Article:

Alsaedi, Wijdan, Ahmadi, Hamed orcid.org/0000-0001-5508-8757, Khan, Zaheer et al. (1 more author) (Accepted: 2023) Spectrum Options and Allocations for 6G: A Regulatory and Standardization Review. IEEE Open Journal of the Communications Society. ISSN 2644-125X (In Press)

https://doi.org/10.1109/OJCOMS.2023.3301630

Received XX Month, XXXX; revised XX Month, XXXX; accepted XX Month, XXXX; Date of publication XX Month, XXXX; date of current version XX Month, XXXX.

Digital Object Identifier 10.1109/OJCOMS.2022.1234567

Spectrum Options and Allocations for 6G: A Regulatory and Standardization Review

Wijdan K. Alsaedi∗ (Student Member, IEEE), Hamed Ahmadi∗ (Senior Member, IEEE), Zaheer Khan‡(Member, IEEE), and David Grace∗ (Senior Member, IEEE)

[1]Institute for Safe Autonomy and School of Physics, Engineering and Technology, York, YO10 5DD, UK
[2]School of Physics Engineering and Technology, University of York, UK
[3]Centre for Wireless Communications, University of Oulu, 90014 Oulu, Finland

CORRESPONDING AUTHOR: H. AHMADI (e-mail: hamed.ahmadi@york.ac.uk).

This work was supported in part by the Engineering and Physical Sciences Research Council (EPSRC) Impact Acceleration Accounts (IAA) (Green secure and privacy aware wireless networks for sustainable future connected and autonomous systems) under Grant EP/X525856/1.

ABSTRACT The upcoming sixth generation (6G) mobile communication system is expected to operate across a wide range of spectrum that includes not only the bands used by previous generations but also higher frequency bands such as millimeter wave (mmWave), which are currently assigned to fifth generation (5G) networks, terahertz (THz), and optical spectrum. By utilizing a broader range of frequencies, it will be possible to support 6G applications with faster data rates, higher capacity, and lower latency. However, the higher frequency bands pose unique challenges such as higher path loss, absorption loss, and engineering difficulties for antennas and radio frequency (RF) circuitry design, which require advanced technologies and innovative solutions. Given that the spectrum is a scarce resource, efficient management is crucial to ensure the most effective exploitation of frequency bands. The spectrum management has evolved over the years, with different approaches being used to assign and utilize frequency bands. In this paper, we provide a review of spectrum management approaches, including their use in awarding 5G spectrum, and explore their expected use in 6G. We then offer a brief overview of spectrum sharing and its role in enabling the efficient use of spectrum resources. The regulations, standardization, features, limitations, and potential use cases of higher frequency bands such as, mmWave, THz, and visible light (VL) are analyzed to provide a comprehensive understanding of the spectrum options available for the upcoming 6G technology.

INDEX TERMS 6G communications, millimeter wave, THz band, optical wireless communication, spectrum management approaches, spectrum sharing.

I. INTRODUCTION

IN recent years, a myriad of use cases have emerged due to constantly evolving societal needs [1]. These include a wide range of applications, such as extended reality (XR) services (augmented reality (AR), mixed reality (MR), and virtual reality (VR)), telemedicine, haptics, flying vehicles, brain-computer interfaces (BCI), connected autonomous systems, holographic telepresence, tele-surgery, and digital twins (DTs) [2], [3], [4], [5]. In addition, the demand for mobile data traffic/wireless connectivity has increased exponentially [6]. This trend of exponential growth in data demand is expected to continue, and the total mobile data traffic will reach five zettabytes (ZB) per month by 2030 as estimated by International Telecommunication Union (ITU) [6], [7]. Consequently, networks with capabilities beyond what is offered by 5G systems will be required to meet this demand.

In terms of use cases, 5G differs from previous generations by expanding the domain of mobile services from humans to things, as well as from consumers to vertical industries [8]. This expansion has led to the integration of millions of sensors in various environment such as cities, vehicles, homes, industries, food, and games to create a smart living spaces and automated systems [6]. However, the full potential of emerging Internet of Everything (IoE) applications will require a convergence of communication, sensing, control,

GLOSSARY	DEFINITION	GLOSSARY	DEFINIATION
3D	three-dimensional	LBT	Listen-Before-Talk
3G	third generation	LDs	Laser diodes
3GPP	Third Generation Partnership Project	LEDs	light-emitting diodes
4G	fourth generation	LiFi	Light Fidelity
5G	fifth generation	LOS	Line of Site
6G	sixth generation	LTE	Long Term Evolution
AI	artificial intelligence	LTE-U	LTE Unlicensed
AR	augumented reality	MIMO	Multi-Input Multi-Output
BCI	brain-computer interfaces	mmWave	millimeter wave
CBRS	citizens broadband radio service	MNOs	mobile network operators
DTs	digital twins	MR	mixed reality
ETSI	European Telecommunication Standards Institute	NRAs	National Regulatory Authorities
FCC	Federal Communications Commission	NR	New Radio
FSO	Free-space Optics	NR-U	NR Unlicensed
Gbps	Gigabits per second	OCC	Optical Camera Communication
GSM	Global System for Mobile communication	OFDM	Orthogonal Frequency-Division Multiplexing
IMT	International Mobile Telecommunications	OWC	Optical wireless communication
IoT	Internet of Things	QoS	quality of service
IoNT	Internet of Nano-Things	RAT	Radio Access Technology
IR	infrared	RF	radio frequency
IRS	intelligent reflecting surfaces	THz	terahertz
ISM	Industrial, Scientific, and Medical	VR	virtual reality
ITU	International Telecommunication Union	VLC	Visible Light Communication
ITU-R	ITU- Radiocommunication	WRC	World Radiocommunication Conference
LAA	License Assisted Access	XR	extended reality

and computing functionalities that are not fully addressed by 5G technology [9]. Moreover, some emerging applications in XR services and connected autonomous systems may require microsecond-level latency and Terabits-per-second (Tbps) level data rates, and achieving such high-performance requirements may be a challenge when solely relying on 5G networks [1]. Additionally, it is projected that 5G networks may face capacity limitations in handling the growing demand for data and new applications within the next ten years [7]. Both the industry and academia are currently exploring what the 6G should be and what are the service requirements behind [10]. Although the exact aim of 6G is not yet fully known, 6G is expected to address the limitations and bottlenecks of existing 5G networks by accommodating advanced use cases and associated technologies [4], [11].

The upcoming 6G is also expected to shift the focus from "connected things" to "connected intelligence", which requires more advanced technologies [12], [13]. To enable this shift, 6G will leverage a diverse set of technologies, including enhancements to existing 5G technologies and the adoption of new ones [6], [14]. Technologies that are expected to drive the development and implementation of 6G include exploring new spectrum at higher frequencies, integrating artificial intelligence (AI) [7], [14], [15], [16], [17], implementing three-dimensional (3D) networking, deploying unmanned aerial vehicle (UAV), utilizing intelligent reflecting surfaces (IRS), and enabling wireless power transfer [6].

To meet the expected increase in data traffic, exploring new bands at higher frequencies has been a common approach in every new generation of wireless communication technology. In the case of 6G, it is expected to utilize a vast spectrum range, including all bands used by the previous generations, in addition to higher frequency bands such as mmWave, THz, VL, and so on, to achieve a wider bandwidth. Flexible frequency sharing technology can also be employed in 6G to optimize spectrum utilization [18]. However, wireless communications rely on a limited resource- the radio spectrum, which is expensive to license [19], [20]. The limited availability and high cost of radio spectrum licensing highlights the importance of efficient use of frequency bands [19]. Policymakers are actively seeking ways to facilitate spectrum sharing among operators and service providers, and this has led to exploration of more flexible licensing approaches beyond traditional spectrum allocation methods [21], [22]. Consequently, novel concepts for spectrum management have been introduced and are

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

being incorporated into standards, such as licensed shared access (LSA) and spectrum access system (SAS) [21], [23].

A. Review of 6G Literature: Key Studies and Perspectives

Extensive research in the literature has focused on the vision, requirements, and enabling technologies of 6G networks. Multiple studies emphasize the incorporation of new frequency bands, including mmWave, THz, and optical spectrum, as crucial components of 6G technology [1] - [3], [6] - [9], [11] - [18], [24], [25], [26], [27], [28], [29]. For instance, in [6], the vision of 6G communication is presented, emphasizing higher system capacity, data rates, and security, along with technologies like THz communications, AI, and blockchain. In [24], Rappaport et al. emphasize the significance of THz frequencies in 6G wireless communication. Their work explores the revolutionary potential of utilizing THz spectrum above 100 GHz for high-speed communication and transformative applications. Another comprehensive review in [25], discusses architectural changes, AI integration, and technologies like THz communication and blockchain for green 6G networks. In [26], the authors provide insights into key enabling technologies, applications, and research topics in 6G, with a specific emphasis on disruptive technologies like mmWave and THz communications. Additionally, top-down approach in [29], addresses various aspects of 6G networks, highlighting the importance of frequency bands within the 100 GHz to 1 THz range. To our knowledge, existing survey papers on 6G networks have not comprehensively covered all aspects in the field. In order to bridge this gap, our paper aims to provide a thorough analysis of spectrum options and regulatory considerations in the context of 6G. We have also compiled Table 1, which highlights published survey papers in the domain of 6G networks.

B. Motivation and Contributions

The motivation behind our paper is to explore the spectrum options in 6G networks, focusing on higher frequency bands such as mmWave, THz, and VL. We aim to address the escalating demands for faster data rates, higher capacity, and lower latency in advanced applications by analyzing the potential of these spectrum bands. Additionally, we recognize the need to consider regulatory and standardization aspects in 6G spectrum management. This includes re-evaluating current policies, developing new assignment models, and promoting technology development in areas like THz. Unlike previous works that primarily concentrate on specific aspects of 6G, such as its vision, requirements, and enabling technologies, our survey paper takes a comprehensive approach. The key contributions of our survey can be summarized as follows:

- Comprehensive Spectrum Management Review: We delve into the realm of spectrum management, examining various approaches and their applications in 5G networks. We also explore the potential use of these approaches in 6G, highlighting the importance of spectrum sharing for effective and adaptable spectrum management.
- Analysis of Higher Frequency Bands: We specifically focus on the utilization of new spectrum in higher frequency bands, such as mmWave, THz, and optical spectrum, which have been identified as crucial components for 6G networks. We analyze the regulatory framework, standardization efforts, features, limitations, and potential applications of these bands, providing a comprehensive understanding of the spectrum options available for 6G technology.
- Insights for Policymakers and Regulators: By addressing the regulatory and standardization dimensions of spectrum management, our survey offers valuable insights for policymakers and regulators. We emphasize the need for re-evaluating current spectrum management policies to align with the unique requirements of 6G. We also highlight the importance of developing new spectrum assignment models that accommodate flexible deployment and define access rights.

Overall, our paper aims to provide valuable insights into spectrum options, challenges, and regulatory considerations for the successful deployment of 6G networks.

C. Organization of the Remaining Paper

The remainder of this paper is structured as follows: Section II reviews spectrum management approaches and explores those that may be applicable in 6G. Section II- D presents spectrum sharing schemes in both licensed and unlicensed bands. Section III discusses spectrum management approaches in 5G and way towards 6G. Section IV explores the available options of radio spectrum for 6G, with a particular focus on mmWave, THz and optical spectrum, as well as examines their standardization and regulatory considerations. Finally, the last section V provides our concluding remarks.

II. SPECTRUM MANAGEMENT

Spectrum management, as defined by the ITU, refers to the set of administrative and technical procedures aimed at ensuring the effective and efficient use of radio frequency spectrum by all radiocommunication services identified in the ITU radio regulations (RRs) while ensuring that radio systems operate without causing harmful interference [30]. Spectrum management can also be defined as the government function that organizes and regulates the utilization, allocation, and assignment of blocks of frequencies (a particular frequency band) to promote efficient use of spectrum and minimize interference between users in neighboring bands [31]. In general, spectrum management decisions are made by regulators [32], and these decisions relate to who, where, when, how and for what purpose to use a particular frequency band [33]. To be specific, spectrum allocation decisions are taken at international level, while national regulatory authorities (NRAs) make decisions on spectrum assignment

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

TABLE 1. **Summary of recent significant studies on 6G and their contributions.**

Ref.	Year	Area of Research in 6G	Contributions
W. Saad et al. [2]	2019	Applications, trends, technologies, and open research problems	Contributes significantly to the understanding and development of 6G by presenting a holistic vision, identifying drivers and performance requirements, exploring enabling technologies.
B. Zong et al. [9]	2019	Key drivers, core requirements, system architectures, and enabling technologies	Identifies 6G drivers, explores enabling technologies and architectures, and emphasizes the need for ubiquitous ultrabroadband, high-speed low-latency communications, and high data density.
K. B. Letaief et al. [12]	2019	AI-empowered wireless networks for 6G	Emphasizes the role of AI in designing and optimizing 6G networks, outlining the roadmap to the next generation beyond 5G.
Zhang et al. [15]	2019	Vision, requirements, architecture, and key technologies for 6G	Explores the vision, requirements, architecture, and key technologies for 6G wireless networks
T. S. Rappaport et al. [24]	2019	Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond	Explores the potential of frequencies above 100 GHz for wireless communication systems and discusses the challenges and opportunities for 6G and beyond
T. Huang et al. [25]	2019	A survey on green 6G network: Architecture and technologies	Presents a comprehensive survey on the architecture and technologies of green 6G networks, emphasizing architectural changes and related technologies for sustainable networks
L. Bariah et al. [26]	2019	Key enabling technologies, applications, and open research topics in 6G networks	Discusses major enabling technologies in 6G networks and their potential applications. Highlights requirements, challenges, and open research problems.
M. Alsabah et al. [27]	2019	6G wireless communications networks: A comprehensive survey	Provides a comprehensive review and survey of the key enabling technologies for 6G networks. Discusses operation principles, applications, and challenges
I. F. Akyildiz et al. [1]	2020	Future of wireless communication systems	Provides a comprehensive survey of 6G, addressing applications, requirements, technologies, and research directions.
M. Z. Chowdhury et al. [6]	2020	Applications, requirements, technologies, challenges, and research directions	Provides comprehensive coverage of various aspects of 6G, including applications, requirements, technologies, challenges, and research directions.
F. Tariq et al. [7]	2020	Speculative study on 6G	Explores 6G technology, identifies enabling technologies beyond 5G, presents visionary use cases, and discusses the shift towards the optical era.
G. G ur, [16]	2020	Exploiting spectrum sharing for capacity boost and 6G vision	Explores spectrum sharing issues, security implications, and enablers like distributed ledger technology and machine learning.
M. Giordani et al. [17]	2020	Toward 6G networks: Use cases and technologies	Explores potential use cases and technologies for evolving wireless networks towards 6G
S. Chen et al. [18]	2020	Vision, requirements, and technology trend of 6G	Provides a comprehensive discussion on the vision, requirements, and technology trends of 6G
X. You et al. [28]	2021	Vision, enabling technologies, and new paradigm shifts	Provides a comprehensive survey of recent advances and future trends in 6G
C. De Alwis et al. [3]	2021	Trends, applications, technologies, challenges, and research directions	Explores the trends, applications, requirements, technologies, and future research directions of 6G. It addresses the limitations of existing 5G networks and highlights the key factors driving the development of 6G.
W. Jiang et al. [8]	2021	Advancements, challenges, and research directions in the field of 6G wireless communication systems	Contributes by providing a comprehensive survey of 6G, envisioning its future, identifying key technologies, and highlighting expanded use cases and performance improvements.
H. H. H. Mahmoud et al. [11]	2021	Comprehensive survey on technologies, applications, challenges, and research problems	Presents a comprehensive overview of the system requirements, trends, technologies, services, and research progress related to 6G.
K. B. Letaief et al.[13]	2021	Edge artificial intelligence for 6G	Explores edge AI's role in 6G networks, highlighting benefits, challenges, and research directions.
H. Tataria et al. [29]	2021	Vision, requirements, challenges, insights, and opportunities	Provides a comprehensive overview of the vision, requirements, challenges, insights, and opportunities in 6G wireless systems
M. Banafaa et al. [14]	2022	Requirements, targets, applications, challenges, advantages, and opportunities	Providing a comprehensive overview of 6G system requirements, highlighting the advantages of 6G, and discussing enabling techniques for its implementation.

by balancing a set of public policy objectives [34]. There is a diversity of spectrum management approaches which regulators can employ for spectrum assignment, and these approaches have evolved from administrative allocation to market-based mechanisms, and unlicensed commons approaches [35]. Next we briefly review these approaches.

