# Multi-band Wireless Communication Networks:
Fundamentals, Challenges, and Resource Allocation

<table>
<thead>
<tr>
<th>Item Type</th>
<th>Article</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Aboagye, Sylvester; Saeidi, Mohammad Amin; Tabassum, Hina; Tayyar, Yamin; Hossain, Ekram; Yang, Hong-Chuan; Alouini, Mohamed-Slim</td>
</tr>
<tr>
<td>Eprint version</td>
<td>Post-print</td>
</tr>
<tr>
<td>DOI</td>
<td>10.1109/tcomm.2024.3366816</td>
</tr>
<tr>
<td>Publisher</td>
<td>Institute of Electrical and Electronics Engineers (IEEE)</td>
</tr>
<tr>
<td>Journal</td>
<td>IEEE Transactions on Communications</td>
</tr>
<tr>
<td>Rights</td>
<td>(c) 2024 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.</td>
</tr>
<tr>
<td>Download date</td>
<td>2024-02-28 04:33:14</td>
</tr>
<tr>
<td>Link to Item</td>
<td><a href="https://repository.kaust.edu.sa/handle/10754/697346">https://repository.kaust.edu.sa/handle/10754/697346</a></td>
</tr>
</tbody>
</table>
Multi-band Wireless Communication Networks: Fundamentals, Challenges, and Resource Allocation

Sylvester Aboagye, Member, IEEE, Mohammad Amin Saeidi, Graduate Student Member, IEEE, Hina Tabassum, Senior Member, IEEE, Yamin Tayyar, Ekram Hossain, Fellow, IEEE, Hong-Chuan Yang, Senior Member, IEEE, and Mohamed-Slim Alouini, Fellow, IEEE

(Invited Paper)

Abstract—This paper explores the evolution of wireless communication networks from utilizing the sub-6 GHz spectrum and the millimeter wave frequency band to incorporating extremely high frequencies like optical and terahertz for 6G and beyond. While these higher frequencies offer broader bandwidths and extreme data-rate capabilities, the transition from single-band and heterogeneous networks to multi-band networks (MBNs), where various frequency bands coexist introduces novel challenges in channel modeling, transceiver and antenna design, programmable simulation platforms, standardization, and resource allocation. This paper provides a tutorial overview from the communication design perspective of the various frequency bands, elaborating on the above issues. Then, we introduce and examine typical MBN architectures for future networks and provide a detailed overview of state-of-the-art resource allocation problems for existing MBNs that typically operate on two frequency bands. The considered resource allocation optimization problems and solution techniques are discussed comprehensively. We then identify key performance metrics and constraints that should be considered for resource allocation optimization in future MBNs and provide numerical results to depict how various system parameters and user behaviors can influence their performance. Finally, we present several potential research issues as future work for the design and performance optimization of MBNs.

Index Terms—Multi-band networks, Terahertz, visible light communication, free space optics, resource allocation, machine learning

LIST OF ACRONYMS

ABG Alpha-Beta-Gamma
ADMM Alternating Direction Method of Multipliers
AO Alternating Optimization
ADC Analog-to-Digital Converter

This work was supported by a Discovery Grant funded by the Natural Sciences and Engineering Research Council of Canada. At the time of this work, Sylvester Aboagye was with the Department of Electrical Engineering and Computer Science at York University, Toronto, ON M3J 1P3, Canada. He is currently with the School of Engineering at University of Guelph, Guelph, ON N1G 2W1, Canada (e-mail: sabaagye@uoguelph.ca).

Mohammad Amin Saeidi, Hina Tabassum and Yamin Tayyar are with the Department of Electrical Engineering and Computer Science at York University, Toronto, ON M3J 1P3, Canada. (e-mail: amin96a@yorku.ca; hinatabassum@yorku.ca; yamin@yorku.ca).

Ekram Hossain is with the Department of Electrical and Computer Engineering at University of Manitoba, Winnipeg, MB R3T 5V6, Canada. (e-mail: ekram.hossain@umanitoba.ca).

Hong-Chuan Yang is with the Department of Electrical and Computer Engineering at University of Victoria, Victoria, BC V8W 2Y2, Canada. (e-mail: hcyang@uvic.ca).

Mohamed-Slim Alouini is with the Computer, Electrical and Mathematical Science and Engineering Division at King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. (e-mail: slim.alouini@kaust.edu.sa).

Acronyms:

AoA Angle of Arrival
AP Access Point
APD Avalanche Photodiodes
BS Base Station
CA Carrier Aggregation
CSI Channel State Information
CI Close-In
CIF Close-In Free Space
CMOS Complementary Metal-Oxide Semiconductor
C-RAN Cloud-Radio Access Network
CNN Convolutional Neural Network
DCE Deployment Cost Efficiency
DD Delay-Doppler
DAC Digital-to-Analog Converter
DFBLDs Distributed Feedback LDs
EELDs Edge-Emitting LDs
EDFA Erbium-Doped Fiber Amplifier
ECMA European Computer Manufacturers Association
EHF Extremely High Frequency
ELAA Extremely Large-Scale Antenna Array
EM Electromagnetic
EMF Electromagnetic Field
FCC Federal Communications Commission
F-RAN Fog-Radio Access Networks
FNN Feedforward Neural Network
FDTD Finite Difference Time Domain
FoV Field-of-View
FSO Free Space Optics
GNN Graph Neural Network
GHz Gigahertz
HDMI High-Definition Multimedia Interface
HetNet Heterogeneous Network
HEMT High Electron Mobility Transistor
HITRAN High Resolution Transmission Molecular Absorption
HO Handoff
IAB Integrated Access and Backhaul
ICNIIRP International Commission on Non-Ionizing Radiation Protection
IR Intermediate Frequency
I-G Inverse Gaussian
Int-MBN Integrated Multi-Band Network
IR Infrared
IrDA Infrared Data Association
ISM Industrial, Scientific and Medical
ITU International Telecommunication Union
ITU-R International Telecommunication Union-Radiocommunication
JEITA Japan Electronics and Information Technology Industries Association
KPI Key Performance Indicator
LD Laser Diode
LED Light Emitting Diode
LiFi Light Fidelity
LO Local Oscillator
LoS Line-of-Sight
MTC Machine Type Communication
MAC Medium Access Control
MBN Multi-Band Network
MEMS Microelectromechanical System
MIMO Multiple-Input Multiple-Output
Spreading loss, atmospheric loss, diffuse scattering, weather effects, and the need for precise beam alignment. Consequently, there is no one-size-fits-all spectrum solution, and next-generation wireless networks, known as multi-band networks (MBNs), are expected to co-exist with all frequencies. MBNs are different from heterogeneous networks (HetNets) as the former deal with diverse frequencies and channel propagation characteristics requiring innovation from the hardware design to the physical (PHY) and medium access control (MAC) layers design.

MBNs enable devices to simultaneously connect to multiple BSs/APs across different frequency bands and brings several advantages as compared to traditional wireless networks. Such advantages include:

- **Enhanced Capacity and Throughput**: MBNs allow devices to utilize multiple spectrum, increasing overall network capacity and improving data throughput. By distributing the traffic across multiple spectrum, MBNs can handle massive connectivity.

- **Mobility-Aware and QoS-Aware Services**: MBNs expand the coverage area and range of wireless networks depending on their specific quality-of-service (QoS) and mobility requirements. It is anticipated that the features and applicability of different spectrum would enable optimized services.

- **Enhanced Reliability and Robustness**: By connecting to different spectrum, MBNs enhance the reliability of wireless networks and make them fault-tolerant and robust. If one spectrum experiences congestion or signal degradation, devices can switch to another connection seamlessly, ensuring uninterrupted service and reducing the risk of dropped connections.

- **Reduced Latency**: MBNs can reduce latency by utilizing dense deployment of high frequency APs, thus enabling multiple high quality connections simultaneously. It is noteworthy that high data rate EHF transmission links become nearly static from the data perspective, i.e., the transmissions become almost “instantaneous”. Although users’ channel can vary over time, the variations are slow than the bit transmission.

- **Traffic Offloading**: MBNs enable load balancing across multiple spectrum bands, distribute traffic efficiently and offer a new degree-of-freedom. This ensures optimal utilization of network resources and enhances the overall performance. However, novel offloading mechanisms that consider different channel peculiarities like molecular absorption, beam squint and misalignment, and users’ mobility in MBNs are required.

Motivated by the advantages and characteristics of MBNs, it is crucial to investigate how the spectra from the different bands, the various APs, and their corresponding transmission resources can be exploited to efficiently design versatile MBNs capable of supporting diverse use cases and performance impact, and scintillation effects. Visible light communication (VLC) signals are affected by the field-of-view (FoV) of the transmitter and receiver, random device orientation, and link blockage. Free space optics (FSO) encounters transmission challenges such as atmospheric attenuation, scintillation effects, and the need for precise beam alignment.

I. INTRODUCTION

Over the years, wireless networks have evolved significantly from homogeneous cellular networks to heterogeneous ones, with multiple access technologies (e.g., pico and femto access points (APs)) and network architectures (e.g., macrocell-picocell and macrocell-femtocell coexistence). At the same time, wireless technology has been developed primarily to broadcast data over the radio frequency (RF) or sub-6 GHz spectrum and the millimeter wave (mmWave) spectrum, recently introduced in 5G systems. However, these bands cannot meet the massive connectivity, higher data rate, ultra-low latency, and better coverage requirements of next generation wireless networks (NGWNs) [1]. Extremely high frequencies (EHF) such as optical and terahertz (THz) offer much wider transmission bandwidths with extreme data rate capabilities (in the order of multi-Gbps and Tbps), providing higher network capacity, spectral efficiency, and better user experience. However, EHF transmissions are susceptible to unique channel propagation impediments resulting in smaller coverage zones and frequent AP switching for moving users. THz band transmissions suffer from molecular absorption, spreading loss, atmospheric loss, diffuse scattering, weather
demands. A vital area of research is developing a comprehensive and unified framework for resource allocation within MBNs. This framework should consider the different bands’ distinct propagation characteristics and practical constraints. Furthermore, it is essential to delve into novel network architectures, transceiver designs, antenna systems, and simulation environments specifically tailored for MBNs. These efforts are pivotal in ensuring sustainable growth in capacity for the forthcoming generation of wireless networks.

In a nutshell, 6G and beyond networks are expected to leverage RF, mmWave, THz, VLC, and FSO bands in MBNs to address various quality-of-service (QoS) requirements. This convergence of diverse technologies necessitates a fresh perspective on the design of MBNs by examining existing architectures, offering a visionary outlook on potential future MBN structures, tackling the challenges linked to design and deployment, proposing viable remedies, and introducing a comprehensive, unified framework for resource management in MBNs.

A. Existing Surveys and Tutorials

Several survey articles have been published in the past five years, focusing on stand-alone (SA) THz, mmWave, VLC, and FSO technologies. These articles covered various aspects such as PHY procedures, network deployment, and architectures, transceiver and hardware design, MAC protocols, and network optimization, as summarized and classified in Table I and detailed below.

1) PHY Procedures: Many papers relating to PHY procedures (e.g., channel modeling, channel estimation, coding and modulation, beamforming techniques) have appeared in the literature. Among these works, mathematical channel models were examined in [2]–[27]. Channel estimation and measurement techniques were covered in [5], [7], [23], [28]–[33]. Coding and modulation related aspects were discussed in [5], [9], [11], [16], [17], [19], [20], [22], [25], [30], [34]–[40]. Beamforming techniques were covered in [7], [8], [24], [29]–[31], [37], [41]–[45].

2) Network Deployment and Architectures: In [28], the authors discussed ways to efficiently and reliably deploy and operate next-generation THz wireless systems. The authors in [18] focused on network architecture, design factors, and research challenges for FSO networks, while [23] discussed network architectures for FSO and hybrid FSO systems. On the other hand, the authors in [5] presented a network architecture for mmWave massive multiple-input multiple-output (MIMO) networks.

3) Transceiver Design: The key hardware blocks of a THz transceiver, their associated performance metrics, and the various design approaches were discussed in [27]. In [46], the authors gave a detailed overview of VLC transceiver design and prototypes. The authors in [9] discussed recent advancements in VLC system design and programmable platforms. FSO transmitters and receivers’ typical structure and the transceiver device trends were examined in [2], [17], [23] and [19]. In [21], the authors reviewed wireless networks-on-chip architecture design and provided a state-of-the-art survey on on-chip antennas. The authors in [39] discussed transceiver design testbeds for visible light ad-hoc networks.

4) MAC Protocols: In [47], the authors surveyed MAC protocols for the THz band and highlighted key features to consider in designing efficient MAC protocols. The authors in [3] and [40] discussed MAC protocols for THz band communication and VLC, respectively. The study in [37] explored various MAC protocols for mmWave ad-hoc networks, mesh networks, wireless personal area networks (WPANs), and cellular networks. In [45], the authors discussed MAC-related technologies for mmWave wireless local area networks. The existing MAC protocols for general VLC systems and visible light ad-hoc networks were examined in [39].

5) Network Optimization: Network optimization is a comprehensive concept that encompasses various strategies and techniques, such as interference management, load balancing, handoff optimization, network planning, and resource allocation. The authors in [28] discussed the steps needed to efficiently and reliably deploy and operate next-generation THz wireless systems. They discussed real-time THz network optimization and the application of meta/multi-task learning. The authors in [29] focused on optimization techniques for mmWave-enabled unmanned aerial vehicle (UAV) deployment control, trajectory design, and resource management. In [13], various optimization techniques for hybrid RF/VLC and SA VLC networks were examined. The authors in [48] summarized network optimization performance metrics and interference management techniques for hybrid light fidelity (LiFi)/wireless fidelity (WiFi) networks. Additionally, the authors discussed various handoff (HO) and load balancing techniques.

It is evident from Table I that the existing surveys have mainly concentrated on aspects such as PHY procedures, network architectures, transceiver design, and MAC protocols. However, with the evolution of wireless networks in MBNs, more complex network architectures in varying environments have emerged, leading to new challenges in network optimization. Conventionally, resource allocation is one specific aspect of network optimization that deals with efficiently distributing limited and homogeneous spectrum resources among users within the network. However, in MBNs, it becomes important to consider both the physical network characteristics, diverse transceiver and antenna designs, and the heterogeneity of the spectrum resources to balance the performance trade-offs.

The subsequent subsection provides a discussion and summary (presented in Table II) of recent surveys that focused on network resource optimization for the mentioned technologies while highlighting our main contributions.

B. Novelty and Contributions

There have been comprehensive surveys on resource management in RF networks. Notably, [49] and [50] surveyed resource allocation algorithms for HetNets. [51] covered resource management schemes based on machine learning and deep learning in cellular wireless and internet-of-things networks. [52] and [53] discussed resource allocation approaches for ultra-dense and cognitive radio networks, respectively.
Recently, [28] and [29] touched on the optimization of network resources in spectrum bands other than the sub-6 GHz (i.e., RF band), and [13] discussed resource allocation for hybrid RF/VLC networks.

Different from the existing works, this paper provides a comprehensive survey-cum-tutorial that focuses on the channel modeling, transceiver designs, and resource allocation design of networks operating on mixed transmission frequencies. It can be observed from Table II that a comprehensive survey on MBNs is still lacking. As far as the authors are aware, no study has discussed key challenges and various resource allocation approaches in MBNs. Furthermore, resource allocation in SA THz, VLC, and mmWave networks has been only sparingly investigated, and there is no existing study on resource allocation in FSO networks. This assessment also highlights the critical need to discuss open issues and potential research directions for MBNs in a comprehensive manner.

To that end, the contributions of this article are summarized as follows:

1) We review the fundamentals of the different spectrum bands, their transceiver designs, as well as recent progress on standardization and simulation testbeds.

2) We provide a thorough discussion on the channel modeling, unique propagation properties and challenges of mmWave, VLC, FSO, and THz spectrum bands.

3) We examine the envisioned MBN architectures and discuss the key technical advantages and challenges relating to practical deployment, multi-band transceiver design, and multi-band antenna systems. These challenges are induced by the unique characteristics of the different bands that coexist in MBNs.

4) We provide an exhaustive survey on resource allocation methods for existing MBNs under the following classification: RF/THz MBNs, RF/VLC MBNs, RF/mmWave MBNs, RF/FSO MBNs, mmWave/FSO MBNs, VLC/THz MBNs, mmWave/THz MBNs, mmWave/VLC MBNs, RF/VLC/mmWave MBNs, and RF/mmWave/THz MBNs. The considered resource allocation optimization problems, proposed solution techniques and their main limitations are discussed comprehensively.

5) We identify key performance metrics and constraint sets and discuss fast and scalable solution approaches that should be considered for resource allocation optimization in the envisioned MBNs. Additionally, we provide numerical results to compare the performance of the different MBN architectures and illustrate how various system parameters and user behaviors can influence their performance.

6) We present several potential research issues for the design and performance optimization of MBNs.

### C. Significance to Community

This paper has the potential to bring significant impact and benefits for the scientific community, industry, and society. For the scientific community, this study addresses the evolving landscape of wireless networks, specifically the transition from homogeneous cellular networks to heterogeneous cellular networks, and finally MBNs. This paper provides valuable insights into the unique channel propagation impediments, coverage limitations, and transmission challenges encountered in different frequency bands. It can therefore serve as a great starting point for beginners in this field and a valuable resource for senior researchers. Furthermore, the findings of this study can serve as a foundation for future research endeavors aimed at developing efficient and robust MBN solutions.

From an **industry** perspective, the discussions significantly influence the development and deployment of next-generation wireless communication technologies and have significant potential implications for business models. By understanding the strengths and limitations of different frequency bands and transmission technologies, industry stakeholders can make informed decisions regarding the design, optimization, and deployment of MBN solutions, including the development of innovative MBN products, aligning their products with emerging industry standards, and leveraging the insights gained from this study to enhance the performance and efficiency of wireless networks.

From a **societal** perspective, the development of MBN solutions can bridge the connectivity gap and extend the reach of wireless networks to under-served areas. By exploring transmission technologies beyond traditional RF and mmWave, this research opens up possibilities for providing high-speed internet access in space, underground, underwater, and remote terrestrial regions, enabling digital inclusion and empowering communities. The improved spectral efficiency and network capacity offered by MBN solutions can support the growing demand for data-intensive applications and services, ranging from telemedicine and distance learning to smart cities and internet-of-things deployment.

### D. Paper Organization

The rest of the paper is organized as shown in Fig. 1. Section II presents an overview of different spectrum bands, their transceiver design, related standardization activities, and the experimental and simulation testbeds. Section III discusses the various channel modeling schemes that capture the different frequency bands’ channel characteristics and propagation phenomena. Section IV introduces our envisioned architectures for MBNs and highlights the associated challenges and potential solutions to realize multi-band transceivers and tunable multi-band antenna systems. Section V provides a comprehensive survey of architectures, system models, and optimization techniques for resource allocation in existing MBNs. Section VI focuses on a unified resource allocation framework for beyond 5G MBNs by outlining new performance metrics, practical constraints, and relevant solution approaches. The section also shows a quantitative comparison (i.e., a case study) of how network parameters and user behaviors influence the performance of different MBNs. Section VII discusses the challenges and future research directions for MBNs, and Section VIII concludes the paper.
### TABLE I

**EXISTING SURVEY ARTICLES ON A VARIETY OF TRANSMISSION BANDS IN THE PAST 5 YEARS**

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Ref.</th>
<th>Year</th>
<th>Notes on PHY Procedures and Type of MBN</th>
<th>PHY Procedures</th>
<th>Network Architecture</th>
<th>Transceiver Design</th>
<th>MAC Protocols</th>
<th>Network Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>THz</td>
<td>[41]</td>
<td>2018</td>
<td>BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[47]</td>
<td>2020</td>
<td>BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[27]</td>
<td>2022</td>
<td>CM, CP</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[5]</td>
<td>2021</td>
<td>CM, BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[22]</td>
<td>2021</td>
<td>CM, C &amp; M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[32]</td>
<td>2022</td>
<td>CEM, CP</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[33]</td>
<td>2022</td>
<td>CEM, CP</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[28]</td>
<td>2022</td>
<td>CEM</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mmWave</td>
<td>[43]</td>
<td>2016</td>
<td>BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[45]</td>
<td>2018</td>
<td>BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[44]</td>
<td>2018</td>
<td>BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[37]</td>
<td>2018</td>
<td>C&amp;M, BMF, MAC</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[29]</td>
<td>2019</td>
<td>BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[30]</td>
<td>2021</td>
<td>CEM, C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[31]</td>
<td>2022</td>
<td>CEM, BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[7]</td>
<td>2022</td>
<td>CM, CEM, CP, BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[8]</td>
<td>2022</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VLC</td>
<td>[26]</td>
<td>2015</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[9]</td>
<td>2015</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[10]</td>
<td>2016</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[46]</td>
<td>2017</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[12]</td>
<td>2018</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[39]</td>
<td>2019</td>
<td>CM</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[40]</td>
<td>2019</td>
<td>CM</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[14]</td>
<td>2020</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[16]</td>
<td>2020</td>
<td>CM, C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[54]</td>
<td>2022</td>
<td>C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSO</td>
<td>[17]</td>
<td>2014</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[18]</td>
<td>2017</td>
<td>CM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[35]</td>
<td>2017</td>
<td>C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[36]</td>
<td>2019</td>
<td>C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[19]</td>
<td>2019</td>
<td>CM, C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[23]</td>
<td>2020</td>
<td>C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[22]</td>
<td>2022</td>
<td>CEM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[38]</td>
<td>2022</td>
<td>C&amp;M</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-Band</td>
<td>[20]</td>
<td>2013</td>
<td>FSO/VLC: CM, CP</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[54]</td>
<td>2020</td>
<td>RF/Optical, Optical/Optical</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[21]</td>
<td>2020</td>
<td>mmWave, THz, Optical: CM, CP</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[48]</td>
<td>2021</td>
<td>Wi-Fi/VLC</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[42]</td>
<td>2022</td>
<td>THz-mmWave: CP</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[42]</td>
<td>2022</td>
<td>THz-mmWave: BMF</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CM: channel modeling; CEM: channel estimation and measurement; CP: channel propagation; C&M: coding and modulation; BMF: beam management and beamforming; MAC: MAC protocols

### TABLE II

**SURVEY AND MAGAZINE PAPERS ON RESOURCE ALLOCATION**

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>RF</th>
<th>THz</th>
<th>VLC</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td>[28]</td>
<td>2022</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[29]</td>
<td>2019</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>2019</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td></td>
</tr>
<tr>
<td>[48]</td>
<td>2021</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[49]</td>
<td>2021</td>
<td>✓✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[51]</td>
<td>2020</td>
<td>✓✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[52]</td>
<td>2019</td>
<td>✓✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[53]</td>
<td>2017</td>
<td>✓✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[50]</td>
<td>2022</td>
<td>✓✓</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

✓: resource allocation was discussed in a section or partially covered; ✓✓: the survey thoroughly discussed resource management.
II. OVERVIEW OF DIFFERENT SPECTRUM BANDS, TRANSEIVER DESIGN, STANDARDIZATION, AND SIMULATION PLATFORMS

This section focuses on an overview of the characteristics of different spectrum bands, their transceiver design, related standardization activities, and advancement of experimental and simulation testbeds. Specifically, the section first discusses the characteristics of the THz, mmWave, VLC, and FSO spectrum bands. Then, this section describes typical transceiver architectures for THz, mmWave, VLC, and FSO transmissions. Next, this section summarizes up-to-date standardization efforts and pin-point the various working groups dealing with related specifications, protocols, and standards. Finally, this section highlights existing experimental platforms and state-of-the-art simulation and emulation software for different spectrum bands.

A. Fundamentals of Spectrum Bands

1) THz Spectrum: The THz and sub-THz spectrums, occupying the frequency range from 0.1 THz to 10 THz (wavelength 0.1 mm to 30 µm) and 0.1 to 0.3 THz, respectively, lies between microwave and infrared (IR) regions in the electromagnetic (EM) spectrum. THz waves exhibit unique properties, sharing characteristics of both RF signals and light [55]. Notably, THz waves possess superior penetration capabilities compared to optical signals, resulting in less scattering and better depth for non-conducting materials. Moreover, the shorter wavelengths of THz waves enable enhanced spatial imaging resolution and render them non-ionizing due to lower photon energies. Furthermore, the low free-space diffraction of THz signals makes them more directional, providing inherent interference mitigation benefits. The THz band offers ultra-broad bandwidth and exceptionally high data rates compared to sub-6 GHz and mmWave spectra and is largely unregulated, leading to significant growth in research interest in applications such as THz spectrometers, and imaging systems in laboratories, communications, non-destructive evaluation, quality control, medicine, and vehicular connectivity [56].

However, THz signal propagation is vulnerable to high molecular absorption loss, path and reflection losses, and limited availability of line-of-sight (LoS) paths, constraining communication distance. Furthermore, scintillation effects caused by time-varying fluctuations in the atmospheric refractive index can degrade signal quality. Additionally, the lack of off-the-shelf components and technologies for efficient THz wave generation, detection, and manipulation poses implementation difficulties [27], [57].

Despite these challenges, THz spectrum is considered for several indoor, kiosk, and security applications. Moreover, THz can complement existing frequencies and thus contribute to ultra-reliable and extreme data rate applications such as autonomous vehicles and satellite communications.

2) mmWave Spectrum: The mmWave band refers to the portion of the EM spectrum with frequencies typically ranging from 30 to 300 GHz, corresponding to wavelengths between 1 mm and 10 mm. One of the key advantages of the mmWave spectrum is its wide bandwidth and smaller wavelength, enabling the deployment of large-scale antenna arrays within a...
compact area. This characteristic facilitates the achievement of high antenna gain and effective beamforming, even in handheld devices. As a result, mmWave has been used in 5G new radio (NR) [58], and is expected to play a critical role in 6G and beyond systems.

