective beamforming. These technologies not only improve spatial resolution and coverage precision but also allow for better spectral efficiency, making higher frequency bands indispensable for future wireless systems. As shown in Fig. 5, the sub-THz band (142 GHz) can achieve overall throughput rates of up to 100 Mbps and 10 Mbps for users while maintaining tight delay constraints of 1 ms and 0.1 ms, respectively. Even, these capabilities surpass those of THz bands (due to reduced attenuation) as well as lower frequency bands (due to higher number of antenna), making the sub-THz spectrum a compelling choice for short-range devices and Wi-Fi hotspots in scenarios like industrial automation, XR, CRAS, where ultra-fast data transfer and minimal latency are crucial. Both use cases demonstrate that cmWave and sub-THz offer a superior capacity-coverage-bandwidth trade-off compared to other spectra.

C. Experimental Results on Airy Beams: Full Utilization of EM Waves with sub-THz

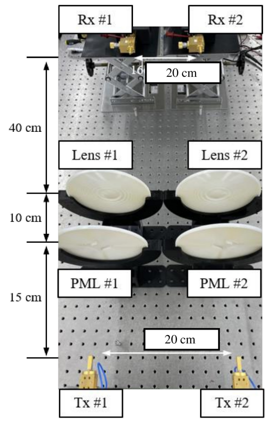
Shortened wavelengths in the sub-THz range extend the near-field range to hundreds of meters, allowing for advanced beam control that leverages electromagnetic near-field phenomena such as orbital angular momentum, bent propagation, and non-diffractive propagation [14]. The manipulation of sub-THz electromagnetic waves using RIS enables more customized beam control and the application of Airy and Bessel beams, which have not been extensively utilized until now. Fig. 6 shows the unique properties of Airy beams with asymmetric sidelobe distributions and sidelobe-free regions, the experimental parameters at sub-THz frequencies, and the experimental setup for two-stream transmission using Airy beams, respectively. The total transmission rate for two-stream transmission without using Airy beams was 25.33 Gbit/s due to interference. In contrast, the total transmission rate for two-stream transmission using Airy beams was 46.67 Gbit/s, by exploiting sidelobe-free regions. We have experimentally



(a)

Parameters	Value
Frequency	139 - 149 GHz
Bandwidth	10 GHz
Tx power	-13 dBm
Channel coding	LDPC & BCH (DVB-S.2)
Code rate	1/4 to 9/10
Modulation	QPSK-16 QAM
Waveform	SC-FDE
Frame length	64,800 bits
Antenna gain	15 dBi (Tx), 10 dBi (Rx)

(b)



(c)

Fig. 6: (a) Propagation of the Airy wave and its sidelobe characteristics, (b) Experimental parameters, (c) Experimental setup of parallel wireless transmission using Airy beam (PML: phase modulation lens).

confirmed that the Airy beam enables parallel transmission of multiple streams without traditional MIMO channel estimation and equalization.

V. Industry Perspectives, Standardization and Experimentation on CmWave/sub-THz

6G spectrum policy requires collaboration among vendors, MNO, regulators, service representatives, and research organizations to assess needs, recommend regulatory changes, and balance societal requirements.

A. Field Trials and Industry Efforts on sub-THz

T. S. Rappaport *et al.* carried out two extensive outdoor wideband measurement campaigns in downtown Brooklyn, focusing on the sub-THz band at 140 GHz with transmitter-receiver separation distances up to 117.4 m. These campaigns included: i) a terrestrial urban microcell measurement campaign, and ii) a rooftop surrogate satellite and backhaul measurement campaign. Japan has fostered pioneering work at sub-THz frequencies. NTT DOCOMO, INC., NTT Corporation, NEC Corporation, and Fujitsu Limited have collaboratively announced the creation of an advanced wireless device capable of achieving ultra-high-speed transmissions of 100 Gbps in the 100 GHz and 300 GHz bands. DOCOMO has developed wireless transmission equipment that can deliver data rates of up to 100 Gbps over a distance of 100 m. Other MNOs such as Ericsson, Nokia, Keysight, and Qualcomm have developed a testbed RAN system operating in the sub-THz frequency range, specifically in the 92–100 GHz band, at D-Band (142 GHz) and H-Band (285 GHz), which is capable of achieving peak throughputs exceeding 100 Gbps [15].

B. Standardization Aspects of cmWave and sub-THz bands

A study item was made available in Release 16 for 3GPP in Jan 2021 [6], which discusses the potential for cmWave for 5G spectrum. IEEE Std. 802.15.3d marks a significant milestone as the inaugural IEEE-family standard tailored for wireless communications spanning up to 69-GHz-wide channels within the sub-THz spectrum range, specifically from 253 to 322 GHz. While spectrum access can be secured through ITU WRC decisions, regional agreements, or country-specific allocations, harmonizing frequency bands and technical specifications globally or regionally is essential for economies of scale and benefits to consumers and businesses. Although an IMT identification does not impose an obligation for implementation in any particular country, it serves as a pivotal step in harmonizing IMT frequency bands, signaling to the Information and Communications Technology industry the need for equipment development. For instance, the designation of the frequency range from 14.62 to 15.23 GHz as a harmonized NATO band for fixed and mobile services underscores the importance of coordinated efforts through WRC resolutions and regional decisions. Moreover, the ITU's framework establishes a structured process for evaluating technical conditions for various frequency bands worldwide, incorporating sharing studies to mitigate harmful interference between different services. The ITU WRCs remain the preferred avenue for comprehensive harmonization. However, given the time-intensive nature of the process, with an IMT identification preceding regional licensing, efforts to finalize ITU's work must commence well before 2030. This urgency underscores the ongoing research endeavors in both industry and academia, aiming to validate the usability and technical feasibility of cmWave and sub-THz spectrum by WRC-2027.

