Received 28 April 2025; revised 4 June 2025; accepted 21 July 2025. Date of publication 24 July 2025; date of current version 19 August 2025.

Digital Object Identifier 10.1109/OJCOMS.2025.3592365

Terahertz Communication: State-of-the-Art and Future Directions

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This work was supported in part by SPARC-UKIERI under Grant SPARC-UKIERI/2024-2025/P3342, and in part by the CEFIPRA Project with Code DST INRIA 9th Call 2022-23/3/404. The work of Praveen Kumar Singya was supported by the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), New Delhi, India, through the Startup Research Grant (SRG), under Project SRG/2023/001550.

ABSTRACT Terahertz (THz) communication is a cutting-edge technology poised to address the increasing demand for ultra-high data rates in next-generation wireless networks. THz frequencies offer a vast spectrum supporting ultra-massive connectivity for applications like high-definition video streaming, virtual reality, and advanced Internet-of-Things (IoT) devices. Additionally, THz communication can enable new technologies such as high-resolution imaging and sensing. This paper presents a comprehensive survey on THz communication's advancements, challenges, and potential applications. We provide an overview of the fundamental concepts, including THz band characteristics, transmission mechanisms, and channel models. Additionally, we discuss the current state-of-the-art in THz communication technology, covering aspects such as modulation techniques, radio frequency (RF) front-end design, and signal processing algorithms. Furthermore, we analyze the challenges and limitations associated with THz communication, such as propagation losses, atmospheric absorption, beam split, and hardware constraints. This paper aims to provide researchers and practitioners with a comprehensive understanding of THz communication design and analysis and inspire further advancements in this rapidly evolving field.

INDEX TERMS THz communication, reconfigurable intelligent surfaces (RIS), AI/ML, 6G and beyond, beamforming, THz algorithms, channel modeling, non-orthogonal multiple access (NOMA), multiple-input multiple-output (MIMO), THz orthogonal frequency-division multiplexing (OFDM), THz orthogonal time-frequency space (OTFS) modulation.

I. INTRODUCTION AND MOTIVATION

THE FREQUENCY range utilized for wireless communications is progressively expanding toward higher frequency bands, driven by the availability of larger bandwidths in those regions. For instance, 5th Generation (5G) networks allocate communication bands above 20 GHz, in contrast to 4th Generation (4G) communications. Millimeter wave (mmWave) communications have the potential to significantly enhance network speed and capacity, however, they might not fully suffice to accommodate the escalating future of wireless data traffic [1]. This limitation arises from the consistent introduction and adoption of novel devices with enhanced capabilities and intelligence across diverse form factors each year. Research into high-speed, wide-bandwidth radio frequency (RF) spectrum is accelerating due to growing demands in wireless communication, aiming for terabits-per-second (Tbps) data rates [1], [2].

Among the available frequency ranges, the terahertz (THz) band, has garnered extensive attention. The THz band holds potential due to its unique characteristics. In particular, it is viewed as a significant prospect to meet the requirements of the wireless communication landscape

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and cater to the aspirations of future generations, including beyond 5G endeavors such as the envisioned 6th Generation (6G) wireless systems [2], [3], [4], [5].

A. 6G WIRELESS NETWORK

Substantial rise of intelligent devices and the swift proliferation of Internet-of-Things (IoT) networks, the evolution of 5G has necessitated a delicate balancing act involving considerations like throughput, latency, energy efficiency, deployment cost, hardware intricacy, and end-to-end reliability. Looking ahead to 2030 and beyond, 6G development is set to take a comprehensive approach to meet demanding network requirements [2]. The envisaged capabilities of 6G encompass the delivery of autonomous, ultra-scale, highly dynamic, and fully intelligent services, all while ensuring a high quality-of-experience (QoE) for users as highlighted in IMT-2030 (6G) vision.

The anticipated application scenarios within 6G communication systems are poised to revolve around pervasive mobile ultra-broadband connectivity, highly dependable and low-latency communications, ultra-massive machine-type communications (uMTC), remarkably dense data transmission, and exceptionally low-power communication solutions. Further, key 6G technologies are summarized below:

- *Artificial Intelligence (AI) Integration:* AI-driven network optimization, resource allocation, and decision-making will play a pivotal role in enhancing efficiency, adaptability, and user experience in the next-generation wireless networks.
- *Integrated Terrestrial and Non-terrestrial Networks (IT-NTN):* Seamless integration of terrestrial and satellite networks to provide ubiquitous and uninterrupted connectivity, particularly in remote or challenging areas, which is referred to ubiquitous connectivity.
- *Quantum Technology:* Implementation of quantum cryptography and communication for enhanced security and protection against cyber threats for networks.
- *Holographic Beamforming:* Leveraging innovative beamforming techniques to create holographic-like spatial signal distributions, enabling more precise and efficient communication using ultra-massive (UM) multiple-input and multiple-output (MIMO) and reconfigurable intelligent surfaces (RIS)[1] [6].
- *Bio-integrated Communication:* Exploring communication interfaces integrated with the human body to enable new applications in healthcare, augmented reality (AR) and virtual reality (VR), and bio-informatics.
- *Integrated Sensing and Communication (ISAC):* ISAC is a key enabler for 6G networks, integrating wireless communication and radio sensing into a unified framework. Unlike traditional systems where sensing and communication operate separately, ISAC allows networks to simultaneously transmit data and extract environmental information using the same spectral resources. This enables applications such as autonomous vehicles, smart cities, Industry 4.0, and extended reality.

[1]RIS is also called intelligent reconfigurable surfaces (IRS) in the literature.

B. THz COMMUNICATION

THz communication is an emerging field that exploits the THz frequency spectrum, lying between the microwave and optical ranges [7], [8], [9]. THz frequency range, typically spanning from 0.1 to 10 THz (including the sub-THz band), holds great promise for enabling high-speed wireless data transmission, imaging, sensing, and other applications [10], [11], [12], [13], [14], [15]. Frequency range from 0.1 to 0.3 THz is also referred to as the sub-THz spectrum. The THz spectrum offers unique advantages due to its abundant available bandwidth, capable of accommodating massive data transfer rates. Unlike traditional communication bands, THz frequencies remain relatively unexplored, offering opportunities for novel communication techniques and technologies [16], [17], [18], [19], [20], [21].

Notably, the first standard designed for wireless communication operations in the THz band is IEEE 802.15.3d [4], [22], [23], obtained official approval in Fall 2017. This standard introduces switched point-to-point links operating at sub-THz frequencies, approximately around 300 GHz, enabling data rates of up to 100 Gbit/s. As such, THz communications are poised to play a pivotal role in fulfilling the forthcoming demands of wireless technology evolution, encompassing realms beyond the 5G and the perspective of 6G wireless systems.

However, THz communication also comes with various challenges. THz waves experience greater absorption and scattering in the atmosphere, limiting their propagation range and requiring innovative solutions for efficient signal transmission [24], [25], [26]. Overcoming these obstacles necessitates advancements in antenna design, signal processing, and modulation techniques tailored to the unique characteristics of the THz spectrum [27], [28], [29]. Despite these challenges, researchers and engineers are actively investigating THz communication's potential to unlock new applications and redefine wireless communication capabilities. As this field continues to evolve, it holds the promise of enabling high-speed, secure, and versatile wireless communication solutions for the future [30], [31], [32].

C. MOTIVATION OF THz COMMUNICATION

The motivation behind THz communication stems from the need to address the increasing demand for higher data rates, improved wireless connectivity, and the exploration of uncharted frequencies between the RF and the optical frequency bands. Some key factors that drive the interest and enthusiasm in THz communication are highlighted below.

- As existing wireless networks become more congested, there is a growing need for additional frequency bands to accommodate the ever-increasing demand for data. The THz frequency range (above 100 GHz, including the sub-THz frequency) offers a vast, relatively

untapped spectrum that can alleviate spectrum scarcity issues [33], [34], [35], [36], [37].
- THz frequencies provide a significant amount of available bandwidth, enabling the transmission of massive amounts of data at extremely high rates. This makes THz communication a promising solution for upcoming applications such as ultra-high-definition video streaming, AR and VR [38], [39], [40], [41].
- THz waves have inherently short wavelengths, making them suitable for short-range communication scenarios. This property can be leveraged for applications like wireless personal area networks (WPANs), high-speed connections between devices, nano-networks, and in-building communication [42], [43], [44]. Further, ultra-large antennas can be used at the transceivers due to the small wavelength of the THz signal. Thus, higher spatial diversity can be utilized in THz communications [45].
- THz waves have limited propagation through materials like clothing and walls, offering enhanced security and privacy for communication. This makes THz communication a potential solution for secure wireless data transfer, such as in sensitive environments or for confidential data [46], [47], [48], [49], [50].
- THz communication has the potential to revolutionize various industries. It can enable new imaging techniques for medical diagnostics, security screening, and industrial quality control. Moreover, THz sensors can be utilized for detecting explosives, drugs, and other substances [51].
- Advances in semiconductor technology and device fabrication have enabled the development of THz transceivers, antennas, and other components. These advancements have opened doors to exploring the potential of THz communication [52], [53], [54].
- The challenges posed by the THz frequency range, such as atmospheric absorption and propagation issues, offer researchers an exciting domain to innovate and develop new solutions in antenna design, signal processing, modulation techniques, and more [52], [55], [56]

D. IMPORTANCE OF THz IN NEXT-GENERATION WIRELESS NETWORKS

For next-generation wireless networks, THz communication is emerging as a crucial technological frontier. THz communication is poised to address the insatiable demand for bandwidth-intensive applications and emerging technologies like AR/VR and the IoT [57], [58], [59]. Its unique capability to transmit vast amounts of data in extremely short timeframes holds the promise of transforming industries and enabling innovative use cases, including high-resolution imaging, real-time sensing, and immersive multimedia experiences. As wireless networks continue to evolve, the integration of THz communication represents a pivotal step toward meeting the diverse and ever-expanding connectivity requirements of our increasingly interconnected world [60], [61], [62]. Incorporating THz communication into next-generation wireless networks offers transformative advancements, paving the way for a future where high-speed, secure, and versatile wireless connectivity reshapes industries and societies. Figure 1 illustrates a few key use cases for THz communication.

Motivation: Conventional mechanisms for THz networks have been extensively explored in various survey papers, which will be elaborated upon later. However, after the publication of these surveys, a multitude of innovative waveform designs, technological advancements, THz system architectures, and signal processing algorithms have emerged, all underpinned by the enablers of 6G technology. Moreover, there is a notable scarcity of comprehensive surveys concerning THz sources and detectors, beamforming techniques, and the incorporation of RIS in THz designs. Inspired by these observations, we undertake an in-depth investigation into the most recent developments within THz-based 6G wireless systems.

Our Survey Scope and Contributions: This paper undertakes a thorough and specialized survey encompassing the emerging research accomplishments associated with THz system design, beamforming mechanism, waveform design, RIS-aided THz network, non-orthogonal multiple access (NOMA) schemes for THz, THz-enabled ISAC, and their applications. The primary contributions of this survey are emphasized as follows.

- This paper covers details of the THz spectrum characteristics and THz channel modeling. We have summarized various THz channel measurement methods. We have also highlighted various THz sources and detectors used in THz system implementation.
- This paper surveys various beamforming mechanisms with their possible advantages and disadvantages. Beam management and its estimation and tracking part are also considered in the THz system design.
- THz waveform design and its analysis are considered. We have also highlighted that a carrierless THz system can also be designed with low complexity for short-range communication and ultra-high-accuracy localization.
- THz signal processing aspects are summarized by considering compressive sensing (CS) and artificial intelligence (AI)/machine learning (ML)(AI/ML) methods. CS-based THz system design significantly reduces system complexity and power consumption. AI/ML can be used for channel estimation, signal detection, and resource management in THz systems.
- The amalgamation of THz with RIS and NOMA is summarized by considering ultra-massive MIMO (UM-MIMO), orthogonal frequency-division multiplexing (OFDM), and orthogonal time frequency space (OTFS)-based system architecture.

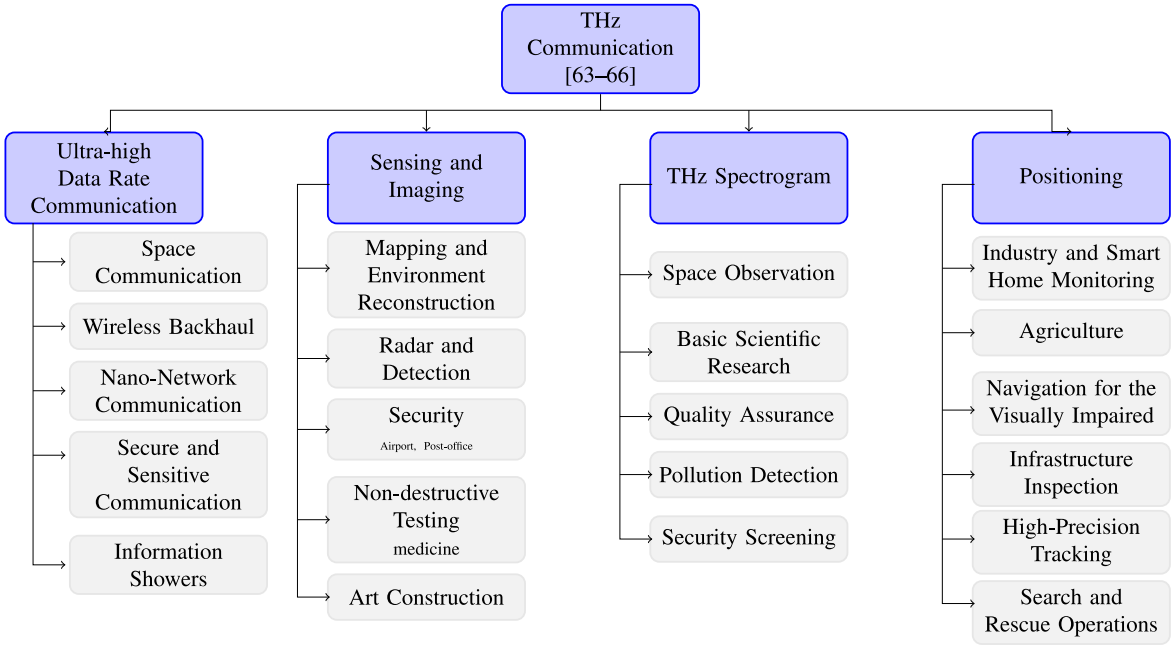

FIGURE 1. Type-based THz use-cases.

- The importance of THz-integrated sensing and communication systems for next-generation 6G communication is highlighted. Furthermore, various challenges in THz systems, such as regulatory hurdles and spectrum allocation, are discussed. Future directions, including exploring new materials for THz devices, advancements in beamforming and antenna design, and signal processing aspects, are also outlined.

Figure 2 summarizes the flow of the paper. The common abbreviations used in this survey are listed in Table 1. A comparison with existing THz survey papers is provided in Table 2, and we emphasize that this paper offers a broader and deeper exploration of THz technology for next-generation wireless networks. Unlike existing survey papers that have conducted in-depth surveys on particular sub-topics of the THz system, this paper provides a comprehensive overview.

II. TERAHERTZ SPECTRUM: BASICS AND PROPERTIES

The International Telecommunication Union (ITU) and most national regulatory bodies have allocated spectrum resources up to 275 GHz. In ITU Region-1, which includes Europe, there is a total allocation of 81 GHz for fixed and mobile communications within the frequency range of 100–275 GHz. Out of this allocation, 23 GHz falls within the frequency range of 252–275 GHz [15], [78]. During the World Radio-communication Conference 2019 (WRC-19), it was determined that 137 GHz of spectrum within the 275–450 GHz band would be available for fixed mobile services, without imposing specific conditions to protect passive services such as Earth exploration-satellite service operating in THz frequencies [78]. Consequently, there is now a total of 160 GHz of spectrum available for fixed and mobile communications within the frequency range of 250–450 GHz.

A. PROPAGATION CHALLENGES AND OPPORTUNITIES

Propagation in the THz spectrum presents both challenges and opportunities for various applications. One of the main challenges is the strong absorption of THz waves by water vapor in the atmosphere, leading to limited propagation distances in open air. However, this absorption can also be leveraged for applications like humidity sensing. Additionally, obstacles and buildings can cause signal blockage and reflection, requiring careful design of signal paths.