However, mmWave signals face specific challenges due to their higher path-loss than lower frequency bands, which restricts their transmission range. Additionally, the small wavelength of mmWave signals, measuring less than a centimeter, makes them more susceptible to environmental attenuation and absorption, which can cause signal degradation. Moreover, when mmWave signals encounter large structures, they experience more diffused scattering effects than sub-6 GHz signals. MmWave systems may also suffer from channel sparsity and high power consumption as they heavily rely on beamforming techniques and antenna arrays to direct signals toward specific users or devices.

Despite these challenges, ongoing research and development efforts such as beamforming, advanced antenna designs, and MIMO systems aim to overcome the restricted range and attenuating effects. By leveraging these techniques, it becomes feasible to establish robust and reliable mmWave links for high-capacity access networks and backhaul data transmission.

3) **VLC Spectrum:** The visible light spectrum spans 400 to 800 THz, covering wavelengths from 380 to 760 nm. This spectrum is divided into six colors: red (610-760 nm), orange (590-620 nm), yellow (570-590 nm), green (500-570 nm), blue (450-500 nm), and violet (380-450 nm). VLC capitalizes on the green or white light spectrum, which is easily perceivable by the human eye and boasts high luminosity. VLC offers numerous advantages, including vast unlicensed bandwidth, heightened security due to its directional nature and short transmission distance, efficient spatial reuse, low energy consumption, and reduced electromagnetic field (EMF) exposure as it uses visible light.

However, VLC transmission is confined to the LoS link connecting the transmitter and the receiver. Various factors impact its performance, including the presence of static and dynamic blockers, the unpredictable orientation of users' devices, the constrained FoV for both the transmitter and receiver, and signal losses in the receiver attributable to the use of convex lenses as optical concentrators. Moreover, VLC transmission is susceptible to interference from noise sources like ambient light, flicker, thermal variations, and shot noise. Despite these hurdles, VLC remains a popular area of research and holds immense potential for various applications such as indoor positioning, LiFi, hybrid/aggregated RF/VLC systems, underwater communications, and automotive communication, among others.

4) **FSO Spectrum:** The FSO spectrum refers to the range of optical EM waves that propagate through free space without using a physical medium. It operates in the near-IR range of optical EM waves that propagate through free space without a physical medium. The FSO link is limited to the LoS between the transmitter and the receiver. It requires high-accuracy pointing and tracking of the beam, which may be challenging in mobile applications.

Despite these challenges, FSO offers several applications, including high-speed point-to-point communication for last-mile connectivity, wireless backhauling, satellite communication, and disaster recovery communication.

**B. Transceiver Designs**

1) **THz Transceiver Design:** The hardware building blocks of a THz transceiver includes the analog front-ends, the antenna systems, and the digital back-ends [27]. These blocks are discussed in the sequel.

At the transmitter side, the analog front-end is in charge of generating the THz carrier signal or pulse-based waveform, modulation, signal amplification and filtering out-of-band emissions prior to radiation. At the receiver side, the analog front-end performs signal detection, filtering, amplification, and recovering the transmitted information. The main technology pathways to developing THz front-ends consist of the electronic, the photonic, and the plasmonic solutions [27]. The electronic solution utilizes existing techniques for microwave and mmWave devices to generate THz signals. The photonic technique pushes the limits of optical wireless communications while the plasmonic solution involves the design of devices that intrinsically operate at THz frequencies without the need to up-convert from the microwave range or down-convert from optics.

- **Electronic Solutions:** Generating THz signals through electronics primarily involves the process of up-conversion from lower frequencies, using silicon-based solutions. Compact transceiver designs can be achieved through electronic solutions based on complementary metal-oxide semiconductor (CMOS) and bipolar CMOS technologies [59]. However, utilizing CMOS technologies for THz transceivers poses challenges in power handling and speed, with a maximum power gain frequency limit of 320 GHz. In addition to CMOS, the utilization of III-V-based semiconductors (i.e., compound semiconductors composed of elements from Group III and Group V of the periodic table), such as Indium Phosphide, Indium Arsenide, Gallium Arsenide, Gallium Nitride, and Indium Antimonide, in high electron mobility transistors (HEMTs) presents promising solutions for higher operating frequencies, such as 720 GHz and 1.5 THz [60], [61].

- **Photonic Solutions:** Frequencies above 300 GHz can be generated by down-converting optical signals using photoconductive antennas and uni-travelling carrier PDs [62]. However, these methods face limitations in terms
of output power and expensive production processes. An alternative solution is the hybrid integration of electronic and photonic approaches, which requires more accurate synchronization at the receiver side. Integrating a miniature microelectromechanical system (mMEMS) into this hybrid solution offers advantages due to the reconfigurability provided by mMEMS. By dynamically and electronically controlling frequency and polarization, mMEMS can outperform existing electronic and photonic solutions in THz transceiver design [60], [63].

- **Plasmonic Solutions**: The third approach to THz transceiver design involves plasmonic solutions, which utilizes plasmonic materials, including graphene, known for its high electron mobility and reconfigurability. By leveraging the intrinsic properties of plasmonic nanomaterials, transceivers can operate at THz frequencies without performance degradation caused by losses in up and down conversion found in electronic and photonic solutions. Additionally, graphene-based materials can be employed for manufacturing modulators and on-chip THz antennas while minimizing electronic noise temperature [64], [65].

Antenna design for the THz band is challenging due to its small wavelength, necessitating exceptionally minute structures, as well as the skin effect induced by the shallower current penetration in conductive materials. A concise overview of antenna design techniques is given below.

- **Planar Antennas**: Patch antennas employing microstrip line technology and configured as a planar array offer a valuable solution. As outlined in [66], the THz short wavelength can trigger substrate mode concerns. Also, the partial propagation of EM waves within a dielectric substrate may contribute to elevated losses. Nonetheless, planar antennas offer manufacturing versatility, compact dimensions, and adjustable antenna propagation patterns [67].

- **Horn Antennas**: Horn antennas have emerged as a favorable choice for THz transmission owing to their notable directivity, reaching up to 25 dBi. Horn antennas are employed in various applications, including radar systems, radiometers, and wireless communication, due to their simple structure. Also, these antennas tend to exhibit superior performance when contrasted with planar antennas. Moreover, horn antennas possess the capacity to accommodate a diverse spectrum of frequencies, rendering them suitable for transmitting broadband signals. However, the fabrication of horn antennas in the THz domain is intricate due to the exceedingly minute THz wavelength. To overcome this challenge, the utilization of laser melting 3D printing technology has enabled the creation of conical horn antennas operating within the ranges of 60 GHz to 90 GHz and 110 GHz to 170 GHz [68].

- **Substrate-integrated Waveguide (SIW) Antennas**: SIW technology involves the creation of a rectangular waveguide within a substrate by utilizing metallic vias. The adjustment of the distances between these vias enables control over the cut-off frequency. A significant advantage of SIW technology lies in its capability to integrate various passive, active components, and antennas onto a single substrate, facilitating a comprehensive solution [69].

- **Graphene-based Antennas**: Unlike electronic and photonic front-ends which can use the above-mentioned conventional antennas, plasmonic antennas are needed for plasmonic front-ends [27]. As opposed to metallic materials, plasmonic materials such as graphene and carbon-based materials exhibit favorable conductivity characteristics within the THz band, attributed to the propagation of plasmon modes. These materials offer the capability to manipulate conductivity through magnetic and electric fields, thereby enabling the development of tunable antennas.

In addition to the THz analog front-ends and antenna systems, the design of digital signal processing back-end devices such as analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) is very important. In [70], a 128 Giga-samples-per-second 2-bit multiplexer DAC that can sample at frequencies in excess of 100 Giga-samples-per-second was developed. A high speed ADC converter for THz transmissions based on active-controlled spoofed surface plasmon polarization architecture has been developed in [71]. Moreover, the design of power amplifiers (PAs) for THz transceivers has recently attracted a lot of attention. Designing PAs at THz frequencies is challenging due to the short wavelengths, miniaturization difficulties, limited available technologies, and nonlinearity issues as well as power consumption due to increased system ohmic and interconnect losses and reduction in device efficiencies [72]. Over the years few design methods have been reported in the literature. Key among them are silicon-based sub-THz PAs [73], [74], inductor-capacitor (LC)-based sub-THz PAs [75], and Marchand balun-based sub-THz PAs [76].

2) **Millimeter-Wave Transceiver Design**: The three principal design methodologies for mmWave transceivers are quasi-optical antenna design, phased array antenna design, and planar antenna design. The quasi-optical antenna design approach stands out as it draws inspiration from optics, employing lenses to analyze and optimize antennas operating at mmWave frequencies. By treating electromagnetic waves similarly to optical signals, engineers can effectively shape and direct these waves, enhancing antenna performance. This approach is particularly valuable for lens antennas, where dielectric materials are utilized to focus and control the radiation pattern. In phased array antenna design, multiple antenna elements and electronic phase shifters enable dynamic beam steering. By adjusting the relative phase of signals arriving at different ports, phased arrays can electronically manipulate the direction of the main radiation pattern. Planar antennas, notably microstrip antennas, have gained popularity in mmWave transceivers due to their ease of integration into printed circuit boards and other planar structures. Their planar form factor allows for straightforward manufacturing and cost-effective mass production. MmWave transceiver antennas can be classified into five types: reflector antennas, lens antennas, horn antennas (explained in the THz
technologies-based designs were examined in [82].

to-analog converters (DACs), Silicon Germanium and CMOS was proposed in [81]. With regards to mmWave ADCs/digital-
A dual-band filtering PA based on gallium arsenide process [80], the authors developed a three-way Doherty PA prototype.
Silicon Germanium technology was designed in [78], [79]. In
efficiency class-E PA based on Texas Instruments BiCMOS for THz/sub-THz which also work for mmWave bands, a high
cencies, PAs at such bands typically have lower output powers and
A typical mmWave transmitter configuration can be divided
into three parts: RF transmitter cell modules, IF/LO modules and power supply module [77]. All these parts are integrated into a compact mechanic structure. The transmitter module includes an antenna, PA, frequency multiplier, upconverter and antenna feeding transition structure. The front-end of the receiver has a similar structure as the transmitter and includes antenna arrays, low noise amplifier, frequency multiplier, downconverter and antenna feeding transition structure, LO power amplifier, and an IF signal amplifier.

In addition to the higher pathloss (PL) at mmWave frequencies, PAs at such bands typically have lower output powers and single digit efficiencies. In addition to the PA design methods for THz/sub-THz which also work for mmWave bands, a high efficiency class-E PA based on Texas Instruments BiCMOS Silicon Germanium technology was designed in [78], [79]. In [80], the authors developed a three-way Doherty PA prototype. A dual-band filtering PA based on gallium arsenide process was proposed in [81]. With regards to mmWave ADCs/digital-to-analog converters (DACs), Silicon Germanium and CMOS technologies-based designs were examined in [82].

3) VLC Transceiver Design: VLC uses visible light to transmit data by modulating the light intensity of a light emitting diode (LED) or laser diode (LD) to encode data, which is then detected by a receiver equipped with a PD to capture the light signal and decode the data. Among LEDs and LDs, the former is typically used in VLC since it can provide a larger coverage area and more uniform illumination. Depending on the type of LED used, the various VLC transmitters can be summarized as follows:

- **Single-color Transmitter:** This transmitter uses single-color LEDs that emit light of specific wavelengths. It is relatively simple and finds applications in basic VLC systems for short-range communications, such as indoor and proximity-based transmissions.

- **Multi-color Transmitter:** This transmitter employs red, green, and blue LEDs that can emit various colors by adjusting the intensity of each color component. It offers color-mixing capabilities, allowing for more sophisticated data modulation techniques. By varying the intensity of red, green, and blue channels, multi-color transmitters can achieve higher data rates and support multiple communication channels.

- **White VLC Transmitter:** This transmitter uses white LEDs with phosphor coatings that emit a broad spectrum of light and is commonly used for illumination. White VLC transmitters can provide indoor lighting while enabling high-speed data communication, making them suitable for applications like LiFi.

- **IR-enhanced VLC Transmitter:** VLC transmitters can be enhanced by integrating IR LEDs and visible light LEDs. This hybrid approach allows to operate in both the visible light spectrum for downlink data communication and the IR spectrum for control or synchronization purposes and uplink data transmission.

- **High-power VLC Transmitter:** High-power LEDs are used in VLC transmitters to achieve longer communication distances. These transmitters are suitable for outdoor applications, such as street lighting networks with data communication capabilities.

- **Organic LED-based VLC Transmitter:** VLC transmitters can utilize organic LEDs that generate light using an organic layer sandwiched between positive and negative carriers for data transmission. Organic LEDs offer unique advantages such as flexibility, thin form factor, and color-tunable emission. Due to their low modulation bandwidth, organic LED-based VLC transmitters are promising for displays and lighting systems and less suitable for communication channels.

Optical communication wireless receiver structures can be broadly categorized into two classes based on the detection type, namely, coherent and direct (also called non-coherent) detection [17]. In the former, amplitude, frequency, or phase modulation can be used. At the receiver side, the received field is optically mixed before photo-detection with a locally generated optical field. In direct detection systems, the intensity of the emitted light is employed to convey the information. At the receiver side, the PD directly detects changes in the light intensity without the need for a local oscillator. These systems are also known as intensity-modulation direct-detection. Although coherent systems offer superior performance in terms of background noise rejection, mitigating turbulence-induced fading in FSO, and high receiver sensitivity [83], [84],
TABLE III
COMPARISON OF DIFFERENT LENS TYPES IN mmWAVE ANTENNA DESIGN

<table>
<thead>
<tr>
<th>Lens Type</th>
<th>Configuration</th>
<th>Beam Steering Capability</th>
<th>Side Lobe Levels</th>
<th>Focal Point Characteristics</th>
<th>Size and Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruz lens</td>
<td>Planar lens with grid of dielectric material</td>
<td>Yes</td>
<td>Higher</td>
<td>Multiple beams can be formed</td>
<td>Relatively simple</td>
</tr>
<tr>
<td>Rotman lens</td>
<td>Series of feed horns and phase shifters</td>
<td>Yes</td>
<td>Lower</td>
<td>Precise beam steering control for phased array systems</td>
<td>Moderate</td>
</tr>
<tr>
<td>Luneburg lens</td>
<td>Spherical shape with gradient refractive index</td>
<td>Yes</td>
<td>Minimal</td>
<td>Wide-angle coverage with minimal distortion</td>
<td>Larger</td>
</tr>
<tr>
<td>Dielectric slab lens</td>
<td>Flat dielectric slab</td>
<td>No</td>
<td>Moderate</td>
<td>Antenna directivity determined by aperture size</td>
<td>Relatively simple</td>
</tr>
<tr>
<td>Horn lens</td>
<td>Conical shape with dielectric material</td>
<td>Yes</td>
<td>Moderate</td>
<td>Beamwidth and directivity can be controlled</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

intensity-modulation direct-detection systems are commonly used in optical wireless systems due to their simplicity and low-cost. For this reason, we only focus on direct detection receiver structures in this paper and refer interested readers to [17] for coherent detection system.

A typical VLC receiver comprises of a convex lens, a filter, a PD characterized by a small physical area, $A_{PD}$, and an FoV, and a trans-impedance amplifier which is a current-to-voltage converter made of operational amplifiers. The trans-impedance amplifier converts the PD’s output current to a voltage signal as required by the ADC. The incoming light from the transmitter must fall within the FoV of the PD in order to successfully recover the transmitted data. To achieve that, most VLC receivers use convex lenses as etendue reducers to collect and focus the incoming light onto the PD. However, as discussed in [85], using a convex lens can result in up to 30% losses in the incident light power due to reflection at the lens’s upper surface.

The widely used PDs are the positive-intrinsic-negative (PIN) diode and avalanche PD (APD). PIN PDs offer faster response times and higher bandwidth, making them ideal for high-speed data transmission, but they lack internal gain. In contrast, APDs provide higher sensitivity and an internal gain mechanism through avalanche multiplication, allowing them to detect weaker signals effectively, although at the expense of slightly slower response times and lower bandwidth than PIN PDs. The materials used for PIN PDs and APDs include silicon, indium gallium arsenide, and indium gallium arsenide phosphide [17]. In addition to PDs, optical cameras can be used to detect modulated light signals by capturing the spatial distribution of light intensity and using image processing techniques to decode the transmitted data. Although cameras provide wide coverage, spatial information, and imaging capabilities, making them suitable for broader communication coverage and NLOS communication, PDs offer simplicity, high-speed data rates, and cost-effectiveness, making them ideal for VLC systems.

Unlike VLC transmitter design where the type of LED used mainly distinguishes the various transmitters, the structure of a typical VLC receiver remains basically the same irrespective of the type of LED used. Specifically, many fundamental components (e.g., PD, amplifier, filter, etc.) and their functionalities remain similar across various types of transmitters. The only difference would be the filter type and the required number of PDs. For example, a multi-color transmitter would need multiple filters and PDs sensitive to different colors while a single color transmitter would only require a PD and a filter.

4) FSO Transceiver Design: FSO transmitters consist of an optical source, modulator, beamforming optics, and optical amplifier. Usually, the optical source is an LD that emits coherent light in a focused and collimated beam, making them ideal for long-distance transmission. However, high-power LEDs with beam collimators can also be used. LDs types vary in construction, operating principles, and applications. The three most common types are:

- **Edge-Emitting LDs**: Edge-Emitting LDs (EELDs), also known as Fabry-Perot LDs, operate based on the principle of stimulated emission, producing a highly focused and collimated beam between two end facets with high reflectivity and output. They offer high output power and efficiency, enabling long communication ranges with a narrow beam, making them well-suited for medium to long-range point-to-point communication. They are often deployed in outdoor FSO links for backhaul connections and are well-suited for applications requiring reliable and efficient data transmission in various weather conditions. However, EELDs are more complex and expensive to manufacture than other laser types, and their wavelength tunability is relatively limited (635 nm - 1500 nm).

- **Vertical-Cavity Surface-Emitting Lasers (VCSELs)**: VCSELs also operate on the principle of stimulated emission but have a distinct design compared to EELDs. In VCSELs, light is emitted perpendicular to the surface of the semiconductor wafer, facilitated by multiple pairs of distributed Bragg reflectors that form a resonant cavity. VCSELs provide an alternative to EELDs with advantages in easier fabrication, lower production costs, and efficient coupling to optical fibers due to their perpendicular emission. They also have high-speed modulation capabilities, making them ideal for short-range FSO systems, such as indoor or inter-building connections. However, VCSELs typically have lower output power than EELDs, and their emission wavelength range is narrower (850 nm - 1300 nm).

- **Distributed Feedback LDs**: Distributed Feedback LDs (DFBLDs) are specialized LDs that operate in the near-IR wavelength range, with typical operating wavelengths around 1310 nm and 1550 nm. DFBLDs utilize a dis-
tributed grating structure in their active region, providing distributed feedback for a specific wavelength, resulting in a single longitudinal mode emission. This property ensures a highly stable and coherent output, making DFB LDs ideal for high-capacity and long-distance FSO links. Their narrow linewidth enables spectral efficiency and reduces dispersion effects during propagation through the atmosphere. DFB LDs are employed for point-to-point communications, optical interconnects, and long-range data transmission, providing reliable and efficient optical links in various environmental conditions.

- **Quantum Cascade LDs**: Quantum Cascade LDs (QCLDs) represent specialized semiconductor LDs operating based on quantum mechanics principles. Unlike traditional lasers that rely on electron-hole recombination, QCLDs use inter-subband transitions within quantum wells to generate laser emission. Their advantages lie in wide wavelength coverage, high output power, and tunability over various wavelengths, primarily in the mid-IR and THz regions. Although QCLDs are not typically used for indoor or outdoor FSO communication, they have unique advantages for specialized FSO applications, i.e., in scenarios requiring wavelengths in the mid-IR and THz regions. QCLDs are more complex in design and fabrication, leading to higher costs than conventional LDs.

- **Photonic Crystal Surface-Emitting Lasers**: Most of the transmitters discussed above require the use of external elements such as lenses and telescopes for beam focusing and beam steering, and have not been capable of on-chip beam pattern, polarization, and direction control [86], [87]. The use of such external elements often make FSO transmitters bulky, which increases their complexity. The development of photonic-crystal surface-emitting lasers (PCSELs) offers a promising solution to overcome these limitations and enable the design of more compact and integrated solution. PCSELs leverage the unique properties of photonic crystals such its two-dimensional structure to manipulate properties of the laser beam, including its direction, polarization, and pattern. Although PCSELs have been explored in applications such as light detection and ranging and laser processing [88], its characteristics like single-mode coherent lasing, large emission areas, high-power operation, and excellent beam profiles, making them promising candidates for FSO communication systems. A recent study in [89] experimentally demonstrated the realization of these benefits in an FSO system for the first time, opening up new possibilities for FSO communication systems.

In comparison to the receiver front-end of a VLC system, an FSO receiver differs from that of a VLC system by using a receive telescope instead of a convex lens. Different from a convex lens that uses a single, curved lens to converge incident light rays to a focal point on the PD, the receive telescope generally consists of multiple lenses or mirrors which have been arranged to gather light over a larger area and focus it onto the PD [90]. In commercial FSO receivers, solid-state PDs are commonly used due to their suitable quantum efficiency for various wavelengths and wide availability. Two main types of PDs are employed: PIN PDs, which work well for distances of a few kilometers but are affected by thermal noise, and APDs, used for long distances but suffer from excess noise [17]. A newer and promising addition to the PD landscape is graphene PDs [91]–[93]. These devices boast broadband sensitivity, making them adaptable to various FSO applications with different wavelength requirements. Graphene PDs also exhibit high responsivity, efficiently converting incident light into electrical signals, which is crucial for detecting weak optical signals over long-range FSO links. Additionally, graphene’s fast response time ensures high-speed data transmission and low-latency communication in FSO systems. Due to graphene’s two-dimensional nature, the compact and flexible design possibilities facilitate seamless integration into diverse FSO setups. However, numerous challenges, including low quantum efficiency for specific wavelengths, high fabrication complexity, and poor environmental stability, require further investigation to optimize their performance fully.

### C. Existing Standardization Activities

#### 1) THz Standardization:

Standardization activities for THz communication are still in the early stages due to the relatively nascent nature of the technology. The various initiatives related to THz communication standardization are summarized as follows.

- **IEEE 802.15 THz Working Group**: The IEEE 802.15 group focuses on WPANs and is responsible for standardizing technologies like WiFi. The THz Working Group was formed to explore the possibilities of THz communication and identify potential requirements and use cases. The group published the first standard for wireless communications at the 300 GHz sub-THz band, capable of supporting data rates of up to 100 Gbps [94]. The standard targets wireless applications such as intra-device communication, proximity communication (e.g., device-to-device communications), wireless data centers, and backhaul/fronthaul links. It follows the MAC layer defined in IEEE 802.15.3e [95], supporting both single carrier and on-off keying (OOK) modes. While the THz-single carrier mode can support data rates of 100 Gb/s using eight distinct bandwidths between 2.16 GHz and 69.12 GHz, the THz-OOK has been designed for cost-effective devices that require low power, low complexity, and simple design and can support data rates between 1.3 Gb/s, using a single channel with a bandwidth of 2.16 GHz, and the maximum 52.6 Gb/s, using a bandwidth of 69.12 GHz.

- **International Telecommunication Union (ITU)**: ITU is actively studying THz communications’ spectrum requirements and usage. Active services’ spectrum allocation currently ends at 275 GHz, but bands from 275 to 1,000 GHz are assigned for passive services like earth exploration satellite services and radio astronomy [96]. Moreover, all frequencies between 1,000 and 3,000 GHz may also be used for active and passive services. To
enable THz communications over several tens of GHz bandwidth, active and passive services must share spectrum while taking all practicable steps to protect these passive services from harmful interference. To that end, the ITU radiocommunication sector (ITU-R) has been conducting studies to identify suitable frequency bands for THz communication while considering interference, propagation characteristics, and compatibility with other existing systems. In [97], ITU-R proposed reference data and mathematical models to estimate the attenuation levels at different frequencies (up to 1000 GHz) due to various atmospheric gases. The most recent report on the technical feasibility of international mobile telecommunications technologies in bands above 100 GHz focused on propagation mechanisms and channel models, as well as newly developed technology enablers such as active and passive components, antenna techniques, deployment architectures, and the results of simulations and performance tests [98].

- **High-Frequency Communications Initiatives:** In addition to the IEEE 802.15 THz working group and the ITU, the IEEE communications society radio communications committee special interest group on THz communications has been established, with one of its core mandates as promoting and supporting standardization activities on THz communications.

2) **VLC Standardization:** Several organizations have been involved in working on standards for VLC/LiFi. We briefly discuss the activities in the following.

- **IEEE 802.11bb Task Group:** The IEEE 802.11bb Task Group is dedicated to making vital enhancements to the core IEEE 802.11 standards, specifically focusing on the PHY and MAC layers, to enable seamless communication using the light medium. In July 2023, the organization achieved a significant milestone by publishing the IEEE 802.11bb standard for light-based wireless communications [99]. This groundbreaking standard accomplishes the following key objectives:

1) The standard defines precise modifications to the existing PHY and MAC layers, ensuring they are optimized for light-based communications.
2) The standard enables bidirectional communication in the 800 nm to 1000 nm band, providing a broad range of usability for VLC technology. It allows data rates ranging from a minimum of 10 Mbps to an impressive maximum of 9.6 Gbps, ensuring efficient data transfer over the light medium.
3) This standard facilitates interoperability among different solid state light sources, even those that vary in modulation bandwidths. This ensures seamless integration and compatibility between devices from different manufacturers.