A. ADMINISTRATIVE COMMAND-AND-CONTROL APPROACH

Administrative allocation or a hierarchical command-and-control approach has been the predominant method of spectrum management, through which regulators implement a fixed allocation of spectrum to a given entity through beauty contests or direct awards for decades [35]. Accessing spectrum by following this method leads to difficulties in meeting the increasing demand for spectrum based-wireless services [36]. In addition, this traditional approach of spectrum management has exposed some critical barriers over time, such as inefficient utilization of spectrum, political influence and a lack of economic justification [37]. Although it has been instrumental in reducing harmful interference between the different wireless systems and in supporting expansion of few services like Global System for Mobile Communications (GSM) worldwide through coordination and harmonization [38]. Administrative allocation has continued to be used by national regulatory authorities in some countries for awarding third generation (3G) and fourth generation (4G) spectrum [32], whereas this trend is used for spectrum grant in local 5G networks [33]. However, this approach has faced criticism over the fairness of decision-making by regulators [32]. As a result of the shortcomings of this approach in accommodating spectrum demands for new wireless use cases, inflexibility in responding to changing market conditions and technological advances, in addition to creating high barriers to entry for small businesses and new entrants. Therefore, it is likely that this approach will become less dominant in the 6G and beyond. However, national regulators have adopted more flexible approaches to spectrum management, such as market-based mechanisms that can better accommodate the needs of new wireless use cases and promote greater competition in the industry.

B. MARKET- BASED MECHANISMS

Market-based mechanisms represent the second generation of radio spectrum management approaches. The primary regulatory objective of these methods is to promote static efficiency by ensuring optimal allocation of radio spectrum [37]. Market-based mechanisms can introduce flexibility into the market by allowing spectrum to be shared through secondary spectrum markets, where license holders have the opportunity to lease or trade unused or underutilized portions of their spectrum [32]. Within this approach, spectrum property rights are established through the issuance of licenses to a limited number of applicants via market mechanisms [35], [39]. Under this licensing approach, the licensee is granted exclusive rights to use a specific spectrum within a defined geographical area. Technical regulations are put in place to govern usage rights and prevent interference among spectrum users. Additionally, licensees are allowed to trade or lease their rights to third parties [40], [41]. In particular, spectrum property rights are determined through spectrum auctions, where licenses are awarded on the basis of bids between competing applicants [37]. From the viewpoint of regulations and policies, spectrum auctions offer an effective means of allocating spectrum to the entities that value it most, while also generating revenue for governments [42]. Compared to administrative procedures, auctions are generally preferred as they ensure more efficient distribution of the limited spectrum resource, especially in cases where demand exceeds supply [34]. However some of the challenges encountered in this approach are that auctions do not always leads to superior market outcomes due to unanticipated problems in their design leading to unexpected bidder behavior such as collusion and over-bidding [42], [43]. To mitigate these challenges, regulators need to recognize the complex relationship between spectrum management and market outcomes [35]. One approach is using learning algorithms to predict bids and also detect anomalies [44].

Regulatory authorities have various instruments at their disposal that can be utilized during auctions to achieve efficiency goals based on specific national circumstances. These tools include, but are not limited to, spectrum packaging, license duration, geographical scope, and obligations [34]. In fact, auctions have become the main mechanism for granting spectrum usage rights to mobile operators for deployment of 3G, 4G [35], and 5G networks [34]. The trend of using market-based mechanisms for spectrum management is expected to continue in 6G, with increasing complexity in the design of auctions due to the wide range of spectrum bands (low, mid, and high) that will be utilized, along with coverage obligations, spectrum trading, and other factors. More details on this topic will be provided in Section III.

C. UNLICENSED COMMONS APPROACH

An unlicensed commons approach, also known as a licence-exempt approach, provides access to the a portion of the radio spectrum without the need for a license or registration [37]. In this approach, different wireless systems operate in the same frequency band (share the same spectrum) under rules and conditions defined by the national regulator [45]. The licence-exempt operation uses the Industrial, Scientific, and Medical (ISM) bands [46]. The most notable example of such use is the 2.4 GHz spectrum to provide Wireless Fidelity (Wi-Fi) access services [47]. Traditionally, the IEEE 802.11/ Wi-Fi family of standards, including (802.11b/g) at 2.4 GHz, (802.11a/n) at 5 GHz, and (802.11ad/ay) at 60 GHz, have been designed to operate in license-exempt bands and without the need to obtain a license from the regulatory authorities. Similarly, cellular technologies can also operate in one or more of these unlicensed spectrum bands [48]. Various standardization bodies and industry alliances, such as the Third Generation Partnership Project (3GPP) and the IEEE, have made significant efforts to develop technologies that enable cellular networks to operate in these unlicensed frequency bands. These efforts have led to the creation of technologies such as Long Term Evolution unlicensed (LTE-U), License Assisted Access (LAA), MulteFire, and new radio unlicensed (NR-U), which allow cellular networks to share frequency bands with other wireless technologies. These technologies offer potential benefits such as increased network capacity, improved coverage, and new use cases for cellular connectivity [45]. In general, the unlicensed commons approach is built entirely on spectrum sharing, where multiple different type of wireless systems and several deployments of the same systems use the same unlicensed band [35]. Coexistence of Wi-Fi and cellular networks in the unlicensed spectrum is another example of this approach [49]. From a technical perspective, the coexistence of Wi-Fi and cellular networks can increase the overall capacity of heterogeneous wireless networks, provided that the mutual interference between Wi-Fi and cellular systems is addressed properly [49]. In particular, the main challenges of allowing cellular networks to operate in the unlicensed spectrum is ensuring a fair coexistence with other unlicensed systems and avoiding interference [50]. One approach to achieving fair coexistence and avoiding interference requires compliance with regulatory requirements, which include using a Listen-Before-Talk (LBT) mechanism to access the channel [51] [52]. Technologies designed for spectrum sharing in unlicensed bands, such as LTE-U and NR-U avoid interference with neighbor networks by using LBT mechanism to detect and avoid Wi-Fi transmissions in the same band [53]. Under this approach, potential gains from unlicensed use include eliminating the requirement for administrative licensing that would lower barriers to market entry [40]. However, ISM bands have not been very attractive for cellular networks due to their associated interference environment which can lead to unpredictable quality of service (QoS) [38] , [46].

Moreover, incorporating unlicensed spectrum management techniques in higher frequency bands, including mmWave, presents additional complexities for ensuring coexistence. The distinctive characteristics of these higher frequency bands bring forth unique challenges that must be tackled. As emphasized in [51], some of these challenges encompass hidden and exposed node issues, channel access procedures, dynamics of interference, and beam training and measurement. The coexistence of cellular and Wireless Gigabit (WiGig) users over unlicensed mmWave bands poses several challenges, as highlighted in another study [54]. Specifically, the study addresses the challenges of directional transmission and high propagation loss in cellular communications. It emphasizes that mmWave signals, due to their short wave-

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

length, exhibit directional transmission characteristics and suffer from significant propagation losses. To overcome these challenges, the study emphasizes the importance of implementing hybrid beamforming techniques. By using hybrid beamforming, the transmitting power can be concentrated in desired directions, thereby maximizing the signal strength and improving overall system performance. This effective beam management approach is crucial for fully exploiting the spatial resources available in the unlicensed mmWave spectrum for cellular communications. The study's findings underscore the significance of addressing these challenges and implementing appropriate coexistence mechanisms to ensure the harmonious coexistence of cellular and WiGig users in the unlicensed mmWave bands.

These challenges emphasize the importance of conducting research, establishing standards, and implementing regulatory measures to tackle/address the specific complexities of coexistence in higher frequency bands. Developing solutions and optimizations in areas such as node coordination, interference management, channel access, and beamforming will be vital for enabling successful coexistence among different systems operating in the mmWave spectrum. It is worth noting that these difficulties are not limited solely to mmWave bands but serve as an example of the challenges encountered in higher frequency bands in general.

D. SPECTRUM SHARING IN 6G

In the past fifteen years, numerous studies have investigated the efficiency of spectrum utilization, and the findings have consistently revealed that certain portions of the spectrum allocated or assigned with exclusive usage rights are not being utilized to their full potential [52]. As such, an appropriate spectrum resource management scheme is critical for dealing with the conflict between the huge demand for mobile data traffic (e.g. Internet of Things (IoT) connections) and limited spectrum resources, accommodating use cases in future generations (e.g. 6G) and improving performance [55]. According to a study from Europe, around 76 GHz spectrum resource is needed (to accommodate mobile data traffic) if the spectrum is exclusively used in 5G networks [55], [56]. Nevertheless, this amount can be significantly reduced to 19 GHz by adopting spectrum sharing [55], [56]. Consequently, new models for spectrum access rights have emerged, with the general aim of allowing more dynamic access to the spectrum [52].

Recent examples of emerging models are licensing-based sharing which includes the LSA developed in Europe and SAS developed in the U.S [35]. The ongoing standardization process for LSA and SAS follows the European Conference of Postal and Telecommunications Administrations (CEPT) recommendations, with a focus on the 2.3 GHz band, which is considered as supplementary spectrum for mobile operators [21]. This band has been globally allocated to the mobile service and identified for use in International Mobile Telecommunications (IMT) [57]. LSA is a regulatory concept specific to the European region that enables opportunistic access to spectrum through the use of databases, with a primary focus on the (2.3 – 2.4) GHz frequency range for initial deployment [58]. Several regional regulatory and standardization organizations, including the Electronic Communications Committee (ECC), CEPT, European Telecommunications Standards Institute (ETSI), European Commission (EC), and the Radio Spectrum Policy Group (RSPG) of the European Union, have contributed to the development the concept of LSA by establishing the necessary regulatory framework [57], [58].

In 2013, the RSPG defined the LSA concept as a *"regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA approach, the additional users are authorized to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their spectrum rights of use, thereby allowing all authorized users, including incumbents, to provide a certain QoS"* [37], [59]. The sharing of licensed spectrum is facilitated by the two-tier framework of the LSA access model [60]. In the first tier, incumbent users are provided with protection of their spectrum and the option to monetize any unused spectrum. The second tier involves secondary LSA licensees who are granted short-term access to the underutilized spectrum licensed by the incumbents, with a guaranteed quality of service [60]. Under the LSA approach, regulators have the flexibility to decide on the spectrum assignment methods used to grant LSA licenses [35]. Furthermore, through the LSA framework, spectrum resources can be shared across different dimensions, such as frequency, time, and geography [61]. The sharing framework involves a series of terms and conditions that are mutually accepted by the incumbent user, the licensee of the LSA, and the national regulatory authority (NRA) [62]. These conditions are determined at the national level, and the license agreements may differ considerably from one country to another [62]. The LSA framework guarantees exclusive access to the spectrum for LSA licensees when it is not being utilized by the incumbent and ensures protection from any interference that might be caused by other LSA licensees or incumbents, thus ultimately ensures a predictable level of QoS [63].

In general, the LSA framework relies on a centralized database that is generated by leveraging previous usage information provided by authorized users [64]. As shown in Figure 1 [65], the LSA Repository (LR), is a centralized database that stores information related to incumbent protection [66]. The LSA Controller (LC) is another critical component of the LSA framework, which obtains the LSA spectrum resource availability information (LSRAI) from the LR [66]. To be specific, the previous LSA work (2013 - 2014) mainly focused on providing additional spectrum for existing mobile network operators (MNOs) [67]. However, LSA work that began in 2017 had a different objective, which was to address temporary spectrum access for locally deployed high-quality 5G networks [67]. The main objective of high-quality wireless networks is to provide dependable and secure services and applications with predictable levels of QoS, which are limited to a specific geographic or temporal area [35]. Additionally, ETSI in 2018, proposed some improvements to the LSA architecture, particularly in the LSA repository and controller, to accommodate the introduction of the third category of players [57].

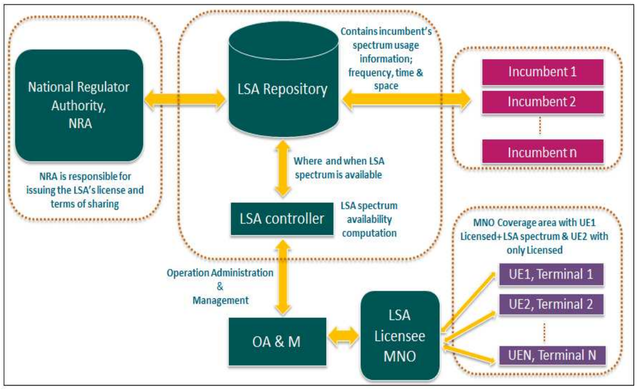

FIGURE 1. **LSA Framework, in LSA, incumbent users are primary license holders who have exclusive rights to use a specific portion of the radio spectrum. New users, such as mobile network operators MNOs, can request access to the spectrum in areas where it is not being fully occupied by the incumbent users.**

LSA can be considered as a solution to facilitate the implementation of 5G applications in various vertical sectors, including industrial automation, utilities, and e-health [57]. In particular, the LSA sharing framework is being explored for feasibility in the (3.4 – 3.8) GHz band to allow for coexistence between incumbent services, including satellite systems, and emerging 5G use cases [57]. This second use case for LSA in European regulation differs from the first (2.3 GHz band) due to the more static nature of the incumbent usage on the band, which may require different implementation and tools for LSA [62].

SAS is another database sharing model introduced by the Federal Communications Commission (FCC), which supports spectrum sharing with a three-tier/layer hierarchical regulatory model [32] , [66], [68]. The FCC has introduced SAS for providing citizens broadband radio service (CBRS) on a shared basis in the 3.5 GHz band [21], [67]. Initially, CBRS was used exclusively by the US Federal Government for Navy radar systems and commercial satellite operators [66]. The CBRS system is structured into a three-tier framework [20]. The highest tier is the incumbent access tier, occupied mainly by federal government entities, who receive the most protection from interference from other CBRS users [62]. The second tier consists of commercial users who have been granted Priority Access Licenses (PALs) by the NRA [45]. The PAL users in the second tier are also entitled to receive protection against the lower-tier users in order to prevent harmful interference [45]. In addition to PALs, a third layer of access called General Authorized Access (GAA) has also been defined in the SAS approach, which functions similarly to the operation of users in license-exempt bands [45]. In other words, GAA users are able to utilize portions of the CBRS spectrum without incurring license fees, but they are not guaranteed protection against interference from other users [67]. In comparison to commercial users with PALs, GAA users have limited access guarantees to the CBRS spectrum under certain rules and conditions set by the regulator [45], [60]. The SAS approach offers greater flexibility compared to traditional approaches, and is designed to ensure coexistence with incumbent users, even when they cannot provide prior information to a central access database [21].

In the previous examples, the spectrum sharing models were a multi-tiered sharing scheme based-on two-tiers or three-tiers, and each network had a specific/defined priority for band usage. In contrast, in single-tiered sharing schemes, all networks have the same priority to use the spectrum [20]. The examples of single-tiered sharing scheme includes:

- Spectrum commons: This type of spectrum sharing is in relation to unlicensed bands, and can be divided into two categories; (i) spectrum sharing in unlicensed bands with an anchor in the licensed bands, technologies that use sharing with an anchor are LTE-U (developed by the LTE-U Forum based on Long Term Evolution (LTE) Release 12) and LTE-LAA (Release 13, 14 and 15) [50] , [53]. Both LAA and LTE-U are based on carrier aggregation (CA) to occupy licensed and unlicensed bands [51], [69]. (ii) IEEE 802.11 standards (which includes Wi-Fi), MulteFire (developed by the MulteFire Alliance based on LTE Release 14), and NR-U (Release 16 2020) are all examples of technologies that are designed to operate standalone in unlicensed bands or shared spectrum bands without the need for a licensed band as an anchor [51], [53]. However, the high density of Wi-Fi users in unlicensed bands poses a challenge to MNOs who adopt spectrum sharing methods, resulting in more restrictions such as the requirement to use LBT [66], [70].
- Authorized light-licensing: This type of spectrum sharing provides a more flexible regulatory framework for spectrum authorization that falls somewhere between traditional exclusive licensing and unlicensed operations [62], [71] in which a limited number of equal priority license-exempt networks can use the band temporarily upon registration [20]. Bands such as the 60 GHz (57 - 64 GHz) and 80 GHz (71 - 76/81 - 86 GHz) are reasonable options for this access mode due to their propagation characteristics that enable operations with minimum risk of interference and high data rate capacities [71].

The LSA and the SAS spectrum sharing schemes have garnered significant attention as a means to rapidly access sub-6 GHz frequency bands, which are crucial for supporting 5G use cases across various vertical sectors [57]. Although spectrum sharing is considered essential for 5G, the implementation of the LSA sharing framework in the C-band in Europe remains a national decision, and European NRAs have shown limited interest in utilizing the LSA framework for 5G [57]. In the US, the initial approach to managed spectrum sharing did not succeed for TV White Spaces (TVWS) due to a lack of commercial demand. However, it worked well for CBRS because there was a strong demand for mid-band 5G frequencies, especially due to the lack of awards for the rest of the band until the end of 2021 (3.45 – 3.55) GHz [72]. Despite recent regulatory activities in Europe that have made the LSA and CBRS frameworks broadly similar, the LSA framework is still in its early stage of development, whereas CBRS is already being implemented [57].