On the flip side, these propagation characteristics offer opportunities. The limited range can enhance security and privacy in localized communications. Furthermore, THz waves can penetrate some materials that are opaque to visible light, enabling applications like non-destructive testing, medical imaging, and material characterization. Advances in beamforming, lens design, and waveguide technologies can help mitigate propagation challenges, potentially enabling THz communication for high-capacity, short-range links, and innovative sensing applications in diverse fields [79], [80].

B. PATHLOSS, ATTENUATION, AND FADING EFFECTS

This subsection highlights the different detrimental effects in THz link such as pathloss, molecular absorption, and fading [81].

Pathloss: Pathloss refers to the reduction in signal strength as it propagates through space. Pathloss can be substantial

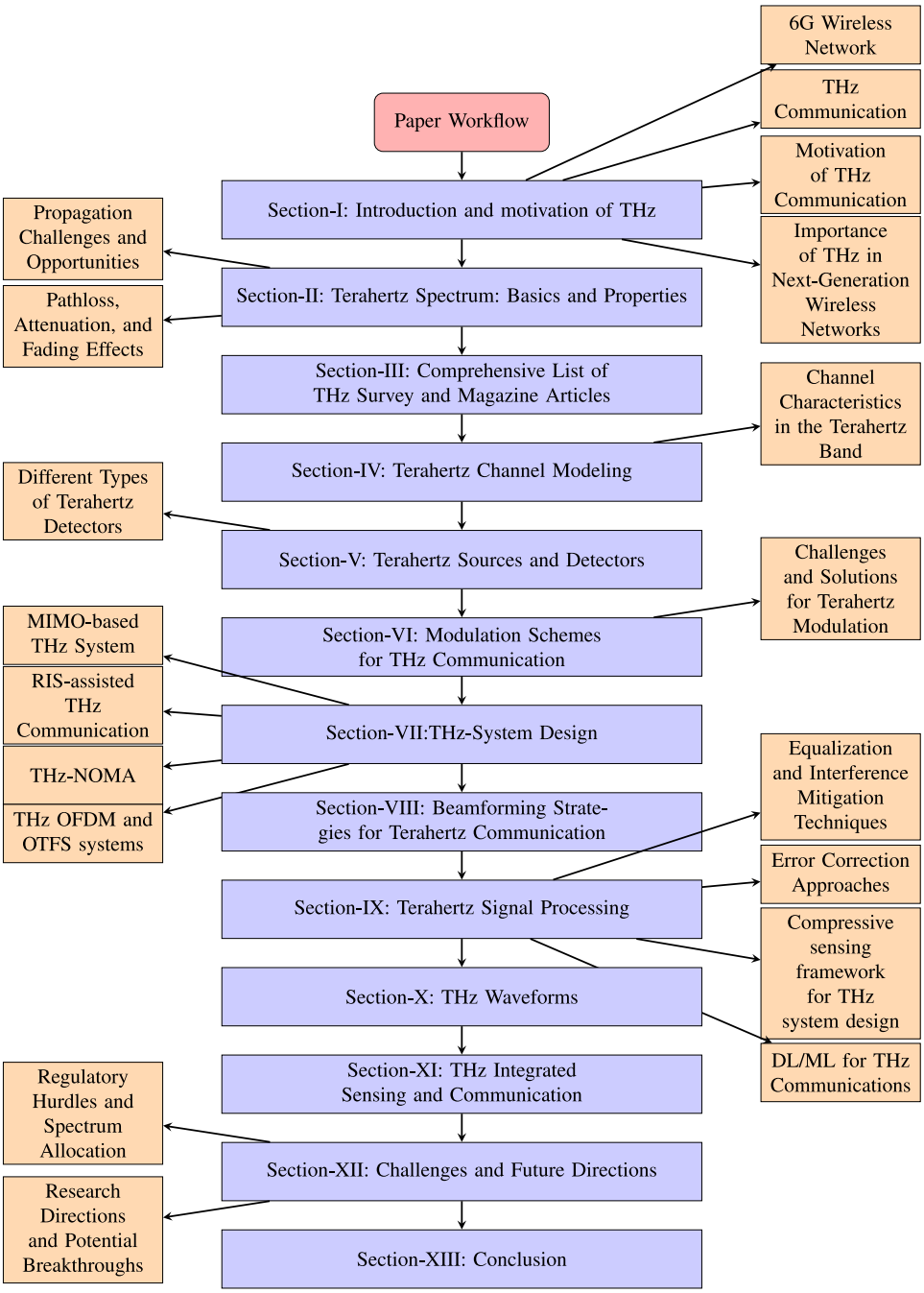

FIGURE 2. Structure of the paper.

in THz communication due to the short wavelengths of THz waves. Free-space path loss increases with the square of the distance between the transmitter and receiver, which can limit the coverage range of THz links. Pathloss depends on the distance d and transmit THz frequency f and it is expressed as

$$\text{Path loss} = \left(\frac{4\pi df}{c}\right)^2. \tag{1}$$

Here, c denotes the speed of light.

Molecular Absorption: THz waves are susceptible to significant absorption by atmospheric gases, particularly water vapor and oxygen. These gases have absorption lines in the THz spectrum, leading to attenuation of signals over certain frequency ranges. This attenuation can limit the range and reliability of THz communication systems, especially in outdoor environments. Certain frequencies (e.g., around 0.35 THz, 0.6 THz) have high absorption peaks [72].

Water vapor (H_2O) is a significant contributor to THz signal absorption, causing notable attenuation peaks at

TABLE 1. A list of common abbreviations used in this survey.

Abbreviation	Description	Abbreviation	Description
5G	Fifth-Generation	OFDM	Orthogonal frequency-division multiplexing
6G	Sixth-Generation	OTFS	Orthogonal time frequency space
AoA	Angle of arrival	PA	Power amplifier
AoD	Angle of departure	PN	Phase noise
ADC	Analog-to-digital converter	PAPR	Peak-to-average-power ratio
AN	Artificial noise	PLS	Physical layer security
BS	Base station	PPM	pulse position modulation
BSE	Beam split effect	PS	Phase shifter
CS	Compressive sensing	QAM	Quadrature amplitude modulation
CSI	channel state information	RAN	Radio access network
DAC	Digital-to-analog converter	RF	Radio frequency
DD	Delay-Doppler	RIS	Intelligent reflecting surface
DL	Deep learning	RL	Reinforcement learning
DFT	Discrete Fourier transform	RSMA	Rate-splitting multiple access
D2D	Device-to-device	RT	Ray-Tracing
DRL	Deep reinforcement learning	SCMA	Sparse code multiple access
FDTD	Finite-Difference Time-Domain	SIMO	Single input multiple output
FFT	Fast-Fourier transform	SINR	Signal-to-interference ratio
HI	Hardware impairment	SNR	Signal-to-noise ratio
ICI	Inter-carrier interference	SU-MIMO	Single-user MIMO
IoT	Internet of things	Tbps	Terabits per second
ISAC	Integrated sensing and communication	TDL	Time-delay lines
ISFFT	Inverse Symplectic Finite Fourier Transform	TF	Time-frequency
ITU	International Telecommunication Union	THz	Terahertz
KPI	Key performance indicator	UAV	Unmanned aerial vehicle
LoS	Line-of-sight	UE	User Equipment
LTE	Long-Term Evolution	UPA	Uniform planar array
MAC	Medium access control	UL	Uplink
MIMO	Multiple-input multiple-output	ULA	Uniform linear array
mmWave	Millimeter wave	URLLC	Ultra-reliable low-latency communication
ML	Machine learning	UM-MIMO	Ultra-massive MIMO
MPC	Multipath components	VLC	Visible light communication
MU-MIMO	Multi-user MIMO	V2I	Vehicle-to-infrastructure
NFC	Near field communication	V2X	Vehicle-to-everything
NLoS	Non-line-of-sight	WLAN	Wireless local area network
NOMA	Non-orthogonal multiple access		

0.56 THz, 0.75 THz, and 1.1 THz, as observed in the path loss analysis of THz systems. Oxygen (O_2) exhibits absorption peaks around 0.06 THz and 1.2 THz. Its impact is less severe compared to water vapor but still notable at higher THz frequencies. Further, carbon dioxide (CO_2) absorption in the THz band is relatively low, with peaks observed around 0.07 THz and 1.4 THz. Other gases, such as ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and nitrogen (N_2), have negligible absorption effects in THz communication [72]. Furthermore, high-altitude and vacuum environments (e.g., satellite links and space applications) significantly reduce molecular absorption effects in THz systems.

Fading Effects: Fading refers to the rapid variation in signal strength over short distances or time intervals. In THz communication, fading effects can be caused by multipath propagation, scattering, and diffraction. Multipath propagation results in constructive and destructive interference, causing fluctuations in signal strength known as fast fading. Slow fading, caused by changes in the environment, can lead to longer-term variations in signal strength. For example, higher paths at the THz receiver

TABLE 2. Comparing this survey to existing studies.

Reference, Year	6G	ISAC	THz Protocols	THz Waveforms	THz Channels	THz Transceiver	RIS-THz	MIMO-THz	AI/ML	THz-NOMA	Security and Privacy
[67], 2020	✓							✓			
[1], 2020	✓					✓				✓	✓
[68], 2022	✓				✓			✓			
[69], 2023	✓				✓	✓		✓			
[70], 2023	✓			✓							✓
[2], 2021	✓								✓		✓
[71], 2022	✓				✓			✓			
[72], 2022	✓				✓			✓			
[73], 2022	✓				✓			✓			✓
[74], 2022	✓	✓					✓	✓			
[75], 2022	✓				✓	✓		✓			
[76], 2022	✓				✓			✓	✓		
[77], 2024	✓	✓			✓						
[16], 2024	✓				✓			✓			
This Survey	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

end lead to more variation and require a more complex equalizer for signal detection. For large-scale fading, the log-distance path loss model is commonly used, while for small-scale fading, Rayleigh, Rician, Nakagami-m, $\alpha - \mu$ (generalized) fading models are applied in THz links.

Fading in THz links is significantly more severe compared to microwave and mmWave frequencies due to high free-space path loss, molecular absorption, and surface roughness effects. Signal strength fluctuations in THz links can range from 5 dB to 40 dB due to multipath fading and sudden LoS blockage [72].

Doppler Shift: The high mobility of objects or devices within the THz communication environment can cause Doppler shifts in the received signal frequency. Doppler is proportional to the THz signal carrier frequency and speed of the UE, thus it is very important parameter for the system design in THz links and high mobility communication scenarios like Satellite and vehicle-to-vehicle. Doppler effects can lead to frequency shifts that impact signal quality due to fast channel variation and need to be compensated for in high-mobility scenarios. THz signals experience higher Doppler spread than conventional communication frequency bands (lower frequency bands) and require specific signal algorithms for estimation and compensation within a system.

Doppler shift causes phase distortion in the received signal, which can affect signal demodulation. Higher-order modulation schemes, like 256 QAM (quadrature amplitude modulation), are more susceptible to the Doppler effect. In system designs based on OFDM or OTFS, which rely on tight frequency and time synchronization, Doppler shifts can cause high errors in demodulation.

III. COMPREHENSIVE LIST OF THZ SURVEY AND MAGAZINE ARTICLES

A summary of THz survey articles is mentioned in TABLE 3 for MAC protocols [1], physical layer security [2], THz wireless channels [68], localization [73], etc. Our paper focuses on more comprehensive directions in THz system design and analysis, in contrast to the specific areas highlighted in existing survey papers.

We have also summarized various magazine articles on THz communication from existing literature. These articles highlight possible THz system architectures, channel modeling, and beamforming, along with different signal-processing algorithms. In [83], an innovative three-layer architecture for 6G networks is devised to achieve uniform and comprehensive cell-free radio access, delivering adaptable and close-range support for diverse applications. Furthermore, a radio access network (RAN) architecture that embodies full spectrum uniform cell-free networks is proposed. In [84], [85], [86], THz signal processing algorithms are summarized including the machine learning (ML) methods. In [87], the latest progressions in computational imaging techniques within the THz range are analyzed. Areas such as system setup, models for wave propagation and interaction, as well as algorithms rooted in physics that contribute to the digital representation of internal information within the imaged objects, are considered. Further, in [5], [88], an overview of the current state of electromagnetic nanoscale communication and networks is considered.

In [4], [84], [89], [90], [91] a comprehensive survey of essential technologies within 6G THz wireless communication systems are considered by encompassing various aspects, including THz channel modeling,

TABLE 3. A comprehensive list of existing THz survey papers.

[#]	Year	Brief Summary	Key Areas
[1]	2020	Various existing THz communication MAC protocols are presented.	THz MAC protocols, nanoscale and macro scale networks
[2]	2021	Overview of security and privacy issues related to prospective technologies for 6G including the THz communications.	Physical layer security, AI in 6G security
[68]	2022	A comprehensive overview of THz wireless channels is considered by studying THz channel measurement methodologies in frequency-domain based on a vector network analyzer (VNA), in time-domain based on sliding correlation, and in time-domain based on THz pulses from time-domain spectroscopy (THz-TDS).	THz channel measurement, Channel modeling
[71]	2022	Definitions of channel non-stationarity and channel physical perspectives are given for the 5G and beyond the wireless networks. Recent developments in the field of capturing and exploring the non-stationarity and consistency of channels are extensively discussed and examined.	Non-stationarity channel modeling, 5G and 6G systems
[72]	2022	A perspective into the attributes of THz channel propagation is considered. The potential of measurement methodologies, and the modeling approaches tailored for 6G communication applications is discussed. Additionally, some insights that can enhance forthcoming endeavors in characterizing the THz band are also suggested.	THz channel modeling and analysis
[73]	2022	Paper delved into the most recent breakthroughs within THz communications, along with the introduction of specialized channel and system models specific to the THz spectrum. 3D position and orientation estimation in the THz band for localization purposes is considered. A comprehensive overview of geometry-based localization techniques and expansions for THz-based localization and sensing is explored.	THz localization, channel modeling
[74]	2022	Paper examines seven distinctive and defining attributes of THz wireless systems: quasi-optical nature of the band, tailored architectures for THz, synergy with lower frequency bands, CS and communication systems, physical layer processes, spectrum utilization techniques, and real-time network optimization.	A comprehensive view of the THz systems to support both communication and sensing services
[75]	2022	A generalized mathematical approach is used for evaluating the effectiveness of algorithms designed to enhance performance reliability in mmWave and THz systems.	mmWave and THz channel modeling, resource allocation
[76]	2022	Paper summarizes a comprehensive review of the possibilities and technologies that underpin mmWave communications in mobile contexts. An overview of the mobile scenarios where mmWave communications find applications such as indoor WLAN or WPAN, cellular access, V2X communication, high-speed train (HST) connectivity, UAV connections, and emerging space-air-ground-sea communication setups is considered.	mmWave, application scenarios
[70]	2023	A comprehensively review of the existed solutions for the TCP & QUIC performance is considered in high-frequency bands by considering different layers of the protocol.	Transmission Control Protocol, Quick UDP Internet Connections (QUIC), 6G
[82]	2025	This work investigates the joint sub-THz and FSO potentials and challenges in short multi-hop sub-THz-FSO networks as a candidate technology for future backhaul communications.	Joint sub-THz and FSO channel modeling and their applications in various backhaul networks

multibeam antenna design, front-end chip design, baseband signal processing, and resource management. In the work by Chen et al. [92], four interdisciplinary approaches are discussed. These aim to address several key goals: (1) Achieving terabit-per-second data rates, (2) Reducing latency to one-tenth of a millisecond with zero jitter, (3) Providing millimeter-precision sensing and positioning, and (4) Ensuring seamless connectivity. These efforts aim to unlock the full potential of THz communications. Further, THz link budget [93], MIMO architecture [86], [91], channel characterization [94], [95], AI/ML in THz [96], RIS-aided THz [5], [97], [98], radar sensing [99], NOMA-THz system [100], THz imaging [3], [89], [92], [101], [102], etc. are explored in the literature.

IV. TERAHERTZ CHANNEL MODELING

The unique radio characteristics of THz bands, such as channel sparsity, near-field propagation effects, and large-scale antenna deployments, introduce both opportunities and challenges for channel modeling, requiring a balance between complexity and accuracy. Modeling THz channels is essential for understanding and optimizing communication systems in this frequency range [103], [104], [104]. Wireless

communication channel models are generally classified into three main categories: stochastic, deterministic, and hybrid models.