- **IEEE 802.15.7 Task Group:** The IEEE 802.15.7 Task Group has launched and developed several standards that define modulation techniques, encoding schemes, and data rates for VLC technology. These standards include the 2011 approved version IEEE Std 802.15.7-2011, IEEE standard for local and metropolitan area networks–Part 15.7: Short-range wireless optical communication using visible light [100], and the approved revised version IEEE 802.15.7-2018 [101]. Note that this was after significant revisions of various drafts (e.g., [101], [102]). Compared to the original version of IEEE 802.15.7, which has three PHY categories, the IEEE 802.15.7-2018 divides the VLC PHY into six: PHY I for outdoor applications requiring low data rate (11.6 - 266.6 kbps); PHY II for outdoor and indoor applications requiring high data rate (1.25 - 96 Mbps); PHY III to support VLC systems with multiple APs and receivers and can support data rates of 12 - 96 Mbps; PHY IV

<table>
<thead>
<tr>
<th>Feature</th>
<th>VLC</th>
<th>mmWave</th>
<th>THz</th>
<th>FSO</th>
<th>Sub 6 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>400-800 THz</td>
<td>30-300 GHz</td>
<td>0.1-10 THz</td>
<td>190 THz - 382 THz</td>
<td>Sub-6 GHz</td>
</tr>
<tr>
<td>Licensed or unlicensed?</td>
<td>Unlicensed</td>
<td>Mixed</td>
<td>Mixed</td>
<td>Unlicensed</td>
<td>Licensed</td>
</tr>
<tr>
<td>Noise sources</td>
<td>Thermal noise</td>
<td>Shot noise</td>
<td>Ambient light</td>
<td>Thermal noise</td>
<td>Molecular absorption noise</td>
</tr>
<tr>
<td>Interference</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Security</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Coverage</td>
<td>Limited</td>
<td>Limited</td>
<td>Limited</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Multipath effects</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>EM field exposure risk</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>LEDs/LDs and PDs</td>
<td>Antenna</td>
<td>Antenna</td>
<td>LEDs/LDs and PDs</td>
<td>Antenna</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Mobility support</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Services</td>
<td>Illumination</td>
<td>Ultra high capacity wireless transmission</td>
<td>Ultra high capacity wireless transmission</td>
<td>Ultra high capacity wireless transmission</td>
<td>Limited speed wireless transmission</td>
</tr>
<tr>
<td>Limitations</td>
<td>Blockages</td>
<td>Device orientation</td>
<td>Limited FoV</td>
<td>Blockages</td>
<td>Atmospheric conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Attenuation by atmospheric conditions</td>
<td>Beam misalignment</td>
</tr>
</tbody>
</table>

### TABLE IV
**A Comparison Among Various Spectrum Bands in a Multi-band Wireless Network**

This article has been accepted for publication in IEEE Transactions on Communications. 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/TCOMM.2024.3366816

Authorized licensed use limited to: KAUST. Downloaded on February 18,2024 at 10:26:53 UTC from IEEE Xplore. Restrictions apply.

© 2024 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.
is intended for use with discrete light sources with data rates up to 22 kbps; PHY V is intended for use with diffused surface light sources with data rates up to 5.71 kbps; and PHY VI is intended for use with video displays with data rates in kbps [103]. These standards defined three classes of VLC devices, namely, infrastructure (has an unconstrained form factor and ample power supply), mobile (has constrained form factor and limited power supply), and vehicle (has unconstrained form factor and moderate power supply).

- **IEEE 802.15.13 Task Group**: The IEEE 802.15.13 multi-Gbps optical wireless communications Task Group defines a new standard for the PHY and MAC layers in optical wireless communications, utilizing light wavelengths ranging from 10,000 nm to 190 nm in optically transparent media [104]. This standard supports data rates of up to 10 Gbps over distances of approximately 200 m in unrestricted LoS and is designed for point-to-point and point-to-multi-point communications, accommodating both non-coordinated and coordinated topologies. In coordinated topologies, multiple peer coordinators will have a master coordinator. The standard also incorporates adaptive features to handle varying channel conditions and maintain connectivity while moving within the range of a single coordinator or transitioning between different coordinators. Unlike the IEEE 802.17.7, this standard targets industrial applications that require secure, high-performance, long-range optical camera communication (up to 200m) and high-speed VLC (up to 10 Gbps).

- **VLC Consortium**: The VLC Consortium (VLCC) together with the Japan Electronics and Information Technology Industries Association (JEITA) proposed the CP-1221 (for VLC systems), CP-1222 (for visible light identification system), and CP-1223 (for visible light beacon system) standards to avoid fragmentation and proprietary protocols, and to avoid interference between different optical communication equipment [105]. Light in the range of 380 to 750 nm is used for all three, and many recommendations for the PHY are specified in JEIPA CP-1222.

3) **MmWave Standardization**: Multiple international organizations have developed standards for mmWave communications. We review the various standardization activities by different organizations as follows.

- **European Computer Manufacturers Association (ECMA)**: developed the ECMA-387 standard [106], defining PHY, MAC, and HDMI protocol adaptation layer protocols for high-speed wireless communication at 60 GHz, particularly for multimedia applications and HDMI connectivity. The standard also defines two types of referred to as Type A and Type B. Type A is positioned as the high-end, high-performance device, boasting a wide array of advanced features such as high data rates (up to 6.35 Gbps), extended communication range, robustness against multipath interference, and support for adaptive antenna arrays, allowing for optimized signal reception. Additionally, Type A devices offer multi-level QoS capabilities, ensuring efficient data prioritization for diverse applications. On the contrary, Type B devices are tailored for handheld devices and prioritize simplicity, low power consumption, and cost-effectiveness. It can support data rates of up to 1.588 Gbps. Both devices can coexist and interoperate with each other seamlessly, and can also operate independently.

- **IEEE 802.15.3 Task Group 3c**: The IEEE 802.15.3c Task Group focuses on developing a mmWave-based alternative PHY layer for the existing IEEE 802.15.3 WPAN standard. Up to date, a few drafts of these standards have been approved including IEEE 802.15.3-2016 for 2.4 GHz and 60 GHz high data rate (over 200 Mbps) wireless connectivity for fixed, portable, and moving devices [107], IEEE 802.15.3e-2017 for up to 100 Gbps data rates using 60 GHz band MIMO and aggregation methods for close proximity point-to-point communications [95], IEEE 802.15.3d-2017 to support data rates of up to 100 Gbps for switched point-to-point links operating in the frequency ranges 2.16-69.12 GHz and 252-325 GHz [94], IEEE 802.15.3f-2017 to extend the PHY specification for mmWave to operate from 57 GHz to 71 GHz [108], and finally, the active draft P802.15.3-Rev.B/D6.0 for 2.4 GHz, 60 GHz, and 300 GHz radio transmissions [109].

- **IEEE 802.11 Task Group ad**: The IEEE 802.11ad standardization group developed the 802.11ad [110], which defines modifications to both the 802.11 PHY and the 802.11 MAC layers to enable operation in the 60 GHz frequency band capable of very high data rate (up to 7 Gbps) [110]. An improvement of this standard by defining new PHY and MAC specifications that can support 100 Gbps data rate by using several technical advancements such as MIMO, channel bonding, improved channel access, and enhanced beamforming training resulted in the IEEE 802.11ay [111].

- **WirelessHD Consortium**: This group developed the WirelessHD specification that enables high-definition video and audio streaming over the 60 GHz frequency band. It defines a novel wireless protocol that enables consumer devices to create a wireless video area network that operates at 60 GHz [112].

- **European Telecommunications Standards Institute (ETSI)**: The ETSI developed the following standards: EN 302 567 for radio equipment with integral antennas operating indoors or outdoors at data rates of multiple Gbps in the 60 GHz frequency range [113], EN 302 217 for point-to-point links and standalone antennas (that do not use integral antennas) operating on frequency bands of up to 86 GHz [114], and EN 302 326 for multipoint links and SA or integral antennas operating on frequency bands of up to 35 GHz [115], and EN 301 215 for point-to-multipoint systems operating in 24 GHz to 30 GHz range [116].

4) **FSO Standardization**: Different standardization bodies have developed various standards for indoor, terrestrial (i.e., outdoor), and space FSO links as highlighted below:
• **Infrared Data association**: The IR data association (IrDA), formed in 1993 [117], created several standards for half-duplex indoor LoS FSO links, including the serial IR, medium IR, fast IR, very fast IR, ultra fast IR, and gigabit IR standards. These standards are for 6 - 100 cm FSO links that operate at 850-900 nm and can support data rates up to 1.024 Gbps [36].

• **IEEE 802.11 Working Group**: In addition to the IrDA, IEEE has also made several standardization efforts for FSO. The IEEE 802.11 standard was developed for data rates of 1 and 2 Mbps – corresponding to a 16 and 4 pulse position modulation scheme, respectively–using IR signals [103]. The standard was developed for indoor NLOS links with a link range of 10 m, and for transmission in the range of 850 nm to 950 nm. Note that IEEE discontinued the IR version of 802.11 in 1999 and, since then, it has released WLAN standards that use radio waves.

• **ITU**: Though the IrDA and IEEE standards were centred around indoor OWC links, the ITU has focused more on terrestrial links. Specifically, the ITU recommendations ITU-R P.1814-0 [118] and ITU-R P.1817-1 [119] considered power budgets of LoS FSO links and emphasized the importance of considering environmental factors like weather conditions, physical obstructions, and transceiver mounting arrangements in FSO communication set up. The ITU-R P.1817-1 discussed protocols for predicting propagation parameters necessary for planning FSO links, and detailed visibility measurement at the maximum intensity of the solar spectrum (i.e., around 550 nm). The ITU-R F.2106-1 [120] covered recommendations for fixed service scenarios using FSO point-to-point LoS links. Laser diodes with transmission power of order 10 mW were used, with wavelengths in the ranges of 1300 nm to 1500 nm and 780 nm to 800 nm being used.

• **Interagency Operations Advisory Group-14**: For space applications of FSO, the Optical Link Study Group (OLSG) defined the requirements for the ground terminal solution that maximize the data returned for various mission scenarios, and analyzed the effects of weather and aviation interference using 1550 nm and 1064 nm wavelengths.

• **International Electrotechnical Commission (IEC)**: has published the following standards on laser safety.

1) IEC 60825-1:2014 [121]: This standard provides guidance on the classification of laser products and specifies safety requirements for their design and use. It categorizes lasers into different classes based on their potential hazards, and it outlines safety measures and warning labels required for each class.

2) IEC 60825-2:2004+A1:2006+A2:2010 [122]: This standard specifically addresses safety requirements for optical fiber communication systems that use lasers for transmitting information. It defines the safety precautions and measures that must be taken during the installation, operation, and maintenance of optical fiber communication systems to prevent harm to personnel and surroundings.

3) IEC 60825-12:2004 [123]: This standard focuses on the safety requirements for FSO communication systems. It outlines safety guidelines for the design, installation, operation, and maintenance of FSO systems to ensure the protection of users and the public from laser hazards.

**D. Advancement of Experimental and Simulation Testbeds**

1) **THz/mmWave**: Focusing on THz signal generation, Bell Labs experimentally demonstrated data rates of up to 2.5 Gbps for a transmission distance of 0.2 m, a carrier frequency of 625 GHz, and transmit power of 1 mW by using duobinary baseband modulation and a Schottky diode at the receiver side [124]. In [125], the authors showed a high-speed data transmission rate of 64 Gbps over 850 nm fixed wireless link at 240 GHz carrier frequency. The transmission utilized quadrature phase shift keying (QPSK) and 8-phase shift keying (PSK) modulation techniques in a single-channel approach without spatial diversity concepts.

In [126], the authors demonstrated data rates of up to 5 Gbps at 140 GHz for a transmission distance of 21 km using two Cassegrain antennas with 50 dBi gain each and 16 quadrature amplitude modulation (QAM). In [127], [128], the authors presented a single-input and single-output single and multi-carrier 100 Gbps wireless system operating at 237.5 GHz over a distance of 20 m. The modulation schemes considered were 16QAM, QPSK, and 8QAM. In [129], the authors successfully demonstrated a 120 Gbps QPSK-based MIMO wireless system operating within 375 GHz to 500 GHz for a transmission distance of over 10 km. An experimental demonstration of a QPSK-based MIMO system operating at 340-510 GHz and capable of achieving a data rate of 100 Gbps for a transmission distance of 3 m was done in [130]. The authors in [131] reported an experimental demonstration of a 64QAM, 320-380 GHz band THz wireless system capable of achieving data rates of up to 612.65 Gbps over a 2.8 m wireless distance.

In [132], the authors proposed a simplified THz receiver design based on the Kramers-Kronig method for optical communications. They demonstrated experimentally that this new receiver could offer data rates of 115 Gbps at a frequency of 300 GHz over a link distance of 110 m. By using suitable dielectric lenses and digital signal processing algorithms, the authors in [133] demonstrated data rates of up to 124.8 and 44.8 Gbps for transmission distances of 54 and 104 m, respectively, for a 64QAM THz wireless system that does not use THz amplifier. In [134], the authors proposed and experimentally demonstrated a wireless transmitter that uses a single photo-mixer to support simultaneous multiple transmissions over millimeter and terahertz channels (i.e., 40 to 510 GHz).

Certain introduced platforms necessitate costly or readily available commercial equipment. For instance, to assess the performance of 60 GHz IEEE 802.11ad systems, a solution involving multipath TCP is put forth, wherein protocol control is confined to reprogramming the devices’ firmware is proposed in [135]. While manipulating low-level codes enables
beam control, the overall programmability remains confined to specific tasks [136]. In contrast, makeshift configurations can be established through custom-designed testbeds for small-scale experimental setups, empowering researchers with control over both the communication stack and devices. A testbed named OpenMili, outlined in [137], leverages open-source software and hardware along with FPGAs. This framework provides a bandwidth of 1 GHz and a modifiable protocol stack while allowing for a customizable phased array. OpenMili has demonstrated its utility in applications involving integrating sub-6 GHz and 60-GHz transmissions.

An experimental platform for mmWave and THz (60-240 GHz) signal transmission, named MilliMere, has been developed in [138]. This open-source testbed offers a scalable, versatile, programmable, and affordable approach for end-to-end wireless transmissions as compared to the earlier works (e.g., [135], [136], [139]). Moreover, TeraSim and TeraNova, open-source network simulation platforms for THz wireless networks, have been developed in [140] and [141], respectively. While TeraSim is a built-in extension for the ns-3 simulator and is typically used for nanoscale communication networks (average transmission range usually below one meter) and macroscale communication networks, TeraNova is an integrated testbed for ultra-broadband communication networks.

2) VLC: In the realm of experimental studies on VLC, the study mentioned in [142] introduced an approach centered around camera on-off keying (OOK) combined with MIMO technology. Unlike the conventional zero-crossing filter, the MIMO-OOK scheme capitalizes on a matched filter. Notably, this scheme attains a bit error rate of 0.1 at a distance of 20 meters. In [143], researchers perform tests on a non-imaging VLC setup, employing a receiver of five photodetectors (PD) with a cubic configuration and using four LEDs as transmitters. By implementing OFDM and employing algorithms for bit and power allocation, the experimental outcomes showcase a spectral efficiency of 14.5 bit/s/Hz, and the attained maximum multiplexing gain reaches as high as 2.134.

The work in [144] investigates multi-hop vehicular VLC systems through practical experiments conducted during daytime and nighttime scenarios. In these experiments, two vehicles are positioned 20 meters apart. The findings reveal that PD become saturated during specific daylight hours in the daytime experiment. Additionally, the performance of BER is notably influenced by background noise in the daytime experiment, whereas it remains relatively stable during the nighttime experiment. In [145], the researchers investigate a multi-user MIMO LiFi system within a hospital’s operating room, employing four strategically positioned transmitters and six distributed receivers. A range of multiplexing strategies, comprising TDMA, TDMA with spatial reuse, and SDMA with and without ZF, are implemented during the experimental phase. The outcomes illustrate that SDMA with ZF can enhance the data rate by a factor of 2.7 compared to TDMA, resulting in a data rate achievement of 600 Mbps.

Experimental setups for VLC can vary based on the specific experiment and objectives. In [146], the testbed employs a Dell server R740 for signal processing tasks such as precoding, FFT, and windowing. The 5G RF front end is managed using a USRP 2944R, while the VLC transmission is facilitated through LEDs linked to a control board. The work in [147] introduces a simulation implementation for IEEE802.15.7 PHY using the OMNET++ simulation tool. In [148], the authors introduced a simulation program using MATLAB and SIMULINK designed explicitly for indoor VLC. This framework can compute received signal waveforms, illumination distribution, and RMS delay spread. In [149], Zemax is employed to simulate the environment, and the authors establish a channel model for VLC to capture diverse channel responses across various indoor scenarios. These suggested frameworks are not available as open-source solutions, which can create difficulties for researchers to utilize them.

The authors of [150] utilized GNURadio, an open-source toolkit renowned for signal processing and software-defined radios. Alongside GNURadio, they integrated the low-frequency transmitters (LFTX) and receivers (LFRX) from USRP-N210 as the interface for the VLC front end, effectively replacing conventional RF components with optical transmitters and PDs. In [151], [152], the authors developed an open-source, flexible, and low-cost VLC general-purpose software-defined research platform called OpenVLC. This platform comprises a BeagleBone Black board, a VLC front-end transceiver, and a Linux-based software-defined system implementation. The front-end transceiver adopts a single LED and a few basic electronic components for transmission and reception. The transmitter and receiver modes can be switched using a tri-state buffer in the front-end circuit.

3) FSO: A hardware testbed emulator for satellite-to-ground FSO downlinks that allows real-time evaluation of the weather effects and performance tests of various PDs was developed in [153]. For this testbed, the atmospheric scintillation data were obtained from the Radiosonde Observation databases combined with a statistical design approach and the cloud attenuation was introduced using Mie theory together with empirical Log-Normal modeling. A self-constructed breadboard is employed to validate the performance of a photon-starved FSO system in [154]. The testbed incorporates a 2-array superconducting nanowire single-photon detector receiver unit. To simulate real free space in laboratory conditions, narrowband optical fiber couplers are employed. Additionally, the master oscillator power amplifier unit, a component utilized in deep-space terminals, consists of a continuous wave DFB laser operating at 1550 nm. The study notes that performance can be enhanced by utilizing a superconducting nanowire single-photon detector with an array greater than 16. A software-defined experimental testbed for analyzing the impact of various atmospheric conditions (mainly fog and turbulence-induced attenuation and geometric losses) on the performance of medium-to-long FSO links was proposed in [155]. A software-defined experimental testbed for analyzing the impact of various atmospheric conditions (mainly fog and turbulence induced attenuation and geometric losses) on the performance of medium-to-long FSO links was proposed in [155].

A hybrid FSO/RF testbed based on enhanced gated recurrent unit neural network channel prediction scheme to reduce the...
link switching frequency and link interruption duration was explored in [156]. In [157], a similar hybrid FSO/RF system is examined. An upper computer control system (UCCS) generates transmitting data and controls the link switching via serial-port communications. To address FSO link turbulence, a 2-by-1 optical link with a 1550 nm wavelength transmits the same data, and the RF component employs a 16-QAM modulator. For power control, a module integrates switch management, UCCS, lower computer control system, and an erbium-doped fiber amplifier (EDFA). The UCCS adjusts the transmitting power by modifying the EDFA’s power gain. A Meteorological Environmental Simulating Chamber is used to emulate channel conditions, incorporating factors such as natural illumination, temperature, humidity, partial pressure, and wind speed. The FSO receiver’s lens captures optical signals, and the UCCS obtains the received signal strength indicator. Additionally, a feedback laser with a 980 nm wavelength sends the received signal strength indicator back to the transmitter. Data recovery involves sending the optical signal to an EDFA and optical-electrical converter, and then the demodulated and filtered signal to the UCCS.

E. Summary and Lessons Learned

This section discussed the general characteristics and applications of THz, mmWave, VLC, and FSO spectrum bands and state-of-the-art approaches to their transceiver designs. Specifically, the main approaches for THz transceiver design are electronic, photonic, and plasmonic solutions. The design methodologies used for mmWave transceivers are quasi-optical antenna design, phased array antenna design, and planar antenna design. Since VLC and FSO transceivers use light sources and PDs, which are commercially available and relatively mature technology, we discussed the various LED types and PDs. Although THz transceiver design based on graphene-based antennas is more promising, this area has received little attention. For VLC applications that require high sensitivity, especially in low-light conditions, APDs would be a better choice at the expense of added complexity and potential nonlinearities. On the other hand, if the VLC system designer prioritizes lower noise, linearity, and cost-effectiveness, a PIN diode might be more suitable. This section further revealed that existing PAs for higher frequency bands have primarily been designed for sub-THz bands and not for true THz. Finally, it is of utmost importance to develop open-source software-defined simulation testbeds that support the analysis of MBN.

III. FUNDAMENTALS OF CHANNEL PROPAGATION AND CHALLENGES

This section presents various mathematical channel models that capture the channel characteristics and propagation phenomena in different frequency bands. Specifically, this section examines recent channel models and characteristics for propagation mmWave, VLC, FSO, and THz signals.

A. MmWave Spectrum Band

Different standardization bodies have investigated various mmWave channel models for indoor, outdoor, urban or rural scenarios. Table-V depicts an overview of the channel modelling works by organizations/projects such as The 3rd Generation Partnership Project (3GPP TR 38.901) [158], 5G channel model-special interest group (5GCM-SIG) [159], mobile and wireless communications enablers for the twenty-twenty information society (METIS) [160], mmWave evolution for backhaul and access (MiWEBA) project [161], ITU-R Mobile, radiodetermination, amateur and related satellite services (ITU-R M) [162], New York University (NYU) wireless [163], [164], the IEEE 802.11 Task Group ay [165], the mmWave-based mobile radio access network for 5G integrated communications (mmMAGIC) project [166], and the QUasi-Deterministic Radio channel Generator (QuaDRiGa) by the Fraunhofer Heinrich Hertz Institute [167], [168]. In mmWave frequencies, the presence or absence of LoS can significantly affect the propagation characteristics due to the high sensitivity of these signals to obstacles. The PL of a mmWave link can generally be given as [169]:

$$PL(d) = \mathbb{B}(\delta) PL_{LoS}(d) + (1 - \mathbb{B}(\delta))PL_{nLoS}(d),$$

where $\delta = P_{LoS}(d)$ represents the probability of establishing a LoS link between the transmitter and the receiver which depends on their distance and the environment, and $PL_{LoS}(d)$ and $PL_{nLoS}(d)$ denote the PL of LoS and nLoS links, respectively. The parameter $\mathbb{B}(\delta)$ is a Bernoulli random variable. The expressions for $P_{LoS}(d)$, $PL_{LoS}(d)$, and $PL_{nLoS}(d)$ according to the 3GPP and 5GCM are discussed below. Note that details on the remaining channel models are not provided as some are either based on the theoretical foundations of 3GPP/5GCM models (e.g., METIS, mmMAGIC, ITU-R, NYU, QuaDriGa) or are limited to specific scenarios and frequency range (e.g., MiWEBA). Thus, the major difference could be the parameter values. Moreover, NYU Wireless and QuaDriGa provide open source mmWave wireless channel simulators. Furthermore, the IEEE 802.11ad/ay models are for mmWave WLANs.