From a technical standpoint, the adoption of higher carrier frequencies in mmWave, such as (24.25 - 27.5) GHz in 5G, shifts deployment models from wide coverage areas to local service areas, this shift enables more feasible spectrum sharing as potential interference is limited to local areas [35]. However, this shift also requires new spectrum assignment models that define and grant access rights for deploying 5G networks to cater to the specific needs of different verticals [35]. In 2018, ETSI published a technical report that explores the practicality of temporary spectrum access solutions for local high-quality wireless networks, which are specifically designed to be deployed in particular geographic areas for either a short or long period of time, and can be either fixed or nomadic in nature [72]. The development of 5G networks has expanded beyond the traditional MNOs-centric deployment models to alternative local network operator models, emphasizing the significance of local spectrum availability and the increasing reliance on spectrum sharing for the emergence of high-quality 5G wireless networks alongside regulatory approaches for assigning local spectrum licenses [35]. There are several practical options available to ensure spectrum access for local high-quality 5G networks. One option is to deploy them as a managed service by MNOs, which is also known as a ”network slice”. Another option is to create a private network that utilizes locally sub-leased MNO spectrum. Finally, a private network can be established that utilizes locally individually licensed spectrum [72].

Based on the trend observed in 5G deployment, 6G is also expected to rely on higher frequency bands, such as mmWave, leading to a similar shift in deployment models from wide coverage areas traditional (MNOs-centric) to local service areas (e.g., local high-quality networks), which in turn will increase the reliance on spectrum sharing. Therefore, it is likely that new spectrum assignment models will need to be developed to define and grant access rights for deploying 6G networks.

E. Integration of Advanced Technologies for Spectrum Sharing in 6G Networks

The advancement of spectrum sharing techniques in 5G/6G networks has been driven by the integration of cutting-edge technologies such as AI and distributed ledger technology (DLT) [15], [16], [20], [73]. These technologies provide new avenues for optimizing resource allocation, addressing the dynamic nature of wireless networks, and enhancing spectrum sharing mechanisms. AI techniques, specifically Reinforcement Learning (RL) and Deep Learning (DL), have emerged as a prominent approach in spectrum sharing. By leveraging RL and DL algorithms, intelligent spectrum allocation based on real-world data can be achieved. These algorithms have the ability to learn from past experiences, adapt to changing network conditions, and optimize spectrum utilization in real-time [73]. DLT and Machine Learning (ML) algorithms are another key focus area for efficient and secure spectrum sharing in 6G networks [15], [16]. DLT, such as blockchain technology, can establish a decentralized and trustless environment, ensuring fairness, transparency, and security among network participants. By integrating DLT with ML algorithms, spectrum sharing mechanisms can be designed to optimize resource allocation, enable dynamic sharing among multiple stakeholders, and enhance spectrum access [16], [74]. The concept of sharing frequency bands among unlimited networks with configurable priorities and interference protection criteria is discussed in [20]. This spectrum sharing scheme emphasizes the importance of efficient resource allocation in dynamic network environments. By incorporating ML algorithms, the approach ensures fair and effective spectrum sharing among multiple networks, leading to improved overall network performance and enhanced resource utilization [75]. Additionally, blockchain-based solutions address limitations in existing spectrum sharing systems, such as three-layer spectrum system, offering a decentralized and transparent environment for optimized spectrum utilization and broader participation [15]. These advancements pave the way for more efficient and intelligent 6G networks.

III. SPECTRUM MANAGEMENT APPROACHES IN 5G AND WAY TOWARDS 6G

The main European bands for 5G include 700 MHz, 3.5 GHz and 26 GHz, and many countries in Europe have completed their spectrum awards for 5G in these frequency bands [33]. In a case study of 3.5 GHz band in different countries, national regulators have adopted very different approaches in their 5G spectrum awarding decisions, the study showed that all three spectrum management approaches are still in use including administrative allocation (Japan), market-based mechanisms (Finland, Germany, Ireland, Italy, USA) and the unlicensed commons approach (USA) [35]. According to this study, it is clear that a market based mechanism is the preferred approach in awarding 5G spectrum by many regulators, due to the fact that the auction is a transparent

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

mechanism for assigning licensed spectrum and generating revenue for the government. Furthermore, we can also infer from this study that different regulators may have different priorities and considerations when deciding on the approach to awarding 5G spectrum. Furthermore, an analytical study of European auctions of C-band (3.4 - 3.8) GHz for 5G between 2017 and 2020 in [34], show that the market-based mechanism method was adopted in sixteen European countries. In this approach, regulators adopted different types of auctions formats for spectrum grants such as the simultaneous multiple round (ascending) auction (SMRA), the clock auction, and the combinatorial clock auction (CCA). Moreover, according to this study, there is no consistent pattern observed in the auctions analyzed with regard to the instruments used to improve efficiency and equity. The SMRA format was found to be the most widely used auction format for the C-band, adopted by seven countries. However, some countries have modified the auction format they use, such as SMRA, CA, or CCA, to prevent ineffective outcomes such as fragmented or unsold spectrum [34].

Overall, recent developments and decisions regarding 5G spectrum indicate that a diversity of spectrum management approaches are now being included into mobile networks in great contrast to previous generations of cellular networks, and this trend is expected to continue towards the 6G era [32], [33]. Moreover, spectrum sharing is expected to play an increasingly important role in the future, particularly to allow the deployment of 5G networks in new spectrum bands that are likely to have incumbent spectrum users, whose rights need to be protected [35]. Table 2 summarizes the various spectrum management approaches in the context of 5G, with an emphasis on how local networks are considered [33].

The development of 6G is expected to entail significant changes that will build upon the progress achieved in 5G and elevate it to a higher level. This transformation will involve converting the radio communication network from relying solely on electronic technologies to a hybrid system that also takes advantage of optical and photonics free-space technologies in order to exploit the abundant spectral resources in terahertz and visible light bands, to meet the growing demand for higher system capacity and peak data rates [8]. As a result, spectrum management in 6G is expected to expose a new level of complication that arises from the diversity of spectrum bands (e.g., mmWave, THz, and VL), and thus 6G technology will need the flexibility to operate in multiple bands under different spectrum management approaches [32]. Moreover, these frequencies have different propagation characteristics and may require different sharing mechanisms compared to traditional microwave bands. Additionally, 6G is expected to integrate terrestrial mobile communication networks, satellite communications, aerial, and maritime communications to realize ubiquitous coverage, whereas radio coverage is mainly limited to terrestrial mobile communication in all previous generations. These new paradigm shifts compared to previous mobile generations are leading to new use cases, create new business models, and will transform many aspects of society. As a result, regulators needs to rethink current spectrum management approaches and policies to align with the developments in future 6G networks models.

IV. SPECTRUM OPTIONS FOR 6G: RADIO AND LIGHT

The demand for higher peak rates and capacity in mobile communication systems has driven the exploration of higher spectrum bands. For 5G networks, new spectrum bands ranging from 3 GHz to 6 GHz and mmWave bands ranging from 24 GHz to 50 GHz have been allocated, with additional bands are expected to be allocated as 5G evolves [76]. However, the next generation of applications, such as holographic videos, VR, and ubiquitous connectivity, will require even higher bandwidth than what can be supported by the mmWave band alone [77]. The trend of using higher frequency bands is expected to continue with 6G systems, which are projected to operate at even-higher frequency spectrum than 5G, delivering data rates that are 100 to 1000 times faster [78]. In this context, researchers are exploring new spectrum options for upcoming 6G and beyond, such as higher frequency in the mmWave, THz band and optical spectrum, which includes the VL, infrared (IR), and ultraviolet (UV) bands, to address the high traffic demands [17], [79]. In the following subsections, we examine these frequency bands and their characteristics in more detail.

A. mmWAVE BAND

The classical sub-6 GHz cellular bands have become extremely crowded and cannot support the massive increase of the communication capacity alone [80]. In response to the growing demand for wireless data and the increasing congestion in the traditional sub-6 GHz bands, regulators have been exploring new spectrum in higher frequencies above the sub-6 GHz range. These higher frequencies include the centimeter-wave (cmWave) ranges from 3 to 30 GHz, and mmWave bands ranges from 30 GHz to 300 GHz, which have the potential to provide abundant spectral resources while enabling a wider carrier bandwidths of up to 1 GHz [81]. The cmWave band is generally referred to as the super high frequency (SHF) band, and the mmWave band is also referred to as extremely high frequency (EHF). The spectrum from 3 GHz to 300 GHz is also collectively called mmWave bands with wavelengths ranging from 1 to 100 mm, as the radio waves in the SHF and EHF bands share similar propagation characteristics [82], [83]. Despite the abundance of spectrum resources in the mmWave band, not all frequency bands within this range are used in practical wireless cellular communication systems [84]. Some frequency bands in the mmWave range are underutilized or not used at all for various reasons, such as technical limitations, regulatory restrictions, and the lack of suitable equipment. Examples of underutilized mmWave frequency bands include [84];

TABLE 2. Approaches for managing spectrum in the context of 5G networks [33]

Assigning and Licensing Spectrum Resources Framework	Choices Made in 5G Deployment	Consideration at a Local Network Level
Administrative Approach	This method is rarely used for spectrum granting in 5G, but it has regained its significance in spectrum awarding to local 5G networks.	The awarding of spectrum is carried out on a first come first served basis.
Market-based Mechanisms	Auctions, which rely on a market-based mechanism, are the dominant method of assigning spectrum licenses in 5G. MNOs obtain licenses through these auctions.	MNOs have the choice of leasing or trading their allocated spectrum to third-party entities for the purpose of establishing local networks.
Unlicensed Commons	This approach is one of the operational methods available for 5G.	Unlicensed deployment of networks is possible if regulatory requirements for the band are met.

- 28 / 38 GHz is licensed but underutilized with available bandwidth in total 3.4 GHz.
- 57 - 64 GHz is unlicensed with available bandwidth in total 7 GHz.
- 71 – 76 GHz, 81 – 86 GHz, and 92 – 95 GHz is light licensed with available bandwidth in total 12.9 GHz.

Efforts to allocate mmWave spectrum for cellular communications were initiated by the ITU- Radiocommunication (ITU-R) sector through the World Radiocommunication Conference (WRC) in 2015 as several frequency bands were proposed for discussion at WRC- 2019, more details in the following subsection:

1) Spectrum Regulation of mmWave for Cellular Communication

At the WRC-15, the ITU-R sector suggested 11 potential frequency bands between 24.25 GHz and 86 GHz, to assess the feasibility of coexistence between IMT and existing services like fixed and satellite services, both in shared and adjacent frequency bands [86]. These candidate frequency bands were further discussed during the WRC-19, and their details are presented in Table 3 [85]. Additionally, Table 4 provides information on the allocation of frequency bands within the range of 52.6 – 116 GHz in ITU-R, including details on the frequency band, allocation status, and primary services authorized to use each band [84].

Furthermore, there are several regions that are also promoting 5G development in the mmWave spectrum in addition to the ITU-R process [86]. More details on this are provided in the following:

- The FCC in the USA has allocated large bandwidths in the mmWave bands for 5G development, including 3.85 GHz of licensed spectrum in the (27.5 – 28.35) GHz and (37 – 40) GHz bands (with 37 – 37.6 GHz allocated to 5G on a shared basis), as well as 7 GHz of unlicensed spectrum in the (64 – 71) GHz band [85]. Additionally, there is a 12.9 GHz band from the E-band located at (71 – 76) GHz, (81 – 86) GHz, and (92 – 95) GHz [83], [87]. Although these choices do not fully align with the ITU plans, the FCC is considering the possibility of opening up to 18 GHz of additional spectrum in all ITU candidate bands, except for (42.5 – 47.2) GHz [85].
- In the UK, the pioneer band centered at 26 GHz has been released by The United Kingdom Office of Communications (Ofcom) for potential 5G use ranging between (24.25 – 27.5) GHz [83].
- China has been exploring the use of frequency bands around 45 GHz for both licensed and unlicensed communication systems, including 5G applications [83]. Within these bands, spectrum between (40.5 - 42.3) GHz and (48.4 - 50.2) GHz has been designated for fixed point-to-point wireless access systems with light license management, and spectrum between (42.3 - 47) GHz and (47.2 - 48.4) GHz has been allocated for mobile point-to-point wireless access systems with unlicensed management [88].

2) mmWave Features and Limitations

Abundant spectral resources in mmWave bands offer a promising solution to satisfy QoS requirements of wireless communications beyond 5G and 6G such as multi-Gigabits per second (Gbps) peak throughput, ultra-reliable delivery, and end-to-end latency at the order of 1 ms, and thus the adoption of mmWave communications brings advantages [84], including:

- Wide Bandwidth: Utilizing mmWave frequencies centered around 35, 94, 140, and 220 GHz can offer significant advantages for wireless communication,these advantages include high data rates of up to 10 Gbps and ultra-low latency of around 1 ms [88]. The larger bandwidth available in the mmWave spectrum allow for faster data transmission compared to lower frequency bands.
- Short Wavelength and Narrow Beamwidth: The use of mmWave frequencies offers the benefit of having a shorter wavelength compared to sub-6 GHz bands. This makes it possible to pack a large number of antennas

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

TABLE 3. **Candidate mmWave Bands for IMT-2020 Considered in WRC-15 [84], [85]**

Frequency Range (GHz)	Radio Communication Service			Allocation Band Mainly for Mobile Service ?
	Shared with Fixed Service	Shared with Fixed Satellite Service	Shared with Space Radio Communication	
24.25 - 27.5	-	-	-	✓
31.8 - 33.4	(31.8 - 33.4) GHz	-	-	✗
37 - 40.5	(37 - 40) GHz	(39 - 40) GHz in Region 1, (40 - 40.5) GHz worldwide	-	✓
40.5 - 42.5	(40.5 - 43.5) GHz	(40.5 - 42) GHz in Region 2	-	✗
42.5 - 43.5	(40.5 - 43.5) GHz	-	-	✓
45.5 - 47	-	-	(43.5 - 47) GHz	✓
47 - 47.2	-	-	-	✗
47.2 - 50.2	-	(47.5 - 47.9), (48.2 - 48.54), and (49.44 - 50.2) GHz in Region 1. (48.2 - 50.2) GHz in Region 2	-	✓
50.4 - 52.6	(51.4 - 52.6) GHz	-	-	✓
66 - 76	-	-	(66 - 71) GHz	✓
81 - 86	-	-	-	✓

into a compact array. With a greater number of antenna elements, a narrow directional beam can be achieved, which has several advantages. Firstly, it suppresses multi-path reflection, which can improve signal quality. Secondly, it provides high immunity against jamming and eavesdropping attacks, as the narrow beam is more difficult to intercept or interfere with. Lastly, it offers robustness to co-user interference, as the wireless channels will be largely uncorrelated [87], [89], [26]. These features make mmWave highly attractive for various wireless communication applications, particularly those where high data rates, low latency, and reliable connectivity are essential.

Despite the many benefits of mmWave communications, there are still several challenges that need to be addressed for effective design, deployment, and operation. These challenges arise from several limitations, including:

- Poor Propagation Characteristics: The mmWave communication system faces inherent challenges such as; high free-space path loss, atmospheric gaseous absorption, rainfall attenuation [90], [91], and sensitivity to blockage (e.g., solid construction, plants, etc.) [92], [93]. Directional beamforming and beam tracking techniques can be utilized to overcome the challenges posed by harsh propagation loss and expanding the coverage area. However, when cell sizes are reduced to enhance spectral efficiency, the impact of rain attenuation and atmospheric absorption becomes less significant for cell sizes around 200 meters. Consequently, mmWave communication is primarily used for indoor environments, small cell access, and backhaul, with cell sizes generally on the order of 200 meters [94].
- Integrated Circuits and System Design: Designing circuit components and antennas for mmWave communications can be quite challenging due to the high carrier frequency and wide bandwidth. In particular, the high equivalent isotropic radiated power (EIRP) and wide bandwidth in higher frequency bands, such as the 60 GHz band, can potentially result in severe nonlinear distortion of power amplifiers (PA). Furthermore, the design of RF integrated circuits also faces significant challenges related to phase noise, in-phase and quadrature phase (IQ) imbalance [94].
- Industrially, the industrial production of small mmWave components involves a higher level of precision, which in turn leads to increased manufacturing costs. [88].

3) Spectrum Allocation for 5G New Radio (NR)

The mmWave spectrum bands are being recognized as a promising solution for dealing with the high data rate and capacity requirements of 5G and beyond [68]. Compared to previous generations (e.g., 3G, 4G), 5G has the advantage of allocating mmWave bands in cellular communications [95]. In 2018, the first 5G communications standard, called new radio (NR), was defined by 3GPP in Release 15 [96]. Compared to previous generations of mobile communication systems, NR has a key feature of being able to be deployed over a much wider range of spectrum for radio access technology [51], [97]. In this regard, ITU-R and 3GPP have specified the use of two frequency ranges for 5G NR, namely FR1 and FR2, with the latter mainly using frequencies in the mmWave band [98]. In particular, FR1 is defined in the frequency range from 410 MHz to 7.125 GHz, while FR2 covers two mmWave frequency ranges: (1) from 24.25 GHz to 52.6 GHz (FR2-1), and (2) from 52.6 GHz to 71 GHz (FR2-2) [69].