- *Deterministic Models:* Deterministic THz channel models [72], [105] can be broadly classified into three categories: Ray-Tracing (RT) methods, Finite-Difference Time-Domain (FDTD) methods, and Measurement-Based approaches [106]. Among these, RT is considered a promising approach for 6G THz channel modeling due to the unique characteristics of THz waves, including their sparsity, reliance on dominant propagation paths, and high susceptibility to blockages. These factors necessitate site-specific channel modeling to ensure accurate representation. RT, grounded in electromagnetic field theory and geometrical optics, provides precise modeling of the dominant THz wave propagation paths in specific environments. Unlike stochastic models, deterministic methods naturally address the challenges of modeling physical wave propagation by leveraging detailed environmental information. Empirical models are based on measurements and observations of THz propagation in real-world environments. They provide insights into channel behavior but may have limitations in terms of generalization to different scenarios. These models provide THz propagation, considering factors like atmospheric absorption, oxygen and water vapor attenuation, and free-space pathloss [107], [108]. However, we need to conduct channel measurements for different operating areas and environmental conditions, which may not always be suitable or may be complex. Deterministic models can be computationally expensive, especially for large-scale environments, making them less practical for real-time simulations in some cases.
- *Statistical Channel Models:* These models characterize THz channels using statistical parameters such as delay spread, coherence bandwidth, and Doppler spread [72], [105]. They help analyze channel performance and fading effects. Further, statistical models consider randomness such as log-normal and pathloss in propagation conditions [109]. Further, stochastic channel models describe wireless channel parameters, such as the distribution of received signals, the number of multipath components (MPCs) or clusters, and the azimuth/elevation angles of arrival and departure. Their relatively low computational complexity allows for efficient simulations at both the link and system levels. While these models effectively capture channel statistics with minimal computational overhead, they lack the ability to accurately represent real-world wave propagation. This limitation makes them less suitable for environments with high mobility or complex scattering conditions, where precise modeling of wave interactions is crucial.
- *Hybrid Models:* These combine different modeling techniques to capture various propagation aspects accurately. For instance, a geometric model might be combined with a stochastic model to include both deterministic and statistical effects [110]. For instance, key paths in the THz spectrum, including the line-of-sight (LoS) and reflected rays, are determined using deterministic methods. Meanwhile, other paths, such as those involving scattering and diffraction, can be generated using statistical techniques [68].

The choice of THz channel modeling depends on the specific applications such as sensing and communication, scenario such as indoor and outdoor, and available data for modeling and analysis. A summary of THz channel modeling is shown in Table 4. THz channel modeling continues to be an active research area due to the unique propagation characteristics of the THz spectrum and its emerging applications in wireless communication, sensing, and imaging [111], [112], [113].

A. CHANNEL CHARACTERISTICS IN THE TERAHERTZ BAND

Channel characteristics in the THz band are shaped by the unique properties of THz waves and the environment they propagate through. THz waves have much smaller wavelengths compared to lower-frequency radio waves. This results in finer spatial resolution and the potential for higher data rates [115], [116]. Further, due to the small wavelengths, THz signals experience higher blockage and free-space pathloss compared to lower-frequency signals. This limits the range of THz communication links and makes them suitable mainly in backhaul applications. This necessitates careful link budget calculations [82], [117], [118]. The THz spectrum contains absorption lines due to atmospheric constituents like water vapor and oxygen. This leads to significant signal attenuation over specific frequency ranges and can impact communication range and link quality.

Like other wireless frequencies, THz signals can undergo multipath propagation, leading to constructive and destructive interference. THz waves interact with objects, surfaces, and atmospheric particles, causing diffraction and scattering. These effects can lead to signal power variations and affect signal coverage. Further, the small wavelengths of THz waves cause rapid fluctuations in signal strength over short distances. Spatial fading, also known as small-scale fading, necessitates advanced antenna techniques and adaptive signal processing. The short wavelengths enable highly directional beamforming, allowing the creation of focused and narrow beams for point-to-point communication and reducing interference. Due to high atmospheric absorption and short wavelengths, THz communication requires LoS paths between transmitters and receivers and obstacles cause

TABLE 4. Summary of THz channel modeling [6].

Features	Deterministic Models	Stochastic Models	Hybrid Models
Approach	Based on physical wave propagation (e.g., ray tracing, full-wave EM simulation)	Uses statistical distributions for channel parameters (e.g., path loss, multipath components)	Combination of deterministic and stochastic methods
Accuracy	High accuracy, site-specific	Moderate accuracy, general statistical trends	Balances accuracy and computational efficiency
Computational complexity	Very high (requires detailed environmental data and simulation)	Low (relies on statistical approximations)	Moderate (mix of deterministic accuracy with stochastic efficiency)
Real-world Representation	Models actual propagation paths and blockages	Captures statistical trends but lacks physical accuracy	Improves realism with low complexity
Flexibility	Limited (requires detailed site information)	High (can be adapted for different environments)	Moderate
Applicability	Best for urban, indoor, and site-specific scenarios	Best for large-scale network simulations and generic environments	Suitable for large-scale simulations with improved realism
Multipath effects	Precisely modeled using ray optics and EM field analysis	Approximated statistically (e.g., Rician, Rayleigh fading)	Uses deterministic paths combined with statistical variations
Examples	Ray tracing (RT), Finite-difference time-domain (FDTD), Measurement-based models [17, 29, 47, 114]	Geometry-based stochastic models (GBSM), Clustered delay line models (CDL) [17, 29, 47, 114]	Geometry-based hybrid models (e.g., Semi-deterministic RT models)[17, 29, 47, 114]

signal blockage. Rapid movement of objects or devices within the THz band can lead to significant Doppler shifts, impacting signal frequency and requiring compensation techniques.

The channel within the THz band exhibits distinct characteristics such as higher molecular attenuation in contrast to channels found in conventional frequency bands. Consequently, there is a heightened need for further research aimed at comprehending the propagation dynamics of THz channels. In the literature, various THz channel models are explored. A generative adversarial network (GAN) to achieve a precise estimation of frequency-selective channels with a limited number of pilots is introduced in [119]. Various channel estimation methods are suggested such as dynamic alteration of pilot locations within the data frame [120], deep learning (DL) algorithm for a wideband THz system based on single-carrier frequency domain equalization (SC-FDE) [121], [122], wideband channel estimation [123], sparse Bayesian learning (SBL) to simultaneously estimate the channel and beam-split [124], [125], CS-based channel estimation [126], channel estimation techniques for wideband THz-MIMO systems [127], RIS-assisted channel estimation [128], etc. The THz channel is sparse and has a time-varying impact on receiver design. Designing low complexity and accurate THz channel estimation method is essential, especially for higher-order modulation schemes. In general, pilots are used to estimate the channel and other hardware imperfections in THz system design. Further, THz channel modeling approaches based on application scenarios, path losses, and methods are shown in Figure 3.

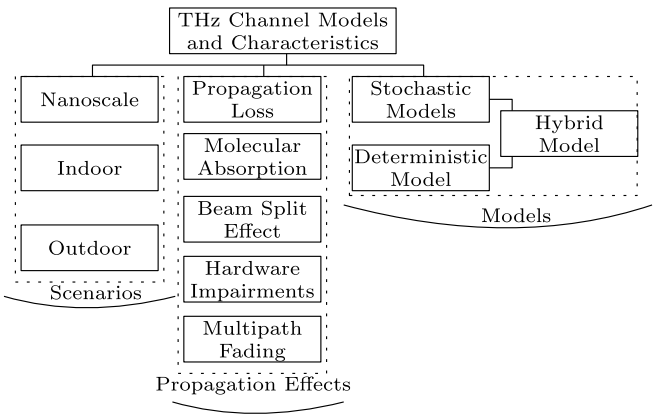

FIGURE 3. THz channel modeling approaches and various pathloss associated with THz links [129].

V. TERAHERTZ SOURCES AND DETECTORS

THz sources and detectors play a pivotal role in harnessing the potential of THz communication. THz sources encompass technologies like quantum cascade lasers, synchrotron radiation, and nonlinear optical processes, enabling the generation of coherent THz waves [130], [131], [132]. On the detection side, various techniques include THz quantum cascade detectors, bolometers, and photomixers. These

sources and detectors facilitate applications spanning high-capacity wireless communication, spectroscopy, medical imaging, security screening, and more [133], [134], [135]. However, challenges remain in achieving compact, efficient, and tunable sources and sensitive detectors, driving ongoing research and innovation to unlock the full capabilities of the THz spectrum.

THz wave generation sources can be broadly categorized into electronic, photonic, and hybrid sources, each with unique advantages and applications. We summarize a few generation mechanisms of THz waves as

- *Photoconductive Switching:* In this method, a photoconductive material is illuminated with a short laser pulse, creating a transient photocurrent that emits THz radiation as it switches on and off [21], [136]. The process begins with an ultrafast laser pulse, typically in the femtosecond range, which is focused onto a photoconductive material such as low-temperature-grown gallium arsenide (LTG-GaAs) or indium gallium arsenide (InGaAs). When the laser pulse strikes the material, it generates electron-hole pairs, creating free charge carriers. These carriers are then accelerated by an external bias voltage applied across the material, producing a transient current. The rapid acceleration and deceleration of these charge carriers result in the emission of electromagnetic radiation in the THz frequency range. The emitted THz waves are typically coupled into free space using an antenna structure integrated with the photoconductive material.
- *Difference Frequency Generation:* By mixing two laser beams of different frequencies in a nonlinear medium, the difference between their frequencies results in THz radiation generation [21], [130], [137], [138].
- *Coherent Synchrotron Radiation:* Electrons moving at near-light speeds emit coherent THz radiation when they pass through magnetic fields, as observed in particle accelerators [21], [130], [137].
- *Quantum Cascade Lasers:* These semiconductor lasers utilize quantum transitions in a series of semiconductor layers to emit THz radiation through inter-subband transitions [136], [139]. THz Quantum Cascade Lasers are widely used in scientific research, security screening, and medical imaging, where their high power and precision enable detailed analysis of materials and biological tissues.
- *Terahertz Parametric Oscillators (TPOs):* These devices exploit the nonlinear interaction of an optical pump beam with a nonlinear crystal to generate THz radiation [135], [138]. One of the key advantages of TPOs is their ability to generate narrowband and tunable THz waves, which is particularly useful for applications requiring precise frequency control, such as THz spectroscopy and molecular sensing. Additionally, TPOs can produce relatively high output power compared to other THz generation methods like photoconductive antennas. They also operate at room temperature, eliminating the need for cryogenic cooling, which is a significant advantage over technologies like Quantum cascade lasers.
- *Terahertz Mixing Devices:* Devices such as Schottky diodes can mix different frequencies to produce THz radiation through nonlinear processes [21], [135], [136], [137]. Initially, signals are generated at a lower frequency and then up converted to the desired THz bands. Schottky diode frequency multipliers, resonant-tunneling diodes (RTD), high-electron-mobility transistors (HEMTs), Gunn diodes and backward wave oscillators (BWO) are used to generate low-frequency THz waves especially below 1 THz frequency.

A. DIFFERENT TYPES OF TERAHERTZ DETECTORS

THz detectors play a crucial role in 6G wireless networks, high-speed communication, and sensing applications. Electronic detectors (e.g., FETs, RTDs) are suitable for compact THz receivers, while photonic and heterodyne detectors enable high-speed, high-sensitivity applications. Various types of THz detectors are reported in the literature [142], [143], [144], [145] such as Bolometers [15], [131], [146], [147], [148], Photoconductive Detectors [15], [131], [145], Pyroelectric Detectors [15], [149], Schottky Diode Detectors [15], [150], Golay Cell Detectors [151], Resonant Tunneling Diode Detectors [15], [131]. The existing schemes mentioned above are used to generate the THz waveform and detect the signal for the THz system design. These existing technologies are used to measure THz channel models and system performance in various scenarios. A summary of THz detectors is mentioned in Table 5.

A fully integrated on-chip frequency-stabilization feedback mechanism is introduced in [133] that eliminates the need for external frequency dividers and off-chip references. This innovation significantly reduces power consumption and lowers system integration costs. This approach is realized through the design of two circuit prototypes employing a 0.13 μm SiGe BiCMOS technology. The first prototype is a frequency-stabilized source operating in the 302–332 GHz range, exhibiting an impressive -13.9 dBm probed output power while consuming a mere 51.7 mW of DC power. The second design is a frequency-stabilized high-output-power radiating array, operating in the 308–317 GHz range, achieving a peak-radiated power and effective isotropic radiated power (EIRP) of 4.6 mW and 24.7 dBm, respectively, with a total DC power consumption of 1.18 W [130], [133]. Recently, the FPGA-based processor utilizing tensor-based CS achieved an impressive throughput of 1127 frames per second, showcasing the highest normalized hardware efficiency among comparable state-of-the-art studies in the literature [21], [152].

TABLE 5. Comparison of THz detectors for wireless communications [80], [136], [140], [141].

Detector Type	Principle	Advantages	Limitations	Application
Schottky diodes	Electronic (Rectification)	Fast response, compact	Limited sensitivity	THz receivers, demodulators
FET-based detectors	Plasma-wave detection	CMOS-compatible, high sensitivity	Limited bandwidth	THz IoT, 6G systems
RTD-based detectors	Quantum tunneling	Low-power, direct THz-to-DC conversion	Low dynamic range	Compact THz wireless receivers
Bolometers	Thermal absorption	Ultra-sensitive for weak signals	Slow response	Long-distance THz links
Pyroelectric detectors	Thermal (infrared response)	Room-temperature operation	Low bandwidth	Passive THz imaging
Photoconductive antennas	Optical excitation	Fast response, broadband	Requires laser source	THz-TDS, sensing
Electro-optic detectors	Optical modulation	High speed, coherent detection	Complex setup	6G THz communication
Hot-electron Bolometers mixers	Superconducting mixing	High sensitivity	Needs cryogenic cooling	Space communication, deep sensing
Graphene-based detectors	Quantum effect	Ultra-fast response, broadband	Still under development	Future 6G THz systems

A series of oscillators and a heterodyne image receiver, functioning around 600 GHz, were developed [135]. The measured oscillation frequency ranges for the three oscillators, varying in coupled-line lengths, were 628–682 GHz, 556–610 GHz, and 509–548 GHz. The tuning capability is achieved through bias variation [135], [144]. Specifically, photonic components operating in extended optical wavelengths, such as 1.321-1.55 mm, are imperative to effectively utilize optical fiber cables as transmission mediums for mmWave/THz-wave signals [15], [131].

Currently, there are challenges in designing low-cost THz devices that consume minimal power and have a smaller size to facilitate the design of cost-effective THz systems. The commercial viability of THz systems also depends on high-rate analog-to-digital converter (ADC) and digital-to-analog converter (DAC) with low power consumption. The ADC/DACs currently in use can consume a significant amount of power, which can restrict the design of battery-operated THz systems. Furthermore, nonlinearity in components at THz bands can also limit the system performance. TABLE 6 summarizes key performance metrics such as achievable data rates, path loss, beamforming requirements, energy efficiency, and implementation complexity for different THz communication approaches like photonic-based, electronic-based, and hybrid-based systems.

TABLE 6. Performance metrics comparison of THz communication techniques [153], [154], [155].

Parameter	Electronic THz	Photonic THz	Hybrid Systems
Frequency range	Up to 1 THz	0.1–10 THz	0.3–3 THz
Data rate	10–100 Gbps	Order of 100 Gbps	50–200 Gbps
Transmit power	Less than 1 mW	mW level	order of mW
Range	<10 m (NLoS)	<100 m	(LoS) 10–50 m
Integration	High (CMOS)	Low (bulky)	Moderate

VI. MODULATION SCHEMES FOR THz COMMUNICATION

Several modulation schemes are explored for THz communication such as amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), QAM, spatial modulation (SM), etc. [39], [49], [120], [154], [156], [157], [158], [159], [160]. Further, a distance-aware multi-carrier modulation (DAMC) has been devised to accommodate both single-transmitter single-receiver and single-transmitter multiple-receiver scenarios within the THz frequency range. This innovative DAMC modulation scheme leverages the unique characteristics of THz band channels, which are contingent on both distance and frequency. It delivers adaptive exploitation of the exceptionally wide bandwidth available in the THz band [39], [120].Single-carrier, multi-carrier, and pulse-based modulation schemes are used in THz communication, as summarized in Table 7.

Further, pulse position modulation (PPM) [161], [162], polarization modulation [163], [164], and hybrid modulation [126], [165] are explored for short-range communication in THz bands. PPM encodes data by timing pulses within a fixed interval. This method resists amplitude fluctuations caused by absorption. Polarization modulation uses the polarization state of THz waves to encode data. This approach takes advantage of the unique properties of THz waves. The choice of modulation scheme depends on several

TABLE 7. THz modulation.