1) 3GPP Channel Model in TR 38.901: The PL models (i.e., LoS and nLoS) and the LoS probability for various rural, urban, and indoor scenarios are summarized in Table 7.4.1-1 and Table 7.4.2-1, respectively, of [158]. The 3GPP channel model also account for outdoor-to-indoor building penetration loss. By considering penetration loss, the total PL of a mmWave link can be given as:

$$TPL = PL + PL_{tw} + PL_{in} + N(0, \sigma_p),$$

where $PL_{tw}$ is the building penetration loss through external wall, $PL_{in}$ is the inside loss dependent on the depth into the building, and $\sigma_p$ is the standard deviation for the penetration loss. The parameter $PL_{tw}$ can be modeled as:

$$PL_{tw} = PL_{npi} - 10\log_{10} \sum_{i=1}^{N} p_i \times 10^{\frac{L_{material}}{10}},$$

where $PL_{npi}$ is an additional loss due to the external wall loss for non-perpendicular incidence, $L_{material}$ is the penetration loss of material $i$, and $p_i$ is the fraction of material $i$ out of $N$ materials, where $\sum_{i=1}^{N} p_i = 1$. 
TABLE V
COMPARISON OF mmWAVE CHANNEL MODELS

<table>
<thead>
<tr>
<th>Channel Modeling Work</th>
<th>Frequency Range</th>
<th>Approach</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP TR 38.901</td>
<td>0.5 - 100 GHz</td>
<td>Stochastic &amp; Deterministic</td>
<td>Urban, Rural, Indoor, Outdoor; Supports bandwidth of up to 10% of center frequency but no larger than 2 GHz</td>
</tr>
<tr>
<td>5G Channel Model (5GCM)</td>
<td>0.5 - 100 GHz</td>
<td>Stochastic &amp; Deterministic</td>
<td>Urban, Open square, Indoor, Outdoor; Supports bandwidths in the range 100 MHz to 2 GHz</td>
</tr>
<tr>
<td>METIS Channel Models</td>
<td>6 - 100 GHz</td>
<td>Stochastic &amp; Deterministic</td>
<td>Urban, Rural, Indoor, Outdoor; Supports bandwidth of up to 10% of center frequency but no larger than 1 GHz</td>
</tr>
<tr>
<td>MiWEBA Channel Models</td>
<td>57 - 66 GHz</td>
<td>Quasi-deterministic</td>
<td>University campus, street canyon, hotel lobby, backhaul/fronthaul, D2D; Supports bandwidth of up to 800 MHz</td>
</tr>
<tr>
<td>ITU-R M Channel Models</td>
<td>0.5 - 100 GHz</td>
<td>Stochastic &amp; Deterministic</td>
<td>Urban, Rural, Indoor; Bandwidth of up to 10% of the center frequency</td>
</tr>
<tr>
<td>NYU WIRELESS Models</td>
<td>28 - 100 GHz</td>
<td>Empirical &amp; Stochastic</td>
<td>Various Scenarios; Urban, Rural, Indoor, Outdoor; Supports bandwidth of up to 1 GHz</td>
</tr>
<tr>
<td>802.11 ad/ay Models</td>
<td>45 - 65 GHz</td>
<td>Stochastic &amp; Deterministic</td>
<td>Indoor, Outdoor, D2D; Supports bandwidth of up to 2.16 GHz</td>
</tr>
<tr>
<td>mmMAGIC</td>
<td>6 - 100 GHz</td>
<td>Empirical &amp; Stochastic</td>
<td>Urban, Outdoor, Indoor; Supports bandwidth of up to 2 GHz</td>
</tr>
<tr>
<td>QualDRiGa</td>
<td>0.45 - 100 GHz</td>
<td>Empirical &amp; Stochastic</td>
<td>Indoor, Outdoor, Satellite; Supports bandwidth of up to 1 GHz</td>
</tr>
</tbody>
</table>

2) 5GCM-SIG Channel Model: Three PLs models are proposed by the 5GCM-SIG; namely the close-in (CI) free space reference distance PL model, the CI free space reference distance model with frequency-dependent PL exponent (CIF) and the Alpha-Beta-Gamma (ABG) PL model. The CI PL model is given as:

\[
\text{PL}^{\text{CI}}(f_c, d_{3D})[\text{dB}] = \text{FSPL}(f_c, 1\text{m}) + 10n \log_{10}\left(\frac{d_{3D}}{1\text{m}}\right) + X^{\text{CI}}_{\sigma},
\]

where \( f_c \) is the center frequency in GHz, \( n \) is the PL exponent, \( d_{3D} \) is the 3D distance in m, \( X^{\text{CI}}_{\sigma} \) is the shadow fading term in dB that is modeled as a zero mean Gaussian random variable with the standard deviation \( \sigma \), and \( \text{FSPL}(f_c, 1\text{m}) \) is the free space PL (FSPL) at 1 m and frequency \( f_c \) and is calculated by:

\[
\text{FSPL}(f_c, 1\text{m}) = 20 \log_{10}\left(\frac{4\pi f_c \times 10^9}{c}\right) = 32.4 + 20 \log_{10}(f_c) [\text{dB}].
\]

The CIF model, an extension of the CI model that uses a frequency-dependent PL exponent, is given as:

\[
\text{PL}^{\text{CIF}}(f_c, d_{3D})[\text{dB}] = \text{FSPL}(f_c, 1\text{m}) + 10n \log_{10}\left(1 + b \left(\frac{f_c - f_0}{f_0}\right)\right)\left(\frac{d_{3D}}{1\text{m}}\right) + X^{\text{CI}}_{\sigma},
\]

where \( b \) is an optimization parameter that captures the slope, and \( f_0 \) represents the weighted frequencies of all measurement (or Ray-tracing) data applied to the model. The ABG PL model is given as:

\[
\text{PL}^{\text{ABG}}(f_c, d_{3D})[\text{dB}] = 10\alpha \log_{10}(d_{3D}) + \beta + 10\gamma \log_{10}(f_c) + X^{\text{ABG}}_{\sigma},
\]

where \( \alpha \) captures how the PL increases as the distance gets higher, \( \beta \) is a floating offset value in dB, \( \gamma \) models the PL variation over \( f_c \), and \( X^{\text{ABG}}_{\sigma} \) is the shadow fading term in dB. The parameters of the CI, CIF, and ABG PL models for different environments (i.e., scenarios and LoS/nLoS conditions) have been provided in Table 6 of [159]. Note that the penetration loss and the LoS probability for different scenarios of the 5GCM-SIG follows the same model of the 3GPP TR38.901.

B. VLC Spectrum Band

Figure 2 depicts the geometry of a LoS propagation for a VLC system. In this figure, the LoS path of the transmitter and the receiver is the straight line between them, and the corresponding Euclidean distance is denoted as \( d \). The angles of irradiance and incidence related to the LoS path are denoted by \( \phi \) and \( \vartheta \), respectively. At the transmitter side, the Lambertian emission pattern follows a cosine dependence on the irradiance angle \( \phi \). The intensity is highest for emission normal to the LED surface (i.e., for \( \phi = 0^\circ \)). At an angle of \( \phi_{1/2} \) which is the LED’s semi-angle at half power, the intensity decreases to half of its maximum value [170]. At the receiver side, the detection of a single PD is modeled by means of a Lambertian detection pattern. Similar to the LED, the FoV of a PD, \( \vartheta_{\text{FoV}} \), is defined as the angle between the points on the detection pattern, where the directivity is reduced to 50% [171].

The VLC channel suffers from optical PL and multi-path induced dispersion, and the configuration of the VLC system typically determines how the channel impacts the transmitted signal. For LoS configurations, the reflected light components do not need to be considered. Consequently, the VLC channel is impacted by PL which can be easily calculated from the knowledge of the transmitter beam divergence, receiver size,
and separation distance between the transmitter and receiver. By considering Fig. 2, the LoS channel gain is given by [172]:

$$G_{\text{LoS}} = \left\{ \begin{array}{ll}
\frac{(m+1)A_{\text{PD}}}{2\pi d^2} \cos^m(\phi) T(\vartheta) G(\vartheta) \cos(\vartheta), & 0 \leq \vartheta \leq \vartheta_{\text{FoV}} \\noalign{\vspace{1mm}}
0, & \text{otherwise,}
\end{array} \right. \quad (8)$$

where $m = -1/\log_2 \left(\cos(\Phi_{1/2})\right)$ is the Lambertian index, $A_{\text{PD}}$ is the physical area of the PD, and $T(\vartheta)$ and $G(\vartheta)$ are the gains of the optical filter and the non-imaging concentrator, respectively. The gain of the concentrator can be expressed as $G(\vartheta) = f^2 / \sin^2 \vartheta_{\text{FoV}}, 0 \leq \vartheta \leq \vartheta_{\text{FoV}}$, where $f$ is the refractive index. (8), the link distance $d$ can be modelled in 2D [34], where the height of the receiver is considered to be fixed, or in 3D [173], where the height may vary, to better address the spatial random terminal locations inside the coverage volume of the transmitter. With regard to non-LoS configurations (which occur mainly in indoor deployments), reflections from wall surfaces and furniture need to be considered. According to [172], the optical power received from reflections more than once is negligible. As a result, only the signals from the LoS path and those from the first reflected links are typically considered. By focusing on the effect of reflective light by any wall surface $k$, the channel gain of the first reflection is given as [172]:

$$G_{\text{wall}k}^{\text{LoS}} = \left\{ \begin{array}{ll}
\rho_{\text{wall}} \frac{(m+1)A_{\text{PD}}}{2\pi d_k^2} \cos^m(\Phi_{k}) d_{k}^2 \cos \left( \phi_{k} \right) T(\vartheta_k) \cos(\vartheta_k) G(\vartheta_k), & 0 \leq \vartheta_k \leq \vartheta_{\text{FoV}} \\noalign{\vspace{1mm}}
0, & \text{otherwise,}
\end{array} \right. \quad (9)$$

where $\rho_{\text{wall}}$ denotes the reflection coefficient of the wall surface, $d_k^2$ is the distance between the AP and reflective surface $k$, $d_{k}^2$ is the distance between reflective surface $k$ and the user, $\Phi_{k}$ is the angle of irradiance from the AP to reflective surface $k$, $\vartheta_{k}$ is the angle of incidence on the reflective surface $k$, $\Phi_{k}$ is the angle of incidence from the reflective surface $k$ towards the user, and $\vartheta_{k}$ is the angle of incidence of the reflected signal from surface $k$.

Unlike the RF channel, VLC links do not suffer from the multipath fading since the receivers use PDs with a surface area typically of magnitude much bigger than the transmission wavelength. Another unique feature of the VLC channel is its susceptibility to blockages and shadowing as well as impact of the device’s orientation. Due to short wavelength of VLC signals, specific shadows are formed when the light signals encounter an opaque obstacle such as a human body. Thus, a receiver in the shadowed area will be in communication outage. With regard to the impact of device orientation, PDs have limited FoVs. This restricts the angle at which a PD can receive the optical signals as the angle of the incident light significantly affects the intensity of the received optical signal. While the angle of irradiance is not affected by the random orientation of the user’s device, the angle of incidence is highly influenced by it. It is shown in [175] that the cosine of the angle of incidence $\vartheta$ can be expressed in terms of the device’s polar angle $\alpha$ and the azimuth angle $\beta$ as:

$$\cos(\vartheta) = \left( \frac{x_u - x_a}{d} \right) \sin(\alpha) \cos(\beta) + \left( \frac{y_u - y_a}{d} \right) \sin(\alpha) \sin(\beta) + \left( \frac{z_u - z_a}{d} \right) \cos(\alpha), \quad (10)$$

where $(x_a, y_a, z_a)$ and $(x_u, y_u, z_u)$ denote the position vectors specifying the locations of the AP and the user, respectively.

Channel modeling in VLC can be categorized into deterministic and non-deterministic approaches. The deterministic approach predicts the behavior of the VLC channel with a high degree of accuracy by considering the physical properties of the environment and the light propagation characteristics. It involves detailed modeling of individual light paths and reflections, taking into account the geometry and materials of the surrounding surfaces, and uses recursive calculations [176]–[179], and geometric-optic-based techniques [180]–[182]. Non-deterministic channel modeling, specifically using the Monte Carlo ray-tracing technique [183]–[186], involves repeated random sampling to calculate impulse responses in VLC systems.

C. FSO Spectrum Band

Signal propagation in the FSO band suffers from two main channel impairments, namely, atmospheric losses and atmospheric turbulence detailed in the following.

**Atmospheric losses** in FSO refer to the reduction in signal power and quality due to the interaction of light with various gases, water vapor, pollutants like aerosols, dust, and smoke, in the Earth’s atmosphere during propagation. These losses include signal absorption and scattering, free space loss, beam divergence loss (i.e., geometric loss), and pointing loss. Signal absorption occurs when the signal energy is absorbed by the particles present in the atmosphere resulting in the loss of signal energy while scattering happens when signal energy is redistributed (or scattered) in arbitrary directions. Signal attenuation resulting from absorption and scattering effects can be described by Beer-Lambert law, which states that:

$$P_R = P_T e^{-\gamma(\lambda)L}, \quad (11)$$

where $P_T$ and $P_R$ are the transmitted power and received power at a distance $L$, respectively, and $\gamma(\lambda)$ is the coefficient.
(m\(^{-1}\)) for the attenuation due to absorption and scattering and is given as:

\[
\gamma(\lambda) = k(\lambda) + \alpha_{al}(\lambda) + \beta_{ml}(\lambda) + \beta_{al}(\lambda),
\]

where \(k, \alpha_{al}, \beta_{ml}\) and \(\beta_{al}\) are the molecular absorption coefficient, aerosol absorption coefficient, molecular scattering coefficient, and aerosol scattering coefficient, respectively. Often, FSO system wavelengths (i.e., transmission windows) are chosen in consideration of the atmospheric absorption spectra such that the absorption is minimal, and so absorption is negligible in comparison to the scattering effects. Typical transmission windows are 780-750 and 1520-1600 nm.

Thus,

\[
\gamma(\lambda) \approx \beta_{ml}(\lambda) + \beta_{al}(\lambda),
\]

On the other hand, signal scattering depends on the size of the particles encountered during signal propagation and can be classified as Rayleigh scattering and Mie scattering. Rayleigh scattering occurs when the size of the particles encountered during propagation is smaller than the optical wavelength (e.g., air molecules), usually affect wavelengths of under 800 nm. According to [187], the simplified model for the estimate of Rayleigh scattering coefficient is:

\[
\beta_{ml}(\lambda) = 0.827N_pA_p^2\lambda^{-4},
\]

where \(N_p\) denotes the number of particles per unit of volume, and \(A_p\) denotes the cross-sectional area of scattering. Mie scattering is caused by aerosol particles that are larger or comparable to the optical wavelength. According to [188], the Mie scattering coefficient is modeled as:

\[
\beta_{al}(\lambda) = \frac{3.91}{V} \left(\frac{\lambda}{\lambda_0}\right)^{-q},
\]

where \(\lambda_0\) denotes the visibility reference wavelength, usually set as 550 nm, \(V\) denotes the visibility range in km, and \(q\) denotes the size distribution of the scattering particles which is given as follows:

\[
q = \begin{cases} 
0, & \text{for } V < 0.5 \text{ km}, \\
V - 0.5, & \text{for } 0.5 \text{ km} < V < 1 \text{ km}, \\
0.16V + 0.34, & \text{for } 1 \text{ km} < V < 6 \text{ km}, \\
1.3, & \text{for } 6 \text{ km} < V < 50 \text{ km}, \\
1.6 & \text{for } V > 50 \text{ km}.
\end{cases}
\]

Free space loss represents the attenuation of signal strength while propagating through free space. This is the largest contributor to signal energy loss in FSO communication systems and this loss is much higher than in RF systems due to the shorter wavelengths used. As the optical beam propagates through the atmosphere, it experiences beam divergence due to diffraction effects. This causes the beam to spread out over a larger area resulting in a decrease in the power density and beam divergence loss since the receiver has a narrow FoV. Pointing loss refers to the reduction in signal power or quality due to misalignment or pointing errors between the transmitter and receiver. This misalignment can be caused by both static (e.g., incorrect initial alignment during system setup) and dynamic factors (e.g., wind, vibration, thermal effects, or platform instability).

**Atmospheric turbulence** is the fluctuation of light intensity and phase caused by the movement of air in the Earth's atmosphere. When a laser beam propagates through the atmosphere, it encounters variations in temperature, humidity, and air pressure due to natural phenomena such as solar heating and wind, leading to the formation of turbulent eddies and pockets of air with different refractive indices. These variations cause the laser beam to experience random bending, spreading, and focusing of light, resulting in fluctuations in the intensity and phase of the received optical signal that can heavily impact system performance. These fluctuations are known as scintillation and are measured in terms of scintillation index (SI), defined as:

\[
s^2 = \frac{E[I^2]}{E[I]} - 1
\]

where \(I\) is the intensity of the received optical wave and \(E\{\cdot\}\) denotes the expected value [17]. Scintillation effects are often characterized by statistical models that represent intensity fluctuations caused by atmospheric turbulence. Common models for turbulence include the log-normal distribution and gamma-gamma distribution, depending on the severity and specific characteristics of the turbulence.

Lognormal distribution is the most commonly used model of irradiance owing primarily to its simplicity, despite its restriction to weak turbulence conditions. Lognormal distributions are also prone to underestimate behavior in the tails. The normalized irradiance is denoted as [35], [90], [187]:

\[
I = I_xI_y,
\]

where \(I_x\) and \(I_y\) represent large and small scale turbulent eddies, and both follow gamma distribution. The gamma-gamma PDF is given as [90]

\[
f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\alpha-1} \kappa_{\alpha-\beta}(2\sqrt{\alpha\beta I}), \quad I > 0,
\]

where \(\kappa_{m}(\cdot)\) is the modified Bessel function of the second kind and order \(m\). \(\alpha\) and \(\beta\) are the effective number of small and large-scale eddies of the scattering environment and are defined as:

\[
\alpha = \left[\exp\left(\frac{0.49\chi^2}{(1 + 0.18d^2 + 0.56\chi^{12/5})^{3/2}}\right) - 1\right]^{-1},
\]

\[
\beta = \left[\exp\left(\frac{-0.51\chi^2(1 + 0.69\chi^{12/5})^{-5/6}}{(1 + 0.9d^2 + 0.62d^2\chi^{12/5})^{3/2}}\right) - 1\right]^{-1},
\]

where the parameter \(\chi^2 = 0.5C_2^2\lambda^2/L^{11/6}\) is the Rytov variance which indicates the strength of the turbulence fluctuations and \(d = (kD^2/4L)^{1/2}\) is the circular aperture radius. The parameter \(k = 2\pi/\lambda\) is the optical wave number, \(D\) is the diameter of the lens aperture of the receiver, \(L\) is the link distance measured in m, and \(C_2^2\) is refractive index structure parameter whose values range from \(10^{-17} m^{-2/3}\) for weak turbulence to \(10^{-13} m^{-2/3}\) for strong turbulence. The Hufnagel-Valley model is the most commonly used parametric model to describe \(C_n^2\) and is given as [189]:

\[
C_n^2(h) = 0.00594(v/27)^2(10^{-5} 5)^{10} \exp(h/1000) + 2.7 \times 10^{-6} \exp(-h/1500) + A \exp(-h/1000)
\]
where $h$ is the altitude in m, $v$ is the rms wind speed in m/s, and $A = 1.7 \times 10^{-14} \text{ m}^{-2/3}$ and $A = 1.7 \times 10^{-14} \text{ m}^{-2/3}$ are the turbulence strengths at the ground level at daytime and night, respectively [190].

For strong turbulence regime, or when SI is 1, negative exponential (NE) distribution can be used for longer distance applications over a length of several km. The PDF of irradiance under the NE distribution is:

$$p(I) = \frac{1}{I_0} \exp(-I/I_0), \quad I_0 > 0$$

where $I_0$ is the mean irradiance. Another option for strong turbulence is the K-Distribution, the product of exponential and gamma distributions whose PDF is:

$$f(I_{mn}) = \frac{2^{\alpha_{mn}+1/2}}{\Gamma(\alpha_{mn})} \frac{I_{mn}^{\alpha_{mn}-1/2}}{I_{mn}} \times \kappa_{\alpha_{mn}-1}(2\sqrt{\alpha_{mn}I_{mn}}), \quad I_{mn} > 0$$

where $\alpha_{mn}$ is the parameter related to the number of scatterers, $\kappa_{\cdot}(\cdot)$ is the modified Bessel function of second kind of order $\cdot$, and $\Gamma(\cdot)$ is the Gamma function. The I-K distribution is modelled for weak to strong turbulence atmospheric conditions [90], [191]. I-G distribution is used in weak turbulence fading channels, and is an alternative to Log-Normal distribution [90], [192]. It is important to note that the I-K and I-G distributions are often considered for coherent FSO systems since they can more accurately model the statistical properties of the phase fluctuations introduced by atmospheric turbulence due to the presence of extra variables like the coherence and mean of fluctuation parameters [90], [193]. Double Weibull distribution is the product of 2 Weibull variables, which are random. It is used for moderate and strong atmospheric turbulence condition [194]. Exponentiated Weibull distribution is based on the Weibull distribution with an extra variable, and is best suited for weak and moderate turbulence [195]. Double generalized Gamma distribution is the product of two generalized Gamma distributions, and is suitable for all turbulence conditions [193]. A summary of these models is provided in Table VI.

D. THz Spectrum Band

THz propagation suffers from high free-space PL, which significantly reduces the power of the transmitted wave as the distance between the source and receiver increases. The well-known Friis transmission equation indicates that the received power at a point is proportional to the square of the wavelength. Due to the very small wavelength in the THz band, the power of the signal diminishes dramatically as it travels toward the receiver. As a result, installing highly directional antennas with high array gains at both transmitters and receivers becomes essential to compensate for the free-space PL.

Another characteristic of THz band channels is molecular absorption, which is negligible in lower frequencies used in traditional cellular networks. Even in clear air in terrestrial communications, oxygen and water molecules cause absorption loss. Different environmental factors, such as weather conditions, pressure, temperature, humidity, pollution, and altitude, the abundance of certain gas molecules, all affect THz transmission. More specifically, molecular absorption occurs when traveling EM waves interact with gas molecules, leading to vibrations and rotations in the polar molecules. This process exhibits large absorption peaks at various frequencies [196]. Different methods for predicting the molecular absorption for a given medium exist in the microwave and IR regions, the most common being the ITU’s Recommendation P.676-6 for 1 to 1000 GHz, though alternatives are available, such as radiative transfer theory. For IR waves, the HITRAN database line catalog or related databases are used as a useful resource [197]. By using the Beer-Lambert Law, the molecular absorption is modeled as:

$$\tau(f, d) = \frac{P_0}{P_f} = e^{-k(f)L},$$

where $\tau$ is the transmittance of a medium, $f$ is the frequency of the EM wave, $L$ is the total path length, $P_t$ and $P_f$ are the incident and radiated powers and $k$ is the absorption coefficient of the medium, defined as a function of the composition of the medium such that:

$$k(f) = \sum_{i,g} k^{i,g}(f),$$

where $k^{i,g}$ is the individual absorption coefficient for the isotopologue $i$ of gas $g$, which can itself be modeled as:

$$k^{i,g}(f) = \frac{pT_{STP}Q^{i,g}A^{i,g}(f)}{P_0T},$$

using pressure $p$, temperature $T$, molecular volumetric density $Q^{i,g}$ and absorption cross section $\sigma^{i,g}$. Molecular volumetric density is defined as:

$$Q^{i,g} = \frac{p}{RT} q^{i,g} N_A = \frac{p}{RT} q^{i,g} N_A,$$

where $p$ is the total number of moles of the considered gas mixture, $V$ stands for the volume, $q^{i,g}$ is the mixing ratio, $N_A$ is the Avogadro constant, and $R$ is the gas constant, whereas absorption cross section is defined as:

$$\sigma^{i,g}(f) = S^{i,g} G^{i,g}(f),$$

where $S^{i,g}$ and $G^{i,g}$ are the line intensity and line shape, respectively. In order to derive the line shape, we need to first obtain the position of resonant frequency $f_{c}^{i,g}$ for the isotopologue $i$ of gas $g$ as follows:

$$f_{c}^{i,g} = f_{c0}^{i,g} + \delta_{c}^{i,g} \frac{p}{p_0},$$

where $f_{c0}^{i,g}$ is the zero-pressure position of the resonance, and $\delta_{c}^{i,g} p/p_0$ is the linear pressure shift. The absorption by a given molecule spreads over a range of frequencies, which is mainly decided by the collisions of molecules of the same gas in systems where the pressure exceeds 0.1 atm. The extent of widening is contingent upon the molecules participating in the collisions and is commonly denoted as the Lorentz half-width, $\alpha_L$, which is given as:

$$\alpha_L^{i,g} = \left(1 - q^{i,g}\right) \alpha_0^{i,g} + q^{i,g} \alpha_0^{i,g} \left(\frac{p}{p_0}\right) \left(\frac{T_0}{T}\right)^{\gamma},$$

where $T_0$ is the reference temperature, $\gamma$ is the temperature broadening coefficient, and the values of $\gamma$, $\alpha_0^{i,g}$, and $\alpha_0^{i,g}$ are...
TABLE VI
COMPARISON OF CHANNEL MODELS FOR ATMOSPHERIC TURBULENCE IN FSO LINKS

<table>
<thead>
<tr>
<th>Channel Model</th>
<th>Pros</th>
<th>Cons</th>
<th>Conditions for Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log-Normal Channel Model</td>
<td>Simple and widely used</td>
<td>Limited accuracy for strong</td>
<td>Weak-to-moderate turbulence conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>turbulence conditions</td>
<td>Small-scale fluctuations dominate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quick estimation or rough analysis of</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>link performance</td>
<td></td>
</tr>
<tr>
<td>Gamma-Gamma Channel Model</td>
<td>Captures scintillation effects</td>
<td>May not accurately model all</td>
<td>Moderate-to-strong turbulence conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>turbulence conditions</td>
<td>Significant scintillation effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Detailed statistical characterization</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>of the turbulence-induced fading</td>
<td></td>
</tr>
<tr>
<td>K-Distribution Channel Model</td>
<td>Accounts for severe turbulence effects</td>
<td>Requires accurate estimation of</td>
<td>Severe turbulence conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>parameters</td>
<td>Long-range or high-altitude FSO links</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deep fades and heavy scintillation</td>
</tr>
<tr>
<td>Intensity (I)-K Distribution</td>
<td>Models both intensity and phase</td>
<td>Requires empirical parameter estimation</td>
<td>Moderate to severe turbulence conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Long-range or high-altitude FSO links</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Joint statistical characterization of both</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>intensity and phase fluctuations</td>
</tr>
<tr>
<td>Double Weibull Distribution</td>
<td>Captures small and large scale</td>
<td>Empirical nature may require</td>
<td>Various turbulence conditions</td>
</tr>
<tr>
<td></td>
<td>fluctuations</td>
<td>specific parameter estimation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Light-tailed or heavy-tailed fading</td>
</tr>
<tr>
<td>Exponential Weibull Distribution</td>
<td>Flexibility to model different fading</td>
<td>Requires accurate estimation of</td>
<td>Various turbulence conditions</td>
</tr>
<tr>
<td></td>
<td>behaviors with mixture of distributions</td>
<td>parameters</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Light-tailed or heavy-tailed fading</td>
</tr>
<tr>
<td>Double Generalized Gamma</td>
<td>Handles complex fading behavior with</td>
<td>Empirical nature may require</td>
<td>Various turbulence conditions</td>
</tr>
<tr>
<td>Distribution</td>
<td>mixture of distributions</td>
<td>specific parameter estimation</td>
<td></td>
</tr>
<tr>
<td>I-G Distribution</td>
<td>Considers both intensity and phase</td>
<td>Requires empirical parameter estimation</td>
<td>Moderate-to-severe turbulence conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Long-range or high-altitude FSO links</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comprehensive modeling of intensity and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>phase fluctuations</td>
</tr>
<tr>
<td>Malaga Distribution</td>
<td>Empirical model specifically developed for</td>
<td>Requires specific parameter estimation</td>
<td>Various turbulence conditions</td>
</tr>
<tr>
<td></td>
<td>FSO links</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Light-tailed or heavy-tailed fading</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Accurate modeling of atmospheric</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>turbulence effects</td>
</tr>
<tr>
<td>NE Distribution</td>
<td>Simple and convenient approximation</td>
<td>Does not capture specific turbulence</td>
<td>Low turbulence levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>effects</td>
<td>Quick estimation of average link</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>performance or baseline comparison</td>
</tr>
</tbody>
</table>

can be directly collected from the HIRTA database. With the knowledge of the molecular absorption coefficient, the channel gain of the LoS link can be derived using:

\[ h_{\text{LoS}}^{\text{THz}} = L_{SP} e^{-k(f)L} \chi, \]  

(32)

where \( \chi \) denotes the Nakagami-\( m \) fading channel, and the spreading loss is obtained using

\[ L_{SP} = G_{Tx} G_{Rx} \left( \frac{\pi fL}{T_{\text{transmitter}}} \right)^{2}, \]

where \( G_{Tx} \) and \( G_{Rx} \) are the antenna array gain of the transmitter and receiver, respectively. Another complication introduced by molecular absorption pertains to molecular absorption noise, which manifests as noise when deriving the SINR for a specific user. Consequently, the cumulative impact of absorption noise and thermal noise for the LoS link can be expressed as follows:

\[ N_C = B_T K_B T_0 + P_{Tx} L_{SP} (1 - e^{-k(f)L}) \chi, \]  

(33)

where \( B_T \) is the bandwidth of the THz band, \( K_B \) is the Boltzmann constant, and \( P_{Tx} \) is the transmit power. Based on the large absorption peaks across various frequencies in the THz, every band within the THz spectrum possesses a specific range known as a transmission window (TW), characterized by a minimal molecular absorption coefficient. In order to effectively evaluate and enhance performance, distinct channel models tailored to the various TWs are essential. The application of curve-fitting methodologies is a viable approach to constructing accurate absorption loss models for each specific TW.