In terms of maximum bandwidth in FR1 and FR2, 5G NR adopts Orthogonal Frequency Division Multiplexing

TABLE 4. **Frequency bands between 52.6-116 GHz as defined in the Radio Regulations [84]**

Frequency Range (GHz)	Service	Is the Mobile Service allocated as the primary user in this frequency band?	Notes
52.6 - 54.25	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✗	Emissions prohibited
54.25 - 55.78	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✗	-
55.78 - 59	Earth Exploration Satellite Service/ Research Service (Passive)/ Fixed Service	✓	High-density applications
59 - 59.3	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✓	-
59.3 - 64	Radiolocation	✓	-
64 - 65	Fixed Service	✓	High-density applications
65 - 66	Fixed Service	✓	High-density applications
66 - 71	-	✓	Frequencies listed under agenda item 1.13 of WRC-19 are undergoing compatibility studies with potential limitations.
71 - 76	-	✓	Frequencies listed under agenda item 1.13 of WRC-19 are undergoing compatibility studies with potential limitations.
76 - 81	Radiolocation	✗	-
81 - 86	-	✓	Frequencies listed under agenda item 1.13 of WRC-19 are undergoing compatibility studies with potential limitations.
86 - 92	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✗	Emissions prohibited
92 - 94	Radiolocation	✓	-
94 - 94.1	Radiolocation	✗	-
94.1 - 95	Radiolocation	✓	-
95 - 100	Radiolocation	✓	-
100 - 102	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✗	Emissions prohibited
102 - 105	Not Applicable	✓	-
105 - 109.5	Research Service (Passive)	✓	-
109.5 - 111.8	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✗	Emissions prohibited
111.8 - 114.25	Research Service (Passive)	✓	-
114.25 - 116	Earth Exploration Satellite Service (Passive)/ Research Service (Passive)	✗	Emissions prohibited

(OFDM) based waveform for both downlink and uplink with a sub-carrier spacing (SCS) of $(2^{n}x15$ kHz) where $(0 \geq n \geq 3)$ [99]. More specifically, NR can adopt SCS in the values (15/30/60) kHz for the data channel in FR1 with channel bandwidth up to 100 MHz, whereas for FR2, NR can only use SCS at (60/120) kHz with channel bandwidth up to 400 MHz [48], [50], [99]. Furthermore, NR differs from LTE Advanced (LTE-A) in that it can only support a single SCS of 15 kHz and CA with up to 5 component carriers (CCs) resulting in a maximum aggregated bandwidth of 100 MHz, whereas NR is capable of aggregating up to (16 CCs) and offers a higher bandwidth. Table 5 summarizes the 5G NR supplementary frequency bands in FR1 and FR2, applied SCSs, and maximum bandwidth with and without CA [99]. In terms of data rate, frequency bands from 24.25 GHz to 52.6 GHz can provide data exchange at the rates of several Gbps [26], [98].

From the 3GPP standardization point of view, 5G NR has been developed under Release 15 and Release 16 defining operation for frequencies up to 52.6 GHz and all physical layer channels, signals, procedures, and protocols have been optimized for uses under 52.6 GHz [100]. However, in Release 17 [101], 3GPP has considered the maximum SCS up to 960 kHz for the frequency band between 52.6 GHz and 71 GHz. The reason for this is that the air interface for Release 15 and Release 16 has been optimized for a 240 kHz SCS under 52.6 GHz [100].

TABLE 5. **5G NR Supplementary Frequency Bands in FR1 & FR2 with Max. Bandwidth [50], [99].**

Frequency Range	Band Index	Uplink (GHz)	Downlink (GHz)	Subcarrier Spacing (SCS)	Max. BW with and without Carrier Aggregation (CA)	Duplex Mode
FR1 (450 ∼7125) MHz	n77	3.3 - 4.2	3.3 - 4.2	15 / 30 / 60 kHz	100 MHz per component carrier, 1.6 GHz with CA up to 16 component carriers	TDD
	n78	3.3 - 3.8	3.3 - 3.8			TDD
	n79	4.4 - 5	4.4 - 5			TDD
FR2 (24.25 - 52.6) GHz	n257	26.5 - 29.5	26.5 - 29.5	60 / 120 kHz	400 MHz per component carrier, 6.4 GHz with CA up to16 component carriers	TDD
	n258	24.5 - 27.5	24.5 - 27.5			TDD
	n260	37.0 - 40.0	37.0 - 40.0			TDD
	n261	27.5 - 28.35	27.5 - 28.35			TDD

In particular, one of the main objectives of Release 16 (July 2020) is to extend the applicability of 5G NR to unlicensed spectrum in mmWave, NR-U [51], [102] as a general purpose technology that allows fair coexistence across different Radio Access Technology (RATs) [97]. NR-U differs from LTE-U and LAA which were standardized based on CA using 5 GHz bands, whereas the design of NR-U considers multiple bands 2.4 GHz (unlicensed worldwide), 3.5 GHz (shared in the USA), 5 GHz (unlicensed worldwide), 6 GHz (unlicensed in the USA and Europe), 37 GHz (shared in the USA) [51], [103], in addition to 60 GHz (unlicensed worldwide) [101], [16]. Furthermore, NR-U is expected to be extended to higher frequencies such as V and W mmWave bands (60 - 114.25) GHz in upcoming releases, including Release 18 or beyond. This expansion is noteworthy because it offers not only a very wide spectrum up to 15 GHz, but also new opportunities to facilitate many high-capacity use cases, such as back/fronthaul, relay, industrial IoT, private network, advanced vehicle-to-everything (V2X), and tightly coupled licensed-unlicensed spectrum usage [99].

4) Access to Licensed/Unlicensed Bands in NR-U mmWave

NR-U for sub 7 GHz and NR-U for mmWave bands (standardized in Release 16 and 17 respectively) support different deployments scenarios for coexistence with other licensed and unlicensed systems [51], [97]. The NR-U supports these modes for coexistence with other systems:

- NR-U Carrier Aggregation: NR-U CA is developed based on the approach of LTE-LAA which was first introduced in Release 13 [97], allows for the aggregation of NR-U in unlicensed frequency bands and NR in licensed frequency bands [51], [103]
- NR-U Dual Connectivity: NR-U DC is built upon LTE-enhanced LAA (eLAA), which was introduced in Release 14 [97], and enables for simultaneous connectivity with NR-U in unlicensed spectrum and either NR or LTE in the licensed spectrum [51].
- NR/UL, NR-U/DL: This scenario involves the combination of a licensed carrier that is serviced by a 5G NR cell for uplink communication, and an unlicensed carrier that is serviced by a 5G NR-U cell for downlink communication [51], [102].
- NR-U Standalone: In 3GPP Release 16, a new approach called Standalone NR-U was introduced, allows for the operation in unlicensed spectrum without being anchored to any licensed carrier, similar to MulteFire approach proposed for LTE [97]. Whereas, Release 15, only supports non-standalone (NSA) operation of 5G NR networks, where 4G LTE and 5G mobile networks coexist [104].

5) mmWave Spectrum Options for 6G

5G uses more spectrum than previous generations and this trend is expected to continue in 6G. One potential spectrum option for 6G is the mmWave band above 52.6 GHz, such as the W-band (75 – 110) GHz, which offers an abundance of available spectrum. Besides, 6G is expected to operate in the mmWave bands defined by the ITU-R and 3GPP for 5G. This broad spectrum in mmWave band provides an opportunity to cover capacity-intensive applications in 6G. However, the challenges related to path loss and expensive hardware costs restrict the use cases and deployment scenario in such higher frequencies. Despite the high propagation loss in bands above 52.6 GHz, relatively large coverage can still be achieved with Line of Sight (LoS) transmission and high gain antennas. This makes urban macro/rural macro scenarios suitable for the fixed wireless access and backhaul applications, which have LoS transmission conditions [84]. Overall, the mmWave bands offer a promising spectrum option for 6G, but more research and development are needed to overcome the challenges and realize the full potential of this frequency range.

6) Use Cases of mmWave in 6G

With the advantages of mmWave mentioned above such as huge bandwidth and narrow beams, mmWave has potential applications that are expected to fulfill/realize the vision of 6G systems. The use cases of mmWave are categorized as;

- Wireless Backhaul: Wireless backhaul using mmWave frequencies is becoming an increasingly popular solution for connecting base stations (BSs) in small cell dense deployment scenarios [26]. In particular, mmWave frequencies in the 60 GHz and E-band (71 – 76) GHz and (81 – 86) GHz provide a huge bandwidth, which can support very high data rates of several Gbps [94]. This makes them suitable to support the high-speed transmission between small cell BSs or between BSs and gateways [105]. Moreover, wireless backhaul solutions, such as microwave and mmWave, can offer several advantages compared to fiber-based backhaul in certain scenarios such as rural areas and mountains regions. In such cases, laying fiber in order to connect core network with small cells is not feasible due to high

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

deployment costs and availability problem, or where it may be time-consuming [106]. Consequently, mmWave wireless backhaul can overcome these challenges and provide a cost-effective and scalable solution for small cell backhaul [26], [106]. As a result of these advantages, mmWave wireless backhaul is projected to have a significant role in the next generation of cellular systems, including beyond (B5G) and 6G.

- Vehicular Networks: The use of mmWave bands, especially those at 24 GHz and 77 GHz, can greatly benefit communication between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), in high-speed transportation systems, such as cars, high-speed railways, and subway systems. These systems require data rates of several Gbps, which are not possible with the 10 MHz channel bandwidths at 5.9 GHz used in current 4G technology [107]. However, the use of mmWave frequencies for vehicular networks also presents challenges related to beam alignment and routing stability due to the high mobility of vehicles, which requires further research and development to be overcome [108].
- Wearable Devices: Wearable devices include smartwatches, smart wristbands, smart (AR, VR) glasses, motion trackers, and so on. Different types of wearable devices generate huge data traffic, which requires massive bandwidth to achieve low latency. Therefore, mmWave is a promising candidate for connecting these wearable devices [89], [109].
- Imaging and Tracking: The mmWave communications, operating at frequencies such as 60 GHz, are a promising option for imaging and tracking systems, as the signals in this band are mostly reflected from objects larger than their short wavelengths. Utilizing the high directional beams of 60 GHz links, dimensions of objects can be precisely measured, which reduces the interference and enhances the accuracy of tracking [26]-[89].

B. THz Band

While the path to higher carrier frequencies clearly supports much greater bandwidth, the total consecutive available bandwidth for mmWave systems remains below 10 GHz, making Tbps data rates difficult to achieve [88]. In this sense, the potential for achieving ultra-high speed data rates of up to 1 Tbps and supporting bandwidth-intensive applications has made THz band communication a promising enabler for 6G technology [27]. The THz band lies in the frequency range 0.3 THz to 10 THz [6], between mmWave and IR bands and shares some properties with both bands [27]. The THz band is also known as the sub-millimeter radiation due to its wavelengths beginning at 1 mm and progressing into shorter wavelengths [110]. The THz frequency range from 275 GHz to 300 GHz falls within the mmWave band, whereas the other part from 300 GHz to 3 THz falls within the far-IR spectrum band [77]. Despite being part of the optical band, the (300 GHz - 3 THz) band exhibits properties similar to the RF band (i.e, is characterized by electronic behavior). This behavior can be explained by the fact that THz radiation lies at the boundary between the RF and optical frequency bands, as shown in Figure 2 [77], [111].

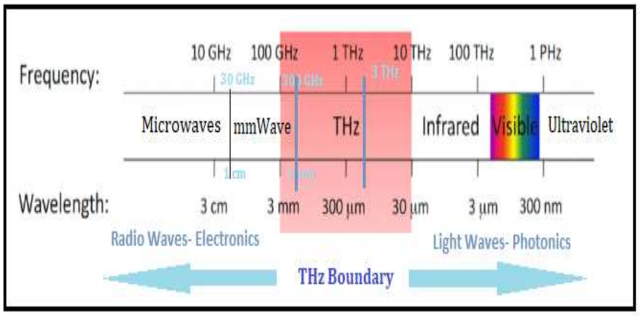

FIGURE 2. **The THz band encompasses frequencies from 0.3 THz to 10 THz and occupies a position between the mmWave band and the infrared IR band. The waves in this band exhibit properties of both electronics and photonics.**

For a considerable period of time, the lack of practical and small-scale techniques for producing and detecting THz signals hindered the practicability of using THz band communication [112]. Specifically, the inadequacy of semiconductor devices to efficiently convert electrical energy into electromagnetic energy at THz frequencies has long posed a challenge for THz communication [113]. However, in the last decade, the THz technology gap has been significantly reduced due to notable advancements in semiconductor technologies and the emergence of new materials, which offer greater potential for THz band communication [114].

1) Standardization of THz Communication

Standardization efforts for THz wireless communications began in 2008, when the IEEE formed an Interest Group on THz communications (IGTHz) under the IEEE 802.15 standard umbrella [115]. In 2014, the group members made key design choices and preliminary performance predictions, which laid the foundation for the IEEE Task Group on 100G Wireless (TG100G, IEEE 802.15.3d) [116]. In 2017, IEEE Std. 802.15.3d was issued as the first wireless communication standard in the 300 GHz band to support 100 Gbps and above wireless point-to-point links [117]. The development of IEEE Std. 802.15.3d- 2017 has been based on the 2016 version of the RRs. The RRs include an allocation of the bands from (252 - 275) GHz for the use by land mobile and fixed service on a co-primary basis [118]. At WRC-2019, 160 GHz of the spectrum in the whole frequency band between 275 GHz and 450 GHz was opened for THz communications and the outcome of WRC-19 has included a new footnote to the RRs (No. FN5.564A), describing the conditions for the use of the spectrum between (275 – 450) GHz by land mobile and fixed service [116], and indicating

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

potential standardization of the low frequency window of the terahertz band for near-future wireless communications [117]. In accordance with ITU-R recommendations, the frequency range from (275 GHz to 3 THz) has been identified as a major part of the THz communications [6], [111]. Since the frequency bands (275 GHz – 3 THz) have not been allocated to any services globally yet, adoption of these higher frequency bands is a potential solution to achieve the desired data rate at the Tbps level [6], [111]. The envisioned capacity for 6G can be achieved by aggregating the THz band (275 GHz – 3THz) with the current mmWave band (30 – 300) GHz, as a result of which the overall band capacity will increase by approximately 11.11 times [6], [111].

2) THz Features and Limitations

With a multi-gigahertz bandwidth, the THz band is likely to be one of the candidate bands as a solution to the problem of spectrum scarcity and to enhance the capacity of the next generation of wireless systems [114]. In general, THz-based communications are characterized by wide frequency range, high speed, good directivity, high security, and good penetration [119]. THz communications have the ability to support the much higher speed data rates from multi-Gbps to several Tbps than mmWave communications [115], [120]. Moreover, the shorter wavelength of THz when compared to mmWave makes it more directional and less prone to free-space diffraction [115]. Because THz band communication exhibits highly directional transmission, this can significantly mitigate intercell interference, dramatically reduce the probability that communications can be listened to, and provide better security [15]. Even though the increased directionality of THz transmissions presents a more challenging environment for eavesdroppers, there is still an opportunity for eavesdropper to intercept signals in LoS transmissions. Therefore, physical layer security techniques, that exploit the physical properties of wireless channels to incorporate security features, have been considered as an important solution for THz links [121]. Furthermore, THz has good penetrating ability to dielectric materials, and it can be used to detect hidden objects [119].

However, there are many challenges facing the THz spectrum, which including:

- Atmospheric/Absorption Loss: When operating at THz frequencies, the losses from path and reflection are joined by molecular absorption, which weakens the received power and amplifies noise. As a result, the molecular absorption produces additional noise, known as molecular absorption noise, in addition to the thermal noise found in lower frequency bands. Specifically, molecular absorption is caused by the energy differences between the molecular states of the physical medium during transmission [113]. Oxygen and water vapor in the atmosphere are the primary components responsible for absorption in the THz frequency [98].
- Beam Tracking, Beam Alignment, and Mobility Management: To combat the high transmission loss at THz frequencies, it is essential to employ large antenna arrays for directional beamforming. This technique utilizes extremely narrow pencil beams for LoS links, which can mitigate attenuation losses and provide natural interference mitigation, thereby extending the communication range of THz networks. However, these pencil beams also pose new challenges such as mobility and handover management, efficient beam tracking, and alignment [113], [122].
- Engineering Challenges for Antennas and RF Circuitry: At higher frequencies such as THz, it becomes challenging to manufacture miniaturized chips that can effectively suppress noise and interference between components, while also overcoming the limitation of impedance. To address these challenges, ongoing research efforts are exploring techniques such as distance-aware physical layer design, supermass Multiple Input Multiple Output (MIMO) communication, smart surface, and graphene transistors [119].
- Power Consumption: The use of large antennas in THz systems presents a significant power consumption challenge, primarily due to the necessary analog-to-digital (A/D) conversion required in broadband THz systems. The power consumption increases exponentially with the sampling rate and the number of samples per bit, which is dependent on the required high-resolution quantization for the vast bandwidth and enormous antennas in the THz band. Consequently, developing low-power and cost-effective devices remains a crucial obstacle [123].

In addition, there are non-technical obstacles associated with policies and regulations for the allocation and usage of frequency spectrum in the THz range [123]. Overcoming all of these challenges is essential to effectively launch THz wireless communications in practice.