Modulation Schemes	Possible Challenges	Ref.
Single Carrier (CDMA, TDMA)	Multipath interference such as ISI, complex equalisation	[166, 167]
Multi-carrier (OFDM, OTFS)	Interference due to Doppler shift such as ICI	[165, 168]
Pulse-based Communication (PPM, ASK)	Carrier-free communication thus multi-user interference	[169, 170]

factors: (1) The communication environment, (2) The link distance, and (3) The available resources [39], [49], [120], [154], [156], [157], [158], [159], [160].

A. CHALLENGES AND SOLUTIONS FOR TERAHERTZ MODULATION

Severe path loss, molecular absorption, phase noise (PN), multipath fading, Doppler effect, beam splitting, hardware impairments, and interference contribute to the BER performance of THz links at a given signal-to-noise ratio (SNR) of the received signal. At high frequencies, hardware impairments such as In-phase and Quadrature (IQ) mismatch and DC offset arise due to the technological limitations of THz devices, significantly degrading THz link performance due to in-band and out-of-band distortions in the received signal. Additionally, power amplifier (PA) nonlinearity and mixer distortions further degrade THz signal integrity [28], [121].

As the carrier frequency shifts into the THz band, the impact of PN on communication system performance becomes increasingly significant. In THz systems, PN originating from the carrier signal and local oscillator (LO) plays a crucial role in determining bit error rate (BER) performance. The degradation in PN is particularly critical for high-frequency signal generation using frequency multipliers. Theoretically, for a frequency multiplier with a multiplication factor f_2/f_1, the PN deteriorates following a logarithmic relationship given by $20\log_{10}(f_2/f_1)$ dB leading to increased signal distortion and performance degradation in THz wireless links.

Further, THz waves experience significant absorption by atmospheric gases. Solutions involve selecting transmission windows with lower absorption frequencies or using error correction techniques to combat attenuation. Further, lower-order and higher-order modulation schemes can be used for long-range and short-range communications, respectively. Further, to overcome pathloss, directional antennas, and beamforming techniques can be used to focus THz signals toward desired receivers. Multi-hop communication systems or relay nodes/ RIS panels can be used to overcome LoS blockage. The movement of transceivers or reflecting objects can induce significant Doppler shifts in THz signals, potentially causing errors in symbol detection. To compensate for Doppler, frequency drift estimation schemes can be applied. Further, delay-Doppler (DD) domain modulation [171], [172] can be used to combat the Doppler effect in the THz system design.

Higher-order modulation schemes like 256 QAM in THz links are sensitive to noise and path loss. To combat severe path loss, lower-order modulation schemes (e.g., QPSK, BPSK, or 16-QAM) should be preferred, as they are more resilient to weak signals. Implement adaptive modulation where the modulation scheme changes based on real-time channel conditions. In high path loss scenarios, simpler modulation can be used, while in more favorable conditions, higher-order modulation can be adopted.

Given the strong absorption characteristics of certain gases (e.g., water vapor, oxygen), choose transmission frequencies that minimize the absorption losses. Focus on frequencies where absorption is low to ensure signal propagation over longer distances. Use frequency diversity in conjunction with adaptive modulation. By switching between different frequencies within the available THz spectrum (in areas with low absorption), systems can minimize the impact of absorption. Further, use modulation schemes that are more tolerant to PN. For example, PSK can be more resilient to PN than higher-order schemes like QAM. A summary of challenges and solutions for THz modulation schemes is highlighted in Table 8.

VII. THz-SYSTEM DESIGN

THz-system design involves crafting communication systems that operate within the THz frequency range, leveraging its unique characteristics, and overcoming its challenges. THz-system design encompasses multiple aspects, including transceiver architecture, antenna design, modulation schemes, and channel modeling [68], [70], [72], [73], [90], [154]. Given the high data rates, short wavelengths, and susceptibility to atmospheric absorption, THz-system designers must carefully balance the trade-offs between system complexity, data rate, and link range.

A. MIMO-BASED THz SYSTEM

MIMO systems can capitalize on the rich available bandwidth in the THz frequency to achieve unprecedented data rates, making them well-suited for bandwidth-hungry applications such as high-definition multimedia streaming, AR, and VR. The fundamental principle of MIMO involves spatial multiplexing, which allows multiple data streams to be transmitted simultaneously on the same frequency, thus increasing the overall throughput. Additionally, MIMO systems benefit from spatial diversity, mitigating the effects of signal fading and improving robustness in challenging propagation environments [13], [46], [173]. MIMO-based THz communication systems emerge as a transformative approach to address the limitations of traditional wireless technologies in the THz frequency range [174], [175], [176].

TABLE 8. Challenges and solutions for THz modulation schemes.

Associated Challenges	Impact on THz Modulation	Possible Solutions	Applicable Modulation Schemes
Severe pathloss	Causes high signal attenuation, limiting transmission distance.	High-gain directional antennas, beamforming, and UM-MIMO, RIS-aided System design.	Lower order schemes like QPSK, DPSK, DQAM
Molecular absorption	Absorption peaks at specific frequencies lead to signal degradation.	Frequency-aware adaptive modulation, spectral windows utilization.	Frequency adaptive: OFDM, SC-FDMA with sub-band selection
PN	Degrades signal quality, affecting high-order modulation schemes.	Low-phase-noise oscillators, PN compensation techniques.	Lower order schemes BPSK, QPSK for robustness; higher QAM with phase correction
Multipath fading	Causes signal distortion and inter-symbol interference (ISI).	Equalization, diversity techniques, OTFS for DD resilience.	OTFS, OFDM with equalization, single carrier (SC) modulation
Doppler effect	Frequency shifts cause synchronization issues in high-mobility scenarios, ICI	Doppler-resilient waveforms, OTFS modulation, adaptive synchronization.	OTFS, DFT-S-OFDM
Beam split	Misalignment in high-gain antennas leads to signal loss.	Beam tracking, adaptive beam alignment, RIS.	Modulation-agnostic, applicable to all schemes
Hardware impairments (IQ Imbalance, PA)	Distortions in THz circuits reduce signal integrity.	Digital predistortion, advanced RF calibration techniques.	OTFS, OFDM with nonlinear compensation, SC-FDMA

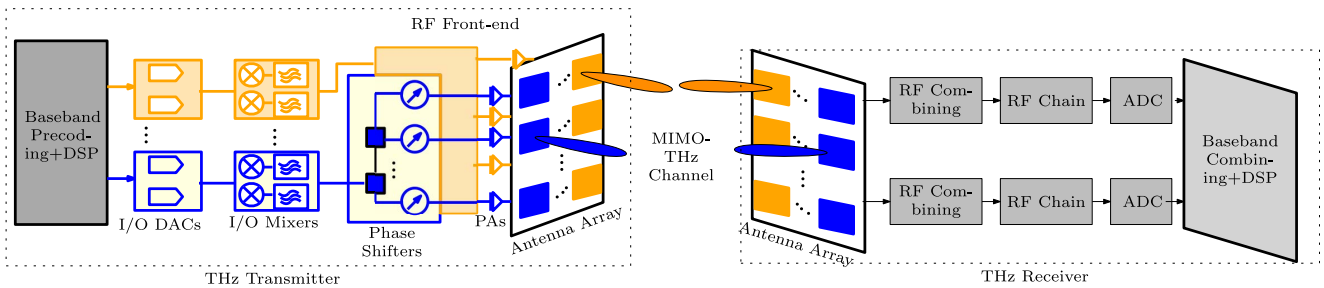

FIGURE 4. THz MIMO system block diagram.

However, the implementation of MIMO in THz communication is not without its challenges [45], [55], [177], [178], [179], [180].

THz MIMO systems often have highly dynamic channel conditions [181] due to rapid variations in the environment [182]. Accurate channel estimation and tracking become challenging, which can impact the effectiveness of spatial multiplexing and beamforming techniques [183]. Building cost-effective and power-efficient THz transceivers and antenna arrays poses significant technological challenges. Components such as mixers, amplifiers, and detectors that operate at THz frequencies are still relatively immature and costly [154], [184], [185].

The convergence of extensive bandwidth and a multitude of antennas leads to pronounced beam split, rendering the conventional hybrid precoding architecture reliant on phase shifters ineffective [160], [186]. By integrating time-delay lines (TDL) into the hardware realization of analog precoders [160], [187], a new approach known as delay-phase precoding (DPP) emerges as a prospective solution to effectively mitigate beam split challenges in the THz system design.

However, TDL-based beamforming in THz MIMO systems leads to increased hardware complexity, power consumption, and cost. To address these challenges, a hybrid approach combining TDLs with conventional phase shifters is more suitable for THz systems. Furthermore, subconnected TDL-based beamforming, where multiple RF chains and subarrays share a single TDL, can be employed to further reduce implementation complexity [160], [186].

Figure 4 shows the block diagram of the THz MIMO system where phase shifters (PS) are utilized to adjust the phase of each antenna to form the beam. Multiple RF chains and power amplifiers (PA) are necessary for the THz MIMO system, as depicted in Figure 4. Transmit and received beams, as shown in Figure 4, are employed to enhance the signal strength of the THz system. A similar beamforming structure is also employed at the UE in the THz MIMO system.

TABLE 9. Performance comparison of RIS-assisted vs. non-RIS-assisted THz communication [198], [199], [200].

Metrics	Non-RIS-assisted	RIS-assisted	Observation
Received signal strength (RSS)	–85 dBm	–65 dBm Approx.	20 dB gain due to signal reflection by RIS
Spectral efficiency	2.5 bps/Hz	7.8 bps/Hz	3x improvement due to improved SNR
Energy efficiency	8 Mbps/W	24 Mbps/W	Significant improvement as RIS is passive and low-power
Coverage reliability	63%	98%	RIS helps overcome LoS blockage and improves link reliability
Latency	3 ms	2.8 ms	Slight improvement due to better link stability
Hardware complexity	Moderate	Slightly higher (or high)	Additional complexity due to RIS controller, channel estimation overhead

B. RIS-ASSISTED THz COMMUNICATION

RIS technology is gaining significant attention within the realm of THz communication. This innovative approach uses specialized surfaces to manipulate and enhance wireless signal propagation, offering numerous benefits and applications in the THz frequency range [188], [189], [190]. The integration of UM-MIMO technology with RIS systems holds significant potential in the realm of THz communications. This integration offers a promising solution to overcome the challenges posed by limited coverage and obstruction caused by LoS blockages [191], [192], [193]. Specially designed surfaces are embedded with reconfigurable elements that can adjust the phase, amplitude, and direction of incoming electromagnetic waves. By intelligently reflecting and redirecting signals, RISs can effectively control signal paths, enhance coverage, mitigate interference, and improve overall communication performance [194], [195], [196], [197]. A comparison between RIS-aided and non-RIS THz systems is highlighted in Table 9.

The THz spectrum offers abundant available bandwidth, allowing RISs to potentially manipulate a wide range of frequencies [201]. Moreover, the short wavelengths of THz waves enable compact and dense arrangements of RIS elements, making it feasible to implement RISs in small form factors [202], [203], [204]. Further, by controlling the phase shifts of individual RIS elements, beam steering and forming can be achieved, enabling targeted signal delivery and reception in specific directions [205], [206]. In RIS-assisted THz system, RISs can suppress unwanted interference by manipulating signal paths, improving the SNR, and enhancing overall communication reliability [207], [208]. RISs can help increase the capacity of THz networks by optimizing signal propagation and enhancing coverage area [209], [210].

The RIS-assisted THz system depicted in Figure 5 illustrates how a conventional RIS THz system encounters the beam split effect at both the transceiver and the RIS panel due to its wideband nature. To address this issue, TD modules can be implemented at both the transmitter and receiver to mitigate the effect of beam splitting. Additionally, delay-phase (DP) precoding techniques can be employed at the RIS to counter the beam split effect. The combination of RIS and MIMO architecture significantly enhances the performance of the THz system by steering the beams in the desired direction. However, this approach involves more complex signal processing and higher power consumption due to the utilization of TD and DP-based architectures.

An innovative hybrid beamforming strategy tailored for multi-hop communication networks assisted by RIS is introduced in [194]. This strategy aims to enhance the coverage radius within THz-band frequencies. An effective beamforming strategy, aiming to minimize the overall transmit power is proposed in [202]. This involves a simultaneous optimization of transmit beamforming and phase shifts of the RIS, while adhering to the constraints on outage rate probabilities. In [211], RIS is developed and each component is linked with a solitary PIN diode, altering resonance behaviors and resulting in an adaptable reflective phase with a resolution of 1 bit. To illustrate this concept, a broad-spectrum electronically reconfigurable reflecting array (RRA) with dimensions of 16×16 elements is formulated in [211]. In this envisioned RRA, every element is linked to an individual bias line, providing independent management of operational status and reflective phase.

Different RIS-assisted THz systems are analyzed in the literature by addressing the possible challenges in system design. For example, in [212] LoS-based MIMO communication via an RIS is analyzed. RIS-aided THz communication system, accounting for the existence of varying numbers of colluding or non-colluding eavesdroppers is considered in [213]. Beam squint effect [214], hybrid channel model [126], [206], wideband THz systems [210], A multi-user multi-RIS [204], [207], RIS optimization [197], [215], spherical wavefronts [216], NOMA system [184], pulse shaping-based BER analysis [217], UAV [208], ISAC [218] based approaches are considered for RIS-assisted THz system design. These schemes highlight the RIS design

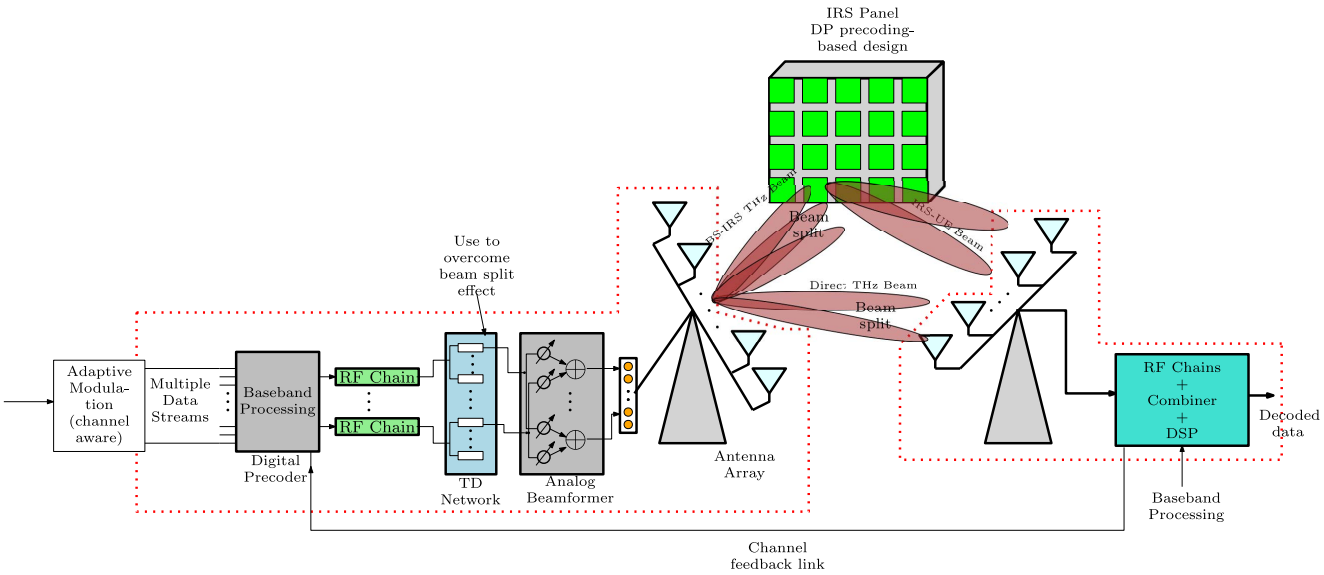

FIGURE 5. RIS-assisted MIMO THz system block diagram.

steps for the THz system to improve the overall system performance with a certain complexity.

RIS in THz communication plays a crucial role in minimizing channel amplitude variation through adaptive beamforming, intelligent phase control, multi-RIS deployment, and interference mitigation. For instance, RIS can dynamically adjust phase shifts to counteract fading and maintain a stable received signal strength. By aligning reflected beams with the direct path, RIS enhances constructive interference, reducing amplitude fluctuations. Deploying multiple RISs along different propagation paths introduces diversity-enhanced reflections, effectively mitigating deep fades.