Weather conditions can also lead to absorption and scattering losses in THz transmission, although they may not be as significant as free-space and molecular absorption losses. However, due to the THz band’s small wavelength, water droplets suspended in snowflakes, clouds, and rain can simply absorb or scatter THz signals, contributing to additional losses on top of free-space and molecular absorption losses [198]. Another challenge posed by the channel characteristics of the THz band is blockage. The dimensions of surrounding objects, relative to the small wavelength of THz electromagnetic waves, are significant, making scattering more probable than specular reflections. This, in turn, increases the likelihood of blockage. Although most studies do only focus on LoS signals, there have been few recent papers (e.g., [199]–[201]) on diffusion-based channels for THz communications that explore how nonspecular scattering can play a valuable role in THz wireless systems, especially when the LoS link is temporarily blocked. Additionally, rough surfaces on normal objects hinder specular reflections at the scale of THz signals’ wavelengths. On the other hand, to overcome the substantial free-space PL in the THz band, directional beams are necessary, making LoS links crucial for THz transmission [202]. Consequently, blockage by objects such as buildings and vehicles is more likely in the THz band, and the human body can cause significant blockage loss to THz signals, reaching up to a virtually 40 dB attenuation [203]. Statistical-based methods, such as a two-dimensional Poisson point process, are proposed in the literature to model and estimate blockage in the THz band, including self-body blockage [204].
modeling, ray tracing is a widely used technique that calculates ray characteristics using geometric optics principles, considering factors like attenuation, angles of departure and arrival, propagation delay, and Doppler shift. This method employs equations like the Friis transmission equation, the Fresnel equation for reflections, and the universal theory of diffraction for diffraction effects. However, ray tracing’s complexity increases with factors like accurate environmental data and multiple-antenna systems [205]. Statistical modeling employs statistical methods to capture THz channel properties. The Saleh-Valenzuela model observes multipath arrivals using Poisson processes, and the Alpha-stable random process models ultra-wideband channel impulse response [206], [207]. Correlation-based stochastic models and beam-domain modeling are used for massive and ultra-massive MIMO systems [208]. Hybrid models combine deterministic and statistical methods for improved accuracy and efficiency. An example is the hybrid cluster-based channel model for indoor THz transmission, which combines ray tracing and statistical models [209].

E. Summary and Lessons Learned

EHF transmissions are susceptible to several unique channel impediments that must be considered in their respective channel modeling. Specifically, mmWave and THz signals propagation are affected by molecular absorption losses and link blockages. VLC signals are impacted by link blockages, random device orientation, and limited FoVs of the transmitter and receiver. FSO signals are affected by both atmospheric losses and atmospheric turbulence. Various channel models and channel modeling approaches for the different bands have been discussed in this section to capture all these channel peculiarities. The section has revealed a lack of standardized, unified, and experimentally-verified channel models that can encompass a wide variety of spectrum features. Moreover, open source channel simulators like NYUSIM and QuaDriga for THz channel are required for other frequency bands to allow realistically simulated performance analysis.

IV. OVERVIEW OF MBNs: ARCHITECTURE, ANTENNA, AND TRANSCEIVER DESIGN

This section first discusses our envisioned architectures for MBNs, namely, integrated, stand-alone (SA), cascaded, and hybrid MBNs. Then, it elaborates on the important aspects that should be considered in multiband transceiver design and tunable multi-band antenna systems.

A. MBN Architectures

The deployment of 5G witnessed two innovative designs by telecommunication industry leaders Ericsson and Huawei. Ericsson, together with Qualcomm Technologies, developed and successfully implemented an over-the-air MBN, for sub-6 GHz and mmWave bands, using Ericsson’s 5G NR pre-commercial base stations (BSs) and Qualcomm Technologies’ 5G NR UE prototypes [210]. These interoperability tests led to the design of Ericsson’s commercially available 5G hardware, including its 5G NR radio AIR5121 and baseband products, and a mobile receiver device powered by the Qualcomm Snapdragon X50 5G modem. On the other hand, Huawei also developed SingleRAN Pro, a comprehensive solution that supports sub-6 GHz and mmWave NR for 5G-oriented all-in-one sites [211]. This all-in-one 5G site operates by sharing baseband and other hardware resources among radio access technologies operating on multiple bands. Based on this development, we envision two primary architectures of MBNs for 6G fronthaul transmissions:

- **Integrated-MBN:** The network model of the integrated-MBN (Int-MBN) is depicted in Fig. 3 (a). From the figure, each BS is equipped with multiple radio access technology antennas to operate on multiple frequency bands. Inspired by multi-homing users who can receive data from different frequency bands simultaneously, MBN BSs in 6G and beyond would have the capability to transmit and receive data simultaneously on different frequency bands. This approach allows operators to use existing networks’ hardware and cell sites to deploy new MBN antennas, lowering site energy consumption and reducing overall site deployment, operation, and maintenance costs. However, this approach has limited flexibility in deploying BSs operating on specific bands with different densities to overcome their unique challenges, such as propagation losses.

- **Stand-alone-MBN:** The network model of the SA-MBN is shown in Fig. 3 (b). BSs operating at different frequencies are deployed separately in this architecture, each with its baseband unit. This approach offers simplified network planning as each BS focuses on a single spectrum, flexibility in deploying various types of BSs with different densities to overcome propagation losses, and requires resource management schemes with relatively lower complexity. However, new cell sites and backhaul links are required for each additional BS, which may increase operators’ deployment costs. Also, this approach might offer lower coverage and reliability than the Int-MBN architecture due to single-spectrum support and slow band-switching or handovers among different types of BSs.

The MBNs above can be realized with multi-homing or SA user devices, as illustrated in Fig. 3. Other potential MBN architectures are a cascade configuration where RF and EHF links can be deployed on access and backhaul links, respectively, and hybrid SA/Int-MBNs that involve the coexistence of integrated and SA BSs. Unlike the Int-MBN architecture, various types of SA-MBNs have been recently studied [212]–[217]. Moreover, the integration of traditional networks (e.g., single tier networks and two/three-tier HetNets) with MBNs is another promising architecture. The co-existence of HetNets and MBNs introduces an additional degree of freedom in terms of frequency band of operation for the BSs/APs in different tiers. This can yield significant improvement in network performance.

Similar to the concept of carrier aggregation (CA) in 4G and 4G LTE, users in MBNs should be able to aggregate...
multiple contiguous frequency resources (i.e., component carriers) from the same operating frequency band (i.e., intra-band contiguous CA), multiple non-contiguous carriers from the same band (i.e., intra-band non-contiguous CA), or multiple carriers from different bands (i.e., inter-band CA) into a single logical channel. In both Int-MBN and SA-MBN, intra-band CA can provide wider effective bandwidth, allowing for higher data rates and improved network performance. With regards to inter-band CA, component carriers may vary significantly due to the different propagation characteristics (e.g., sub-6 GHz and THz bands). In addition, inter-band CA involving VLC and FSO bands can be more challenging due to their different modulation techniques and possible hardware limitations (especially since CA has not yet been demonstrated for VLC and FSO). Also, VLC can provide high data rates and secure communication in EM-sensitive areas, which might not allow the inter-band CA. EM sensitive areas typically employ stringent measures to control and contain EM emissions, both for security and confidentiality reasons. These measures might include specialized construction materials that act as EM shields, creating an environment where external signals are attenuated or contained within the secured space. In such a confined environment, the capability to aggregate carriers from different frequency bands may be restricted due to the inherent challenges posed by the shielding materials. Moreover, in-band and adjacent band interference can arise in inter-band CA. These challenges may differ among the various MBN architectures and require customized approaches different from existing CA techniques. Standardization efforts would be necessary to ensure compatibility between different frequency carriers and user devices that support CA.

B. MBN Transceiver Design

While SA-MBNs can utilize existing transmitters that operate on single frequency bands, Int-MBNs require the design of universal hardware capable of reliably transmitting across multiple frequency bands. Also, the limitation of current cell phones that can only transmit and receive data transmission on sub-6 GHz and mmWave frequency bands poses challenges in MBN networks and can result in reduced network coverage, capacity, and potential service gaps in areas where these bands are deployed. To address these limitations, a new MBN transceiver design is imperative and should consider the following essential aspects.

1) MBN Front-End Design: The front-end is responsible for receiving and transmitting signals across multiple frequency bands and should be able to accommodate the different frequency bands of operation. To realize that, appropriate filters, amplifiers, mixers, tunable lasers, detectors, and local oscillator (LO) for each band must be carefully selected, and consideration should be given to factors such as noise figure, gain, linearity, and dynamic range to achieve optimal performance across all bands.

Section II-B focused on transceiver design for the various individual frequency bands and highlighted electronic and photonic solutions for generating THz signals. While electronic and photonic solutions were discussed as possible approaches for generating THz signals, these same approaches can also be explored for generating RF, mmWave, THz, VLC, and FSO signals in MBNs by cascading multiple frequency multipliers to raise the frequency of the local oscillator to the desired output frequency (i.e., up-conversion techniques) [218], [219]. Additionally, in an MBN transceiver, frequency splitters can be applied to generate an intermediate frequency as one of the desired output frequencies. However, operating at EHF bands can cause the CMOS components to exceed their optimal operating range, which limits the output power.

Another approach for MBN transceiver design is through optical down-conversion where MBN front-ends can be realized by down-converting photonic signals to produce EHF signals [220]. For instance, a Mach-Zehnder modulator generates signals at lower frequencies while maintaining the input
photonic signals as the output. While the design of photonic-based transceivers is relatively more straightforward, they are sensitive to environmental conditions, such as temperature and humidity, which can affect their performance.

2) **Frequency Synthesis and LO Generation:** MBN transceivers often require multiple LOs to generate the necessary frequencies for each band. Designing frequency synthesizers that can generate stable and accurate LO signals for each band is important. Techniques like fractional-N synthesis [221] or direct digital synthesis [222], [223] can be utilized to achieve precise frequency control and fast switching between bands.

3) **Band Switching:** Efficient and fast band-switching mechanisms to enable seamless operation across multiple bands are necessary for MBNs. These involve designing switch networks that can quickly route signals to the appropriate paths corresponding to the desired band while considering the trade-offs between switching speed, power consumption, and cost when selecting the switching components. An appropriate band-switching technique is opportunistic frequency switching. According to this technique, a BS equipped with separate EHF and RF transceivers can exploit both links opportunistically with hard and soft switching. Hard switching refers to switching frequencies using mechanical or electronic switches. This method is simple to implement but leads to high power consumption and signal distortion caused by the switch transients. Soft switching, on the other hand, uses a combination of analog and digital signal processing techniques. This method can result in lower power consumption and less signal distortion, but it can also be more complex to implement and may have higher latency. Accurate synchronization of time and frequency is required for successful information transmission in both switching mechanisms.

4) **PAs and ADCs/DACs:** In addition to antenna design, it is important to examine PAs and ADCs/DACs in the context of MBNs due to their significant impact on coverage, energy efficiency, data rates, and interference management. The focus should be to design PAs that can support wide frequency range, while maintaining efficiency and linearity, especially in mmWave, THz, and VLC bands, to mitigate distortion and signal degradation. This approach would alleviate the need for multiple PA modules for each band and associated diplexers. Unlike the conventional multi-mode multi-band PA design approach where a dedicated single-mode single-band PA is added for each band, reconfigurable PAs capable of supporting multiple frequency bands with a single PA core and programmable matching networks are required. Additionally, developing ADCs/DACs with high sampling rates to support the wide bandwidths in MBNs, ensuring adequate resolution and precision to accurately capture and reproduce signal information, and exploring energy-efficient converter architectures are of utmost importance.

C. **MBN Antenna Systems**

The design of MBN antenna systems faces the challenges related to antenna size and form factor, mutual coupling between antennas, radiation pattern control across all bands, impedance matching across all bands, and EMF standard restrictions. However, considering EHF in MBNs and the recent advancement in semiconductor technology and metasurfaces make it possible to overcome such challenges. While EHF allows to build dense arrays of high gain directional antennas, metasurfaces offer the exceptional ability to selectively transmit or reflect signals of different frequencies (i.e., frequency reconfigurability) [224]. There are several approaches to realize arrays of tunable MBN antennas, as discussed below.

1) **Mechanically Adjustable Antennas:** Novel approaches based on MEMS/NEMS can physically change the size of the radiating elements and achieve different resonant frequencies [225]. The challenge is to overcome the delay introduced by the control of the MEMS systems, particularly for fast data rates.

2) **Electrically Tunable Antennas:** Another approach for MBN antenna design is using metasurfaces (e.g., graphene, tunable chips, and ferrite) to construct real-time reconfigurable nano-antenna arrays. As an example, the resonant frequency of a graphene-based reconfigurable antenna can be adjusted by varying its Fermi energy without any physical modifications [226], [227]. The resonant frequency of a ferrite-based tunable antenna can be reconfigured by adjusting the applied magnetic field [228], [229]. However, graphene is primarily useful for the THz and VLC bands, ferrite has been explored for sub-6 GHz and mmWave, and liquid crystals have been examined for mmWave, THz, and VLC bands. Designing a metasurface that can operate across all frequency bands is challenging. **Table VII** summarizes well-known metasurfaces and their operating frequencies.

3) **Distributed Antenna Systems:** One solution is to leverage distributed antenna system to overcome the limited transmit power of existing EHF transceivers and antenna systems operating at EHF bands and antenna space constraints at cell sites. In this approach, large antenna arrays interconnected by the backhaul/fronthaul links are widely distributed over a vast geographical region with multiple separated sites [230]. Signal transmission and reception are achieved via joint signal processing techniques leading to achieving higher data rates. However, the communication overhead and control signals increase compared to centralized systems. Therefore, faster, scalable, and robust algorithms and high backhaul/fronthaul capacity are required for cooperative distributed antenna design.

4) **Hybrid MBN Antenna Systems:** Hybrid antenna designs combine different types of antennas optimized for specific frequency bands. By integrating multiple types of antennas into a single array, the network can cover a wide range of frequencies effectively. Although this approach offers flexibility in array design to accommodate diverse bands, it has high complexity in integrating and managing different antenna elements. It could lead to increased size and weight due to multiple antennas.
TABLE VII

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Operating frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal and dielectric</td>
<td>Nearly passive</td>
<td>Sub-6 GHz band [231], mmWave band [232]</td>
</tr>
<tr>
<td>Graphene</td>
<td>Nearly passive</td>
<td>THz band [233], [234], Visible light band [235]</td>
</tr>
<tr>
<td>Liquid crystal</td>
<td>Nearly passive</td>
<td>mmWave band [236], [237], THz band [238], Visible light band [239], [240]</td>
</tr>
<tr>
<td>Ferrite</td>
<td>Passive</td>
<td>Sub-6 GHz band [241], [242], mmWave band [229], [243]</td>
</tr>
</tbody>
</table>

Fig. 4. Illustration of hybrid RF/THz MBN [244].

D. Summary and Lessons Learned

We have discussed fundamental network architectures, transceiver design and antenna systems for 6G and beyond MBNs. While the Int-MBN architecture offers advantages such as lower deployment and operational costs from using the same hardware and site resources to support transmissions across multiple frequency bands, it also introduces several design challenges, including inadequate space and complex resource allocation and group HO management schemes. On the other hand, while the SA architecture offers simplified network planning and flexibility in deploying various types of BSs to exploit their unique propagation characteristics, it has higher deployment and operational costs and potentially lower reliability. Additionally, MBN transceiver design should focus on front-end design, frequency synthesis and LO generation, and efficient and fast band-switching. Finally, several approaches to realizing MBN antenna systems were discussed, such as reconfigurable, distributed, and hybrid antenna designs.

V. OVERVIEW OF RESOURCE ALLOCATION IN MBNS

Several resource allocation optimization problem formulations and solutions have been proposed for existing MBNs (e.g., RF/THz, RF/VLC/mmWave, RF/VLC, etc.). This section reviews resource allocation methods in MBNs, focusing on the different objective functions, constraint sets, and proposed solution techniques. A qualitative comparison of resource allocation models for RF/VLC MBNs, mmWave/RF MBNs and any other type of MBNs are provided in Tables VIII, IX, and X, respectively.

A. RF/THz MBNs

Figure 4 depicts a typical system model for RF/THz MBNs studies [244]. In this figure, the RF band is used for fronthaul and access network transmissions, while the THz band is used only for the access network. The macro BS uses RF band for the fronthaul because of the need for wide coverage while the small BSs use the THz band due to their smaller coverage radius. In [244], the authors considered EE optimization of a cache-enabled SA-RF/THz non-orthogonal multiple access (NOMA)-based MIMO MBN as depicted in Fig. 4 by optimizing user clustering, hybrid precoding, and power allocation under fronthaul capacity constraint and power budget. An alternating optimization (AO) scheme that uses an enhanced K-means machine learning scheme for user clustering, a zero-forcing algorithm for hybrid precoding, and an alternating direction method of multipliers (ADMM) for power allocation was proposed. Two user association algorithms based on unsupervised learning were proposed in [245] to minimize the standard deviation of network traffic load in a SA-RF/THz MBN while considering users’ QoS requirements. In [1], the authors proposed a deep reinforcement learning-based joint network selection and subchannel allocation for a SA-RF/THz MBN, while considering QoS and reliability constraints. A reinforcement learning-based algorithm to jointly optimize vehicle-to-infrastructure network selection and autonomous driving policies under constraints on number of vehicles each BS can serve was designed in [246].

B. RF/VLC MBNs

Figure 5 illustrates commonly used system models for RF/VLC MBNs. Since there are many resource allocation papers on RF/VLC MBNs, we classify them under sum rate maximization, energy-efficiency maximization, fairness maximization, and transmit power minimization.

1) Sum-Rate Maximization: An iterative power and time slot allocation approach to optimize the sum rate of a SA-RF/VLC MBN subject to constraints on QoS requirements, power budget, and maximum slot allocation was proposed in [253]. The proposed approach involved the integer relaxation and rounding technique for the slot allocation subproblem and a Lagrangian decomposition-based power allocation scheme. In [254], the authors examined a deep Q-network learning-based algorithm to jointly optimize user association, transmit power allocation, and bandwidth allocation under bandwidth, transmit power, and QoS constraints. A two-staged AP assignment and power allocation scheme to optimize the sum rate of a multi-tier SA-RF/VLC network under transmit power budget, QoS requirement and illumination constraints was developed in [258]. The proposed scheme involved the application of matching theory to assign APs to the users and a heuristic PA algorithm to optimize the transmit power of the assigned users. In [248], the authors considered a SA-RF/VLC MBN and studied a sum-rate maximization problem via uplink timeslot optimization subject to total available time constraint and transmit power budget. Additionally, a multi-objective optimization framework to maximize uplink and downlink sum rate by...
optimizing the timeslots and transmit power under total time allocation constraint, power budget, and minimum harvested energy requirements was examined. The formulations for the uplink and downlink transmissions were shown to be convex and Lagrange dual method-based solution techniques were proposed. A coalition game-based user grouping scheme and power allocation was examined in [261] to maximize a utility function in a NOMA-based SA-RF/VLC MBN.

A sum-rate maximization problem that optimizes access mode selection, the direct current offset at the VLC AP, the peak amplitude of the alternating current component of the VLC AP, and the power allocation of a hybrid RF/VLC system with energy harvesting capability was investigated in [249]. Under the constraints on energy harvesting requirement, peak amplitude, and transmit power budget, the authors decomposed the joint problem into two subproblems and proposed successive convex approximation (SCA)-based algorithms. In [255], the authors proposed a Q-learning-based power allocation scheme to satisfy the QoS requirements of multi-homing users in a SA-RF/VLC network while considering transmit power budgets. A power allocation optimization scheme to maximize the sum rate and energy efficiency of an Int-RF/VLC MBN subject to QoS requirement, transmit power constraint, and dimming control consideration was explored in [250]. A semidefinite relation (SDR)-based solution was proposed for the sum rate optimization problem while the Dinkelbach approach was utilized for the energy efficiency problem.

2) Energy-Efficiency Maximization: The authors in [251] proposed a Dinkelbach-type algorithm to optimize power and bandwidth allocation in a SA-RF/VLC MBN under QoS requirements, power, and bandwidth constraints. In [259], a Dinkelbach-style approach for subchannel and power allocation to optimize the energy efficiency of a software-defined SA-RF/VLC MBN subject to power budgets, QoS requirements, and backhaul capacity, interference, and subchannel scheduling constraints was examined. The proposed two-step approach involved a subchannel allocation scheme based on channel quality and an ADMM method for power allocation. In [256], the authors considered a SA-RF/VLC/power line communication MBN and proposed a Dinkelbach-style energy-efficient joint power and backhaul flow optimization algorithm under power, backhaul capacity, and QoS constraints. The authors in [217] examined the energy efficiency maximization problem for a SA-RF/VLC MBN with multi-homing users by optimizing AP assignment, subchannel allocation, and power allocation under power budgets, QoS requirements, and multi-connectivity and subchannel constraints. An alternating solution method that leverages matching theory for the AP assignment, the strongest channel gain rule for subchannel allocation, and a multi-objective optimization framework for power allocation was proposed. In [262], a power allocation scheme was proposed to maximize the energy efficiency of a SA-RF/VLC MBN subject to QoS requirements and transmit power budget.

3) Fairness Maximization: The authors in [247] explored the optimization of power, bandwidth, and timeslot allocation to maximize the weighted proportional fairness of a SA-RF/VLC MBN with common backhaul infrastructure under backhaul capacity, power budgets, timeslot, and bandwidth constraints. The proposed approach involved transforming the original nonconvex problem to a convex one and solving it via Lagrange dual decomposition method. In [252], the authors considered a SA-RF/VLC MBN with two types of users: multi-homing and multimode (i.e., always select a single network). For this system model, a fairness maximization problem subject to QoS requirements and total transmission probability via network selection and transmission probability optimization was developed and a Lagrange dual method proposed. In [260], a cooperative bargaining theory-based spectrum allocation algorithm was developed to maximize fairness in an SA-RF/VLC MBN under spectrum resource restrictions. In [263], the authors considered user scheduling optimization problem to maximize the sum proportional fairness for an RF/VLC MBN with multi-homing users and without multi-homing users.

4) Transmit Power Minimization: In [257], the authors considered a SA-RF/VLC MBN in which the VLC system operates at a large timescale and the RF network at a small timescale. Adaptive network resource allocation based on the Lyapunov optimization technique to minimize transmit power under power budget, resource block, and delay constraints was proposed: (1) large timescale network selection, transmission scheduling, and power allocation for the VLC system; (2) small timescale resource block allocation and power allocation
for the RF network.

C. RF/mmWave MBNs

A typical system model for RF/mmWave MBNs is similar to Fig. 4, where a macro BS is deployed at the cell center and several small BSs are placed within the coverage area of the MBS. The macro BS uses RF band for the access network and mmWave bands for wireless backhaul transmission while the small BSs utilize mmWave for access network transmission and backhaul transmission. Several studies have tackled resource allocation in RF/mmWave MBNs. In the sequel, we classify these studies based on the considered objective function.

1) Sum-Rate Maximization: In [265], the authors proposed a genetic algorithm-based and a heuristic-based user association, power, and subchannel allocation algorithms to maximize the sum rate of a SA-RF/mmWave MBN under single connectivity and power constraints. They discussed both centralized and distributed implementation approaches for the proposed schemes. Simulation results revealed that the centralized genetic and heuristic-based algorithms outperformed the distributed approaches in terms of sum rate and fairness. In [266], the authors developed a user association and downlink-uplink power allocation scheme to maximize the sum rate of a SA-RF/mmWave MBN, in which the macro BS and small cell BSs operate on the RF and mmWave bands, respectively. The proposed scheme considered single connectivity constraints.