3) Use Cases of THz in 6G

THz communication has a broad range of potential applications at both macro and micro/nano scales. These applications can be grouped into various categories depending on the specific sector or scenario, including automotive, indoor networking, aerospace, healthcare, intrinsically safe environments, location-based services, defense, underwater communication, and more [115]. Below, we will explore some of the key applications of THz communications:

- Macroscale use cases: The primary use cases for THz communications at the macroscale are expected to be driven by emerging applications that require Tbps links, which are not possible using the mmWave spectrum. These applications include ultra-high-definition holographic (HD) video conferencing, 3D gaming, XR, and

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

haptic communications, among others [4]. In addition, THz communications show promise as a potential candidate for the next generation of data centers. With THz links, seamless connectivity at ultra-high speeds in fixed networks can be achieved, along with adaptability for hardware reconfiguration, whereas conventional data centers manage connectivity and maintain it using wired networks, resulting in high costs for both installation and reconfiguration of the system [1]. Furthermore, THz communications can play a vital role in wireless local area networks (WLANs) and wireless personal area networks (WPANs) applications by providing a means for seamless interconnection between ultra-high speed wired networks such as fiber optical links, and wireless devices such as laptops or tablets in WLANs, or between personal wireless devices in WPANs [26]. THz communications can also have potential applications in vehicular communication scenarios such as V2V and V2I. In these scenarios, neighboring or cooperating vehicles share perceptual data with each other using THz bands for high-rate and low-latency communication. The shared data can be used to create a satellite view of the surrounding traffic and real-time maps of the environment [115].

- Micro/nanoscale: Enabling communications between nano-machines is another potential application of the THz band. These nano-machines can carry out simple tasks, such as computations, data storage, actuation, and sensing. The transmission distance for such communications depends on the specific application and can range from a few micrometers to a few meters [4]. One of the most significant potential application of nano-machine enabled communications is the ability to transmit information within sub-mm sized regions inside the human body, which is typically inaccessible by any other medical device, making this technology particularly useful in the field of healthcare [124]. Enabling interactions between nano-machines, nano-sensors, and nano-actuators at the same scale as living systems and chipsets can lead to the development of the Internet of Nano-Things (IoNT) [113].

4) Vision of THz Communication System in 6G

While THz systems have shown great promise for revolutionizing wireless networks, they are still in their nascent stage and require further research and development to fully realize the potential of THz systems and to overcome the technical challenges [113]. This means that it will likely take a long time to become mature and commercially available for use. Meanwhile, mmWave and optical wireless communication (OWC) systems have already been extensively studied and commercially deployed in various applications, making them more likely to be the enabling technology for 6G wireless networks than THz systems. However, with the advancements in the infrastructure and computational aspects of communication systems, such as ultra-massive MIMO (UM-MIMO), intelligent surfaces, new signal processing methods, and communication protocols, make it possible for THz communications to mature and become a viable technology for future wireless networks [125].

C. OPTICAL SPECTRUM

Besides THz-based cellular communications, OWC systems are being explored as a means to provide broadband connectivity and coverage for 6G [27]. OWC systems operate in the IR, VL and UV frequency bands and are generally considered to be more mature than THz systems, with deployments in various applications [123]. OWC technologies include, Visible Light Communication (VLC), Light Fidelity (LiFi), Optical Camera Communication (OCC), Free-Space Optics (FSO), and Light Detection and Ranging (LiDAR) [27], [126], [127]. Moreover, OWC can be considered as a complementary technology to existing RF-based wireless communication technologies [123]. Figure 3 illustrates brief architectures of these technologies.

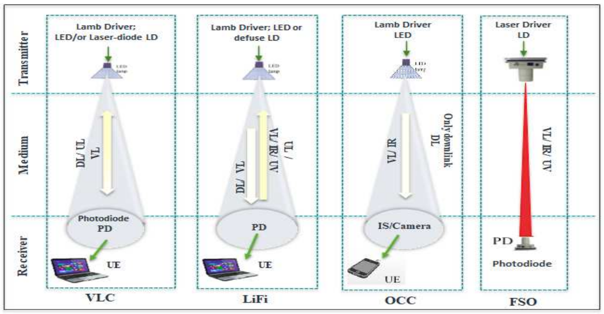

FIGURE 3. **OWC technologies architectures. The figure shows the basic components of an OWC system, including a transmitter, a receiver, and an optical channel (VL- IR- UV) for different OWC technologies; VLC, LiFi, OCC, and FSO.**

Table 6 shows the optical sub-bands for possible wireless 6G communications, THz and mmWave [6]. The optical regions encompass a range of wavelengths, including (750 nm - 1 mm) for IR, (380 nm – 750 nm) for VL, and (10 nm – 400 nm) for UV [128].

OWC technologies are expected to have wide-ranging applications, including V2X communication, indoor mobile robot positioning, VR, and underwater [6]. A variety of OWC technologies are currently being developed to address the requirements of future communication systems beyond 5G [129]. Generally, wireless optical technologies offer several advantages such as high data rates, low latency, secure communications, and reduce power consumption [27]. The possibility of combining OWC and RF technologies, known as hybrid RF/OWC systems, could offer an efficient solution to meet the high user demands expected in the near future [130]. Hybrid RF/optical and optical/optical wireless systems, such as OWC/RF, FSO/RF, WiFi/LiFi, VLC/femtocell, VLC/FSO, and LiFi/OCC [129], offer a promising approach

TABLE 6. mmWave, THz, Optical Spectrum [6]

mmWave		**mmWave**	mmWave Range1	30 - 275 GHz	10 - 1.1 mm
	THz		mmWave Range 2	275 - 300 GHz	1.1 - 1 mm
Optical		**Infrared (IR)**	Far IR- Range 1	0.3 - 3 THz	1 - 0.1 mm
			Far IR- Range 2	3 - 20 THz	0.1 - 0.015 mm
			Thermal IR	20 - 100 THz	0.015 - 0.003 mm
			Short-wavelength IR	100 - 214.3 THz	3000000 - 1400 nm
			Near IR	214.3 - 394.7 THz	1400 - 760 nm
		Visible Light (VL)	Red	394.7 - 491.8 THz	760 - 610 nm
			Orange	491.8 - 507.6 THz	610 - 591 nm
			Yellow	507.6 - 526.3 THz	591 - 570 nm
			Green	526.3 - 600 THz	570 - 500 nm
			Blue	600 - 666.7 THz	500 - 450 nm
			Violet	666.7 - 833.3 THz	450 - 360 nm
		Ultraviolet (UV)	UVA	750 - 952.4 THz	400 - 315 nm
			UVB	952.4 - 1071 THz	315 - 280 nm
			UVC	1.071 - 3 PHz	280- 100 nm
			NUV	0.750 - 1 PHz	400 - 300 nm
			Middle UV	1 - 1.5 PHz	300 - 200 nm
			Far UV	1.5 - 2.459 PHz	200 - 122 nm
			Hydrogen Lyman-alpha	2.459 - 2.479 PHz	122 - 121 nm
			Extreme UV	2.479 - 30 PHz	121 - 10 nm
			Vacuum UV	1.5 - 30 PHz	200 - 10 nm

to overcome the limitations of individual systems while leveraging the advantages of each technology [131].

1) Visible Light Communication -VLC

VLC is a wireless communication technology that utilizes visible light to transmit high-speed data wirelessly. It operates within a frequency range of (400 – 800) THz, which is not subject to licensing requirements [6], [125], [132]. The transmitter in VLC systems employ light-emitting diodes (LEDs) and intensity modulation (IM) technique to transmit data at high-speeds [27]. On the receiver side, VLC typically uses photodiodes (PDs) or laser diodes (LDs), along with direct detection (DD) technology to detect the intensity (power) of the received optical signal [27]. DD employs photodiode to convert the incident optical signal power into a corresponding electrical current that is proportional to the signal power [133].

a: VLC Features and Limitations

VLC technology provides various distinctive benefits compared to radio communication. Firstly, it can leverage multiple available spectra, providing a wider range of potential frequencies [123]. Secondly, external electromagnetic interference has minimal impact on VLC-based communication [17]. Thirdly, the transmission medium used in VLC technology is visible light, which makes the network more secure, as the signal cannot penetrate walls and other obstacles. Fourthly, the spectrum occupied by VLC systems is free and unlicensed [125]. Additionally, VLC can be combined with RF systems to form a hybrid RF/VLC wireless communication, enabling highly energy-efficient communication and enhancing the user experience [27].

Although VLC technology has several advantages, it has limitations that must be addressed. For instance, it is not suitable for outdoor use and cannot support long-distance communication [129]. Moreover, there are several technical challenges that require further investigation, including channel modeling, fast switching mechanisms between optical and radio-frequency systems, development of new theoretical bounds for channel capacity, and improving physical layer security and coding techniques. Addressing these challenges is crucial for improving the overall performance and reliability of VLC technology [27].

b: Standardization of VLC

The optical wireless technologies are addressed by IEEE standards, including IEEE 802.15.7-2011 (VLC), IEEE 802.15.13 (Li-Fi), and IEEE.802.15.7m OCC [134]. However, it is worth noting that the standardization efforts of OWC systems, including VLC, is not limited to IEEE. Other large-scale organizations, such as the Visible Light Communication Consortium (VLCC) in Japan and the European OMEGA project, have also played a significant role in the standardization and development of VLC technology [126]. In 2003, Japan began the standardization of VLC systems, and interest in the technology has been increasing since then [135]. In 2007, the Japan Electronics and Information Technology Industries Association (JEITA) introduced two standards based on visible light communication [136], namely (CP-1221) and (CP-1222) respectively [136], [137].

JEITA CP-1221 standards emphasizes the fundamental design requirements of VLC systems, and JEITA CP-1222 provides details about visible light ID systems [137]. Following the introduction of JEITA CP-1222, a new standard named CP-1223, also known as the visible light beacon system standard, was proposed by the Japanese six years later [136], [138]. The development of VLC technology continued, and in September 2011, the IEEE established a standard for VLC systems, named IEEE 802.15.7, which includes physical and medium access control (MAC) layers [139]. This standard encompasses three physical (PHY) types for VLC: PHY, I which operates from (11.67 to 266.6) kbps, PHY II, which operates from (1.25 to 96) Mbps, and PHY III, which operates between (12 and 96) Mbps for indoor and outdoor applications [140]. The two modulation schemes supported by PHY I and PHY II are on-off keying (OOK) and variable pulse-position modulation (VPPM), both of which utilize a single light source. On the other hand, PHY III employs multiple light sources of different colors to implement color shift keying modulation (CSK) [141]. The standard also covers topics related to link mobility, the impairments caused by noise, and the interference from other light sources [139]. The IEEE 802.15.7-2018 standard, which was revised in 2018, provides additional information on various aspects of VLC technology. These include security, compatibility of VLC infrastructure with existing illumination infrastructure, selection of modulation schemes, and addressing dimming and flickering issues of light sources, among others [137].

c: VLC For Expected Use Cases of 6G

VLC technology is expected to have significant use cases in 6G, given its numerous benefits. VLC can be applied in various IoT applications, including smart homes, smart cities, smart transportation, smart buildings, smart grids, smart factories, and hospitals [27], [125], [129]. Because VLC is considered safe for all electronic equipment, which makes it suitable for use in RF restricted areas such as airplanes, chemical plants or hospitals [139]. Furthermore, VLC has the potential to be use in outdoor environments, such as V2V and V2I communications, to provide crucial information about road conditions, accidents, and traffic-off loading [27]. In comparison to RF, VLC can also transmit data underwater communication over longer distances since RF electromagnetic waves are highly absorbed in water [27], [129].

2) Light Fidelity - LiFi

LiFi is a wireless communication technology that operates using the IR and VL spectrum to transmit data at high speeds [142]. It is often seen as an extension of VLC technology. Although LiFi and VLC share some similarities, such as using light as a medium for communication, they have some distinct differences. Firstly, LiFi is a bidirectional communication system that utilizes transceivers at both ends of the connection, whereas VLC systems can be either unidirectional or bidirectional [131]. Secondly, LiFi must support multiuser communications, specifically point-to-multipoint and multipoint-to-point communications, whereas VLC systems can support point-to-point, point-to-multipoint, and multipoint-to-point communications [129]. Thirdly, LiFi uses VL for the forward link and VL or IR for the reverse link, whereas VLC uses VL as the communication medium [131]. Additionally, LiFi is capable of supporting user mobility and handover [27]. To be considered as LiFi, a VLC system must possess LiFi features such as multi-user connectivity, point-to-multipoint and multipoint-to-point communications, and seamless user mobility. Conversely, a LiFi system can only be classified as VLC when VL is utilized as the transmission medium [127]. Like VLC, LiFi communication systems use LEDs and photodetectors as transmitters and receivers, respectively [26]. However, it is also possible to use LDs integrated with an optical diffuser as transmitters and light sources [129]. Moreover, LiFi is envisioned as complementary technology to Wi-Fi [26].

a: LiFi Features and Limitations

LiFi has the potential to be a cost-effective solution as it can easily integrate with the current RF wireless networks, allowing for the creation of heterogeneous wireless networks that combine optical and RF fields [27]. In comparison to Wi-Fi, LiFi offers several advantages, such as extremely high data rates, lower cost, easily available spectrum capacity, and superior security [129]. These features and advantages make LiFi a promising technology for the development of future 6G networks [27].

However, LiFi systems have limitations in outdoor applications due to interference from natural and artificial light sources and cannot provide long-range communication [27], [129]. In addition, technical challenges such as channel modeling and feasible interference mitigation techniques need further research [27].

b: Standardization of LiFi

After the publication of the first two VLC standards JEITA CP-1221 and JEITA CP-1222 by JEITA in 2007, and the IEEE 802.15.7 standard in 2011, the IEEE 802.15 working group continued its efforts to standardize VLC technology. In 2015, IEEE established the 802.15.7r1 Task Group (TG) to revise the IEEE 802.15.7 standard. The goal of 802.15.7r1, later referred to as 802.15.m, was to expand the standard to cover not only visible light but also near-UV and IR wavelengths, and to include options such as OCC and LiFi [143]. Task Group 13 (TG13) was launched by the 802.15 Working Group in March 2017 with the aim of developing an OWC standard (802.15.13) that can support point-to-point and point-to-multipoint configurations with data rates up to 10 Gbps over a range of 200 m. This standard is designed to operate over a range of wavelengths from 10,000 nm to 190 nm [144]. One drawback of 802.15.13 is that it is

This article has been accepted for publication in IEEE Open Journal of the Communications Society. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJCOMS.2023.3301630

intended for industrial use and is not targeted towards mass market consumers, meaning it is unlikely to be integrated into widespread wireless network systems. Additionally, 802.15.13 is limited to LoS scenarios [145]. A task group named IEEE 802.11 Light Communications Amendment - Task Group “bb” (TGbb) was formed alongside TG13, with the aim of integrating LiFi technology into the IEEE 802.11 ecosystem [146]. IEEE 802.11bb aims to create a distinct ecosystem for chipset vendors, network infrastructure, device integrators, and operators of IEEE 802.11, utilizing high-layer specifications. This will enable LiFi to coexist and cooperate with other WiFi standards and leverage the well-established commercialization phases of IEEE 802.11 for mass-market adoption [147]. Additionally, the ITU launched the G.vlc project in 2018 to create a system architecture and define the PHY/Data Link Layer functionality of LiFi transceivers for high-speed indoor networking applications. As a result, a new set of PHY recommendations known as G.9991 was published in 2019. G.vlc is currently the only LiFi standard that has available chipsets [144].

3) Optical Camera Communication - OCC

OCC is an OWC technology that is currently receiving significant attention due to the recent advancements in camera technology and the widespread use of smart devices equipped with LED flashlights [148]. OCC is considered as promising technology for indoor positioning and navigation applications [26]. In comparison to VLC, OCC has a wider spectral range, as it can use both VL and IR as a communication medium [128]. In an OCC system, the receiver is typically equipped with built-in cameras or image sensors (IS), while the transmitter is a conventional commercial LEDs [26], [129], [131].

a: OCC Features and Limitations

OCC offers several advantages over other OWC technologies. Firstly, OCC can be easily integrated or implemented with existing smart infrastructure such as smartphone and laptop cameras [27], rear vehicle cameras, and security cameras [134], allowing for ubiquitous coverage in both indoor and outdoor scenarios [27]. Secondly, OCC uses non-interference communication, which means that when using image sensors as a receiver, lights from different sources are almost perfectly separated on a focal plane due to the large number of pixels in image sensor [129]. As a result, OCC can mitigate interference caused by light coming from different sources and directions. This is made possible by advanced lenses used in portable cameras that can display lights from different sources and separate different signals, which can then be sampled using different pixels [27]. Lastly, One more advantage of OCC is its ability to provide interference-free communication and a high Signal-to-Noise Ratio (SNR), even in outdoor environments [129].

Despite its advantages, OCC has some limitations. For instance, the data rate is relatively low due to the limited sampling rate at the receiver, and random blockages can occur [134]. Moreover, the OCC system faces synchronization challenges related to the limited pulse rates of LEDs within the camera’s frame [27]. Additionally, since the optical channel is LoS, any object that obstructs light penetration [27], such as walls, buildings, thick fog, or gas, can block the OCC communication links [129].

b: Standardization of OCC

The development of camera-based optical communication was greatly stimulated by the release of the IEEE 802.15.7:2011 standard for short-range visible light communication. This led to the formation of a task group (TG7m) in 2014 to revise the standard, which is known as the IEEE 802.15.7m standard, specifically for camera-based optical communication [149]. TG7m has been working on specifying the technical requirements of OCC, including the OCC transceivers, system architecture, and PHY and MAC layers [134].

c: OCC For Expected Use Cases of 6G

Based on the advantages of OCC, it is expected to have a wide range of applications in 6G, including V2X communication, AR/VR, drone-to-drone communication [27], and digital signage [129]. Another potential use case for OCC in 6G is in the area of localization (positioning) for indoor environments such as shopping malls and large supermarkets [27].