Moreover, RIS can adapt to mobility-induced variations (e.g., UAVs, vehicles) by tracking user positions and adjusting reflection angles in real time. Hybrid analog-digital beamforming at the THz transceiver, when jointly optimized with RIS-assisted reflection, ensures power-efficient and stable amplitude gains. Additionally, RIS can be programmed to suppress interference and molecular absorption noise, thereby reducing random amplitude fluctuations in the received signal. AI/ML-driven RIS control further enhances real-time adaptation, making RIS a key enabler for stable, high-performance THz wireless networks in 6G and beyond.

C. THz-NOMA

NOMA techniques exhibit a range of benefits compared to orthogonal multiple access (OMA) approaches. These advantages encompass enhanced user equity and spectral efficiency, increased throughput at the cell edges, robust support for massive connectivity, and minimized transmission delays. Given these strengths, transmission methodologies empowered by NOMA are progressively emerging as auspicious choices for forthcoming wireless network multiple access strategies [219], [220], [221], [222], [223]. Although the THz band offers a wide spectrum, the upcoming 6G network will bring a large number of users and various applications, leading to uncertain data demands. A key challenge with the THz band is its limited coverage area, which could increase transmission load and quickly drive up energy consumption. In this context, NOMA presents an opportunity by enabling multiple user equipment (UE) to share the same subchannel. This approach has the potential to accommodate substantial volumes of data services and enhance the efficient use of resources within THz networks [224], [224], [225], [225], [226], [227], [228]. Further, RIS-assisted NOMA transmission in THz band has been investigated to improve the coverage and reliability in the literature [41], [227]. When spatial beams have already been set up to cater to the needs of primary users, we can explore methods for leveraging these established spatial beams to accommodate supplementary secondary users, all while maintaining the performance standards of the existing network [219], [228], [229], [230].

The NOMA-based THz design depicted in Figure 6 illustrates the pairing of cell center and cell edge users for data transmission over the same time-frequency (TF) resources, utilizing different power levels. TD and DP precoding schemes are employed to generate THz beams for each user pair. It's important to note that only a single receiver is depicted for each NOMA pair in the illustration. Beamforming in NOMA can be achieved by either splitting users or jointly forming beams for all users, depending on the complexity and specific applications. During the formation of NOMA user pairs, it's crucial to consider the effects of THz pathloss and band characteristics, unlike in conventional sub-6 GHz NOMA systems.

The concept of amalgamating the three emerging technologies—namely, NOMA, THz, and UAVs—into NOMA-based THz-enabled UAV communication systems

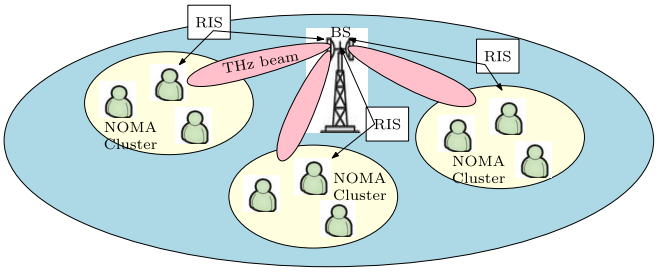

FIGURE 6. Block diagram of the RIS-assisted THz-NOMA system.

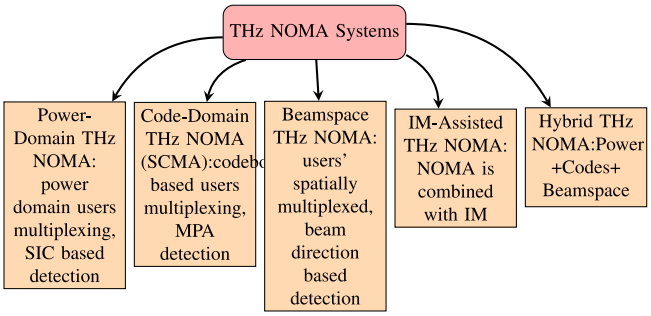

FIGURE 7. Different THz NOMA systems.

has also been explored in the literature [231]. In the literature, NOMA, spatial-division multiple access (SDMA), and rate-splitting multiple access (RSMA) are used as non-orthogonal access schemes. In NOMA, a successive interference cancellation (SIC) technique is employed to decode interference comprehensively. On the other hand, SDMA treats interference primarily as noise. RSMA encompasses both NOMA and SDMA, bridging these two schemes to enhance overall performance. This is achieved by enabling RSMA to decode interference partially. This capability arises from the establishment of a shared stream and the application of SIC, while also treating the remaining interference partly as noise [221]. RSMA partitions the messages from UE into private and common components. Private segments are individually encoded into private streams, while the common components are collectively encoded into a shared stream. From the perspective of the UE, the common stream is initially decoded, treating the private streams as potential noise. Subsequently, after eliminating the decoded common stream, the intended private stream is decoded with reduced interference. Research has demonstrated that RSMA encompasses both SDMA and NOMA as its endpoints, offering enhanced performance in scenarios involving both perfect and imperfect channel state information (CSI). Various data transmission and decoding approaches are addressed in the THz NOMA system in the literature [67], [100], [219], [220], [221], [224], [225], [232], [233], [234] by considering THz frequency characteristics.

In general, NOMA system users are grouped based on their distance from the access point. Near and far users are combined for data transmission in the NOMA system. However, THz signals experience significant molecular absorption and pathloss; thus, these effects should also be considered in THz NOMA user pairing [235]. Furthermore, power allocation in THz NOMA also depends on the large pathloss along with THz signal propagation characteristics, unlike the conventional NOMA system.

Different THz NOMA systems, illustrated in Figure 7, utilize power-domain, code-domain, beamspace-domain, and hybrid-domain NOMA techniques. In code-domain NOMA, users employ predefined codebooks designed based on the number of users, available resources, and THz channel conditions. Sparse code multiple access (SCMA) is a key approach in this domain, enabling efficient multi-user detection. Additionally, index modulation (IM) combined with NOMA enhances spectral efficiency by encoding data in active antennas, subcarriers, or beams. In beamspace-domain NOMA, massive MIMO THz systems leverage highly directional beams to spatially multiplex users. However, challenges such as beam misalignment and beam split at THz frequencies must be addressed. To ensure reliable performance, issues like hardware impairments, complex channel estimation, and high computational overhead must be mitigated through advanced beamforming techniques, AI-driven optimization, and RIS-assisted architectures.

D. THz OFDM AND OTFS SYSTEMS

THz OFDM: OFDM is a promising waveform for THz communication due to its ability to manage frequency-selective fading and efficiently utilize the ultra-wide bandwidth available in the THz spectrum. THz channels are highly frequency-selective because of molecular absorption and multipath effects. By dividing the wide THz bandwidth into multiple narrow subcarriers, each experiencing flat fading, OFDM simplifies equalization and enhances robustness against frequency-selective fading [236].

To address high path loss in THz systems, massive MIMO is often employed. OFDM is well-suited for massive MIMO systems, as it simplifies precoding and beamforming across multiple subcarriers. Since OFDM is already used in many wireless standards, such as Wi-Fi and 4G/5G, its integration into THz systems ensures compatibility with existing infrastructure and facilitates integration with lower-frequency networks. Dynamic resource allocation is crucial for THz communication to adapt to varying channel conditions and user demands. OFDM enables flexible allocation of subcarriers, power, and modulation schemes, optimizing system performance.

However, designing OFDM-based THz systems presents unique challenges due to the high carrier frequencies, severe path loss, and hardware impairments inherent to THz communication. One such challenge is the beam split effect, where frequency-dependent beam misalignment in UM-MIMO THz systems causes performance degradation across subcarriers. To address this, advanced beamforming techniques, such as AI-driven hybrid beamforming, are necessary.

Additionally, the high PAPR in OFDM can lead to nonlinear distortion due to power amplifier limitations at THz frequencies. Techniques to reduce PAPR, such as clipping, companding, and tone reservation, need to be optimized for THz applications.

Furthermore, THz OFDM systems require high-speed ADCs and DACs with a wide dynamic range, but existing hardware suffers from high power consumption and quantization noise. Given the dynamic nature of THz channels, accurate synchronization and channel estimation are essential. Thus, robust synchronization and channel estimation algorithms need to be developed for THz OFDM systems. Advanced signal processing, AI/ML techniques, and optimized hardware design will unlock the full potential of OFDM in THz communication, enabling ultra-high data rates, integrated sensing, and transformative applications for 6G and beyond.

THz OTFS: OTFS modulation is an emerging waveform technology that has garnered significant attention for its potential in high-mobility and high-frequency communication systems [172], including those in the THz bands. Unlike traditional OFDM, which operates in the TF domain, OTFS works in the DD domain [236], [237], offering unique advantages for THz communication systems.

One of the most notable benefits of OTFS in THz systems is its robustness to high mobility and time-varying channels. THz communication is highly sensitive to blockages and dynamic environments, leading to rapid channel variations. OTFS mitigates this by distributing the information symbols across the entire TF grid in the DD domain. This approach averages out the channel variations, providing a more stable representation of the channel. As a result, OTFS is particularly well-suited for THz systems, where Doppler effects and fast fading are common due to high carrier frequencies and narrow beamwidths. Additionally, OTFS performs exceptionally well in high-mobility scenarios, such as V2X communication and drone networks, which are expected to be key use cases for THz communication. A summary of key differences between THz OTFS and conventional OTFS systems is highlighted in Table 10.

OTFS also excels in handling severe frequency selectivity and multipath effects, which are prevalent in THz channels due to molecular absorption and reflections. By operating in the DD domain, OTFS can capture and leverage multipath diversity, improving spectral efficiency and link reliability. This is crucial for THz systems, where efficient use of the available spectrum is essential due to wide bandwidths and high path loss. Furthermore, OTFS simplifies equalization by transforming the time-varying channel into a quasi-static representation in the DD domain, reducing the complexity of signal processing at the receiver.

In [236], a 2D OTFS modulation scheme is analyzed for space–air–ground integrated networks (SAGINs) to enhance wireless communication performance in doubly dispersive channels. A detailed comparison is provided between conventional TF based OFDM and DD-based OTFS for IRS-aided SAGINs. It is also highlighted that channel estimation is easier in the DD domain than in the TF domain, due to the quasi-static nature of the channel in the DD domain. Additionally, various aspects of system design are discussed and compared for both OFDM and OTFS systems in [236].

TABLE 10. Summary of key differences between THz OTFS and conventional OTFS systems.

Aspect	THz OTFS	Conventional OTFS
Frequency band	0.1–10 THz	Sub-6 GHz, mmWave
Path loss	Severe due to molecular absorption, free-space	Moderate
Doppler effects	More pronounced	Less pronounced
Delay spread	Smaller, finer resolution	Larger, coarser resolution
Bandwidth	Ultra-wide (tens to hundreds of GHz)	Narrower (up to a few GHz)
Beamforming	Highly directional	Less directional
Applications	Short-range, ultra-high-speed (Tbps)	High-mobility, moderate data rates

However, one of the primary challenges associated with OTFS is its relatively high computational complexity of the signal detection. The transformation between the TF domain and the DD domain involves advanced signal processing algorithms, which can be computationally demanding, especially when dealing with ultra-wide bandwidths and large antenna arrays in THz systems. This complexity may lead to higher power consumption and increased latency, raising concerns for energy-efficient and real-time THz communication.

Additionally, integrating OTFS with existing communication standards and protocols presents another challenge. As a relatively new technology, OTFS's compatibility with legacy systems and infrastructure is still under exploration, and full integration with current networks remains an open issue.

VIII. BEAMFORMING STRATEGIES FOR TERAHERTZ COMMUNICATION

Beamforming strategies are crucial in THz communication to exploit the unique characteristics of THz waves and overcome challenges such as beam split, pathloss, atmospheric absorption, and spatial fading [238], [239], [240]. There exist primarily four distinct architectures for beamforming arrays: analog beamforming, digital beamforming, hybrid beamforming, and AI/ML-based beamforming [239]. The design of phase shifters varies significantly among these types, each offering its own set of strengths and weaknesses in the context of RF system design.

Further, analog beamforming, digital beamforming, and hybrid beamforming strategies are employed in THz communication [241]. In analog beamforming, phase shifters are used to steer beams in specific directions. This is achieved through analog devices such as phase shifters and

attenuators, which are typically located in the RF signal path before any ADC takes place. While simple, it may not fully exploit the multipath characteristics of THz channels and the complexity of analog phase shifting can become cumbersome as the number of antennas increases. Digital beamforming involves complex signal processing at the baseband to combine signals from multiple antennas with precise phase and amplitude adjustments. It offers greater flexibility in steering beams and handling spatial fading with compactness. Digital beamforming also offers noise reduction since digital techniques can be employed for effective noise reduction and interference cancellation. However, most digital beamforming systems require individual RF chains for each antenna element, which may increase design complexity and power consumption [242], [243].

THz hybrid beamforming combines both analog and digital techniques. It balances complexity and flexibility by performing coarse beamforming in the analog domain and fine beamforming in the digital domain [244], [245]. A hybrid beamforming technique is explored in [244] in the THz band. The system involves multi-antenna base stations (BS) communicating with multi-antenna users amidst frequency selective fading scenarios. In this context, the BS employs sub-connected hybrid beamforming methods combined with multi-carrier modulation to achieve exceptionally high data rates by considering a comprehensive three-dimensional wideband THz channel with molecular absorption, high sparsity, and multi-path fading. Further, research in THz reveals that practically we should employ frequency selective hybrid beamforming in THz wireless communications. Further, hybrid electronic-photonic approaches have been developed for practical THz transceiver designs [246]. However, hybrid beamforming may not offer the same level of flexibility in steering and shaping beams as fully digital beamforming [165]. Moreover, a simple phase shifter design of THz for phased antenna arrays based on integrally-gated graphene parallel-plate waveguides is proposed in [247].

Adaptive beamforming techniques adjust the beamforming parameters based on real-time channel conditions, mitigating spatial fading and optimizing signal reception [248], [249], [250], [251]. Adaptive beamforming involves continuously modifying the weights and phases of the signals from different antenna elements in response to changing conditions. Adaptive algorithms use feedback from the received signals to calculate these adjustments. It allows the array to adapt its focus and nulls according to the direction of the desired signal and the presence of interference. However, adaptive beamforming may have higher complexity and training issue due to real-time processing capabilities and calibration.

Further, THz systems can employ steered directional beamforming, where beams are steered in specific directions to optimize signal strength and reduce interference [252]. This is particularly useful in LoS scenarios. However, beam tracking in THz signals is challenging because the beams are sensitive to changes in the environment. To maintain optimal signal strength, beam tracking mechanisms constantly adjust the beam direction. Furthermore, utilizing knowledge of the environment and channel conditions, cognitive beamforming adapts beamforming strategies to maximize system performance. However, the choice of beamforming strategy depends on factors such as the communication scenario, environment, available hardware, and computational capabilities. Effective beamforming in THz communication requires sophisticated algorithms, adaptive techniques, and a deep understanding of the THz channel characteristics to achieve high data rates, extended range, and reliable communication [249], [253].

Analog beamforming utilizes a single RF chain and supports a single data stream at the time of transmission and reception. In contrast, digital beamforming can support multiple data streams but is more complex and power-hungry due to the presence of multiple RF chains and ADC/DAC components.

Figure 8 illustrates the beam split effect at THz frequencies. In THz systems, when designing beams based solely on the carrier frequency, beam splitting occurs across different sub-carriers due to the wide bandwidth. Therefore, frequency-dependent beamforming becomes crucial in THz systems, unlike conventional narrowband systems where beams are designed based on a single carrier frequency. Furthermore, the DP precoding architecture, introduced in Figure 9, aims to mitigate the effects of beam splitting in

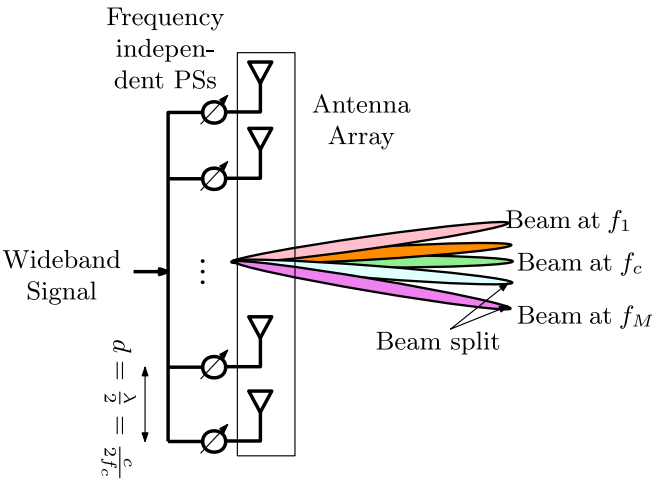

FIGURE 8. Beam split effect over the large bandwidth. *M* is the total number of sub-carrier from f_1 to f_M and f_c is the center carrier frequency band.