### TABLE VIII

A COMPARISON AMONG RESOURCE ALLOCATION MODELS FOR RF-VLC NETWORKS

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Design issue</th>
<th>Objective</th>
<th>Solution technique</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>[253]</td>
<td>Timeslot and Power Allocation</td>
<td>Maximize Sum Rate</td>
<td>Lagrangian Decomposition (Centralized)</td>
<td>QoS Requirements, Power Budget, Timeslot Constraint</td>
</tr>
<tr>
<td>[254]</td>
<td>User Association, Power and Bandwidth Allocation</td>
<td>Maximize Sum Rate</td>
<td>Deep Q-Network Learning (Centralized)</td>
<td>Bandwidth, Power, and QoS Constraints</td>
</tr>
<tr>
<td>[257]</td>
<td>Network Selection, Transmission Scheduling, Resource Block, and Power Allocation</td>
<td>Minimize Transmit Power</td>
<td>Lyapunov Optimization and Lagrange Relaxation Method (Hybrid)</td>
<td>Power Budget, Resource Block and Delay Requirements</td>
</tr>
<tr>
<td>[247]</td>
<td>Power, Timeslot, and Bandwidth Allocation</td>
<td>Maximize Proportional Fairness</td>
<td>Lagrange Dual Decomposition (Distributed)</td>
<td>Power Budget, Backhaul Capacity, and Bandwidth Constraint</td>
</tr>
<tr>
<td>[251]</td>
<td>Power and Bandwidth Allocation</td>
<td>Maximize Energy Efficiency</td>
<td>Dinkelbach Method (Centralized)</td>
<td>QoS, Power, and Bandwidth Constraints</td>
</tr>
<tr>
<td>[259]</td>
<td>Subchannel and Power Allocation</td>
<td>Maximize Energy Efficiency</td>
<td>Dinkelbach Method and ADMM (Distributed)</td>
<td>Power, QoS requirements, Backhaul, Interference, and Subchannel Scheduling Constraints</td>
</tr>
<tr>
<td>[256]</td>
<td>Transmit Power and Backhaul Link Flow Optimization</td>
<td>Maximize Energy Efficiency</td>
<td>Dinkelbach-style Algorithm (Distributed)</td>
<td>Power Budget, QoS Requirements, Backhaul Link Capacity, and Flow Constraints</td>
</tr>
<tr>
<td>[258]</td>
<td>AP Assignment and Power Allocation</td>
<td>Maximize Sum Rate</td>
<td>Matching Theory and Heuristics (Centralized)</td>
<td>Power Budget, QoS Requirements, Illumination Requirements</td>
</tr>
<tr>
<td>[248]</td>
<td>Timeslot and Power Allocation</td>
<td>Maximize Sum Rate</td>
<td>Lagrange Dual Method (Distributed)</td>
<td>Power Budget, Time Allocation and Harvested Energy Constraints</td>
</tr>
<tr>
<td>[252]</td>
<td>Network Selection and Transmission Probability</td>
<td>Maximize Fairness</td>
<td>Lagrange Dual Method (Distributed)</td>
<td>QoS Requirement and Total Transmission Probability</td>
</tr>
<tr>
<td>[263]</td>
<td>User Scheduling</td>
<td>Maximize Proportional Fairness</td>
<td>Convex Solver</td>
<td>User and resource scheduling, multi-connectivity constraints</td>
</tr>
<tr>
<td>[250]</td>
<td>Power Allocation</td>
<td>Maximize Energy Efficiency and Data Rate</td>
<td>SDR Technique and Dinkelbach-type Algorithm</td>
<td>QoS Requirement, Power Budget, and Dimming Control Constraint</td>
</tr>
<tr>
<td>[255]</td>
<td>Transmit Power</td>
<td>Maximize Users' QoS Satisfaction</td>
<td>Multi Agent Q-Learning</td>
<td>Transmit Power Budget</td>
</tr>
<tr>
<td>[261]</td>
<td>User Grouping and Power Allocation</td>
<td>Maximize Utility Function</td>
<td>Coalition Game Theory</td>
<td>Transmit Power Budget</td>
</tr>
<tr>
<td>[262]</td>
<td>Power Allocation</td>
<td>Maximize Energy Efficiency</td>
<td>Dinkelbach Method and SCA</td>
<td>QoS Requirement and Transmit Power Budget</td>
</tr>
</tbody>
</table>
power budgets, and QoS requirements and involved using non-convex solvers to tackle the user association and power allocation subproblems alternatively.

2) Energy-Efficiency Maximization: A SA-RF/mmWave MIMO-enabled MBN that uses the mmWave band for the access and backhaul networks and the RF band for the access network was explored in [267]. The authors formulated an energy-efficiency maximization problem via power and subchannel allocation under backhaul link capacity and users' QoS constraints. A two-layer Dinkelbach-style algorithm that leverages difference of convex programming and Lagrange dual decomposition was proposed. In [268], a system model for a SA-RF/mmWave MBN in which the macro BS and the small cell BSs operate on the mmWave band and RF band, respectively, was proposed. An energy-efficiency maximization framework that optimizes power allocation and bandwidth partitioning for access and backhaul networks' transmissions under QoS requirements, transmit power budget, and backhaul capacity constraint was proposed. This framework, based on AO, utilized Dinkelbach transform, the lower bound technique, and Lagrange dual decomposition for the power allocation subproblem. Additionally, a closed-form solution was developed for the bandwidth partitioning subproblem.

In [269], the authors presented a multi-agent cooperative deep reinforcement learning-based secrecy energy efficiency maximization scheme that optimizes power and channel allocation and beamforming vectors under QoS requirements and transmit power budget. The considered SA-RF/mmWave MBN involved a macro BS operating on the RF band and multiple mmWave enabled-small BSs. Frameworks for maximizing the energy efficiency of a SA-RF/mmWave MBN with mmWave backhaul links via the joint optimization of power, data rate, and backhaul flow were studied in [270]. In particular, the authors proposed bisection-based and Dinkelbach-based optimization approaches while considering design constraints on backhaul capacity, flow conservation, QoS requirement, and transmit power budget. For a similar system model, the authors in [271] proposed an energy-efficient user association, power allocation, and flow control algorithm based on Lagrange dual decomposition, dynamic programming, the subgradient method, and the multiplier adjustment method.

3) Fairness Maximization: A coordinated game theory-based spectrum allocation and user association algorithm to optimize the network utility of a SA-RF/mmWave MBN under a single connectivity constraint was proposed in [272]. The considered MBN utilized both the RF and the mmWave bands for the access network. In [273], the authors considered a SA-RF/mmWave MBN, where both bands were used for the access network. A user association optimization problem to maximize network utility under QoS requirements and single connectivity constraints was developed, for which a Lagrange dual decomposition-based solution was proposed. Similar to [273], a heuristic-based user association scheme to optimize the number of successfully served users while considering single connectivity and resource block constraint was explored in [274].

4) Transmit Power Minimization: In [275], a transmit power minimization problem that optimizes user association, backhaul routing, and BS on-off switching in a SA-RF/mmWave MBN, where the RF is used for the access network and mmWave for the backhaul links was investigated. The constraints included power budget, flow constraints, and backhaul link capacity limit. A solution technique based on a robust approach was proposed.

D. RF/FSO MBNs

In [276], the authors considered an Int-RF/FSO multi-band backhaul network and developed a heuristic-based routing scheme to minimize transmission cost under flow and backhaul link capacity constraints. In [277], a heuristic-based backhaul link selection scheme to minimize cost under data rate, connectivity, and reliability constraints was proposed for an Int-RF/FSO multi-band backhaul network. In [278], the authors developed an RF/FSO multi-band wireless mesh network and focused on sum rate optimization via route selection, topology control, channel allocation, and interface assignment under flow conservation, routing, FSO link allocation, logical topology, link capacity, delay, and fairness constraints. Due to the nonconvex nature of the optimization problem, the authors relied on the commercial solver Gurobi and metaheuristics to propose an iterative local search algorithm. By considering a relay-enabled Int-RF/FSO MBN, the authors in [279] proposed a power and subcarrier allocation scheme based on dual decomposition to maximize the sum rate under transmit power and subcarrier allocation constraints. Similarly, the authors in [280] considered an Int-RF/FSO MBN, where FSO links were used to augment an RF wireless mesh network. For this system model, a branch and bound-based algorithm was designed to maximize the sum rate by optimizing link allocation, flow routing, and flow scheduling under flow conservation and link capacity constraints. In [281], the authors investigated a link-layer transmission policy that optimizes admission control and power allocation to maximize the long-term rate under constraints on power budget and the maximum number of admissible packets for an Int-RF/FSO MBN.

In [282], the authors considered an Int-RF/FSO MBN consisting of an RF/FSO-assisted central processor and a network of connected RF/FSO-enabled radio units. While the central processor uses RF/FSO MBN for fronthaul transmissions, the radio units utilize the RF band to serve users in the access network. A sum rate maximization problem that optimizes the covariance and precoding matrices under fronthaul capacity and transmit power constraints was formulated and solved via AO and semidefinite programming. A drone-assisted Int-RF/FSO MBN architecture was proposed in [283], where FSO links were used for backhauling to the drone BS and the RF band for wireless access links. The authors developed a drone BS placement and bandwidth allocation scheme to maximize the number of satisfied users while guaranteeing total bandwidth, backhaul capacity, minimum rate, and altitude constraints. A high-altitude platform station-assisted terrestrial SA-MBN where the wireless connection to ground station works on RF and FSO bands was proposed in [284]. Additionally, the authors developed a power allocation scheme based on geometric programming to minimize the outage.
probability under transmit power budgets. Furthermore, some recent performance analysis studies have revealed RIS and hybrid automatic repeat request can effectively minimize the outage probability and packet error rate [285], bit error rate and outage probability [286], average symbol error rate and outage probability [287], symbol error rate [288], and secrecy outage probability [289]–[291] in mixed RF/FSO MBNs. Note that in all these works, separate RISs are deployed for the RF and FSO network.

E. mmWave/FSO MBNs

In [294], the authors introduced an Int-mmWave/FSO MBN that utilizes both mmWave and FSO bands for fronthaul transmission and the mmWave band for access network transmission. By considering transmit power budget and bandwidth allocation constraints, the authors proposed a constrained differential evolution-based algorithm to optimize bandwidth and power to maximize the overall network energy efficiency. A SA-mmWave/FSO MBN that operates on the FSO band for fronthaul transmission and mmWave band for access network transmission was considered in [295]. The authors maximize the data rate by optimizing power allocation, fronthaul link selection, data rate arrival, user association, fronthaul rate allocation, and transmission scheduling. This framework was based on AO, Lagrange dual decomposition, matching theory, and heuristics. The optimization constraints included power budget, link selection, single connectivity, load balancing, scheduling, and QoS constraints.

F. VLC/THz MBNs

Only two studies have considered hybrid VLC/THz MBNs to date [292], [293]. The considered system model is illustrated in Fig. 6. More specifically, the authors in [292] considered an indoor SA-VLC/THz MBN that uses VLC to provide accurate indoor positioning services and THz to transmit high-quality virtual reality images. For this system model, a meta-learning-based framework was proposed to maximize the number of successfully served users by selecting the appropriate VLC APs to be turned on and controlling the user association with THz BSs. The constraints were that only three VLC APs could be selected, and each user could be associated with at most one THz BS at a time. Simulation results revealed that the proposed scheme outperforms the trust region policy optimization algorithm in terms of the number of successfully served users. The study in [293] considered a similar system model as [292] but focused on minimizing the service delay. This problem was solved using optimization tools such as CPLEX and YALMIP.

G. Other MBNs

1) mmWave/THz MBNs: Resource allocation in mmWave/THz MBNs has received little attention to date. In [296], the authors considered an integrated terrestrial-space MBN and aimed at maximizing sum rate and minimizing delay and interference while considering energy and computation budgets for CubeSats. A multi-objective resource allocation scheme based on deep learning was proposed to optimize power and bandwidth allocation, center frequency selection, and the directivity of the MBN reflectarray antenna. In [297], a Lagrangian dual decomposition-based user association and power allocation scheme to maximize a network utility function subject to power budget, QoS requirements, and propagation range constraint was developed for a SA-mmWave/THz MBN.

2) mmWave/VLC MBNs: To date, only few studies (e.g., [298], [299]) have investigated mmWave/VLC MBNs. The authors considered an indoor environment with multiple mmWave and VLC APs. The work in [298] proposed a user association scheme to maximize the sum rate under QoS requirements. Simulation results showed that the proposed approach outperforms a pure opportunistic user association scheme in terms of sum-rate performance and convergence speed. In [299], the authors investigated the per user data rate and outage performance of a mmWave/VLC MBN by considering two deployment scenario for the RF system: a fixed spectrum and power allocation and a dynamic spectrum and power allocation based on users’ traffic demands. The system parameters (e.g., power and spectrum allocation) of the VLC system was considered to be fixed.

3) RF/VLC/mmWave MBNs: Only two studies (i.e., [300] and [301]) have considered resource allocation optimization for RF/VLC/mmWave MBNs. The considered system model is illustrated in Fig. 7, where the BSs and UEs are equipped
with multi-band transceivers but can only transmit/receive on a single band at a time. In these studies, the authors proposed a multi-armed bandit-based reinforcement learning approach to the design issue of band and channel selection to maximize the sum rate of the Int-RF/VLC/mmWave MBN under energy budget constraints.

4) RF/mmWave/THz MBNs: There has been only one study on resource allocation in RF/mmWave/THz MBN yet [302]. In this study, the authors considered an Int-MBN where the macro BS operates on RF links and the small cell BSs transmit on either RF or mmWave, or THz bands depending on the application requirement of the user. For this system model, a channel selection optimization problem to maximize the sum rate was proposed and solved by exploiting epigraph reformulation, quadratic transform approach, and Lagrange dual decomposition.

H. Summary and Lessons Learned

This section summarized the available literature on resource allocation in various types of MBNs. First, it has been highlighted that sum rate, energy efficiency, total transmit power, and network fairness are the most widely used performance metrics to date. However, the design of MBNs for future communication networks calls for incorporating and optimizing performance metrics such as deployment cost efficiency (DCE), end-to-end reliability and latency, order of connectivity, and handoff-aware data rate. Also, the resource management solution will need to be scalable, open access, robust, faster, and capable of handling multiple objectives.

To combat short coherence time of EHF in MBNs, the next generation of resource allocations solutions would heavily rely on data-driven machine learning solutions. It is however critical to note that incorporating non-convex constraints in such deep learning solutions is still a fundamental challenge and only a few research works thoroughly addressed this issue [303].

Second, it has been observed that only a few studies (i.e., [301], [302]) have considered MBNs operating on more than two spectrum bands. The optimization constraints for these studies included single network connectivity, QoS requirements, and transmit power budget. However, future MBNs would involve the coexistence of BSs/APs operating on several spectrum bands with integrated computing, communication, and sensing applications. As a result, new design constraints such as multiple network connectivity, sensitivity performance, backhaul capacity, quality-of-experience (QoE) awareness, molecular absorption awareness, and interference threshold for passive antennas are required for resource allocation MBNs.

Moreover, it has been revealed that while RF/VLC, RF/mmWave, and FSO-based MBNs have received significant research attention, the same cannot be said about THz-based MBNs. Since THz communication is expected to play a key role in future networks, research on resource allocation in the THz-enabled MBNs is strongly encouraged. It may not always be straightforward to apply the method proposed for one MBN (e.g., mmWave/RF) to another (e.g., THz/RF). This is attributed to the additional constraints imposed by molecular absorption loss for THz links, molecular absorption noise,
<table>
<thead>
<tr>
<th>Network</th>
<th>Ref.</th>
<th>Design issue</th>
<th>Objective</th>
<th>Solution technique</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF-VLC -mmWave</td>
<td>[300] [301]</td>
<td>Band and Channel Selection</td>
<td>Maximize Aggregate Expected Throughput</td>
<td>Multi-armed Bandit-based Reinforcement Learning (Distributed)</td>
<td>Energy Budget</td>
</tr>
<tr>
<td>mmWave -THz</td>
<td>[296]</td>
<td>Power, Bandwidth, Operating Frequency, and Antenna Directivity</td>
<td>Maximize Sum Rate, Minimize Delay, Minimize Interference</td>
<td>Random Hill Climbing-based Deep Learning (Centralized)</td>
<td>Energy and Computation Budgets</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[276]</td>
<td>Backhaul Route Selection</td>
<td>Minimize Transmission Cost</td>
<td>Heuristic Approach (Centralized)</td>
<td>Flow Conservation and Backhaul Capacity</td>
</tr>
<tr>
<td>mmWave -VLC</td>
<td>[298]</td>
<td>User Association</td>
<td>Maximize Sum Rate</td>
<td>Integer Relaxation and Convex Optimization (Centralized)</td>
<td>QoS requirement and Single Connectivity</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[277]</td>
<td>Backhaul Link Selection</td>
<td>Minimize Cost of Backhaul Network</td>
<td>Graph theory (Centralized)</td>
<td>Data rate, Connectivity, and Reliability</td>
</tr>
<tr>
<td>THz-VLC</td>
<td>[292]</td>
<td>VLC AP Selection and THz BS User Association</td>
<td>Maximize Successfully Served Users</td>
<td>Policy Gradient-based Reinforcement Learning Algorithm with Meta-Learning (Centralized)</td>
<td>AP Selection and Single Connectivity</td>
</tr>
<tr>
<td>RF-THz</td>
<td>[1]</td>
<td>Network Selection and Subchannel Allocation</td>
<td>Maximize Sum Rate</td>
<td>Deep Reinforcement Learning (Distributed)</td>
<td>Reliability and QoS Requirements</td>
</tr>
<tr>
<td>RF-THz</td>
<td>[245]</td>
<td>User Association</td>
<td>Minimize Network Load Standard Deviation</td>
<td>Unsupervised Learning</td>
<td>QoS Requirements</td>
</tr>
<tr>
<td>RF-THz</td>
<td>[246]</td>
<td>Network Selection and Autonomous Driving Policies</td>
<td>Maximize Traffic Flow and Data Rate Minimize Collisions and Handoffs</td>
<td>Q-learning</td>
<td>BS quota</td>
</tr>
<tr>
<td>mmWave -THz</td>
<td>[297]</td>
<td>User Association and Power Allocation</td>
<td>Maximize Fairness</td>
<td>Lagrangian Dual Decomposition (Distributed)</td>
<td>Power Budget, QoS Requirement, Propagation Distance Constraint</td>
</tr>
<tr>
<td>THz-VLC</td>
<td>[293]</td>
<td>VLC AP Selection and THz BS User Association</td>
<td>Minimize Service Delay</td>
<td>Non-convex Solver (Centralized)</td>
<td>VLC APs Selection, Single Connectivity, Time Slot Constraint</td>
</tr>
<tr>
<td>RF -mmWave -THz</td>
<td>[302]</td>
<td>Channel Selection</td>
<td>Maximize Sum Rate</td>
<td>Epigraph Reformulation, Quadratic Transform and Lagrange Dual Decomposition (Centralized)</td>
<td>None</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[278]</td>
<td>Interface Assignment, Channel Allocation, Routing and Topology Control</td>
<td>Maximize Sum Rate</td>
<td>Gurobi and Metaheuristic (Centralized)</td>
<td>Flow Conservation, Routing, Link Allocation, Logical Topology, Link Capacity, Delay and Fairness</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[279]</td>
<td>Power and Subcarrier Allocation</td>
<td>Maximize Sum Rate</td>
<td>Lagrangian Dual Decomposition (Centralized)</td>
<td>Power Budget and Subcarrier Allocation Constraints</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[280]</td>
<td>Link Allocation, Flow Routing and Scheduling</td>
<td>Maximize Sum Rate</td>
<td>Branch and Bound (Centralized)</td>
<td>Flow Conservation and Backhaul Capacity Constraints</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[282]</td>
<td>Covariance and Precoding Matrices</td>
<td>Maximize Sum Rate</td>
<td>Alternating Optimization and Semidefinite Programming (Centralized)</td>
<td>Fronthaul Capacity and Transmit Power Constraints</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[283]</td>
<td>Drone-Mounted BS Placement and Bandwidth Allocation</td>
<td>Maximize Number of Satisfied Users</td>
<td>AO, Genetic Algorithm and Sequential Quadratic Programming (Centralized)</td>
<td>Total Bandwidth, Backhaul Capacity, QoS Requirements and Altitude</td>
</tr>
<tr>
<td>RF-FSO</td>
<td>[281]</td>
<td>Admission Control and Power Allocation and</td>
<td>Maximize Data Rate</td>
<td>Lyapunov Optimization Framework</td>
<td>Power Budget, Maximum Number of Admissible Packets Constraints</td>
</tr>
<tr>
<td>mmWave -FSO</td>
<td>[294]</td>
<td>Power and Bandwidth Allocation</td>
<td>Maximize Energy Efficiency</td>
<td>Constrained Differential Evolution (Centralized)</td>
<td>Bandwidth and Transmit Power</td>
</tr>
<tr>
<td>mmWave -FSO</td>
<td>[284]</td>
<td>Power Allocation</td>
<td>Minimize Outage Probability</td>
<td>Geometric Programming (Centralized)</td>
<td>Power Budget</td>
</tr>
<tr>
<td>mmWave -FSO</td>
<td>[284]</td>
<td>Power Allocation, Fronthaul Link Selection, User Association, Rate Allocation and Transmission Scheduling</td>
<td>Maximize Data Rate</td>
<td>Lagrangian Dual Decomposition, Matching Theory, and Heuristics (Centralized)</td>
<td>Power Budget, Link Selection, Single Connectivity, Load Balancing, QoS Requirement, Scheduling</td>
</tr>
</tbody>
</table>
and beam-split phenomena which impacts beamforming gain across different sub-carriers in the THz band compared to the mmWave band. Thus, we believe that the specifics of the different bands require tailored approaches to solve distinct constraints.

VI. RESOURCE ALLOCATION PROBLEMS AND SOLUTION APPROACHES FOR MBNs

Most studies on resource allocation in MBN considered only two frequency bands, as illustrated in the previous section. This section discusses typical resource allocation optimization problems and solution techniques for MBNs, focusing on relevant objective functions and constraints. Selected numerical results are included to demonstrate the performance of fundamental MBN configurations.

The general mathematical structure of an optimization problem is as follows:

\[
\min f(x) \\
\text{s.t. } g_i(x) \leq b_i, \; i = 1, \ldots, I, \\
\quad h_j(x) = c_j, \; j = 1, \ldots, J,
\]

where \( x \) is the set of optimization variables, \( f(x) \) is the objective function, and \( g_i(x) \leq b_i \) and \( h_j(x) = c_j \) are the inequality and equality constraints, respectively. In the following, few potential objectives and constraints for the design and optimization of MBNs are presented.

A. Objective Functions for MBNs

In addition to conventional data rate, energy efficiency, and fairness metrics, the consideration of the following metrics would be of immediate relevance to most of the key performance indicators (KPIs) of 6G, summarized in Table XI, for MBNs.

- DCE (bps/Hz/$) : This metric quantifies the cost-effectiveness of MBNs by comparing the achievable network spectral efficiency to the total investment made in installing the network infrastructure. This total investment includes capital expenditure, which covers the deployment of BSs and backhauling links, and operational expenditure, encompassing maintenance, energy costs, and land lease. This metric can be generalized to incorporate the cost of energy consumption for communication and sensing services. Optimizing DCE in MBNs will contribute to minimizing the cost of 6G networks and offers several advantages such as (i) minimizes unnecessary expenses and maximizes the return on investment, (ii) allows operators to offer competitive pricing and better services at low operational costs, (iii) facilitates scalability and future growth, and (iv) allows a more sustainable and eco-friendly network deployment.

- HO-aware data rate (bps) : Analyzing the HO-aware data rate in MBN is vital since different frequencies offer distinct coverage zones, a scenario that can lead to unnecessary HOs, especially in 6G and beyond networks that will support high mobility applications such as hyper-high-speed railway. Mathematically, HO-aware data rate can be defined as \( R_{HA} = R(1 - H_c) = R(1 - \min\{H_d, 1\}) \) where \( R \) is the achievable data rate of the user of interest, and \( H_c = \min\{H_d, 1\} \). The HO cost is denoted by \( H_d = h_dH \), where \( h_d \) is HO delay and \( H \) is HO rate [56], [305], [306]. HO-aware resource allocation in MBNs should focus on selecting appropriate HO initiation criteria, establishing HO thresholds, and optimizing the HO execution time to minimize disruptions and data rate degradation.

- Volumetric Connection density (connected devices per m$^2$) : Since the next generation of wireless networks are envisioned to be integrated satellite-aerial-terrestrial networks, volumetric connection density can be perceived as an extension to conventional connection density in two dimensions. Volumetric connection density is a relevant performance metric for MBN since difference frequency bands perform differently in different environments ranging from space to underwater. Volumetric connection density refers to the number of accessible devices fulfilling a required QoS.

- EMF exposure (Watt/m$^2$) : According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP), EM waves can increase the temperature of human body and the exposure may increase as a function of frequency. Hence, an investigation of EMF exposure for MBNs is necessary [307].

- Quality-of-Experience (QoE) [1], [308] : QoE is defined as perceived end-to-end user’s experience and expectation. Also, in 6G, quality of physical experience (QoPE) will be considered which incorporates human physiological factors with QoS and QoE. Optimizing this metric will ensure that user-experience data rate of up-to 1 Gbps is achieved in 6G.