4) Free-Space Optics Communication -FSO

FSO is a wireless communication system that has gained significant interest and development in recent years [150]. FSO technology uses various segments of the electromagnetic spectrum, including near- infrared (NIR), VL, and UV bands, to serve as the communication medium [27], [129]. FSO systems commonly use LDs to transmit data at high data rates [148]. However, some manufacturers employ high power LEDs with beam collimators [151]. The LD transmitter generates a highly focused and coherent laser beam that enables long-distance data transmission [131], allowing for the establishment of high-data-rate communication links between a transmitter and a receiver [129]. FSO technology provides benefits such as high bandwidth and long transmission distances at high data rates [148]. These features make it suitable for high-speed and high bandwidth applications such as wireless backhaul broadband connectivity. Moreover, it is also considered as a promising solution for meeting the massive traffic demands of 6G systems [27]. FSO links offer a significantly higher optical bandwidth compared to RF links, which allows for much higher data rates [151]. Furthermore, FSO can be integrated with existing RF wireless networks to create heterogeneous networks that combine both optical and RF domains, resulting in enhanced capacity and coverage [27]. This integration can be achieved through hybrid FSO, Radio over FSO (RoFSO), and MIMO FSO, which can support the ultra-high-speed demands of 5G/B5G by overcoming the limitations of single technologies [130].

a: FSO Features and Limitations

FSO technology offers several key benefits over other connectivity and backhaul technologies. It is easy to deploy and provides high bit rates with low bit error rates. FSO also enables full duplex transmission, allows independent protocol, and does not require a license [152]. Additionally, FSO systems offer several other advantages, such as the ability to use high-frequency reuse factors, secure communication, immunity against electromagnetic interference, and reduced power consumption [27].

FSO communications have the potential for high-speed data transmission, but their effectiveness can be limited by various factors that negatively impact performance, including absorption, scattering, and turbulence within the atmospheric channel [153], [154], [155]. Of all the challenges faced by FSO communications, atmospheric turbulence is the most significant challenge faced by FSO communication as it can cause severe degradation in the bit error rate performance of the system, making the communication link unfeasible [153]. The amplitude and phase of the FSO signal can experience random fluctuations due to atmospheric turbulence, which is called channel fading. Such fluctuations can cause a decrease in signal quality, an increase in errors, and a reduction in link reliability [148]. Adverse outdoor weather conditions, such as heavy rain, fog, smoke, storms, deep clouds, and snow, can significantly degrade the performance of FSO links, leading to unreliable and unpredictable communication [27], [156]. FSO communications can also be affected by misalignment and geometric losses, which can lead to reduced signal power and degraded communication [157]. Misalignment losses may occur due to building sway or other factors that cause inadequate alignment between the transceivers [154]. On the other hand, geometric losses occur as a result of the light energy being spreading over a larger area as it travels through the atmosphere, which leads to a decrease in the power received by the receiver [155]. Therefore, it is important to address and mitigate these factors to ensure the efficient and reliable performance of FSO communication systems.

b: Standardization of FSO

In light of the potential deployment of FSO in mobile networks, there is a growing demand for simple and widely accepted channel models. However, standardization efforts in the context of FSO have been limited [158]. The Infrared Data Association (IrDA) group has developed a series of standards specifically for high-speed data transmission and short-distances FSO links [159]. These standards are targeted to connect handheld mobile devices with fixed stations or other mobile devices using short-range, low-cost, line-of-sight, point-to-point FSO links [160]. More specifically, IrDA has defined six standards for the IR physical layer, including Serial Infrared (SIR), with data rates ranging from (2.4 to 115.2) kbps, Medium Infrared (MIR) with data rates ranging from (0.576 to 1.152) Mbps, Fast Infrared (FIR) supporting 4 Mbps, Very Fast Infrared (VFIR) supporting 16 Mbps, Ultra Fast Infrared (UFIR) supporting 96 Mbps, and Gigabit Infrared (Giga-IR) supporting 512 Mbps and 1.024 Gbps [161], [162]. In contrast, JEITA CP-1221, CP-1222, CP-1223, IEEE 802.15.7, and IEEE 802.15.7r1, are designed for short-to-medium range VLC that support low-data rate links [159]. In particular, the technical specifications established by IrDA, IEEE (802.11 and 802.15.7), and JEITA are primarily intended to cater OWC links that are deployed indoors, whereas, the ITU is mainly concerned with developing standards and guidelines for terrestrial OWC links [158]. This includes propagation prediction techniques for designing terrestrial FSO links that operate in VL and IR regions of the spectrum (ITU-R P.1814-0 and ITU-R P.1817-1) [158]. Furthermore, ITU is also involved in developing guidelines for planning fixed-service terrestrial FSO links [159]. However, the ITU-R P.1817-1 (2012) guidelines, which are entitled "Propagation data required for the design of terrestrial free-space optical links", provide only general recommendations and has not been updated recently [158].

c: FSO For Expected Use Cases of 6G

FSO systems have a various applications including backhaul for cellular networks, last mile access, and disaster recovery [129], [130], [153]. It also finds its applications in video surveillance, broadcasting, and underwater communication [27], [129], [130]. FSO systems has a wide range of applications across various networks, including aerial, optical, and terrestrial, and has been employed in applications such as ground-to-satellite, satellite-to-ground, satellite-to-airplane, airplane-to-airplane, satellite-to-satellite, satellite-to-UAVs, satellite-to-balloons, and satellite-to-ship connectivity [27], [129], [130]. FSO systems also have potential applications in inter-chip connectivity, as well as providing connectivity between different types of networks, such as MAN-to-MAN, LAN-to-LAN , ship-to-ship communication [129].

In Table 7, a comparison is made between mmWave, THz, and optical spectrum in terms of their frequency ranges, available bandwidths, features, limitations, regulations, and areas of application in the context of 6G technology.

D. Future Research Directions and Standardization

Future research directions in mmWave, THz, and OWC aim to tackle crucial challenges and explore opportunities for advancing these technologies, with the ultimate goal of enabling their effective deployment in 6G wireless communication systems. These research efforts seek to enhance the performance, reliability, and efficiency of mmWave, THz, andOWC technologies, aligning them with the requirements and objectives of the future 6G networks. The following

TABLE 7. **Comparison of mmWave, THz, and Optical Spectrum in terms of Frequency Ranges, Features, Limitations, and Application Areas [77], [88], [129], [163].**

Issue	mmWave	THz	Optical Bands
Frequency Range	30 - 300 GHz	300 GHz - 10 THz	IR 3 - 430 THz VL 430 - 790 THz UV 790 THz - 30 PHz
Wavelength	10 - 1 mm	3 mm - 0.03 mm	IR 0.03 mm - 690 nm VL 690 nm - 380 nm UV 380 nm - 10 nm
Bandwidth	MHz to several GHz	10 GHz- 100 GHz	MHz to several GHz
Spectrum Regulatory	Licensed	Licensed	Unlicensed
Advantages	Wide bandwidth Small element size Narrow directional beam	Extremely wide bandwidth; enable communication rate exceeding Tb/s Suitable for Mssive-MIMO	Wide available spectrum High Security
Limitations	High free-space path loss Atmosheric gaseous absorption Blockage & Technical Challenges; Design circuit components and antennas	Path loss Atmosheric gaseous absorption Strong atmosheric attenuation Blockage & Technical\Engineering Challenges; Design circuit components and antennas	Small coverage area Mobility support is no guaranteed Performance is affected by environment conditions Very limited NLOS communications.
Applications Area in 6G	Wireless backhual, Wearable devices, AR/VR Imaging & Tracking	Holographic Teleportation, Digital Twin, Connected Robotics & Autonomous systems (CRAS); (include autonomous driving, atounomous drone swarms, Vehicle platoons), XR services, Industry 4.0, NTNs.	Smart buildings, smart factories, smart transportation, and hospitals, V2V, V2I communications, Backhaul for cellular networks, Remote sensing and track position and movements underwater communication

are few illustrative examples of future research directions in these domains:

- mmWave-Massive MIMO Optimization: The combination of massive MIMO and mmWave communication offers advantages in terms of improved spectral and energy efficiency, increased capacity, and multiplexing gains. However, there are challenges in optimizing precoding and beamforming, managing complexity and hardware limitations, and balancing performance trade-offs. Overcoming these challenges is necessary to make mmWave-massive MIMO a practical solution in 5G and future networks [164].
- THz Antenna Design: Address challenges in THz band antenna design, fabrication, and measurement to meet the specific requirements of the 6G wireless communication system. This involves developing compact and efficient antennas that can operate at THz frequencies, considering factors such as high path loss and atmospheric absorption [165].
- THz Channel Modeling: Focus on developing complete and flexible THz channel models that accurately capture the unique propagation characteristics of THz waves. This includes factors like atmospheric absorption, scattering, and molecular absorption. Accurate channel models will aid in the design and optimization of THz communication systems [166].
- Comprehensive VLC Channel Models: Further study and develop comprehensive theoretical channel models for VLC that accurately capture the influential factors in both free-space and underwater transmission. Existing models may not fully cover all the complexities of real-world channels, so research in this area is crucial for improving system performance and reliability [167].
- Standardization of FSO Channel Models: Lack of standardization efforts in channel models for FSO communication highlights the need for immediate attention. By addressing this limitation and conducting future research and standardization efforts, it will be possible to establish standardized channel models. These models will provide a common framework for evaluating and comparing FSO system performance, enabling the optimization and interoperability of FSO technologies. Consequently, this will address the current challenges and pave the way for the development of more efficient and reliable wireless communication systems in 6G networks.

Regarding future standardization directions, there are ongoing efforts in standardization. For instance, 3GPP is currently progressing towards the second phase of 5G standardization, referred to as 5G-Advanced. This phase builds upon the foundation established in 3GPP Releases 15, 16, and 17, with the aim of expanding and extending the capabilities and use cases of 5G. Release 18, expected to be available in early 2024, will mark the beginning of 5G-Advanced, followed by subsequent releases including Release 19 and beyond [168]. The upcoming WRC-23, scheduled from 20 November to 15 December 2023, will address several agenda items (1.1, 1.2, 1.3, and 1.5) pertaining to 5G and future spectrum allocation [169], [170]. These agenda items hold significant importance within the framework of WRC-23 as they focus on the allocation and utilization of spectrum for IMT services. Discussions will cover specific frequency bands, including the 4,800-4,990 MHz band, the 3.5 GHz and 6 GHz ranges, as well as the mobile allocation in the 3,600-3,800 MHz band in Region 1. Furthermore, agenda item 1.5 will specifically address the consideration of sub-1 GHz spectrum in Region 1. Looking ahead, the agenda for the subsequent conference, WRC-27, will be shaped based on the outcomes and discussions at WRC-23. Depending on the decisions made during WRC-23 and taking into account the evolving needs and advancements in radiocommunications, additional items may be added to the final agenda for WRC-27.

V. CONCLUSION

Our study highlights the spectrum options for 6G, the importance of addressing technical challenges, promoting technology development, embracing spectrum sharing, and adapting policies and regulations. The key findings can be summarized as follows:

- Spectrum Options: Higher frequency bands such as mmWave, THz, and OW spectra offer potential spectrum options for 6G, enabling faster data rates and higher capacity. However, challenges related to path loss and hardware costs need to be addressed for effective adoption.
- Technology Development: While THz systems hold promise, further research and development are required. More mature technologies like mmWave and OWC (e.g., VLC and FSO) are likely to play a significant role in enabling 6G networks.
- Spectrum Management Paradigm Shift: The deployment of 6G will require a paradigm shift in spectrum management. Spectrum sharing will become increasingly crucial to efficiently utilize limited resources in the context of higher frequency bands and localized service areas.
- Policy Implications: Policymakers and regulators must reevaluate current spectrum management policies to align with the unique requirements of 6G. Developing new spectrum assignment models that accommodate flexible deployment and define access rights will be essential.

These findings provide valuable insights for the successful deployment and utilization of 6G networks.

REFERENCES

[1] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133 995–134 030, 2020.

[2] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE network*, vol. 34, no. 3, pp. 134–142, 2019.

[3] C. De Alwis, A. Kalla, Q.-V. Pham, P. Kumar, K. Dev, W.-J. Hwang, and M. Liyanage, "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 836–886, 2021.

[4] Y. Wu, S. Singh, T. Taleb, A. Roy, H. S. Dhillon, M. R. Kanagarathinam, and A. De, *6G mobile wireless networks*. Springer, 2021.

[5] H. Ahmadi, A. Nag, Z. Khar, K. Sayrafian, and S. Rahardja, "Networked twins and twins of networks: An overview on the relationship between digital twins and 6G," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 154–160, 2021.

[6] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 957–975, 2020.

[7] F. Tariq, M. R. Khandaker, K.-K. Wong, M. A. Imran, M. Bennis, and M. Debbah, "A speculative study on 6G," *IEEE Wireless Communications*, vol. 27, no. 4, pp. 118–125, 2020.

[8] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334–366, 2021.

[9] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang, "6G technologies: Key drivers, core requirements, system architectures, and enabling technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 18–27, 2019.

[10] S. Zhang, C. Xiang, and S. Xu, "6G: Connecting everything by 1000 times price reduction," *IEEE Open Journal of Vehicular Technology*, vol. 1, pp. 107–115, 2020.

[11] H. H. H. Mahmoud, A. A. Amer, and T. Ismail, "6G: A comprehensive survey on technologies, applications, challenges, and research problems," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 4, p. e4233, 2021.

[12] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J. A. Zhang, "The roadmap to 6G: AI empowered wireless networks," *IEEE communications magazine*, vol. 57, no. 8, pp. 84–90, 2019.

[13] K. B. Letaief, Y. Shi, J. Lu, and J. Lu, "Edge artificial intelligence for 6G: Vision, enabling technologies, and applications," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 1, pp. 5–36, 2021.

[14] M. Banafaa, I. Shayea, J. Din, M. H. Azmi, A. Alashbi, Y. I. Daradkeh, and A. Alhammadi, "6G mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities," *Alexandria Engineering Journal*, 2022.

[15] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 28–41, 2019.

[16] G. Gür, "Expansive networks: Exploiting spectrum sharing for capacity boost and 6G vision," *Journal of Communications and Networks*, vol. 22, no. 6, pp. 444–454, 2020.

[17] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Toward 6G networks: Use cases and technologies," *IEEE Communications Magazine*, vol. 58, no. 3, pp. 55–61, 2020.

[18] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wireless Communications*, vol. 27, no. 2, pp. 218–228, 2020.

[19] H. Kour, R. K. Jha, and S. Jain, "A comprehensive survey on spectrum sharing: Architecture, energy efficiency and security issues," *Journal of Network and Computer Applications*, vol. 103, pp. 29–57, 2018.

[20] A. J. Morgado, F. B. Saghezchi, S. Mumtaz, V. Frascolla, J. Rodriguez, and I. Otung, "A novel machine learning-based scheme for spectrum sharing in virtualized 5G networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 10, pp. 19 691–19 703, 2022.

[21] G. K. Papageorgiou, K. Voulgaris, K. Ntougias, D. K. Ntaikos, M. M. Butt, C. Galiotto, N. Marchetti, V. Frascolla, H. Annouar, A. Gomes *et al.*, "Advanced dynamic spectrum 5g mobile networks employing licensed shared access," *IEEE Communications Magazine*, vol. 58, no. 7, pp. 21–27, 2020.

[22] W. Lehr, F. Queder, and J. Haucap, "5G: A new future for mobile network operators, or not?" *Telecommunications Policy*, vol. 45, no. 3, p. 102086, 2021.

[23] M. Parvini, A. H. Zarif, A. Nouruzi, N. Mokari, M. R. Javan, B. Abbasi, A. Ghasemi, and H. Yanikomeroglu, "Spectrum sharing

schemes from 4G to 5G and beyond: Protocol flow, regulation, ecosystem, economic," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 464–517, 2023.

[24] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 ghz: Opportunities and challenges for 6g and beyond," *IEEE access*, vol. 7, pp. 78 729–78 757, 2019.

[25] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang, and D. Zhang, "A survey on green 6g network: Architecture and technologies," *IEEE access*, vol. 7, pp. 175 758–175 768, 2019.

[26] L. Bariah, L. Mohjazi, S. Muhaidat, P. C. Sofotasios, G. K. Kurt, H. Yanikomeroglu, and O. A. Dobre, "A prospective look: Key enabling technologies, applications and open research topics in 6G networks," *IEEE access*, vol. 8, pp. 174 792–174 820, 2020.

[27] M. Alsabah, M. A. Naser, B. M. Mahmmod, S. H. Abdulhussain, M. R. Eissa, A. Al-Baidhani, N. K. Noordin, S. M. Sait, K. A. Al-Utaibi, and F. Hashim, "6G wireless communications networks: A comprehensive survey," *IEEE Access*, vol. 9, pp. 148 191–148 243, 2021.