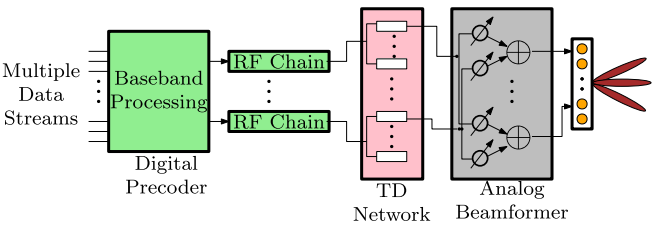

FIGURE 9. DP precoding architecture for THz massive MIMO [175].

TABLE 11. Performance metrics of beamforming methods for THz communications [98], [259].

Metrics	Analog Beamforming	Digital Beamforming	Hybrid Beamforming	DP Beamforming
Beamforming gain	Moderate (10–20 dB)	High (20–40 dB)	Good (15–30 dB)	Moderate (10–25 dB)
Power efficiency	Very high	Low	Moderate (high)	Low-moderate
Complexity	Low	High	Medium-high	High
Scalability	Limited	High	Moderate	Limited
Latency	Low	Moderate	Moderate	High
Flexibility	Low	High	Medium	Low-Medium
Hardware requirements	Phase shifters only	High resolution DACs/ADCs	Phase shifters plus digital baseband	Analog delay plus phase shifters
Remarks	Suitable for low-cost and energy-efficient THz designs	Offers high flexibility, but with high power demand and complexity	Balances performance and complexity, and most suitable for the massive MIMO THz systems	Suitable for beam-splitting scenarios

THz system design. DP precoding incorporates frequency-dependent beamforming, ensuring that all beams at different frequencies are aligned in a single direction.

The DP precoding architecture is a hybrid beamforming technique that combines delay components and phase shifters to precode signals in THz systems. It is specifically designed to address the wide bandwidth and frequency-selective nature of THz channels. Delay components introduce time delays to compensate for frequency-selective fading and ensure coherent signal combining across the entire bandwidth. Additionally, phase shifters adjust the signal phase to steer beams in the desired direction. However, implementing analog delay components at THz frequencies is challenging due to the need for high-precision, low-latency hardware.

A hybrid beamforming technique is developed for a THz communication system that encounters beam squint [214], [254]. This approach is extended into three dimensions (3D) to address the challenges posed by the beam squint in the system. Initially, the complete 3D channel model for the THz massive MIMO (mMIMO) scenario, along with the array gain of the uniform planar array (UPA), is examined in relation to the beam squint phenomenon. Subsequently, a 3D hybrid beamforming architecture is introduced. This architecture harnesses a two-tier TD mechanism, effectively countering the beam squint from both horizontal and vertical perspectives [186], [255].

Three primary types of hybrid array architectures are commonly studied: fully-connected, partially-connected, and dynamically-connected configurations [256]. The fully-connected design requires transmission lines that interconnect all antennas, while the dynamically-connected approach utilizes a switching network to dynamically link antennas. Both setups introduce challenges such as complex wiring and increased heat dissipation. As a result, the partially-connected structure, often referred to as an array of sub-arrays (AoSA), emerges as a cost-effective and practical solution for THz hardware deployment. In this scheme, antenna elements are grouped into several sub-arrays, with each group linked to a shared RF chain. Within each sub-array, individual phase shifters are used to adjust signal phases, thereby enabling analog beamforming [16], [44], [124], [219], [255], [257], [258].

Further, AI/ML based THz precoding schemes are explored to overcome the effect of beamsplit with low complexity. For example, reinforcement learning (RL) can continuously learn and adapt to dynamic THz channel conditions, such as mobility-induced Doppler shifts. RL-based agents optimize beam steering by predicting blockages and mobility patterns. Traditional optimization-based beamforming requires complex real-time calculations, whereas RL models can learn optimal policies offline and apply them efficiently. Additionally, RL can mitigate hardware impairments such as IQ imbalance, PN, and beam split effects. For example, in a massive MIMO THz system, a Q-learning-based beamforming and signal detection system can be designed by formulating the problem as a Markov Decision Process (MDP) and implementing the Q-learning algorithm to optimize beamforming vectors and detect signals efficiently.

Several performance metrics of beamforming methods in THz are typically considered, including beamforming gain, power efficiency, and implementation complexity. Beamforming gain quantifies the signal enhancement in the desired direction, while power efficiency assesses how effectively the system utilizes power resources. Complexity refers to the hardware and computational effort required for implementation, which impacts system scalability and cost of THz systems. A summary of beamforming methods is given in Table 11.

In [45], [176], [183] beamforming techniques are tailored for THz UM-MIMO systems. In [218], [254] the authors harness the combined potential of joint beam-squint and

TABLE 12. Key differences between near-field and far-field THz communication [214], [216].

Parameter	Near-Field THz Communication	Far-Field THz Communication
Beamforming or precoding	Requires spherical wavefront modeling, leading to complex phase corrections	Uses planar wavefront assumption, simplifying beam steering
Path loss	Dominated by spreading loss plus molecular absorption	Dominated by spreading loss plus molecular absorption and atmospheric attenuation
Channel modeling	Requires exact electromagnetic near-field models (e.g., Green's functions)	Uses ray-tracing or statistical models (e.g., Saleh-Valenzuela)
Multipath effects	Limited due to high directivity	Stronger but manageable with beam steering
Applications	Short-range links (e.g., chip-to-chip, nano-networks), high-precision sensing	Long-range backhaul, 6G macro-cell links.

beam-split phenomena, giving rise to a pioneering integrated sensing and communications strategy tailored for massive MIMO systems. In [184], [224], [260], an RIS-enhanced THz MIMO system using NOMA techniques is considered. The beam split phenomenon at RIS is considered in [181], [184], [224], [260]. Thus, in the MIMO THz system beam split effect dominates as the number of antennas increases, and demands TD precoding at the BS and receiver.

A. THz NEAR-FIELD COMMUNICATION

THz near-field communication (NFC) refers to short-range, high-data-rate wireless communication that operates in the THz frequency band under near-field propagation conditions [198], [214]. In NFC, the transmission distances are shorter than the far-field (Fraunhofer) region, where wavefronts are not yet fully planar but rather spherical. In the near-field region, the electromagnetic fields are either reactive or radiative, but not purely propagating. The boundary between the near-field and far-field is typically approximated by [216]

$$d_{\text{ff}} = \frac{2D^2}{\lambda}, \tag{2}$$

where d_{ff} is the minimum distance for far-field propagation, λ is the wavelength of the THz signal, and D is the largest dimension (aperture) of the antenna or array. Due to the small wavelength (in the millimeter or sub-millimeter range) and large aperture size of THz antenna arrays, the NFC range (up to d_{ff}) can extend up to several hundred meters.

Unlike in far-field communication, where the channel depends primarily on angles, in NFC, the channel characteristics depend on both distance and angle. This necessitates modeling based on spherical wavefronts, introducing additional phase variations and enabling spatial focusing. As a result, near-field beamforming and new signal processing techniques are essential. The key differences between near-field and far-field THz communications are summarized in TABLE 12.

IX. TERAHERTZ SIGNAL PROCESSING

THz signal processing plays a crucial role in harnessing the potential of the THz spectrum for various applications, including communication, imaging, and sensing [84]. THz signal processing encompasses a range of techniques tailored to address the unique challenges and opportunities of the THz frequency range. THz signal processing involves adaptive modulation and coding, beamforming techniques using TD precoding, signal equalization, CE, synchronization, interference mitigation, and signal detection. The development of these efficient and innovative signal processing techniques tailored to the characteristics of the THz spectrum is essential for the next-generation wireless network [121], [124], [261].

A CS framework is used to estimate the time-varying sub-THz MIMO-OFDM channels in [262]. Multiple measurement vectors (MMV) are also used to enhance the channel estimation performance in CS. Further, to address the spatial-wideband phenomenon, a collection of frequency-dependent array response matrices is created to maintain the shared channel support. Neural network (NN) models tailored for OFDM THz receivers, embedding domain expertise from wireless communication into various stages and parameters of the model in [168]. This fusion of expert knowledge allows for the development of a versatile receiver capable of adapting to diverse wireless environments. Further, a comprehensive examination of the impact of oscillator PN on the operational efficiency of OFDM systems is considered [263] operating within the sub-THz frequency range. The PN can result in a significant BER floor in OFDM system. In [257], [264] precoding design is considered within wideband THz massive MIMO OFDM systems that experience beam squint.

Figure 10 illustrates the OFDM-based THz system design. Information symbols are arranged in the TF grid. IFFT and FFT operations are used to convert the signal form frequency to time domain and vice versa. At the transmitter and receiver, UPAs are employed to form beams and compensate for THz pathloss effects. To mitigate the beam split effect in the THz system depicted in Figure 10, TD lines are utilized. In conventional OFDM MIMO system, TD lines are not used due to narrow band assumption of signals.

Sparse THz channel estimation is considered in [121], [124]. A dictionary learning algorithm designed for a spatially correlated wideband THz multi-user uplink MIMO system. The goal is to ascertain the dictionary even when confronted with hardware impairments (HIs) and the

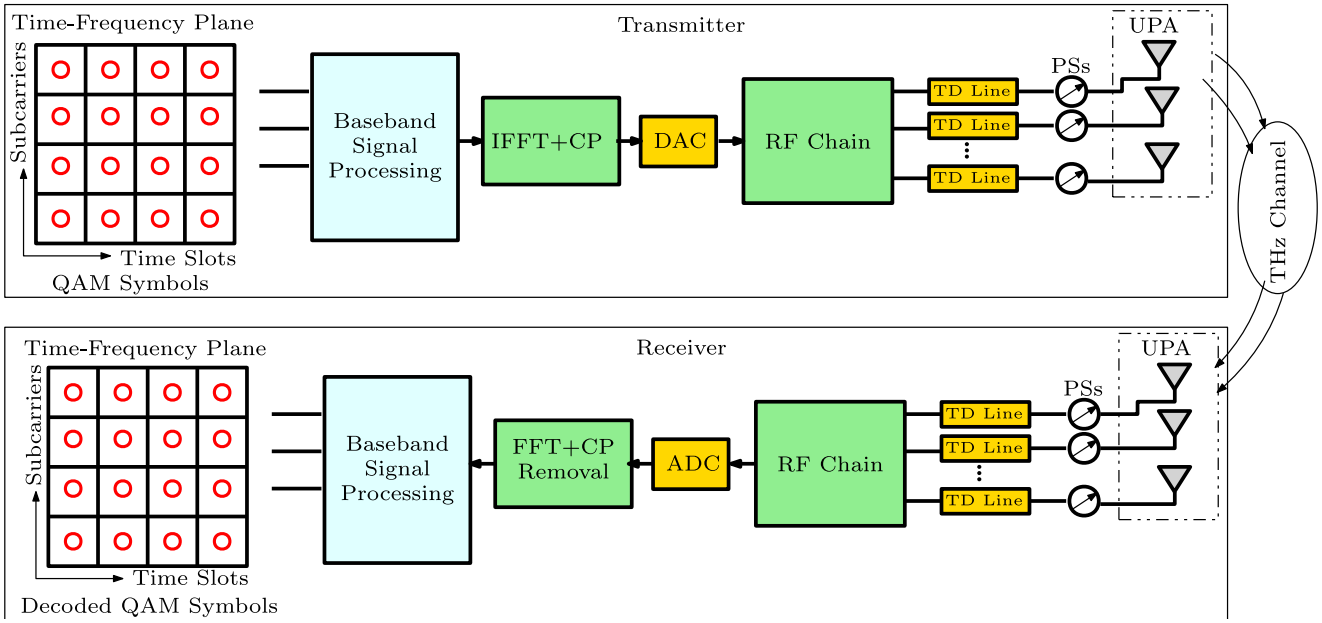

FIGURE 10. DPP architecture for THz OFDM system.

beam squint effect. The dictionary learning algorithm follows an iterative procedure aimed at identifying the most effective sparsifying dictionary. This dictionary is then utilized to recover the sparse THz MIMO channel. The beam-split is conceptualized as an array perturbation, drawing inspiration from array signal processing principles. Subsequently, a simplified method by capitalizing on the predominant LoS characteristic inherent to the THz channel is used [124]. A holographic variant of an RIS and exploring its potential in THz massive MIMO systems is considered in [261]. Leveraging the downsizing of THz electronic elements, RIS can be constructed using closely packed sub-wavelength unit cells. This design enables the creation of continuous or near-continuous apertures, thereby facilitating holographic communications [261]. Further, RIS-assisted THz system design signal processing tools are considered in [261]. We highlight some THz-specific algorithms below.

A. EQUALIZATION AND INTERFERENCE MITIGATION TECHNIQUES

Equalization in THz communication systems is significantly more challenging compared to lower frequency bands due to several factors, including severe path loss, molecular absorption, high-resolution requirements for ultra-wideband signals, Doppler effects, mobility-induced channel variations, hardware impairments, and the beam split effect [28], [121].

For example, the beam split effect (frequency-dependent beam pointing errors) leads [258] to unequal gain across subcarriers, requiring beam-dependent equalization. Moreover, traditional equalizers assume ideal hardware, but THz systems require advanced compensation mechanisms to correct these impairments before equalization. Additionally, frequency-selective fading in THz links necessitates high-resolution equalization across the entire band, making equalization highly complex and computationally demanding.

Due to the susceptibility of THz signals to various propagation impairments and atmospheric absorption, signal distortions and interference can significantly degrade communication performance [160], [187]. Effective equalization methods are essential to compensate for frequency-selective fading and phase distortion [156], [265], [266], [267]. By employing advanced signal processing algorithms and adaptive approaches, these techniques contribute to enhancing the robustness, reliability, and spectral efficiency of THz communication systems [266], [268], [269].

Leveraging the enhanced spatial precision facilitated by extensive antenna arrays and the sparse nature of multi-path mmWave and THz channels, a novel technique for ISI mitigation referred to as delay alignment modulation (DAM) is considered in [160], [187]. DAM's fundamental concepts encompass path delay compensation through pre/post-compensation, coupled with path-oriented beamforming [160]. Specifically, in transmitter-side DAM, symbol delays are intentionally introduced at the transmitter to counterbalance the distinct multi-path delays within the channel. Accompanied by appropriate beamforming based on individual paths, this technique enables the synchronization and constructive alignment of all multi-path signal components upon their reception [160], [187].

Channel estimation and equalization for a THz receiver when confronted with wideband IQ imbalance and PN are considered in [265]. In this scenario, single-carrier frequency-domain equalization is employed. Given that PN is introduced and the wideband IQ imbalance at the receiver, treating the channel impulse response (CIR) and IQ imbalance as a combined channel is not viable. Thus, an innovative two-stage channel estimation approach to

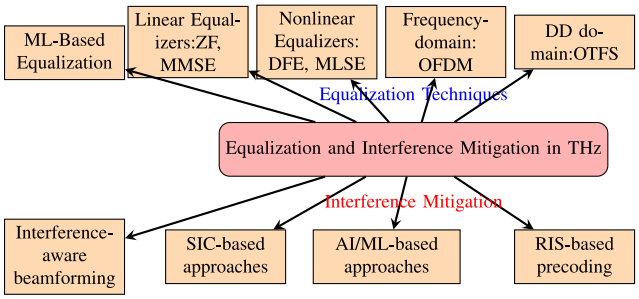

FIGURE 11. Different equalization and interference mitigation techniques in THz systems.

individually estimate the CIR and wideband IQ imbalance parameters is introduced. Subsequently, a corresponding channel equalization technique is formulated to compensate for both wideband IQ imbalance and PN while also addressing the equalization of the CIR in [265]. Summary of various equalization and interference mitigation in THz is highlighted in Figure 11, and DFE and MLSE stand for decision feedback equalizers and maximum likelihood sequence estimation, respectively.