- Data Rate in Finite Block Length Regime [309] : For a

<table>
<thead>
<tr>
<th>KPI</th>
<th>6G</th>
<th>KPI</th>
<th>6G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak data rate</td>
<td>1 Tbps</td>
<td>Spectrum efficiency</td>
<td>≥90 bps/Hz</td>
</tr>
<tr>
<td>User experienced data rate</td>
<td>10 Gbps</td>
<td>Energy efficiency</td>
<td>10$^7$ bps/Hz</td>
</tr>
<tr>
<td>Latency</td>
<td>0.1 ms</td>
<td>Cost efficiency</td>
<td>500 Gbps</td>
</tr>
<tr>
<td>Delay jitter</td>
<td>1 ms</td>
<td>Mobility</td>
<td>1000 km/h</td>
</tr>
<tr>
<td>Area traffic capacity</td>
<td>10 Gbps/m²</td>
<td>Reliability</td>
<td>≥99.99999%</td>
</tr>
<tr>
<td>Connection density</td>
<td>10$^8$ devices/km²</td>
<td>Positioning</td>
<td>10 cm and 1 m</td>
</tr>
<tr>
<td>Coverage</td>
<td>99%</td>
<td>Battery life</td>
<td>20 years</td>
</tr>
<tr>
<td>Security capacity</td>
<td>High</td>
<td>Sensing/Imaging resolution</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Authorized licensed use limited to: KAUST. Downloaded on February 18, 2024 at 10:26:53 UTC from IEEE Xplore. Restrictions apply. © 2024 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.
given channel with Shannon’s capacity, the maximum transmission rate in the finite block length regime is a function of the block-length $N$, the error probability $\epsilon$, and the channel dispersion $V(\gamma) = \frac{\gamma(2+\gamma)}{1+\gamma^2} \log_2 e$, i.e.,

$$R_{FBL} = C - \sqrt{\frac{V(\gamma)}{N}} Q^{-1}(\epsilon),$$

where $\gamma$ is the SINR, and $Q(\cdot)$ is the inverse of Gaussian Q-function. Optimizing the finite block length data rate of MBNs is key to satisfying the URLLC requirements of 6G and beyond networks.

- **QoS/QoE Deviation [310]**: Minimizing the weighted sum of the deviation between the QoS/QoE observed at a given network application and its corresponding QoS/QoE requirement offers a valuable insight into the adequacy of resources to meet the QoS/QoE of the users under the existing service level agreement.

**B. Design Constraints for MBNs:**

The following constraints should be considered together with minimum data rate requirements for access and backhaul links, backhaul flow constraints, latency requirements, and transmit power budgets.

1) **Multi-connectivity**: Existing wireless networks and their corresponding resource allocation schemes typically constrain users to be assigned a single BS (i.e., single connectivity constraint). This traditional constraint needs to be relaxed with the emergence of intelligent user devices with multi-homing capabilities. For a given MBN with $I$ BSs/APs, the multi-connectivity constraint for a single user can be described by:

$$\sum_{i=1}^{I} x_i \leq I,$$  \hspace{1cm} (35)

where $x_i \in \{0,1\}$ is connectivity of a given user to BS $i$. Implementing multi-connectivity would require careful interference management and group HO management.

2) **Backhaul-Aware Data Rate**: Backhaul capacity constraints become more complex in MBNs than in traditional single-band networks and HetNets. This is due to several factors, such as the diverse bandwidths and traffic aggregation in MBNs. For example, BSs in the Int-MBN will require ultra-high capacity backhaul links and more complex back-hauling strategies than SA-MBNs to support simultaneous transmissions across all bands. SA-MBN, which operates with single-band BSs, requires a higher number of backhaul links compared to Int-MBN. This is because each band in SA-MBN requires a separate backhaul link to support its transmissions. As a result, backhaul architecture must be upgraded to handle diverse traffic with distinct QoS and provide sufficient backhaul capacity. Mathematically, the backhaul capacity constraint for a BS in any type of MBN can be expressed as

$$\sum_{s=1}^{S} \sum_{k=1}^{K} R_{s,k} \leq C_{BH}^s,$$  \hspace{1cm} (36)

where $S$ and $K$ denote the number of multiple transmission links operating in different frequency bands and users, respectively, $R_{s,k}$ is the access network traffic for user $k$ on band $s$, and $C_{BH}^s$ is the backhaul link’s capacity for the BS $i$. In addition, each user’s backhaul-aware rate constraint

$$\min \left( C_{BH}^s, \sum_{s=1}^{S} R_{s,k} \right) \geq R_{th}^k,$$  \hspace{1cm} (37)

must be guaranteed, where $R_{th}^k$ denotes the QoS requirement of user $k$.

Integrated access and backhaul (IAB) combines access and backhaul functions within a single network element, enabling more efficient and flexible deployment of wireless infrastructure [311]. IAB in MBNs enables providing access links for end users and wireless backhaul links on a shared frequency or distinct frequency [312]. In the context of Int-MBN, leveraging IAB proves beneficial owing to the diverse transmission bands at its disposal, allowing for the effective use of each band for either access or backhaul links. Hierarchical networks, exemplified by architectures like Cloud Radio Access Networks (C-RAN) and Fog Radio Access Networks (F-RAN), involve the division of BSs into access units serving end users and a central unit responsible for baseband signal processing [313]. In particular, within MBNs, the flexibility is present to use different frequency bands for both access links and fronthaul links in the hierarchical networks.

3) **Required Illumination**: In MBNs, illumination and communication must be optimized jointly to comply with the requirements set by the international organization for standardization on light and lighting. In addition to VLC related transmission factors such as the location of the LEDs, the orientation of users’ devices, the FoV of the LEDs and the receiver, and the LED output power, multi-connectivity can impact illumination in an indoor environment. As an example, consider an indoor user aggregating downlink data transmission from a THz, mmWave, and VLC APs with the transmit powers $P_T$, $P_M$, and $P_V$, respectively. The sum of the corresponding data rates from these APs meets the QoS requirement of the user. However, $P_V$ alone may not guarantee the minimum illumination requirement. In addition, a maximum tolerable illumination $E_{max}$ constraint is required for eye safety. As a result, a constraint is needed to ensure that the minimum and maximum illumination requirements $E_{min}$ and $E_{max}$ are met and can be written as

$$E_{min} \leq X \leq E_{max},$$  \hspace{1cm} (38)

where

$$X = q \sqrt{P_V \left( \frac{(m+1)A_{PD} \cos^m(\Phi) \cos(\theta)}{2\pi d^2 \delta} + \frac{\rho_{wall} (m+1)A_{PD}}{2\pi d^2 (d_k^2)^2 (d_k^2)^2 \delta} \int dA_k \cos^m(\Phi_k) \cos(\theta_k^l) \cos(\Phi_k^l) \right)},$$  \hspace{1cm} (39)

where

1The Shannon’s channel capacity determines the highest achievable data rate with minimal errors, assuming no complexity or delay constraints during encoding and decoding. This calculation assumes that the channel’s mutual information is maximized with infinite blocklength, which means encoding a large number of bits enhances code diversity, improving error resilience. It’s worth noting that this increased reliability comes at the cost of added complexity and encoding/decoding delay.
is the illumination at any surface indoor [13], [258]. In (39), the summation terms inside the bracket denote LoS [13], [258] and first order reflection non-LoS paths [187] for the optical signal, respectively. $q$ is the electrical power to optical power conversion factor, and $\delta$ is the optical power to luminous flux conversion factor.

4) Molecular Absorption Threshold: A constraint on molecular absorption loss in THz communications is essential for effective resource allocation in MBNs. Atmospheric molecules can absorb and attenuate THz signals over long distances and pose a significant challenge in developing reliable and efficient THz communication systems and MBNs. This absorption is frequency-dependent as shown in (40) and is more pronounced in certain frequency bands within the THz spectrum. A typical molecular absorption threshold constraint can be given as

$$k(f_n) x_{n,i} \leq A_{th},$$

where $k(f_n)$ is the molecular absorption loss coefficient at the frequency $f_n$, $x_{n,i}$ denotes the subchannel allocation variable for the $n$-th subchannel with center frequency $f_n$, and $A_{th}$ is the molecular absorption loss threshold. It is important to note that, even when employing Equation (40) to transmit over TWs with minimized overall path loss and establishing frequency-flat channels, the use of equalizers remains essential for addressing phase distortions. Additionally, owing to the high data rates of THz transmission, the channel frequency response differs across various frequencies within each TW, necessitating the application of equalization techniques.

5) Interference Mitigation: In order to improve spectral efficiency in MBNs, a promising approach involves leveraging the same spectrum band for terrestrial and space networks. However, RF and mmWave bands have a limited spectrum and cannot provide the large contiguous bandwidth required for the projected spectrum demands. On the other hand, the THz band offers a vast amount of bandwidth but it is extensively regulated by governing bodies like the ITU and the FCC. These regulatory bodies exclusively reserve narrow subbands within the THz band for passive satellite operations, including climate and weather monitoring. Consequently, allocating large contiguous bands for active satellite operations and ground-to-space transmissions is prohibited. One potential solution to this issue is to permit active transmissions on the reserved subbands for passive satellite operations while ensuring the absence of harmful interference. This necessitates the establishment of an interference threshold constraint, which protects passive satellites in MBNs and allows spectrum sharing between active and passive satellites, as well as ground-based BSs. The interference threshold requirement for the passive satellite $p$ in an MBN with $I$ active satellites and terrestrial BSs sharing the same spectrum can be expressed as follows:

$$\sum_{i=1}^{I} P_i |h_{i,p}(d_{i,p}, f)|^2 \leq \Gamma, \quad (41)$$

where $P_i$ is the transmit power of the $i$-th active satellite (or terrestrial BS), $\Gamma$ is the maximum allowable interference level, and $h_{i,p}(d_{i,p}, f)$ is the channel power gain for the link between the active node $i$ and the passive satellite $p$ with $d_{i,p} = \sqrt{(R \sin \alpha)^2 + 2RH + H^2 - R \sin \alpha}$ [314] being the distance between the active node and the passive satellite orbiting at a height $H$ at an elevation angle $\alpha$, $R$ being the radius of the Earth, and $f$ is the carrier frequency in GHz. Similarly, interference threshold constraints are necessary for CA implementation in MBNs.

6) EMF Exposure: With the proliferation of wireless devices and networks, there is an increasing concern regarding the potential health effects of prolonged exposure to EMF. Studies have been conducted to investigate the possible links between EMF exposure and adverse health outcomes, although the scientific consensus is that current exposure limits are set well below the levels known to cause adverse non-thermal effects by ICNIRP. However, using multiple frequency bands and the coexistence of diverse wireless systems in MBNs can result in complex EMF environments. Without proper constraints, the cumulative EMF exposure levels could exceed recommended limits, posing potential risks to human health and safety. By imposing EMF exposure constraints in MBNs, regulatory bodies, and standards organizations can establish limits on the maximum permissible levels of EMF emissions and help ensure that the EM radiation emitted by wireless devices and network infrastructure remains within safe thresholds. Focusing on the single user $k$ in an MBN with $I$ BSs operating on the frequency $f$, EMF exposure caused by the user’s device itself due to the uplink and from the BSs due to the downlink can be quantified by the specific absorption rate (SAR) and is given as

$$\sum_{i=1}^{I} S_{i,\text{DL}, \text{ref}, \text{DL}} + \sum_{i=1}^{I} P_{i,k, \text{UL}, \text{ref}, \text{UL}} \leq \text{SAR}_{\text{max}}, \quad (42)$$

where $S_{i,\text{DL}, \text{ref}, \text{DL}}$, $P_{i,k, \text{UL}, \text{ref}, \text{UL}}$, $\text{SAR}_{\text{max}}$ denote the received power density, the DL SAR value which is normalized to a reference received power density of 1 W/m$^2$, the uplink transmit power in W, the SAR in the uplink normalized to unit transmit power, and the maximum allowable exposure limit, respectively. Typical values for $\text{SAR}_{\text{max}}$ according to the FCC have been provided in [315].

7) Next Generation Multiple Access Schemes: The choice of multiple access scheme (e.g., NOMA, space division multiple access, rate splitting multiple access (RSMA)) in MBNs can affect the required constraints in resource allocation optimization. As an example, RSMA has recently emerged as a powerful multiple access scheme. According to this scheme, each user splits its data into two parts: common information that is shared by all users and private information intended only for the specific user [316]. The optimization constraints associated with an RSMA-based MBN with $I$ BSs and $K$ users include:

- Power budget: The downlink transmit power constraint for SA-MBN and Int-MBN can be expressed as $\sum_{k=0}^{K} P_k \leq P_{\text{max}}$ and $\sum_{i=1}^{I} \sum_{k=1}^{K} P_{i,k} \leq P_{\text{max}}$, respectively, where $P_0$, $P_k$ for $k \geq 1$, $P_{i,0}$, $P_{i,k}$ for $k \geq 1$ and $P_{\text{max}}$ are the transmit power of the common message for SA-MBN,
the transmit power of the private message for user $k$ in SA/AP $i$ in Int-MBN, the transmit power of the common message for BS/AP $i$ in SA-MBN, the transmit power of the private message of user $k$ from BS/AP $i$ in Int-MBN, and the maximum allowable transmit power.

- **Common message rate:** To guarantee that the common stream can be decoded successfully by all users in an Int-MBN, the constraint
  \[ \sum_{i=1}^{I} C_{i,k} \leq \sum_{i=1}^{I} R_0 \left( P_{i,0}, P_{i,k}, H(f) \right), \quad k \geq 1, \quad \text{with } C_{i,k}, R_0 \text{ and } H(f) \text{ being the portion of the common rate of user } k \text{ from the BS/AP } i, \text{ a function for the common rate of user } k, \text{ and the channel power gain of the BS/AP } i, \text{ respectively, is required.}

- **QoS constraint:** To ensure that the achievable rate of user $k$ meets the minimum rate requirement $R_{th}$ in an Int-MBN, the constraint
  \[ \sum_{i=1}^{I} C_{i,k} + \sum_{i=1}^{I} R_{i,k} \left( P_{i,k}, H(f_i) \right) \geq R_{th}, \quad \text{where } R_{i,k} \text{ is a function for the private data rate of user } k \text{ from BS } i, \text{ is needed.}

8) **Differentiated Service Requirements:** The heterogeneity of user devices (resulting from different capabilities of device front ends/hardware limitations) and the different types of services (e.g., enhanced mobile broadband, URLLC, and massive machine type communication (mMTC)) should be considered when designing resource allocation schemes in MBNs. It is possible that not all user devices would have multi-homing capability since both types of devices could co-exist in MBNs. Also, certain device types (e.g., MTC devices) might be required to operate solely in specific frequency bands due to operational and/or device limitations. Furthermore, different service types have diverse QoS requirements in terms of delay, throughput, priority, reliability and traffic patterns as event-driven, periodic and streaming [317]. As an example, MTC devices typically do not require high data rate and are characterized by periodic traffic. On the other hand, extremely high data rates should always be guaranteed for enhanced mobile broadband services while strict reliability and latency requirements of URLLC services must be ensured always. MTC devices can be low-end devices with lower computational and memory resources as compared to enhanced mobile broadband devices. In such scenarios, resource allocation schemes must be designed to have constraints that support successful operations of heterogeneous user devices and the differentiated QoS requirements.

C. Conventional Resource Allocation Techniques

In this section, we discuss typical approaches to solve resource allocation problems in MBNs.

1) **Alternating Optimization:** This method is an iterative procedure for optimizing a function jointly over all variables by alternating between optimizing subsets of variables while fixing the others. However, it is important to note that AO does have certain limitations. While it can converge to a global solution in some instances, it may also converge to local solutions or saddle points. This means that depending on the problem formulation, there is a possibility of not reaching the global optimum. Therefore, careful consideration should be given to the problem characteristics and convergence properties when applying AO in MBNs.

2) **Block Coordinate Descent (BCD):** Similar to the AO, BCD is an iterative algorithm used to solve complex problems by optimizing subsets of variables. However, the entire set of variables is divided into non-overlapping blocks. During each iteration, one block (or a few blocks) of the variable is selected and optimized while keeping the other blocks fixed. This process is repeated for each block until convergence is achieved. The effectiveness of BCD depends on factors such as the block partitioning strategy, block selection rule, and block update rule. These choices can impact the algorithm’s convergence behavior and solution quality, as discussed in [318]. Between BCD and AO, the former is generally more suitable for problems with a large number of optimization variables and has lower memory requirements. A recent, more generalized version of the BCD algorithm that efficiently handles subproblems with non-convex functions is the block successive upper-bound minimization [319].

3) **Fractional Programming:** Fractional programming theory concerns the optimization of problems containing ratio term(s). For single-ratio problems, classical techniques include the Charnes-Cooper transform [320], [321] and the Dinkelbach’s transform [322]. On the other hand, the quadratic transform approach [323] is more suitable for fractional programming problems with multiple ratios (e.g., sum-of-ratios). This approach transforms the sum-of-ratios function into a quadratic function by introducing an auxiliary variable. The transformed problem with the quadratic objective function can be solved iteratively, where convex optimization techniques are used to solve the primal variables, and closed-form solutions can be obtained for the auxiliary variables. In MBNs, fractional programming techniques can be useful to optimize performance metrics such as DCE, energy efficiency, and connection density.

4) **Successive Convex Approximation (SCA):** The SCA method is an iterative technique used to solve non-convex problems by approximating them with a sequence of tractable subproblems. The key idea is to replace the original non-convex functions with surrogate functions that are simpler and possibly convex. The choice of surrogate functions is crucial for ensuring convergence and accuracy of the method. Surrogate functions should satisfy properties like convexity, tightness, monotonicity, and continuity. Additionally, having separable surrogates facilitates the design of parallel/distributed solution methods. Several techniques can be employed to construct convex surrogates, including first and second-order Taylor expansions, convexity techniques, special inequalities, and the pointwise maximum technique with their corresponding advantages and limitations summarized in Table XII.

5) **Majorization-Minimization (MM):** The MM method, a particular instance of the SCA approach, differs based on the following points:

- Convexity: SCA focuses on approximating non-convex functions by convex surrogates, while MM constructs
Advantages
- Allows incorporation of problem-specific properties
- Provides a simple linear approximation
- More accurate approximation capturing curvature
- Suitable for non-linear functions
- Can handle non-convexity to some extent

Limitations
- Limited accuracy for non-linear and highly curved functions
- Requires knowledge of first derivatives
- Not applicable for non-differentiable functions
- Requires knowledge of first and second derivatives
- Complexity increases with higher-order terms
- May diverge for non-convex functions

TABLE XII
ADVANTAGES AND LIMITATIONS OF SURROGATE FUNCTION CONSTRUCTION TECHNIQUES

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Order Taylor Expansion</td>
<td>- Provides a simple linear approximation</td>
<td>- Limited accuracy for non-linear and highly curved functions</td>
</tr>
<tr>
<td></td>
<td>- Easy to compute and implement</td>
<td>- Requires knowledge of first derivatives</td>
</tr>
<tr>
<td></td>
<td>- Suitable for smooth functions</td>
<td>- Not applicable for non-differentiable functions</td>
</tr>
<tr>
<td>Second Order Taylor Expansion</td>
<td>- More accurate approximation capturing curvature</td>
<td>- Requires knowledge of first and second derivatives</td>
</tr>
<tr>
<td></td>
<td>- Suitable for non-linear functions</td>
<td>- Complexity increases with higher-order terms</td>
</tr>
<tr>
<td></td>
<td>- Can handle non-convexity to some extent</td>
<td>- May diverge for non-convex functions</td>
</tr>
<tr>
<td>Convex Inequality</td>
<td>- Preserves convexity of original function</td>
<td>- May result in conservative approximations</td>
</tr>
<tr>
<td></td>
<td>- Allows for efficient convex optimization</td>
<td>- Limited to convex functions</td>
</tr>
<tr>
<td></td>
<td>- Applicable to various problem domains</td>
<td>- Constraints may become overly restrictive</td>
</tr>
<tr>
<td>Special Inequalities</td>
<td>- Allows incorporation of problem-specific properties</td>
<td>- Limited applicability to specific problem domains</td>
</tr>
<tr>
<td></td>
<td>- Can exploit problem structure</td>
<td>- Requires domain expertise</td>
</tr>
<tr>
<td></td>
<td>- Provides tighter bounds in some cases</td>
<td>- May increase problem complexity</td>
</tr>
<tr>
<td>Pointwise Maximum</td>
<td>- Captures the best approximation point-wise</td>
<td>- Limited to functions that can be expressed as the maximum of multiple</td>
</tr>
<tr>
<td></td>
<td>- Flexibility in choosing simpler functions</td>
<td>simpler functions</td>
</tr>
<tr>
<td></td>
<td>- Can handle non-convexity in parts of the function</td>
<td>- Computational complexity may increase</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- May introduce non-smoothness in the approximation</td>
</tr>
</tbody>
</table>

surrogate functions that majorize the original objective function without necessarily being convex.

- **Objective Function:** SCA replaces the original non-convex objective function with a convex surrogate, while MM constructs a surrogate that is an upper bound on the original objective function.
- **Constraint Set:** SCA convexifies constraints since it cannot deal with non-convex constraints directly. The MM can be easily extended to non-convex constraints.
- **Convergence:** SCA guarantees convergence to a stationary point of the original non-convex problem. MM improves each iteration’s objective value and converges to a locally optimum point of the original non-convex problem. MM converges to a locally optimal point because the surrogate functions used in MM may not perfectly capture the behavior of the original non-convex function as they are tight upper bounds, not necessarily identical to the original function.

6) **Semidefinite Relaxation (SDR):** SDR is a powerful and computationally efficient approximation method for solving non-convex quadratically constrained quadratic programs (QCQPs). The objective function and constraint set in typical QCQP have a quadratic form. To obtain the SDR of a QCQP, the objective function and constraints are first linearized by expressing them in terms of the trace operator. This transformation allows the problem to be reformulated as a semidefinite programming problem with a positive semidefinite (PSD) matrix variable. In the SDR formulation, the objective function becomes the trace of a matrix multiplied by the PSD variable, and the constraints are expressed as linear inequalities involving the trace of matrices. By relaxing the rank constraint of the PSD matrix, the SDR problem can be solved using convex optimization techniques since the objective and constraints are all affine. However, the SDR problem is non-convex due to the relaxed rank constraint. When the globally optimal solution of the SDR problem has a rank larger than one, additional steps are required to obtain a feasible solution for the original QCQP problem. Some common approaches include spectral decomposition, which extracts a low-rank approximation of the optimal solution; rounding techniques, which round the optimal solution to a feasible solution; and matrix completion, which fills in missing entries of the optimal solution matrix to satisfy the rank constraint.

Although SDR has yet to be extensively applied to resource management problems in MBNs, it holds potential for various applications in single-antenna and multiple-antenna systems. Examples include optimizing transmit and receive beamforming in multiple antenna-enabled transmissions, multi-task offloading, and resource allocation in cloud access networks.

7) **Matching Theory:** Matching theory is used to solve combinatorial optimization problems by matching or pairing players from two (i.e., two-sided matching) or more distinct sets based on preference relations. This approach enables matching of resources and users given their individual, often different, preferences and learned information such as quota (i.e., the maximum number of players with which it can be matched). Typically, in a two-sided matching game involving users and BSs, each user and BS first defines a preference list by ranking the other. Then, each user proposes to its favorite (highest ranked) BS while BSs make accept (i.e., each keeps favorite users among its preference list) and reject decisions. This process repeats until a stable matching between users and APs is reached, where stability means there are no blocking pairs.

In the context of resource allocation in MBNs, the application of matching theory will witness a shift from the most widely used one-to-one and many-to-one matching as well as canonical matching [217], [217], [258], [284], [324]–[327] to many-to-many matching, matching with externalities, and matching with dynamics. This is due to the presence of multi-homing devices that enable both BSs/APs and users to have multiple simultaneous connections, the mobile nature of users and satellites, and the unique constraints associated with the different frequency bands. Moreover, in contrast to most existing matching algorithms that require knowledge of global information (e.g., complete knowledge of the preference lists),
novel online matching algorithms capable of attaining stable matching when there is limited or partial information about the preferences or constraints are required.

8) **Deep Learning:** One of the primary challenges associated with conventional optimization-driven resource management and network planning is the presence of high-complexity algorithms, which can become impractical when dealing with large-scale networks. Furthermore, the ever-changing and dynamic nature of wireless communications and short channel coherence time, such as the need to accurately determine user locations and proactively make HO decisions, poses another critical hurdle that traditional approaches may struggle to address effectively, particularly in real-time scenarios. To overcome these obstacles, machine learning-based strategies, including neural networks (NNs), model-free reinforcement learning, Q-learning, graph neural networks (GNNs), and others, offer viable solutions. Notably, NNs, renowned for their robust approximation capabilities, can be effectively deployed to manage intricate algorithms for network resource management. Reinforcement learning, which operates based on feedback in the form of rewards and costs from the environment, has demonstrated its utility by enabling rapid decision-making in dynamic systems once a policy is acquired. GNNs are known for their enhanced scalability.

**D. Performance Analysis of MBNs**

1) **Simulation Set-up:** This subsection uses numerical results to compare the performance of the envisioned MBNs architectures in terms of BS intensity, DCE, HO probability, outage probability, and data rate. Unless stated otherwise, we consider $N_T$ and $N_R$ single antenna THz and RF BSs, respectively, in the deployment of the SA-MBN. With regards to the Int-MBN deployment, we consider $N_{Thz}$ BSs operating on both THz and RF frequencies. The RF and THz transmit power are set to be 10 and 0.3 [Watts], respectively. BSs and users are uniformly distributed across a circular area with a radius of 400 [m]. The array gains of the THz transmitter and receiver are 25 [dBm], and the THz carrier frequency is 1 [THz]. Simulations are repeated over $5 \times 10^4$ experiments.

As proposed in [63], a molecular absorption-aware bias association metric is used for RBS and TBS, which are given by:

$$\text{Bias}_{R} = B_{R|P_{Rx}^{T}}, \quad \text{Bias}_{T} = B_{T|P_{Tx}^{R}} \exp(K(f_T)d),$$

where $B_R$ and $B_T$ denote the RF and THz transmission channel bandwidths, respectively. Also, $p_{Rx}^{T}$, $p_{Rx}^{R}$, $\exp(K(f_T))$, and $d$ denote the RF and THz received powers obtained using (32) and (33), molecular absorption coefficient at carrier frequency $f_T$, and the distance between BS and the typical user, respectively. Figure 8 presents a comparison of various user offloading metrics concerning the average data rate within both SA-MBN and Int-MBN contexts. Among these metrics, the maximum data rate-based association exhibits superior performance. However, the proposed bias-based association method offers a notable advantage by reducing both CSI overhead and computational complexity while still achieving performance levels comparable to the maximum data rate for both SA-MBN and Int-MBN deployments.