VI. Challenges and Opportunities

There exist some challenges and future prospects for these complementary spectrum which are explained as follows:

A. PHY and Higher Layer Design Strategies

Physical (PHY) and higher layer design strategies for the synergy of these bands is an open research challenge, as simplifying interactions across protocol stacks is crucial which can address complex issues such as optimal spectrum allocation, and interference management. Location-aware physical layer design is a promising research direction, focusing on adapting communication systems to the user's location to optimize real-time resource allocation. Well-studied works, like [3], [5], [7], on channel measurements, modeling, and link budget analysis can be leveraged in this context to improve system performance. However, a significant challenge lies in the development of efficient, cost-effective components for sub-THz communication. Specifically, transmitters, receivers, and antennas must be designed to handle the unique requirements of sub-THz frequencies, which remain a technological hurdle. For sub-carrier spacing (SCS), FR1 typically uses 15, 30, and 60 kHz, while FR2 supports 60, 120, and 240 kHz. For cmWave systems, SCS values of 30, 60, 120, and 240 kHz are also viable. In sub-THz communications, SCS is expected to range from 120 kHz to 3840 kHz, following the Rel-15 scaling principle based on powers of two, starting from 15 kHz. More detailed investigation on ISAC with complementary bands is interesting, as highlighted in Section IV.A, should emphasize waveform design, modulation, and security issues adhering spectrum policy and regulation is key research direction.

B. Effective Beamforming and High Mobility

While sub-6 GHz beamforming is largely resolved with prototype, higher bands still struggle with channel sparsity, beam squint, and reliability issues due to blockages and unfavorable propagation, impacting network continuity. Achieving beam coordination, real-time alignment, and link reliability under mobility requires advanced algorithms and high processing power at higher frequencies due to additional errors with near-/far-field modeling. In the near-field, wideband transmissions can cause beam splitting in various directions and distances (beam split). which can cannot be corrected using far-field techniques and poses challenges for ISAC. To mitigate this, BSs can use time-delayer components and HMIMOs as low-cost, smart network-controlled repeaters to compensate for the beam split. Nonetheless, hybrid beamforming combining analog and digital beamforming has emerged as an optimal beamforming solution with reduced hardware complexity, power consumption, and cost. Moreover, dynamic RF chain-based precoding offers notable advantages, including adaptability to changing channel conditions and reductions in both power consumption and hardware costs. Lens-based beamformers, such as Rotman-lens designs, can be explored, as they have been found to perform well at mmWave and higher frequencies due to their compact size, enabling precise 3-D scanning. Mobility in high-frequency spectrum communications presents challenges like beam-tracking, frequent handovers, and increased energy consumption. These transitions lead to synchronization issue, complex scheduling, delays, and potential link interruptions. Optimizing HMIMOs deployment, placement, and scheduling is crucial to address these issues [13]. In context of high Doppler spreads, emerging modulation schemes like orthogonal time-frequency space (OTFS) and media-based modulation (MBM) show promising results. Moreover, a sophisticated ray tracing approach with decentralized machine learning techniques can be beneficial in addressing handover management and adaptive beamforming issues.

C. Spectrum sharing policies and regulation:

A significant portion of the cmWave spectrum is already allocated to incumbents for various applications, such as satellite communications and radar. International agreements and national regulations must be established to ensure efficient spectrum utilization. Also, regulations need to permit higher effective isotropic radiated power (EIRP) limits. A more detailed investigation of ISAC with cmWave, as highlighted in Section IV.A, should emphasize waveform design, modulation, and security issues, while adhering to spectrum policies and regulations, representing a key research direction. While a standard exists for point-to-point links, significant efforts and competition are expected in the coming years within 3GPP and ITU regarding the standardization on sub-THz communications.

VII. Conclusion

The article has presented a tutorial style discussion on the potential role of cmWave and sub-THz spectra as complementary spectrum for various 6G scenarios. Through discussions on their applications as well as emerging spectrum allocation trends, we have underscored the role of both low band cmWave and high band mmWave and sub-THz for the future of wireless communication. Case studies on ISAC, as well as mBRLLC, have illustrated the vast potential for new services and capabilities, both on a network level and in a consumer device of the future. Numerical simulations demonstrated the superior sensing and communication capabilities of cmWave and sub-THz spectrum over extensively studied sub-6GHz, mmWave and THz bands. Finally, challenges such as PHY-layer design, beamforming, mobility, and spectrum policy present promising research avenues, paving the way for timely commercial deployment.

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