B. ERROR CORRECTION APPROACHES

Coding and error correction approaches are crucial in THz communication to mitigate the impact of channel fading and interference. Error correction in THz systems differs significantly from lower-frequency communications due to the unique characteristics of the THz band, which stem from the physical properties of THz waves, hardware limitations, and specific propagation conditions. For instance, THz waves are absorbed by atmospheric molecules such as water vapor, leading not only to signal attenuation but also to re-radiated noise, which error correction must compensate for. Additionally, THz components are less power-efficient, necessitating low-complexity error correction codes to minimize energy consumption. Traditional error correction codes often fail to scale effectively to THz data rates (Tbps), requiring novel solutions such as spatially coupled codes or fountain codes. Moreover, THz signals are highly sensitive to small movements and environmental changes, making adaptive error correction techniques essential. The susceptibility of THz signals to blockage by obstacles can cause sudden signal drops, necessitating robust burst-error handling mechanisms. Furthermore, beam misalignment between the transmitter and receiver can significantly degrade signal quality, requiring sophisticated error correction strategies. Addressing these challenges through efficient, adaptive, and low-complexity error correction techniques is critical to ensuring reliable THz communication.

Several coding and error correction approaches can be used in THz communication such as convolutional codes, Turbo codes, low-density parity-check (LDPC) codes, Polar codes, and hybrid coding schemes [270], [271], [272]. Further, NN decoding can be used to optimize decoding algorithms for THz-specific impairments.

Convolutional codes offer good error correction performance in THz communication systems. They are suited for applications with varying channel conditions and can handle both random and burst errors. Further, Turbo codes use iterative decoding to achieve near-optimal error correction performance [273], [274]. They are well-suited for THz communication systems where reliability is crucial. LDPC codes offer excellent error correction capabilities and low decoding complexity. They are suitable for high-speed THz communication systems. Moreover, Polar codes provide a systematic approach for achieving the capacity of symmetric binary-input discrete memoryless channels [275], [276]. They offer strong error correction performance and are increasingly used in THz communication by polarizing the channel. Furthermore, combining different coding techniques, such as Reed Solomon codes with convolutional codes or LDPC codes, can improve overall error correction performance in THz communication systems [23], [273], [277], [278]. The selection of coding and error correction approaches depends on factors such as the specific application, available computational resources, and desired trade-offs between error correction performance and complexity [23], [273], [277], [278].

C. COMPRESSIVE SENSING (CS) FRAMEWORK FOR THz SYSTEM DESIGN

CS has found significant utility in wireless communication, enabling the reconstruction of sparse signals or data using a relatively small number of measurements. THz systems operate at ultra-high frequencies, resulting in massive data rates and large bandwidths. Traditional Nyquist sampling requires extremely high sampling rates, which is often impractical due to hardware, storage, and processing limitations. For instance, THz ADCs capable of such high sampling rates are expensive, power-intensive, and challenging to implement. CS overcomes these limitations by allowing signal acquisition at sub-Nyquist rates, leveraging the sparsity of THz signals in domains such as time, frequency, or spatial representation. This significantly reduces sampling and storage requirements, making CS a promising approach for efficient THz communication.

Many THz signals are inherently sparse or can be represented sparsely in a suitable transform domain, such as the Fourier or spatial domain. For example, THz channels often exhibit sparse multipath profiles due to the high directionality and limited scattering of THz waves. Additionally, THz signals used in imaging and spectroscopy applications are often sparse in the frequency or spatial domain. CS leverages this sparsity to accurately reconstruct signals from far fewer measurements than required by Nyquist sampling. Moreover, THz systems are widely used in imaging and sensing applications, such as medical imaging, security screening, and material characterization, where CS provides several advantages, including reduced data acquisition time and lower hardware complexity.

Channel estimation in THz systems is challenging due to the wide bandwidth and frequency-selective nature of THz channels. CS can help reduce pilot overhead by exploiting the sparsity of THz channels, enabling channel estimation with fewer pilot symbols and improving spectral efficiency.

In THz communication, CS is employed to efficiently acquire and transmit data while minimizing the amount of information needed to be transmitted. One prominent application is in channel estimation for THz MIMO systems, where the technique leverages the inherent sparsity of wireless channels in spatial and angular domains. CS allows for the estimation of channel characteristics with fewer pilot symbols, reducing overhead and improving spectral efficiency. Furthermore, CS plays a crucial role in localization and positioning THz systems. By considering the sparse nature of the spatial environment, it enables accurate localization using fewer anchor nodes or reference signals [279].

Advanced methodologies have been put forth in the literature to address the concurrent tasks of joint active user detection (AUD) and channel estimation in support of accommodating extensive IoT connectivity. An approach employing a modified Bayesian CS (BCS) algorithm [152] was introduced to tackle joint AUD and channel estimation. The BCS technique capitalizes on the inherent sparsity of active users as well as the correlated sparsity structures evident across multiple receiving antennas. Further, a method integrating orthogonal matching pursuit (OMP) was proposed for simultaneous AUD and time-domain channel estimation to facilitate grant-free massive IoT access. To mitigate complexity, an approach involving the approximate message passing (AMP) algorithm for joint AUD and channel estimation can be used. However, this AMP-based design requires prior knowledge of wireless channel distributions and noise variance, which can be challenging to ascertain in practical scenarios [166], [280], [280], [281]. Further, AUD and channel estimation problems can be extended in MIMO-based THz system design.

Conventional MIMO or SISO (single-input single-output) channel estimation methods become impracticable due to the excessive overhead associated with non-adaptive omni-directional training across a large number of antennas. This overhead can be mitigated by capitalizing on the insight that the MIMO or SISO channel within sub-THz frequency bands is predominantly determined by the geometric configuration of the transmitter and receiver. Additionally, it exhibits notable channel sparsity, characterized by a limited number of propagation clusters. For instance, in a study [188], [282], an average of 6 clusters and 4 MPCs per cluster were observed at 140 GHz, compared to 8 clusters and 5 MPCs per cluster at 28 GHz. Significant sparsity exists in the received signal THz system, thus CS or sparse signal processing can be used to reduce the power consumption and sampling rate with low complexity transceiver design. For example, a channel estimation algorithm is considered in [175], [176], [261] based on CS, which leverages the inherent dual sparsity of THz MIMO channels in both the angular domain and the delay domain. Further, in [262], a compact training framework for the estimation of time-varying sub-THz MIMO-OFDM channels is considered. The DL algorithm proposed in [121] identifies the optimal sparsifying dictionary based on acquired observations.

Thus, CS is a critical framework for THz system design as it addresses the unique challenges of THz communication and sensing, such as high data rates, hardware limitations, and sparse signal characteristics. By enabling efficient signal acquisition, reducing hardware complexity, and improving robustness to noise, CS paves the way for practical and scalable THz systems. However, the performance of THz systems remains influenced by factors such as high path loss and molecular absorption.

D. DL/ML FOR THz COMMUNICATIONS

DL has emerged as a transformative tool in wireless communication. By harnessing the power of artificial NN (ANN) with multiple layers, DL techniques are capable of autonomously learning intricate patterns and representations from vast amounts of wireless data.

DL/ML is highly suitable for THz communications as it offers powerful tools to address the unique challenges of THz systems, such as complex channel modeling, beamforming, interference mitigation, and hardware impairments. By leveraging data-driven approaches, DL/ML enables the development of efficient, adaptive, and robust THz communication systems. For example, DL/ML can learn and model the complex THz channel characteristics from data, enabling accurate channel estimation and prediction. Additionally, DL schemes can capture dynamic THz channel variations by continuously updating channel models in real time.

DL/ML can optimize beamforming by learning the optimal beam directions and shapes based on environmental conditions. THz systems face interference from co-channel users, adjacent channels, and molecular absorption noise. DL/ML can identify and mitigate interference sources using pattern recognition and classification techniques. Additionally, DL/ML can model and compensate for hardware impairments using NN. DL/ML can also optimize resource allocation (e.g., power, bandwidth, and time slots) using RL or optimization algorithms.

In wireless communication, DL is used for signal detection, channel estimation, modulation classification, resource optimization, etc. A summary of various DL/ML applications in THz system is highlighted in Figure 12. Its ability to adapt and generalize to dynamic wireless environments, coupled with advancements in hardware acceleration, has led to significant performance enhancements. DL's capacity to decipher complex relationships within wireless signals and channel characteristics has opened doors to redesigning wireless systems [225], [283], [284], [285], [286], [287], [288], [289], [290], [291], [292].

A DL-assisted THz receiver is designed by considering a single-bit quantization in [290]. Further, the impact of

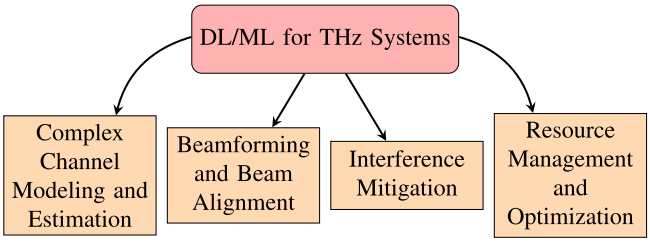

FIGURE 12. Applications of DL/ML in THz Communications.

imperfections of THz devices such as IQ imbalance, PN and nonlinearity are included in DL-based THz system design in [290]. Beamfocusing using the DL for THz is considered in [288]. A low-complexity joint CE and signal detection for THz-band spatial modulation (THz-SM) communications is considered in the presence of HIs in [286]. Furthermore, the integration of RL has also been deliberated as a mechanism for devising solutions in the domains of signal detection and beamforming within massive MIMO THz systems [293]. Deep neural network (DDN) can also be used in THz OFDM system for signal detection and peak-to-average power ratio (PAPR) reduction [289]. Further, the enhancement of QoE is considered in [196] for VR users within an environment encompassing mobile edge computing (MEC) and RIS assistance, and a fresh learning strategy is tailored to effectively optimize the long-term QoE for these users. THz receiver [293], user pairing [225], learning-based prediction [196] are considered. A DNN-based mechanism that integrates self-interference cancellation-free receiver with artificial noise (AN) assistance is proposed [293]. By accounting for randomly distributed eavesdroppers, the proposed solution offers enhanced security measures. An MEC-enabled and RIS-assisted THz VR network is proposed [196] for an indoor scenario, by taking into account the uplink viewpoint prediction and position transmission. Further, in [293] a novel approach using a DNN to address the in-beam security challenge in THz secure communications is considered.

X. THz WAVEFORMS

Designing waveforms for THz communication systems is a complex task due to the unique characteristics and challenges of the THz band. Further, designing and analyzing THz waveforms is a critical aspect of harnessing the potential of THz technology for various applications. These waveforms can be tailored to specific requirements, optimizing signal characteristics for different applications [116], [294], [295], [296]. An overview of the process of designing and analyzing THz waveforms is summarized below.

- *Application Context:* THz waveform characteristics also depend on the specific application requirements. Different applications, such as communication, imaging, sensing, and spectroscopy have distinct waveform needs [297], [298].
- *Modulation Techniques:* The appropriate modulation technique–such as amplitude, phase, frequency, or polarization modulation–based on the application's data rate, sensitivity, and resilience to propagation effects, determines the THz wave design [299], [300]. Therefore, waveform design is also affected by modulation order and characteristics.
- *Pulse Shapes:* The design of the THz waveform pulse shape also depends on properties such as short duration for high-resolution imaging or optimal bandwidth utilization for communication [157], [301]. For example, pulse-based THz communication, waveforms are designed by considering the spectral window of the THz spectrum like the Federal Communications Commission (FCC) emission requirement [297], [301], [302].
- *Frequency Selection:* The central frequency of the waveform, based on factors like atmospheric transmission windows, material properties, and the desired balance between penetration and reflection, affects the waveform design [297], [303].
- *Signal-to-Noise Ratio (SNR):* One should analyze the SNR of the waveform to ensure that the transmitted signal is detectable above noise and interference, considering factors like atmospheric absorption and noise sources [301].
- *Propagation Analysis:* One should simulate or analyze the propagation of THz waveforms in the required environment to understand the effects of atmospheric absorption, scattering, and reflection on the transmitted signal [73], [84], [159], [304], [305].
- *Spectral Analysis:* We should do the spectral analysis to understand the frequency components of the waveform and ensure that the transmitted spectrum aligns with the regulatory constraints and transmission requirements [22], [170]. Analyze the modulation depth of the waveform and its efficiency in carrying information. This is particularly important for applications like THz communication and spectroscopy.
- *Trade-offs:* Balancing trade-offs between waveform characteristics (such as bandwidth and signal power) and the modulation scheme is needed to optimize performance for the target application [297].

Single carrier and multicarrier (e.g., OFDM) based THz system designs are considered [116], [167]. Single carrier THz is more suitable in severe pathloss scenarios. However, it suffers a more complex equalizer in multipath channel cases. Therefore, single-tap equalizer-based receiver can be used for multicarrier THz system in multipath channels. However, large bandwidth of the THz signals, OFDM exhibits heightened sensitivity to errors in time and frequency synchronization. The substantial operational bandwidth of THz systems, often spanning several gigahertz, entails exceptionally high sampling frequencies for ADC and DAC operations. Consequently, achieving precise time synchronization

becomes a challenging endeavor [116], [158], [301]. Thus in the literature [104], [116], adaptive schemes present the opportunity to tailor OFDM parameters for optimal waveform performance. Carrier aggregation, on the other hand, empowers the activation of multiple carriers or OFDM waveforms. Thus, augmenting the system's overall bandwidth, adaptive allocation of waveforms can be used to over the pathloss in OFDM-based THz system design.

In THz communications, there is a preference for carrier-free pulse-based waveforms due to their simplified transceiver architectures compared to carrier-based systems [159], [169], [297], [306]. Therefore, various pulse shapes, such as Gaussian and its derivative and Hermite pulses, are considered. The Gaussian pulse, as demonstrated in [159], [169], [301], [306], offers a practical method for realizing carrier-free pulse-based THz communications. However, the Gaussian pulse exhibits a broad bandwidth that extends from DC to several THz, thereby leading to significant distortions owing to the frequency-dependent molecular absorption inherent to THz channels [265], [267]. Additionally, the dynamic adjustment of center frequencies and bandwidths for the Gaussian pulse proves challenging, thus constraining its adaptability and effectiveness in facilitating THz communications. In a study by Wang et al. [297], a pulse-based waveform was designed for carrier-free THz communications. This waveform has the advantage of allowing continuous adjustment of center frequencies and bandwidths. In particular, a Gaussian pulse uses as the foundational element, and subsequently, a weighted summation of its higher-order derivatives is employed. This approach facilitates the generation of waveforms with adaptable frequencies and bandwidths. These specialized pulse-based waveforms are referred to as frequency and bandwidth continuously tunable (FBCT) pulses. By ensuring that the derivative orders of all weighted terms are either odd or even, it becomes possible to generate a pair of orthogonal FBCT pulses.

In [301], a *sinc-Lorentzian Nyquist pulse* shape is proposed that exhibits superior performance compared to both the conventional raised-cosine and the improved raised-cosine pulse shapes, particularly when subjected to timing-jitter of up to 35% of the symbol duration. Experimental demonstrations show that by employing a 311 GHz photonic-THz system, operating at a standard bit rate of 1.44 Gbit/s, to comprehensively assess the resilience of these three pulse shapes against the impact of timing-jitter. Further, waveform to waveform detection is considered in [307] using DL framework in THz band. A waveform design for the joint sensing and communication systems in mmWave and low-THz bands with ultra-broad bandwidth is investigated [304], [308]. A radar-centric waveform combining linear frequency modulation and PSK is considered in [304], which performs good for both Radar and communication.

For THz communications, the inaugural global standard, officially known as the IEEE 802.15.3d Standard [22], to facilitate the operation of high-speed Ethernet wireless links, supporting speeds of up to 100 Gbit/s. Within this standard, a 69 GHz bandwidth has been dedicated to THz communications, spanning the frequency range from 252 GHz to 321 GHz, commonly referred to as the IEEE THz band. It's worth noting that while the IEEE 802.15.3d Standard doesn't explicitly specify a pulse shaping filter, filtering is inherently inferred through the spectral emission masks outlined by the standard. Despite the generous bandwidth allocation by the IEEE 802.15.3d Standard for THz communications, the power levels attainable with presently available THz wireless transmitters remain relatively constrained [170]. A waveform that adheres completely to the spectral emission mask is specified by the IEEE Standard for THz communications. In [170] designed waveform harnesses 99.3% of the allowable total in-band energy stipulated by this mask, while also offering an additional layer of flexibility for managing out-of-band interference. To validate the proposed approach, a proof-of-concept experiment utilizing a 300 GHz photonics-based THz communications link is considered. This experiment showcases the successful generation and wireless transmission of the proposed waveform developed for the IEEE 802.15.3d THz communications [170].