[28] X. You, C.-X. Wang, J. Huang, X. Gao, Z. Zhang, M. Wang, Y. Huang, C. Zhang, Y. Jiang, J. Wang *et al.*, "Towards 6g wireless communication networks: Vision, enabling technologies, and new paradigm shifts," *Science China Information Sciences*, vol. 64, pp. 1–74, 2021.

[29] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, "6g wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166–1199, 2021.

[30] ITU, Study Group 1 (SG 1). Spectrum management. [Online]. Available: https://www.itu.int/en/ITU-R/study-groups/rsg1/Pages/default.aspx

[31] F. Beltrán, "Accelerating the introduction of spectrum sharing using market-based mechanisms," *IEEE Communications Standards Magazine*, vol. 1, no. 3, pp. 66–72, 2017.

[32] M. Matinmikko-Blue, S. Yrjölä, and P. Ahokangas, "Spectrum management in the 6G era: The role of regulation and spectrum sharing," in *2020 2nd 6G Wireless Summit (6G SUMMIT)*. IEEE, 2020, pp. 1–5.

[33] M. Matinmikko-Blue, "Sustainability and spectrum management in the 6G era," in *2021 ITU Kaleidoscope: Connecting Physical and Virtual Worlds (ITU K)*. IEEE, 2021, pp. 1–9.

[34] A. Kuś and M. Massaro, "Analysing the C-band spectrum auctions for 5G in europe: Achieving efficiency and fair decisions in radio spectrum management," *Telecommunications Policy*, vol. 46, no. 4, p. 102286, 2022.

[35] M. Matinmikko-Blue, S. Yrjölä, V. Seppänen, P. Ahokangas, H. Hämmäinen, and M. Latva-Aho, "Analysis of spectrum valuation elements for local 5g networks: Case study of 3.5-GHz band," *IEEE Transactions on Cognitive Communications and Networking*, vol. 5, no. 3, pp. 741–753, 2019.

[36] A. Ponomarenko-Timofeev, A. Pyattaev, S. Andreev, Y. Koucheryavy, M. Mueck, and I. Karls, "Highly dynamic spectrum management within licensed shared access regulatory framework," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 100–109, 2016.

[37] M. Massaro, "Next generation of radio spectrum management: Licensed shared access for 5G," *Telecommunications Policy*, vol. 41, no. 5-6, pp. 422–433, 2017.

[38] A. Chandra, "Spectrum management for future generation wireless based technology," in *2009 European Wireless Technology Conference*. IEEE, 2009, pp. 201–205.

[39] H. Ahmadi, I. Macaluso, I. Gomez, L. DaSilva, and L. Doyle, "Virtualization of spatial streams for enhanced spectrum sharing," in *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1–6.

[40] J. Hwang and H. Yoon, "A mixed spectrum management framework for the future wireless service based on techno-economic analysis: The korean spectrum policy study," *Telecommunications Policy*, vol. 33, no. 8, pp. 407–421, 2009.

[41] H. Ahmadi, I. Macaluso, I. Gomez, L. Doyle, and L. A. DaSilva, "Substitutability of spectrum and cloud-based antennas in virtualized wireless networks," *IEEE Wireless Communications*, vol. 24, no. 2, pp. 114–120, 2017.

[42] R. Jain, "Spectrum auctions in india: lessons from experience," *Telecommunications Policy*, vol. 25, no. 10-11, pp. 671–688, 2001.

[43] M. Park, S.-W. Lee, and Y.-J. Choi, "Does spectrum auctioning harm consumers? lessons from 3G licensing," *Information Economics and Policy*, vol. 23, no. 1, pp. 118–126, 2011.

[44] "Learning solutions for auction-based dynamic spectrum access in multicarrier systems," *Computer Networks*, vol. 67, pp. 60–73, 2014.

[45] H. Vuojala, M. Mustonen, X. Chen, K. Kujanpää, P. Ruuska, M. Höyhtyä, M. Matinmikko-Blue, J. Kalliovaara, P. Talmola, and A.-G. Nyström, "Spectrum access options for vertical network service providers in 5G," *Telecommunications Policy*, vol. 44, no. 4, p. 101903, 2020.

[46] A. Kliks, O. Holland, A. Basaure, and M. Matinmikko, "Spectrum and license flexibility for 5G networks," *IEEE Communications Magazine*, vol. 53, no. 7, pp. 42–49, 2015.

[47] J. Khun-Jush, P. Bender, B. Deschamps, and M. Gundlach, "Licensed shared access as complementary approach to meet spectrum demands: Benefits for next generation cellular systems," in *ETSI Workshop on reconfigurable radio systems*, 2012.

[48] J. Jeon, "NR wide bandwidth operations," *IEEE Communications Magazine*, vol. 56, no. 3, pp. 42–46, 2018.

[49] F. Beltran, S. K. Ray, and J. A. Gutiérrez, "Understanding the current operation and future roles of wireless networks: Co-existence, competition and co-operation in the unlicensed spectrum bands," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 11, pp. 2829–2837, 2016.

[50] R. Dilli, "Analysis of 5G wireless systems in FR1 and FR2 frequency bands," in *2020 2nd International Conference on Innovative Mechanisms for Industry Applications (ICIMIA)*. IEEE, 2020, pp. 767–772.

[51] S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojović, A. Demir, and M. Beluri, "New radio beam-based access to unlicensed spectrum: Design challenges and solutions," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 8–37, 2019.

[52] A. M. Voicu, L. Simić, and M. Petrova, "Survey of spectrum sharing for inter-technology coexistence," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1112–1144, 2018.

[53] F. A. De Figueiredo, X. Jiao, W. Liu, R. Mennes, I. Jabandzić, and I. Moerman, "A spectrum sharing framework for intelligent next generation wireless networks," *IEEE Access*, vol. 6, pp. 60 704–60 735, 2018.

[54] P. Wang, B. Di, and L. Song, "Cellular communications over unlicensed mmwave bands with hybrid beamforming," *IEEE Transactions on Wireless Communications*, vol. 21, no. 8, pp. 6064–6078, 2022.

[55] L. Zhang, M. Xiao, G. Wu, M. Alam, Y.-C. Liang, and S. Li, "A survey of advanced techniques for spectrum sharing in 5G networks," *IEEE Wireless Communications*, vol. 24, no. 5, pp. 44–51, 2017.

[56] L. Zhang, Y.-C. Liang, and M. Xiao, "Spectrum sharing for internet of things: A survey," *IEEE Wireless Communications*, vol. 26, no. 3, pp. 132–139, 2018.

[57] M. Massaro and F. Beltrán, "Will 5G lead to more spectrum sharing? discussing recent developments of the LSA and the CBRS spectrum sharing frameworks," *Telecommunications Policy*, vol. 44, no. 7, p. 101973, 2020.

[58] A. Medeisis and V. V. Fomin, "Radio spectrum management as a system of innovation: LSA case study," in *2022 IEEE Open Conference of Electrical, Electronic and Information Sciences (eStream)*. IEEE, 2022, pp. 1–6.

[59] M. Matinmikko, H. Okkonen, M. Palola, S. Yrjola, P. Ahokangas, and M. Mustonen, "Spectrum sharing using licensed shared access: the concept and its workflow for lte-advanced networks," *IEEE Wireless Communications*, vol. 21, no. 2, pp. 72–79, 2014.

[60] C. Sexton, N. J. Kaminski, J. M. Marquez-Barja, N. Marchetti, and L. A. DaSilva, "5g: Adaptable networks enabled by versatile radio access technologies," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 688–720, 2017.

[61] S. Bhattarai, J.-M. J. Park, B. Gao, K. Bian, and W. Lehr, "An overview of dynamic spectrum sharing: Ongoing initiatives, challenges, and a roadmap for future research," *IEEE Transactions on Cognitive Communications and Networking*, vol. 2, no. 2, pp. 110–128, 2016.

[62] M. Mustonen, M. Matinmikko, O. Holland, and D. Roberson, "Process model for recent spectrum sharing concepts in policy making," *Telecommunications Policy*, vol. 41, no. 5-6, pp. 391–404, 2017.

[63] V. Frascolla, A. J. Morgado, A. Gomes, M. M. Butt, N. Marchetti, K. Voulgaris, and C. B. Papadias, "Dynamic licensed shared access-a new architecture and spectrum allocation techniques," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*. IEEE, 2016, pp. 1–5.

[64] S. K. Sharma, T. E. Bogale, L. B. Le, S. Chatzinotas, X. Wang, and B. Ottersten, "Dynamic spectrum sharing in 5g wireless networks with full-duplex technology: Recent advances and research challenges," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 674–707, 2017.

[65] M. Mustonen, M. Matinmikko, M. Palola, S. Yrjölä, J. Paavola, A. Kivinen, and J. Engelberg, "Considerations on the licensed shared access (LSA) architecture from the incumbent perspective," in *2014 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*. IEEE, 2014, pp. 150–155.

[66] M. Parvini, A. H. Zarif, A. Nouruzi, N. Mokari, M. R. Javan, B. Abbasi, A. Ghasemi, and H. Yanikomeroglu, "A comprehensive survey of spectrum sharing schemes from a standardization and implementation perspective," *arXiv preprint arXiv:2203.11125*, 2022.

[67] M. Matinmikko, M. Latva-aho, P. Ahokangas, and V. Seppänen, "On regulations for 5G: Micro licensing for locally operated networks," *Telecommunications Policy*, vol. 42, no. 8, pp. 622–635, 2018.

[68] R. K. Saha, "Approaches to improve millimeter-wave spectrum utilization using indoor small cells in multi-operator environments toward 6G," *IEEE Access*, vol. 8, pp. 207 643–207 658, 2020.

[69] W. Chen, J. Montojo, J. Lee, M. Shafi, and Y. Kim, "The standardization of 5G-advanced in 3GPP," *IEEE Communications Magazine*, 2022.

[70] J. Pérez-Romero, O. Sallent, H. Ahmadi, and I. Macaluso, "On modeling channel selection in lte-u as a repeated game," in *2016 IEEE Wireless Communications and Networking Conference*, 2016, pp. 1–6.

[71] R. H. Tehrani, S. Vahid, D. Triantafyllopoulou, H. Lee, and K. Moessner, "Licensed spectrum sharing schemes for mobile operators: A survey and outlook," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2591–2623, 2016.

[72] A. Medeisis, V. Fomin, and W. Webb, "Untangling the paradox of licensed shared access: Need for regulatory refocus," *Telecommunications Policy*, p. 102380, 2022.

[73] P. Yang, L. Kong, and G. Chen, "Spectrum sharing for 5g/6g urllc: Research frontiers and standards," *IEEE communications standards magazine*, vol. 5, no. 2, pp. 120–125, 2021.

[74] E. D. Pascale, H. Ahmadi, L. Doyle, and I. Macaluso, "Toward scalable user-deployed ultra-dense networks: Blockchain-enabled small cells as a service," *IEEE Communications Magazine*, vol. 58, no. 8, pp. 82–88, 2020.

[75] V. Haghighatdoost, S. Khorsandi, and H. Ahmadi, "Fair pricing in heterogeneous internet-of-things wireless access networks using crowdsourcing," *IEEE Internet of Things Journal*, vol. 8, no. 7, pp. 5710–5721, 2021.

[76] H. Viswanathan and P. E. Mogensen, "Communications in the 6G era," *IEEE Access*, vol. 8, pp. 57 063–57 074, 2020.

[77] S. Iyer, A. Patil, S. Bhairanatti, S. Halagatti, and R. J. Pandya, "A survey on technological trends to enhance spectrum-efficiency in 6G communications," *Transactions of the Indian National Academy of Engineering*, pp. 1–28, 2022.

[78] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE network*, vol. 33, no. 4, pp. 70–75, 2019.

[79] A. Slalmi, H. Chaibi, A. Chehri, R. Saadane, and G. Jeon, "Toward 6G: Understanding network requirements and key performance indicators," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 3, p. e4201, 2021.

[80] L. Zhu, Z. Xiao, X.-G. Xia, and D. O. Wu, "Millimeter-wave communications with non-orthogonal multiple access for b5g/6G," *IEEE Access*, vol. 7, pp. 116 123–116 132, 2019.

[81] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5g: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE journal on selected areas in communications*, vol. 35, no. 6, pp. 1201–1221, 2017.

[82] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Key elements to enable millimeter wave communications for 5G wireless systems," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 136–143, 2014.

[83] N. Al-Falahy and O. Y. Alani, "Millimetre wave frequency band as a candidate spectrum for 5G network architecture: A survey," *Physical Communication*, vol. 32, pp. 120–144, 2019.

[84] S. He, Y. Zhang, J. Wang, J. Zhang, J. Ren, Y. Zhang, W. Zhuang, and X. Shen, "A survey of millimeter-wave communication: Physical-layer technology specifications and enabling transmission technologies," *Proceedings of the IEEE*, vol. 109, no. 10, pp. 1666–1705, 2021.

[85] A. Morgado, K. M. S. Huq, S. Mumtaz, and J. Rodriguez, "A survey of 5G technologies: regulatory, standardization and industrial perspectives," *Digital Communications and Networks*, vol. 4, no. 2, pp. 87–97, 2018.

[86] J. Lee, E. Tejedor, K. Ranta-aho, H. Wang, K.-T. Lee, E. Semaan, E. Mohyeldin, J. Song, C. Bergljung, and S. Jung, "Spectrum for 5G: Global status, challenges, and enabling technologies," *IEEE Communications Magazine*, vol. 56, no. 3, pp. 12–18, 2018.

[87] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Björnson, K. Yang, I. Chih-Lin *et al.*, "Millimeter wave communications for future mobile networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1909–1935, 2017.

[88] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, vol. 8, pp. 62 367–62 414, 2020.

[89] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, "Millimeter wave communication: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 1616–1653, 2018.

[90] W. Jiang and H. D. Schotten, "Initial beamforming for millimeter-wave and terahertz communications in 6G mobile systems," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2022, pp. 2613–2618.

[91] R. Hasan, M. M. Mowla, M. A. Rashid, M. K. Hosain, and I. Ahmad, "A statistical analysis of channel modeling for 5G mmwave communications," in *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*. IEEE, 2019, pp. 1–6.

[92] M. Giordani, M. Polese, A. Roy, D. Castor, and M. Zorzi, "Standalone and non-standalone beam management for 3GPP NR at mmWaves," *IEEE Communications Magazine*, vol. 57, no. 4, pp. 123–129, 2019.

[93] W. Attaoui, K. Bouraqia, and E. Sabir, "Initial access & beam alignment for mmwave and terahertz communications," *IEEE Access*, vol. 10, pp. 35 363–35 397, 2022.

[94] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," *Wireless networks*, vol. 21, no. 8, pp. 2657–2676, 2015.

[95] W. Hong, Z. H. Jiang, C. Yu, D. Hou, H. Wang, C. Guo, Y. Hu, L. Kuai, Y. Yu, Z. Jiang *et al.*, "The role of millimeter-wave technologies in 5G/6G wireless communications," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 101–122, 2021.

[96] Y.-N. R. Li, B. Gao, X. Zhang, and K. Huang, "Beam management in millimeter-wave communications for 5G and beyond," *IEEE Access*, vol. 8, pp. 13 282–13 293, 2020.

[97] N. Patriciello, S. Lagén, B. Bojović, and L. Giupponi, "NR-U and ieee 802.11 technologies coexistence in unlicensed mmwave spectrum: Models and evaluation," *IEEE access*, vol. 8, pp. 71 254–71 271, 2020.

[98] D. Moltchanov, E. Sopin, V. Begishev, A. Samuylov, Y. Koucheryavy, and K. Samouylov, "A tutorial on mathematical modeling of 5G/6G millimeter wave and terahertz cellular systems," *IEEE Communications Surveys & Tutorials*, 2022.

[99] Y. Kim, Y. Kim, J. Oh, H. Ji, J. Yeo, S. Choi, H. Ryu, H. Noh, T. Kim, F. Sun *et al.*, "New radio (nr) and its evolution toward 5G-advanced," *IEEE Wireless Communications*, vol. 26, no. 3, pp. 2–7, 2019.

[100] H.-G. Song, K. Park, J.-Y. Park, T.-H. Kwon, J.-S. Seo, and S.-W. Jeon, "5G NR performance evaluation under phase noise distortion for 52.6 ghz to 71 ghz," in *2021 International Conference on*

Information and Communication Technology Convergence (ICTC). IEEE, 2021, pp. 607–610.

[101] X. Lin, "An overview of 5G advanced evolution in 3gpp release 18," *IEEE Communications Standards Magazine*, vol. 6, no. 3, pp. 77–83, 2022.

[102] M. Hirzallah, M. Krunz, B. Kecicioglu, and B. Hamzeh, "5G new radio unlicensed: Challenges and evaluation," *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 3, pp. 689–701, 2020.

[103] R. K. Saha, "Coexistence of cellular and IEEE 802.11 technologies in unlicensed spectrum bands-a survey," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1996–2028, 2021.