Following the proposed scheme, the next best metric in terms of performance is the reference signal received power (RSRP) metric, followed by the SINR metric. It’s worth noting that the SINR metric lags behind due to its failure to account for the impact of transmission bandwidths. Consequently, when using SINR as the association metric, it predominantly selects RF, and even with an increased number of BSs, it cannot attain the high data rates provided by TBSSs.

2) **Deployment Density as a function of QoS:** Figure 9 depicts the number of BSs required to meet various target average network data rate requirements for SA-MBN and Int-MBN with various THz transmission bandwidths, i.e. $B_T$. For this figure, the number of BSs is the same in the SA-MBN and Int-MBN, i.e., $N_T = N_R = N_{Thz}$. We note that, for the same rate threshold, the SA-MBN architecture requires more BSs than the Int-MBN. This observation is true for different bandwidth values. Then, we examine the case of SA-MBN with unequal proportion of RF and THz BSs referred to as SA-MBN-FN. SA-MBN-FN outperforms SA-MBN in terms of the required number of BSs to meet the network rate threshold. That is, optimizing the number of BSs for different bands in SA-MBNs is critical. High interference
in RF transmissions and low communication distance of THz transmissions can be compensated by increasing the number of THz BSs and decreasing the number of RF BSs. However, the cost of deployment can be the decision factor between the three configurations.

3) Network DCE as a function of QoS: The average network DCE for various data rate thresholds is shown in Fig. 10. As can be observed, DCE of all configurations improve when the target rate increases. Int-MBN outperforms SA-MBN since it uses fewer BSs and less transmit power to reach the target data rate threshold. On the other hand, by enabling SA-MBN to independently choose the number of RF BSs and THz BSs, i.e., SA-MBN-FN, while setting a smaller bandwidth for the THz transmission, we notice that the DCE can be larger than Int-MBN before a specific data rate threshold. Raising the THz bandwidth, however, makes the Int-MBN perform better than SA-MBN-FN. It is worth mentioning that for a higher THz bandwidth, the overall THz association increases, reducing the amount of consumed power in the network as THz transceivers utilize less power than RF ones.

4) Handoff Probability in MBNs: Figure 11 demonstrates the HO probability of the user of interest moving at a pre-defined velocity considering both SA-MBN and Int-MBN deployments and THz-Only and RF-Only. It can be observed that both MBN deployments outperform the use of only one frequency band. It is intuitive that for a higher number of BSs and velocity, HO probability increases. For higher number of BSs, Int-MBN has a marginal gain over SA-MBN. In comparison, for a lower number of BSs, Int-MBN consistently outperforms SA-MBN when velocity increases. Seamless group HOs would be critical due to multi-connectivity considerations in MBN.

5) Significance of MBNs over Standalone CounterParts: Fig. 12 illustrates the influence of varying the frequency-dependent molecular absorption coefficient \(k(f)\) values on outage probability for various network architectures. In this figure, the molecular absorption-aware association metric for MBN proposed in [63] is employed. It can be observed that the SA-MBN outperforms all other scenarios as \(k(f)\) increases, eventually approaching RF-Only as no THz transmission is possible at high \(k(f)\). For the same reason, THz-only performance degrades significantly. It is also observed that for small values of \(k(f)\), the use of THz-only is advantageous. Based on the results depicted in figures 12 and 13, it is crucial to select the transmission bands adaptively. Similar insights can be obtained from Figure 13 that depicts the average network data rate for a SA-MBN, an Int-MBN, and THz-only and RF-only networks for various various molecular absorption coefficients.

E. Lessons Learned

This section delved into novel performance metrics that merit inclusion as objective functions while introducing pragmatic design constraints for MBNs. The discussion unveiled the influence of diverse user behaviors (like velocity) and network parameters (including molecular absorption coefficient and network rate threshold) on MBN performance, with the degree of impact varying by MBN architecture. Notably, simulations showcased SA-MBN’s superiority over Int-MBN in outage probability for different molecular absorption coefficient values. Additionally, it was demonstrated that Int-MBN architecture requires fewer base stations than...
SA-MBN for the same network target rate. These findings underscore the significance of factoring in the metrics and constraints highlighted in this section for an enhanced grasp of MBNs and informed decisions regarding their commercial deployment. Furthermore, promising optimization techniques and machine learning approaches adept at addressing the evolving network structure and dynamic wireless environment were presented. The development of advanced optimization techniques such as non-smooth and non-convex optimization [328]–[330], quantum-inspired real-time optimization [331], [332], learning to branch and bound [333], sparse optimization, and bi-level optimization [334], [335] is an open area for future studies.

VII. OPEN CHALLENGES AND RESEARCH DIRECTIONS

This section highlights key tools and techniques for enhancing the performance of MBNs and discusses open issues for future research. The organization follows a layer-wise fashion starting from infrastructure and antenna level, PHY and resource allocation, and then network level.

A. Infrastructure and Antenna Level

1) Cell Tower Design and Deployment: Different MBN architectures require specific cell tower design that offers various advantages as discussed in Sec. IV-A. However, knowing what to look for in the design of multi-band cell towers for various architectures is not always obvious. First, transitioning from traditional networks with three sector antennas to MBNs can have several impacts on antenna space requirements. With multiple frequency bands (characterized by different propagation characteristics) and the need for higher capacity, the number of antennas on each cell tower may increase. For example, higher order sectorization and larger antenna array will replace the traditional three-sector antennas layout [336]. More antennas can require additional power and backhaul resources. As a result, the tower design should guarantee sufficient power supply (static and dynamic) and backhaul connectivity infrastructure, be structurally sound to support the weight of multiple antennas and cable loads, and must allow future upgrades and expansions without significant modifications.

Focusing cell deployment, the different MBNs’ architecture would require customized BS/AP deployment to optimally exploit the characteristics of the various bands. However, building and maintaining separate towers for each frequency band (typical for SA-MBNs) can lead to increased infrastructure costs, including land acquisition, tower construction, and ongoing maintenance. In urban areas or regions with limited available land, setting up multiple towers can be logistically challenging due to space constraints. Furthermore, obtaining approvals and permits for multiple tower installations can be a lengthy and complex process due to environmental and EM exposure regulations.

2) Design of Advanced Multi-Antenna Architectures: Due to the smaller wavelengths of EHFS, extremely large aperture arrays (ELAAs) are critical to obtain vast array gain and spatial resolution in MBNs. An ELAA consists of hundreds of distributed BS antennas that are jointly and coherently serving many distributed users [337]. They dramatically boost antenna numbers and physical size beyond the current massive MIMO systems as all antenna elements with inter-element distance on the order of a wavelength are deployed on a shared contiguous platform. However, many practical limits to how many antennas can be deployed at cell towers and rooftop BSs are yet to be investigated. Conventional cell towers (and rooftop BSs) use compact arrays that point in different directions (i.e., multi-sector antennas). The deployment of ELAAs call for new antenna architectures, deployment strategies, and phase synchronization schemes as over hundreds of antennas cannot be positioned as sector antennas but would be distributed over large geographical areas. Another important future research array is developing extremely large capacity fronthaul links to service ELAAs. Moreover, it is important for ELAAs to have hybrid antenna design that enables flexibility in accommodating diverse bands. In addition to the above-mentioned challenges, beam squint phenomena need to be taken into account when designing multi-antenna systems in MBNs. This matter is more critical when incorporating the THz band into an MBN due to the higher bandwidth and frequency separation in the THz band. Also, switching over different frequency bands can be problematic as each true time delay component used for mitigating beam squint should be adaptive to the target frequency band.

3) MBN Antenna Systems Design: A multi-band antenna system capable of transmitting both sub-6 GHz and mmWave signals through a combination of frequency conversion and filtering techniques has recently been proposed in [338]. The architecture and operation of this antenna system is described as follows. A NI PXI 5791 signal transceiver is used in conjunction with a NI PXIe 7975R field-programmable gate array module for baseband signal processing. The NI-5791 performs frequency up-conversion and down-conversion from the baseband signal to the IF. A 20 MHz baseband signal is generated and converted to an analog signal, up-converted to an IF frequency of 2.5 GHz using the NI-5791’s DACs and frequency up-conversion unit. For mmWave transmission, the IF signal from the NI 5791 is further up-converted to the mmWave band (e.g., 28 GHz) using a frequency up-conversion unit. A bandpass filter is employed after the frequency up-conversion.
to eliminate unwanted signals, including image frequency, LO leakage, and other interference. This IF sampling transceiver design enables the use of ADCs characterized by low power consumption and high bit resolution. Research on how to exploit this setup to design antennas capable of transmitting signals across sub-6 GHz, mmWave, THz, and visible light frequency ranges is strongly encouraged. In addition, multi-band antenna design will witness a transformative paradigm shift driven by the demand for smaller antenna sizes and more compact form factors. However, as antennas become smaller and more tightly integrated, several significant challenges arise that must be addressed to ensure optimal performance and reliability. One of the key challenges is mutual coupling. As antennas are packed closer together in compact devices or arrays, EM interactions between neighboring antennas can lead to interference and reduced efficiency. Another critical concern is radiation pattern control. In the quest for compactness, it becomes challenging to achieve desired radiation patterns for antennas operating at different bands. Moreover, as antennas shrink in size, maintaining proper impedance matching across a wide frequency range becomes intricate. Impedance mismatch can lead to signal reflections, reduced bandwidth, and inefficient power transfer.

B. PHY and Resource Allocation

1) Orthogonal Time Frequency Space Modulation: OTFS is a newly developed modulation technique for high-mobility high frequency communications. The OTFS modulation technique utilizes the delay-doppler (DD) domain for information modulation instead of the TF domain used in traditional OFDM modulation. This feature offers robust delay and Doppler resilience while leveraging the benefits of full diversity, which is essential for ensuring reliable communication. The OTFS technique involves the mapping of data symbols into the DD domain. Each symbol has the capability to be expanded completely in the TF domain. This enables the channel to have a similar impact on every data symbol, effectively minimizing fading and interference. To clarify, this particular technique transforms channels that exhibit fading in the TF domain into a relatively constant channel in the DD domain. It extracts entire TF-angle diversity.

2) Multi-band 3D Beamforming Design: Different from 2D beamforming that steers signals in a specific direction in a two-dimensional plane (i.e., either azimuth 2D beamforming from a horizontal antenna array or elevation 2D beamforming from a vertical antenna array), a 3D beamforming system can shape and steer beams both in the horizontal plane (azimuth) and in the vertical plane (elevation). A combination of horizontal and vertical antenna arrays is often used to achieve this. Although 3D beamforming can help compensate for the high PL and atmospheric attenuation at EHFs, several challenges arise in its design for multi-band communications. First, designing antenna array architectures that support both azimuth and elevation beamforming across multiple bands is complex since different frequency bands might require different antenna configurations due to wavelength variations. Second, allocating resources (e.g., power and bandwidth) across multiple bands while optimizing the 3D beamforming strategy is challenging. Third, the computational complexity and feedback overhead of implementing 3D beamforming in multi-band systems can be significant due to the increased dimensions involved. The beamforming strategy should be adaptable to the changing frequency-dependent environment characteristics, mobility of users, and variations in interference patterns.

3) Near-Field Transmission Models: Traditionally, the near-field ranges from few centimeters to meters because of the low-dimensional antenna arrays and low frequencies. Therefore, the far-field approximation was reasonable. However, in the era of ELAAs and EHFs, MBNs will exhibit a large near-field region on the order of hundreds of meters. As a result, uniform plane wave wireless channel models typically used in the far-field would no longer be valid for ELAAs communications. It is therefore important to develop near-field transmission models for ELAAs-enabled MBNs. Research areas such as near-field channel modelling and measurement campaigns, acquisition of channel features, and prototyping that accurately reflect reflect signal phase and amplitude variations, and projected aperture across array locations are prominent future directions.

4) Reconfigurable Intelligent Surfaces Design and Optimization: The traditional reconfigurable intelligent surfaces (RISs) enable adapting wireless environments by tuning reflection/refraction coefficients and phase shifts for a predefined transmission frequency as shown in Table XIII. While RISs at lower frequencies are mostly used to increase coverage, they can overcome link blockages at EHF bands and also improve communication and illumination performance in EHF [240]. However, a given RIS optimized to operate on a a given frequency may not optimally perform at another frequency. Such issues would arise in an MBN where multiple spectrum transmissions coexist. Therefore optimization of IRSs in an MBN would be immediate relevance. Also, the design of RISs capable of manipulating signals from diverse frequency bands needs to be studied thoroughly due to (i) the material properties required for RISs vary across different frequency bands, (ii) the electronic components and technologies used for signal manipulation have limitations at EHF, and (iii) different frequency bands have different propagation characteristics.

5) Design of Scalable and Robust QoS-Aware Deep Learning Resource Allocation: Traditional optimization based resource allocation solutions can be typically slow, computationally exhaustive, and not scalable. While this was acceptable in the previous decade, it is becoming practically difficult to adopt them in next generation large-scale MBNs. The reason is the short channel coherence time and a variety of unique channel impediments in EHF which necessitate fast, scalable, and robust resource management (i.e., power control, spectrum allocation, beamforming, beam tracking, antenna allocation, etc.) solutions. In this context, deep learning solutions enable online resource management with deep neural networks that can be trained on environment specific CSI datasets. However, a fundamental challenge would be to incorporate convex and non-convex diverse QoS constraints in the DNN architectures and guarantee 100% constraint satisfaction [303]. Constraints associated with different transmission frequencies such as
illumination constraint for VLC, molecular absorption-aware transmission windows in THz, and beam squint/misalignment in FSO and THz should be taken into account. A differentiable projection based framework is proposed very recently in [303].

It is critical to develop new deep learning techniques that are environment agnostic, i.e., the techniques where a given neural network can perform well for a different environment without significant retraining. In this context, meta-learning is a promising approach which enables a DNN to perform in a generalized environment with few-shot training.

C. Network Level

1) Large-Scale Modeling and Analysis: The two fundamental architectures of MBNs are Int-MBNs and SA-MBNs. In addition to these two are (i) the cascade architecture where RF and EHF links are used for access and backhaul links, respectively, (ii) hybrid SA and Int-MBNs architecture, and (iii) the co-existence of HetNets and MBNs (i.e., SA, Int, cascade, hybrid, or multi-band HetNets). The various bands have different signal propagation characteristics. As an example, the received signal power for THz transmission is a function of the spreading loss and the molecular absorption loss which is modeled as an exponential function of the link distance. THz and VLC networks are intrinsically short-range and suffer from link blockages. To better exploit all these bands in a MBN setup, their corresponding BSs/APs will be deployed on large-scale. As a result, interference and coverage analysis become more challenging and may differ for the different MBN architectures. An example of such a large-scale stochastic geometry framework for SA-MBN analysis is given in [339] without mobility and in [213] with mobility. Large scale deployment of these type of networks calls for sophisticated large-scale system modeling techniques and analytical tools to optimize network performance, coverage, and efficiency under various conditions such as traffic loads, user distributions, blockages, and MBN architectures.

2) Mobility and HO Management: BSs/APs and satellites operating on different transmission bands would provide support for numerous types of devices (e.g., handheld devices, internet-of-things devices, and connected autonomous vehicles) in a highly mobile and dynamic environment in MBNs. The high-speed movement of users, vehicles, air-planes, and satellites in MBNs can lead to simultaneous triggering of handovers by multiple users or ground stations, resulting in intense signaling storms (i.e., group HOs) and a higher likelihood of HO process collisions. Moreover, the BSs/APs and devices in MBNs have different communication capabilities (e.g., transmit power, spectrum usage, QoS requirements, antenna). Modeling and managing seamless handovers between such heterogeneous entities demands adaptive algorithms that account for these differences (a recent work in this context is [213]). As an example, a HO may involve shifting users between different bands, necessitating dynamic bandwidth allocation to accommodate changes in user requirements and network conditions. In addressing these challenges, MBNs must rely on advanced mobility management techniques, including predictive algorithms, context-aware decision-making, adaptive threshold settings, and distributed coordination among network entities. The integration of machine learning and artificial intelligence can enhance handover prediction accuracy and optimize handover decisions based on real-time network conditions and the capabilities of the different APs/BSs/devices.

3) Backhaul Traffic Route Selection and Flow Optimization: MBNs would involve wireless data transmission among millions of devices and APs/BSs/satellites which can generate a large amount of backhaul traffic. Backhaul networks must be characterized by high-capacity links to accommodate the huge volume of traffic and must be resilient and fault tolerant. As the locations of users and satellites change and the QoS requirements of users get updated, the backhaul network should adapt to handle the new backhaul traffic distribution. However, different APs/BSs support various transmission bands with varying available bandwidth and transmit power, which affect link capacity and latency. It therefore becomes important to develop highly scalable QoS-aware multi-path routing and flow control algorithms that consider the heterogeneity of BSs/APs and user devices and dynamically adapt to changes in network conditions and application demands, and support satellites and users’ mobility. Owing to the different capabilities and limitations of the different bands and APs/BSs/user devices, it is essential that the routing algorithms consider multiple objective metrics that reflect the QoS requirements of users and the capabilities/limitations of the different network entities. Emerging wireless communication technologies such as network slicing and multi-access edge and fog computing can be leveraged to improve the performance (e.g., latency, reliability, and security) of backhaul networks.
VIII. Conclusion

5G and beyond wireless networks are envisioned to leverage the unique characteristics and benefits of multiple frequency bands within an MBN. This convergence of bands holds the potential to enhance capacity and throughput, support user mobility and diverse QoS requirements, and bolster network reliability and robustness, among others. However, a tremendous amount of work needs to be done in terms of understanding the different architectures of MBNs, characterizing and accurately modeling the channels for the various bands, designing multi-band transceivers and antenna systems, developing low-cost experimental and simulation platforms, and designing innovative resource allocation algorithms. This paper presented visionary MBN architectures and compared their HO probability, outage probability, network data rate, deployment intensity, ad DCE performances. Moreover, we discussed the various channel modeling efforts, standardization activities, and advancements on simulation platforms for the various bands. In addition, we provided an in-depth survey of existing resource allocation methods. The survey revealed that THz/VLC-based MBNs have received little attention, and advanced resource allocation techniques are required for MBNs. It is hoped that this paper will provide researchers and industry players with a holistic view of all the technical aspects and issues required to design and deploy MBNs for 6G and beyond.

REFERENCES


IEEE approved draft standard for multi-gigabit per second optical wireless communications (OWC), with ranges up to 200 meters, for both stationary and mobile devices,” IEEE P802.15.13/D10.0, November 2022, pp. 1–154, Feb. 2023.


IEEE standard for high data rate wireless multi-media networks amendment 1: Extending the physical layer (PHY) specification for millimeter wave to operate from 57.0 GHz to 71 GHz,” IEEE Std 802.15.3-2016 (Revision of IEEE Std 802.15.3-2003, 2016–17), pp. 1–510, Jul. 2016.

IEEE draft standard for multi-gigabit per second optical wireless communications (OWC), with ranges up to 200 meters, for both stationary and mobile devices,” IEEE P802.15.13/D10.0, November 2022, pp. 1–154, Feb. 2023.


IEEE approved draft standard for multi-gigabit per second optical wireless communications (OWC), with ranges up to 200 meters, for both stationary and mobile devices,” IEEE P802.15.13/D10.0, November 2022, pp. 1–154, Feb. 2023.


Authorized licensed use limited to: KAUST. Downloaded on February 18,2024 at 10:26:53 UTC from IEEE Xplore. Restrictions apply. © 2024 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Communications. 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/TCOMM.2024.3368816


IEEE TRANSACTIONS ON COMMUNICATIONS


Authorized licensed use limited to: KAUST. Downloaded on February 18, 2024 at 10:26:53 UTC from IEEE Xplore. Restrictions apply.
passive users above 100 GHz,” Communications Engineering, vol. 1, no. 1, p. 6, May 2022.


Sylvester Abouagye (Member, IEEE) received the B.Sc. degree (Hons.) in telecommunication engineering from the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, in 2015, and the M.Eng. and Ph.D. degrees in electrical engineering from Memorial University, St. John’s, NL, Canada, in 2018 and 2022, respectively. He received many prestigious awards including the Governor General’s Gold medal in graduate studies. He was a Postdoctoral Research Fellow with the Department of Electrical Engineering and Computer Science at York University, Canada, from January to December, 2023, and is currently an Assistant Professor with the School of Engineering, University of Guelph, Canada. His current research interests include the design and optimization of multiband wireless communication systems, terrestrial and non-terrestrial integrated sensing and communication networks, and 6G and beyond enabling technologies. Dr. Abouagye serves as an Editor for IEEE Communications Letters, a Technical Program Committee (TPC) Member for IEEE Vehicular Technology Conference, and a reviewer for several IEEE journals. He was recognized as an Exemplary Reviewer by IEEE Communications Letters in 2023.

Mohammad Amin Saeidi received the M.Sc. degree in electrical engineering – communication systems from the Amirkabir University of Technology, Tehran, Iran, in 2021. Currently, he is pursuing a Ph.D. degree in electrical engineering and computer science at York University. His research focuses on topics in wireless communications, terahertz communication, multi-band networks, and intelligent reflecting surfaces.
Hina Tabassum (Senior Member, IEEE) received the Ph.D. degree from the King Abdullah University of Science and Technology (KAUST). She is currently an Associate Professor with the Lassonde School of Engineering, York University, Canada, where she joined as an Assistant Professor, in 2018. She is also appointed as the York Research Chair of 5G/6G-enabled mobility and sensing applications (2023 - 2028). She was a postdoctoral research associate at University of Manitoba, Canada. She has published over 95 refereed papers in well-reputed IEEE journals, magazines, and conferences. Her research interests include multi-band optical, mm-wave, and THz networks and cutting-edge machine learning solutions for next generation wireless communication and sensing networks. She received the Lassonde Innovation Early-Career Research Award in 2023 and the N2Women: Rising Stars in Computer Networking and Communications in 2022. She was listed in the Stanford’s list of the World’s Top 2% Researchers in 2021, 2022, and 2023. She is the Founding Chair of the Special Interest Group on THz communications in IEEE Communications Society (ComSoc)-Radio Communications Committee (RCC). She served as an Associate Editor for IEEE Communications Letters (2019–2023), IEEE Open Journal of the Communications Society (OJCOMS) (2019–2023), and IEEE Transactions on Green Communications and Networking (TGCN) (2020–2023). Currently, she is also serving as an Area Editor for IEEE OJCOMS and an Associate Editor for IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, and IEEE Communications Surveys and Tutorials. She has been recognized as an Exemplary Editor by the IEEE Communications Letters (2020), IEEE OJCOMS (2023), and IEEE TGCN (2023).

Yamin Tayyar is an undergraduate student at York University in Toronto, Canada. He is currently pursuing a Bachelor’s Degree in Computer Science and is a recipient of Lassonde Undergraduate Research Award (LURA). His research interests include 5G and 6G wireless communication networks, vehicular networks, and machine learning-enabled resource allocation.

Ekram Hossain (Fellow, IEEE) is a Professor and the Associate Head (Graduate Studies) of the Department of Electrical and Computer Engineering, University of Manitoba, Canada. He is a Member (Class of 2016) of the College of the Royal Society of Canada. He is also a Fellow of the Canadian Academy of Engineering and the Engineering Institute of Canada. His current research interests include design, analysis, and optimization beyond 5G/6G cellular wireless networks. He was elevated to an IEEE fellow, for contributions to spectrum management and resource allocation in cognitive and cellular radio networks. He was an Elected Member of the Board of Governors of the IEEE Communications Society for the term 2018–2020. He received the 2017 IEEE ComSoc TCGCC (Technical Committee on Green Communications and Computing) Distinguished Technical Achievement Recognition Award, for outstanding technical leadership and achievement in green wireless communications and networking. He has won several research awards, including the 2017 IEEE Communications Society Best Survey Paper Award and the 2011 IEEE Communications Society Fred Ellersick Prize Paper Award. He was listed as a Clarivate Analytics Highly Cited Researcher in Computer Science in 2017-2023. Previously, he served as the Editor-in-Chief (EiC) for the IEEE Press (2018–2021) and the IEEE Communications Surveys and Tutorials (2012–2016). He was a Distinguished Lecturer of the IEEE Communications Society and the IEEE Vehicular Technology Society. He served as the Director of Magazines (2020-2021) and the director of Online Content (2022-2023) for the IEEE Communications Society (2020-2021).

Hong-Chuan Yang (Senior Member, IEEE) received his Ph.D. degree in Electrical Engineering from the University of Minnesota, Minneapolis, USA, in 2003. Since then, Dr. Yang has been with the Department of Electrical and Computer Engineering at the University of Victoria, Victoria, B.C., Canada, where he is now a professor. From 1995 to 1998, Dr. Yang was a Research Associate at the China Academy of Information and Communications Technology (CAICT), Beijing, China. His current research focuses on the design and analysis of intelligent wireless transmission systems for advanced Internet of Things. Dr. Yang has published over 270 refereed journal and conference papers. He is the author of Introduction of Digital Wireless Communications by IET press and the co-author of Advanced Wireless Transmission Technologies by Cambridge University Press. He is a registered professional engineer (P. Eng.) in British Columbia, Canada.

Mohamed-Slim Alouini (Fellow, IEEE) was born in Tunis, Tunisia. He received the Ph.D. degree in Electrical Engineering from the California Institute of Technology (Caltech), Pasadena, CA, USA, in 1998. He served as a faculty member in the University of Minnesota, Minneapolis, MN, USA, then in the Texas A&M University at Qatar, Qatar Education City, Doha, Qatar before joining King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia as a Professor of Electrical Engineering in 2009. His current research interests include the modeling, design, and performance analysis of wireless communication systems.