[104] S. Tripathi, N. V. Sabu, A. K. Gupta, and H. S. Dhillon, "Millimeter-wave and terahertz spectrum for 6G wireless," in *6G Mobile Wireless Networks*. Springer, 2021, pp. 83–121.

[105] C. Seker, M. T. Güneser, and T. Ozturk, "A review of millimeter wave communication for 5G," in *2018 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*. Ieee, 2018, pp. 1–5.

[106] T. Sharma, A. Chehri, and P. Fortier, "Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 3, p. e4155, 2021.

[107] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, "Overview of millimeter wave communications for fifth-generation (5G) wireless networks—with a focus on propagation models," *IEEE Transactions on antennas and propagation*, vol. 65, no. 12, pp. 6213–6230, 2017.

[108] I. Rasheed, F. Hu, Y.-K. Hong, and B. Balasubramanian, "Intelligent vehicle network routing with adaptive 3D beam alignment for mmwave 5G-based V2X communications," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 5, pp. 2706–2718, 2020.

[109] R. W. Heath, N. Gonzalez-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An overview of signal processing techniques for millimeter wave MIMO systems," *IEEE journal of selected topics in signal processing*, vol. 10, no. 3, pp. 436–453, 2016.

[110] A. Y. Pawar, D. D. Sonawane, K. B. Erande, and D. V. Derle, "Terahertz technology and its applications," *Drug invention today*, vol. 5, no. 2, pp. 157–163, 2013.

[111] Z. Qadir, K. N. Le, N. Saeed, and H. S. Munawar, "Towards 6G internet of things: Recent advances, use cases, and open challenges," *ICT Express*, 2022.

[112] I. F. Akyildiz, J. M. Jornet, and C. Han, "Teranets: Ultra-broadband communication networks in the terahertz band," *IEEE Wireless Communications*, vol. 21, no. 4, pp. 130–135, 2014.

[113] C. Chaccour, M. N. Soorki, W. Saad, M. Bennis, P. Popovski, and M. Debbah, "Seven defining features of terahertz (THz) wireless systems: A fellowship of communication and sensing," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 967–993, 2022.

[114] I. F. Akyildiz, C. Han, Z. Hu, S. Nie, and J. M. Jornet, "Terahertz band communication: An old problem revisited and research directions for the next decade," *IEEE Transactions on Communications*, 2022.

[115] K. M. S. Huq, S. A. Busari, J. Rodriguez, V. Frascolla, W. Bazzi, and D. C. Sicker, "Terahertz-enabled wireless system for beyond-5G ultra-fast networks: A brief survey," *IEEE network*, vol. 33, no. 4, pp. 89–95, 2019.

[116] V. Petrov, T. Kurner, and I. Hosako, "IEEE 802.15. 3d: First standardization efforts for sub-terahertz band communications toward 6G," *IEEE Communications Magazine*, vol. 58, no. 11, pp. 28–33, 2020.

[117] L. Zhang, X. Pang, S. Jia, S. Wang, and X. Yu, "Beyond 100 Gb/s optoelectronic terahertz communications: Key technologies and directions," *IEEE Communications Magazine*, vol. 58, no. 11, pp. 34–40, 2020.

[118] T. Kürner and A. Hirata, "On the impact of the results of WRC 2019 on THz communications," in *2020 Third International Workshop on Mobile Terahertz Systems (IWMTS)*. IEEE, 2020, pp. 1–3.

[119] B. Ji, Y. Han, S. Liu, F. Tao, G. Zhang, Z. Fu, and C. Li, "Several key technologies for 6G: challenges and opportunities," *IEEE Communications Standards Magazine*, vol. 5, no. 2, pp. 44–51, 2021.

[120] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, W. Chen, L. Li, and S. Li, "A survey on terahertz communications," *China Communications*, vol. 16, no. 2, pp. 1–35, 2019.

[121] D. P. M. Osorio, I. Ahmad, J. D. V. Sánchez, A. Gurtov, J. Scholliers, M. Kutila, and P. Porambage, "Towards 6g-enabled internet of vehicles: Security and privacy," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 82–105, 2022.

[122] M. M. Azari, S. Solanki, S. Chatzinotas, and M. Bennis, "THz-empowered UAVs in 6G: Opportunities, challenges, and trade-offs," *IEEE Communications Magazine*, vol. 60, no. 5, pp. 24–30, 2022.

[123] Y. Lu and X. Zheng, "6G: A survey on technologies, scenarios, challenges, and the related issues," *Journal of Industrial Information Integration*, vol. 19, p. 100158, 2020.

[124] D. Serghiou, M. Khalily, T. W. Brown, and R. Tafazolli, "Terahertz channel propagation phenomena, measurement techniques and modeling for 6G wireless communication applications: a survey, open challenges and future research directions," *IEEE Communications Surveys & Tutorials*, 2022.

[125] A. Shahraki, M. Abbasi, M. Piran, A. Taherkordi *et al.*, "A comprehensive survey on 6G networks: Applications, core services, enabling technologies, and future challenges," *arXiv preprint arXiv:2101.12475*, 2021.

[126] S. Idris, U. Mohammed, J. Sanusi, and S. Thomas, "Visible light communication: A potential 5G and beyond communication technology," in *2019 15th International Conference on Electronics, Computer and Computation (ICECCO)*. IEEE, 2019, pp. 1–6.

[127] M. Xiong, Q. Liu, X. Wang, S. Zhou, B. Zhou, and Z. Bu, "Mobile optical communications using second harmonic of intra-cavity laser," *IEEE Transactions on Wireless Communications*, vol. 21, no. 5, pp. 3222–3231, 2021.

[128] A. E. Ibhaze, P. E. Orukpe, and F. O. Edeko, "High capacity data rate system: Review of visible light communications technology," *Journal of Electronic Science and Technology*, vol. 18, no. 3, p. 100055, 2020.

[129] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A comparative survey of optical wireless technologies: Architectures and applications," *ieee Access*, vol. 6, pp. 9819–9840, 2018.

[130] A. Jahid, M. H. Alsharif, and T. J. Hall, "A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction," *Journal of Network and Computer Applications*, p. 103311, 2022.

[131] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 2, pp. 930–966, 2020.

[132] M. Ndiaye, A. M. Saley, K. Niane, and A. Raimy, "Future 6G communication networks: Typical IoT network topology and terahertz frequency challenges and research issues," in *2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)*. IEEE, 2022, pp. 1–5.

[133] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "Led based indoor visible light communications: State of the art," *IEEE communications surveys & tutorials*, vol. 17, no. 3, pp. 1649–1678, 2015.

[134] N. Saeed, S. Guo, K.-H. Park, T. Y. Al-Naffouri, and M.-S. Alouini, "Optical camera communications: Survey, use cases, challenges, and future trends," *Physical Communication*, vol. 37, p. 100900, 2019.

[135] O. Ergul, E. Dinc, and O. B. Akan, "Communicate to illuminate: State-of-the-art and research challenges for visible light communications," *Physical Communication*, vol. 17, pp. 72–85, 2015.

[136] O. Alsulami, A. T. Hussein, M. T. Alresheedi, and J. M. Elmirghani, "Optical wireless communication systems, a survey," *arXiv preprint arXiv:1812.11544*, 2018.

[137] S. Vappangi and V. Mani, "A survey on the integration of visible light communication with power line communication: Conception, applications and research challenges," *Optik*, p. 169582, 2022.

[138] L. U. Khan, "Visible light communication: Applications, architecture, standardization and research challenges," *Digital Communications and Networks*, vol. 3, no. 2, pp. 78–88, 2017.

[139] A.-M. Cailean and M. Dimian, "Impact of IEEE 802.15. 7 standard on visible light communications usage in automotive applications," *IEEE Communications Magazine*, vol. 55, no. 4, pp. 169–175, 2017.

[140] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15. 7 visible light communication: modulation schemes and dimming support," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 72–82, 2012.

[141] P. Namonta and P. Cherntanomwong, "Real time vital sign transmission using IEEE 802.15. 7 VLC PHY-I transceiver," in *2017*

International Electrical Engineering Congress (iEECON). IEEE, 2017, pp. 1–4.

[142] H. Haas, "LiFi is a paradigm-shifting 5G technology," *Reviews in Physics*, vol. 3, pp. 26–31, 2018.

[143] M. Popadić and E. Kočan, "LiFi networks: Concept, standardization activities and perspectives," in *2021 25th International Conference on Information Technology (IT)*. IEEE, 2021, pp. 1–4.

[144] B. Béchadergue and B. Azoulay, "An industrial view on LiFi challenges and future," in *2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*. IEEE, 2020, pp. 1–6.

[145] E. Khorov and I. Levitsky, "Current status and challenges of Li-Fi: IEEE 802.11 bb," *IEEE Communications Standards Magazine*, vol. 6, no. 2, pp. 35–41, 2022.

[146] A. A. Purwita and H. Haas, "Studies of flatness of LiFi channel for IEEE 802.11 bb," in *2020 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2020, pp. 1–6.

[147] H. Haas and T. Cogalan, "LiFi opportunities and challenges," in *2019 16th International Symposium on Wireless Communication Systems (ISWCS)*. IEEE, 2019, pp. 361–366.

[148] S. A. H. Mohsan, A. Mazinani, H. B. Sadiq, and H. Amjad, "A survey of optical wireless technologies: Practical considerations, impairments, security issues and future research directions," *Optical and Quantum Electronics*, vol. 54, no. 3, p. 187, 2022.

[149] M. K. Hasan, M. O. Ali, M. H. Rahman, M. Z. Chowdhury, and Y. M. Jang, "Optical camera communication in vehicular applications: A review," *IEEE Transactions on Intelligent Transportation Systems*, 2021.

[150] S. A. Al-Gailani, M. F. M. Salleh, A. A. Salem, R. Q. Shaddad, U. U. Sheikh, N. A. Algeelani, and T. A. Almohamad, "A survey of free space optics (FSO) communication systems, links, and networks," *IEEE Access*, vol. 9, pp. 7353–7373, 2020.

[151] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE communications surveys & tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014.

[152] P. P. Ray, "A perspective on 6G: Requirement, technology, enablers, challenges and future road map," *Journal of Systems Architecture*, vol. 118, p. 102180, 2021.

[153] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE communications surveys & tutorials*, vol. 19, no. 1, pp. 57–96, 2016.

[154] K. Anbarasi, C. Hemanth, and R. Sangeetha, "A review on channel models in free space optical communication systems," *Optics & Laser Technology*, vol. 97, pp. 161–171, 2017.

[155] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, "Fso-based vertical backhaul/fronthaul framework for 5g+ wireless networks," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 218–224, 2018.

[156] P. Kulshreshtha and A. K. Garg, "Managing 5G networks-a review of FSO challenges and solutions," in *2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*. IEEE, 2020, pp. 1–4.

[157] S. A. H. Mohsan, M. A. Khan, and H. Amjad, "Hybrid fso/rf networks: A review of practical constraints, applications and challenges," *Optical Switching and Networking*, p. 100697, 2022.

[158] R. Nebuloni and E. Verdugo, "FSO path loss model based on the visibility," *IEEE Photonics Journal*, vol. 14, no. 2, pp. 1–9, 2022.

[159] A. S. Hamza, J. S. Deogun, and D. R. Alexander, "Classification framework for free space optical communication links and systems," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1346–1382, 2018.

[160] ——, "Evolution of data centers: A critical analysis of standards and challenges for fso links," in *2015 IEEE Conference on Standards for Communications and Networking (CSCN)*. IEEE, 2015, pp. 100–105.

[161] A. Boucouvalas, P. Chatzimisios, Z. Ghassemlooy, M. Uysal, and K. Yiannopoulos, "Standards for indoor optical wireless communications," *IEEE Communications Magazine*, vol. 53, no. 3, pp. 24–31, 2015.

[162] C. Jenila and R. Jeyachitra, "Green indoor optical wireless communication systems: Pathway towards pervasive deployment," *Digital Communications and Networks*, vol. 7, no. 3, pp. 410–444, 2021.

[163] P. P. Ray, "A review on 6g for space-air-ground integrated network: Key enablers, open challenges, and future direction," *Journal of King Saud University-Computer and Information Sciences*, vol. 34, no. 9, pp. 6949–6976, 2022.

[164] T. Kebede, Y. Wondie, J. Steinbrunn, H. B. Kassa, and K. T. Kornegay, "Precoding and beamforming techniques in mmwave-massive mimo: Performance assessment," *IEEE Access*, vol. 10, pp. 16 365–16 387, 2022.

[165] Z. R. Hajiyat, A. Ismail, A. Sali, and M. N. Hamidon, "Antenna in 6g wireless communication system: Specifications, challenges, and research directions," *Optik*, vol. 231, p. 166415, 2021.

[166] C. Han, Y. Wang, Y. Li, Y. Chen, N. A. Abbasi, T. Kürner, and A. F. Molisch, "Terahertz wireless channels: A holistic survey on measurement, modeling, and analysis," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 3, pp. 1670–1707, 2022.

[167] N. Chi, Y. Zhou, Y. Wei, and F. Hu, "Visible light communication in 6g: Advances, challenges, and prospects," *IEEE Vehicular Technology Magazine*, vol. 15, no. 4, pp. 93–102, 2020.

[168] W. Chen, X. Lin, J. Lee, A. Toskala, S. Sun, C. F. Chiasserini, and L. Liu, "5g-advanced toward 6g: Past, present, and future," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 6, pp. 1592–1619, 2023.

[169] GSMA. WRC-23 – Keep up to date with mobile. [Online]. Available: https://www.gsma.com/spectrum/wrc-series

[170] ITU. WRC-23 booklet: Agenda and relevant resolutions. [Online]. Available: https://www.itu.int/hub/publication/r-act-arr-1-2022/

Wijdan K. Alsaedi (Student Member, IEEE) received the B.S. degree in Electrical Engineering from the University of Technology, Iraq, in 2006. She also obtained the M.S. degrees in Laser and Optoelectronics Engineering from the same university in 2009. Currently, she is pursuing her Ph.D. degree in Electrical Engineering with the University of York, UK. Before starting her Ph.D., she served as the Head of the Radio Spectrum Monitoring and Quality of Service Department in the spectrum regulatory authority of Iraq. Her research interests revolve around spectrum management in 6G and the role of spectrum sharing in mmWave networks.

Hamed Ahmadi is a Reader in Digital Engineering, at the School of Physics, Engineering and Technology, University of York, UK. He is also an adjunct academic at the school of Electrical and Electronic Engineering, University College Dublin, Ireland. He received his Ph.D. from National University of Singapore in 2012 where he was a SINGA PhD scholar at Institute for Infocomm Research, A-STAR. Since then he worked at different academic and industrial positions in the Republic of Ireland and UK. Dr. Ahmadi has published more than 90 peer reviewed book chapters, journal and conference papers. He is a member of editorial board of IEEE Communication Standards magazine, IEEE Systems and Springer Wireless Networks. He is a senior member of IEEE, and Fellow of UK Higher Education Academy. He has been the Networks working group chair of COST Actions CA15104 (IRACON) and CA20120 (INTERACT). His current research interests include design, analysis, and optimization of wireless communications networks, the application of machine learning in wireless networks, Open Radio Access and Networking, green networks, airborne networks, Digital twins of networks, and Internet-of-Things.

Zaheer Khan received his Dr.Sc in electrical engineering from the University of Oulu, Finland, and his M.Sc degree in electrical engineering from University College Borås, Sweden, in 2011 and 2007, respectively. Currently, he is an Associate Professor at the University of Oulu, Finland. He has also worked for a Tenure Track Assistant Professor position at the University of Liverpool, United Kingdom (2016-2017), and as a research fellow/principal investigator at the University of Oulu between 2011-2016. He was the recipient of the Marie Curie fellowship for 2007-2008. He has several years of working experience with Telecomm industry. His research interests include Wireless data processing SoC design, implementation of advanced signal processing and wireless communications algorithms on Xilinx FPGAs and Zynq System-on-Chip (SoC) boards, application of game theory to model wireless networks, prototyping access protocols for wireless networks, and wireless baseband signal processing.

David Grace received the Ph.D. degree from the University of York, in 1999. His Ph.D. dissertation was titled, “Distributed Dynamic Channel Assignment for the Wireless Environment.” Since 1994, he has been a member of the Department of Electronic Engineering, University of York, where he is currently a Professor (Research), the Head of the Communication Technologies Research Group, and the Director of the Centre for High Altitude Platform Applications. In 2000, he jointly founded SkyLARC Technologies Ltd., and was one of its directors. From 2014 to 2018, he was the Non-Executive Director of Stratospheric Platforms Ltd. He is currently a Lead Investigator on H2020 MCSA SPOTLIGHT, U.K. Government funded MANY, dealing with 5G trials in rural areas, and HiQ investigating quantum key distribution from high-altitude platforms. He was the Technical Lead on the 14-partner FP6 CAPANINA Project that dealt with broadband communications from high-altitude platforms. He is the author of over 280 articles and the author/editor of two books. His current research interests include aerial platform-based communications, the application of artificial intelligence to wireless communications, 5G system architectures, dynamic spectrum access, and interference management. He is a Founding Member of the IEEE Technical Committee on Green Communications and Computing. He was the former Chair of IEEE Technical Committee on Cognitive Networks from 2013 to 2014.