Carrier-less modulation within a THz system involves a modulation technique where the need for a specific carrier frequency is eliminated for separate IQ paths [157], [157]. This approach is particularly valuable in THz communication systems, where traditional carrier frequencies might be challenging to generate or maintain due to technical limitations. Pulse design for carrier-less modulation within a THz system involves creating specific waveforms that carry the modulation information without relying on a carrier signal. Different THz waveforms are analyzed and their potentials are also mentioned in the literature [104], [116], [169], [303]. A waveform that aligns entirely with the spectral emission mask mandated by the IEEE Standard for THz communications is designed [170], [309], [310], [311]. In [297], a waveform is meticulously crafted to enable the flexible adjustment of center frequencies and bandwidths in carrier-free THz communications. Summary of THz waveforms is mentioned in Figure 13.

XI. THz INTEGRATED SENSING AND COMMUNICATION

THz ISAC technology enables simultaneous terabit-per-second data transmission and highly precise millimeter-level sensing. However, there are significant challenges in developing THz ISAC transmission signals. The first major issue is the high path loss in the THz frequency range. Additionally, power limitations necessitate the use of UM-MIMO antenna arrays with beamforming techniques.

The Doppler effects are stronger in the THz frequency range because the Doppler shift is proportional to the carrier frequency. This poses significant challenges, especially when dealing with high-speed targets, as it can introduce interference that degrades sensing accuracy. To address these issues, it is crucial to develop advanced

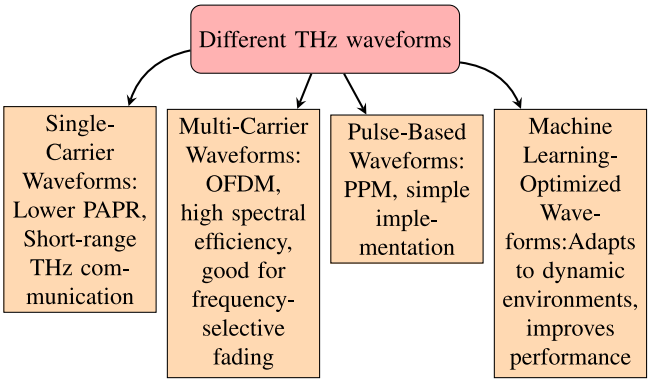

FIGURE 13. Different THz waveforms techniques.

TABLE 13. Trade-off of bandwidth allocation for communication and sensing [313], [314].

Factor	Communication Priority	Sensing Priority
Bandwidth	Needs large contiguous chunks for high throughput	Also needs wideband for resolution, but can tolerate gaps
Interference	Sensitive to noise (low SNR hurts high-order modulation)	Can work with lower SNR (detection application)
Regulation	Needs harmonized global bands (like IEEE/3GPP)	More flexible (medical/industrial may use licensed/unlicensed)
Beamforming	Directional for high SNR	Omnidirectional for object detection

signal processing techniques–particularly enhanced sensing algorithms, to ensure accurate sensing and reliable data recovery. Additionally, the use of UM antenna arrays with directional beamforming can help mitigate the severe signal attenuation characteristic of the THz frequency range [168], [312], [313], [314], [315].

Waveform design for THz ISAC systems involves the careful orchestration of signal characteristics in the THz frequency range. Due to the unique properties of THz waves, waveform design focuses on optimizing modulation schemes, bandwidth allocation, and pulse shaping techniques to achieve efficient data transmission and accurate sensing concurrently. Effective waveform design plays a pivotal role in unlocking the full potential of THz ISAC systems, enabling seamless integration of high-speed communication and fine-resolution sensing [254].

A comprehensive temporal-frequency-spatial transmit design framework is tailored for THz ISAC systems in [312]. This framework is built upon a dynamic subarray hybrid beamforming architecture and a multi-carrier waveform approach. Within this structure, two distinct hybrid precoding algorithms for the dynamic array-of-subarray configuration are used. One is based on vectorization and the other employs a sensing codebook-assisted approach. Further, in [313] an approach involving a discrete Fourier transform spread orthogonal time-frequency space (DFT-s-OTFS) system with overlaid pilots is introduced, aimed at enhancing resistance against Doppler effects and minimizing PAPR concerns within THz ISAC. Subsequently, a two-phase algorithm for estimating sensing parameters is devised, seamlessly incorporating sensing capabilities into the DFT-s-OTFS waveform structure.

The ISAC architecture of the THz system is depicted in Figure 14 employs TD modules to mitigate the beam split effect. This architecture integrates communication and sensing within the same frame. For instance, in the depicted scenario, the qth time slot is allocated for sensing target-1 within the frame, as illustrated in Figure 14. Multiple RF chains are utilized to support multiple data streams in the system. However, sensing in THz bands presents greater challenges due to high pathloss and the requirement for LoS paths. Moreover, careful waveform design for both communication and sensing is essential for the successful implementation of the ISAC THz system.

THz ISAC holds significant potential for next-generation wireless networks, offering ultra-wide bandwidths that support high data rates for communication and provide high spatial resolution for precise sensing applications, such as imaging and localization. THz ISAC can facilitate non-invasive medical imaging and real-time health monitoring, as well as enable high-resolution sensing and ultra-low-latency communication for V2X networks.

However, to realize these benefits, it is crucial to design compact, low-cost, and energy-efficient THz transceivers for ISAC systems. A key challenge is the requirement for large antenna arrays to support both beamforming for communication and sensing, which can lead to bulky and power-hungry devices. Additionally, balancing communication and sensing objectives–such as maximizing data rates versus optimizing sensing accuracy–requires complex optimization strategies.

Furthermore, there is the issue of interference, as sensing signals may interfere with communication signals and vice versa. Therefore, developing effective self-interference cancellation techniques is essential for the successful implementation of THz ISAC. Some trade-off between communication and sensing priorities are mentioned below in Table 13. A summary of the opportunities and potential challenges in THz ISAC is illustrated in Figure 15.

XII. CHALLENGES AND FUTURE DIRECTIONS

Spectrum scarcity demands efficient spectrum utilization and coexistence with incumbent services. For example, devices should support multiple frequency bands including sub-GHz and mmWave. THz transceiver design and integration remain complex due to the need for compact, energy-efficient hardware components and technological limitations. In the near future, THz research will focus on advanced multiple access and modulation schemes, channel propagation modeling for near and far fields, spectrum management, hardware design, and security. Successful solutions to these challenges will drive THz communication's evolution, paving the way

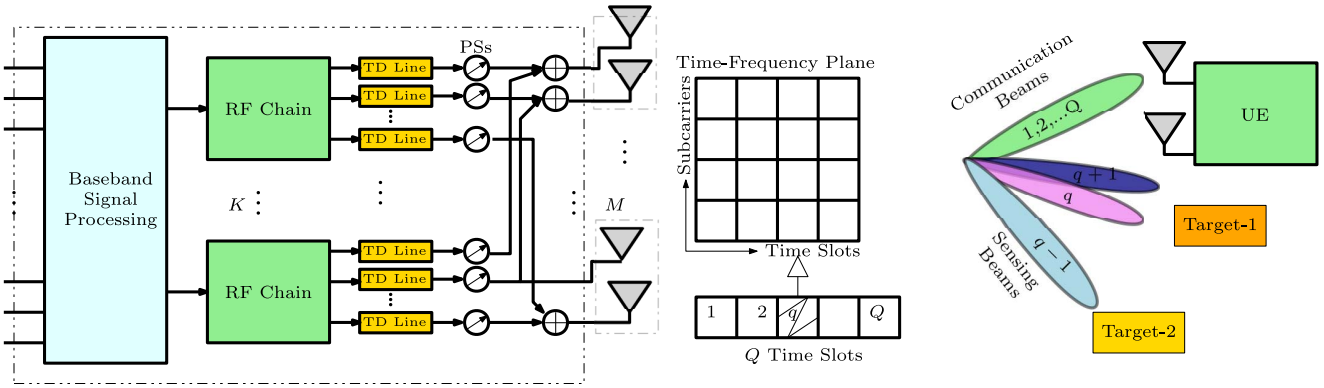

FIGURE 14. DP-based MIMO THz architecture for ISAC. The system generates scanning beams directed towards the *q*th sensing direction, while simultaneously producing stable beams aimed at the communication user during the *q*th time slot.

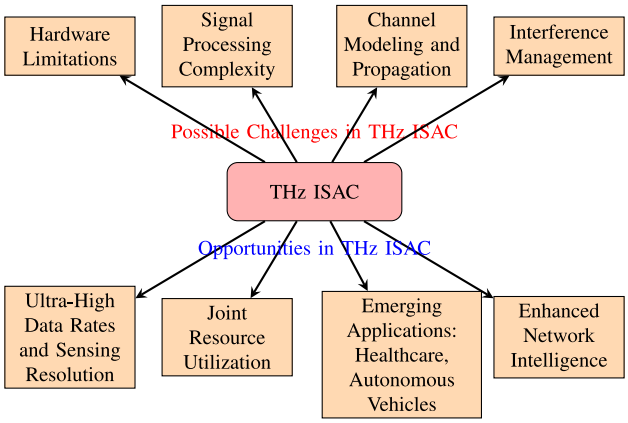

FIGURE 15. Different opportunities and possible challenges of THz ISAC.

for new wireless paradigms and applications of wireless networks.

A. REGULATORY HURDLES AND SPECTRUM ALLOCATION

THz waves pose specific challenges in regulatory frameworks and spectrum management. Some regulatory challenges in THz communication are

- *Licensing and Standards:* THz communication technologies require regulatory approval and standardization to ensure interoperability worldwide and mitigate interference with other services. Some possible works in THz bands for communication are discussed by ITU [22], [102]. For example, The World Radio Communication Conference 2019 approved four globally harmonized frequency bands, with a total bandwidth of 137 GHz (i.e., 275–296 GHz, 306–313 GHz, 318–333 GHz, and 356–450 GHz). These bands were allocated for the implementation of land mobile and fixed service applications in the frequency range of 275 GHz to 450 GHz. However, we still need to study and conduct deep analysis of THz bands for communication applications with global acceptance.
- *Health and Safety:* Regulatory authorities must ensure that THz technologies comply with safety limits to protect human and animal health, and the environment, particularly as THz waves can interact with biological tissues. Thus, health issues must be addressed by considering the ionization problem associated with THz waves.
- *International Harmonization:* Coordination of regulations across borders is essential to enable global deployment of THz technologies and avoid cross-border interference.

The noteworthy standardization activities for THz system are mentioned below. **IEEE 802.15.3d**: It is the first international standard specifically developed for THz band communications, setting the stage for future 6G networks and beyond, particularly in scenarios requiring fiber-like wireless speeds without the need for physical cabling [22]. This standard operates in the 252 to 325 GHz frequency range, offering a total bandwidth of 73 GHz, and is tailored for short-range (1-10m), high-throughput, and low-latency applications with data rates exceeding 100 Gbps. It targets several advanced use cases, including wireless backhaul/fronthaul for 5G and beyond, data centers, wireless personal and local area networks, AR/VR, kiosk-based data transfers, and high-speed intra-device communications. The standard supports both single-carrier and multi-carrier THz system designs and incorporates features such as beamforming and beam tracking at the MAC layer to ensure reliable and directional THz link maintenance [22], [316]. Further, another IEEE 802.15.3e standard for THz is Under development above frequency band 325 GHz [22]. Moreover, IEEE P802.11 standard is analyzing THz band for future Wi-Fi communications.

ITU-R: The 275–450 GHz frequency range was identified for fixed and mobile services by WRC-19, marking a significant step toward enabling THz communications [15], [78]. Similarly, WRC-23 is actively discussing the 92–300 GHz band for a variety of emerging 6G applications. In addition, ITU-R Report M.2376 (2015) explores the use of THz bands

TABLE 14. Comparison of THz standardization efforts [15], [22], [78], [101], [316], [318].

Organization	Standard/ Initiative	Frequency Range	Key Focus
IEEE	802.15.3d	252–325 GHz	Ultra-short-range WPANs
ITU-R	WRC-19/23	275–450 GHz	Global spectrum allocation
3GPP	6G (Post-Rel-18)	100–300 GHz	Cellular & backhaul
ETSI	ISG THz	300 GHz–10 THz	Industrial IoT
ATIS	6G Roadmap	100 GHz–1 THz	North American deployment
IMT-2030	China 6G	100–300 GHz	THz satellite & backhaul

for communications, outlining both opportunities and associated challenges. ITU-R Study Group 5 focuses on terrestrial services, including the evaluation and standardization of THz technologies within the scope of future IMT-2030 (6G) systems. As part of this effort, the ITU is developing the IMT-2030 framework, which identifies THz communication as a key enabler for ultra-high data rate and ultra-low latency applications such as holographic communication, wireless cognition, and real-time digital twins [317].

3GPP (For 6G & Beyond): 3GPP has initiated exploration of THz communication as a pivotal technology for future 6G systems, beginning with Release 19 and continuing into subsequent phases [101], [318]. As part of Release 19, an active study is underway on frequency bands ranging from 52.6 GHz to 114.25 GHz, with a long-term roadmap extending toward THz frequencies above 275 GHz. The study is centered around advanced use cases such as wireless backhaul/fronthaul, D2D communication, high-speed indoor connectivity, holographic displays, and extended reality. A comparison of THz standardization is summarized in Table 14.

Addressing these regulatory and spectrum allocation challenges requires close collaboration between regulatory bodies like IEEE, ITU, industry stakeholders, and researchers. A balance must be struck between promoting innovation, ensuring safe deployment, and optimizing spectrum utilization in the THz frequency range. As THz communication technologies continue to evolve, adaptable regulatory frameworks will play a pivotal role in unlocking their potential for a wide range of applications.

B. THz PRIVACY AND SECURITY

THz links were initially considered inherently secure due to their high directionality, limited range, and sensitivity to blockage. However, as THz communication systems evolve, a comprehensive security analysis becomes essential, and various vulnerabilities must be carefully addressed [2], [319]. Below we highlight cryptographic and physical-layer security (PLS) mechanisms that are relevant for securing THz communication systems.

Cryptographic Security in THz: Traditional cryptographic mechanisms, such as advanced encryption standard (AES)-256 and Rivest-Shamir-Adleman (RSA), remain essential for securing upper-layer communications [320]. However, implementing conventional cryptographic algorithms (e.g., RSA, AES) at THz frequencies poses several challenges, including hardware constraints, processing latency, energy inefficiency, and integration limitations with ultra-fast data links [319]. The ultra-low latency and high-throughput demands of THz links can lead to bottlenecks if traditional software-based encryption is applied directly. Additionally, thermal issues and limited memory in THz transceivers hinder the implementation of complex cryptographic modules.

To address these limitations, hardware-accelerated encryption engines integrated into THz chipsets—using advanced semiconductor technologies like GaN and SiGe BiCMOS—can significantly enhance speed and energy efficiency. Additionally, physical unclonable functions (PUFs) provide lightweight, device-specific key generation with minimal computational overhead, making them suitable for identity verification in THz-based IoT devices.

While post-quantum cryptography (PQC) offers resilience against quantum attacks, it often incurs high computational overhead and must be carefully optimized for THz-specific channel dynamics. Meanwhile, quantum key distribution (QKD) provides information-theoretic security but requires dedicated hardware—such as plasmonic nanoantennas–to be viable for integration into THz-assisted QKD architectures. These approaches highlight the necessity for hybrid security frameworks that combine cryptographic and physical-layer techniques to meet the demands of secure, high-speed THz communications.

PLS in THz: PLS provides an additional layer of protection by exploiting unique characteristics of the THz channel, such as high path loss, beam directivity, and sparsity [321], [322]. Techniques like AN injection, secure beamforming, and channel-based key generation are particularly effective due to the limited eavesdropping range in THz links. Moreover, IRS can be employed to dynamically alter the propagation environment, enhancing secrecy capacity. Some PLS techniques are highlighted in Table 15 for THz systems. For highly sensitive applications like wireless cognition and holographic communications, a hybrid approach combining lightweight cryptography and adaptive PLS strategies is considered ideal. Ongoing research also explores PQC schemes to future-proof THz systems against quantum attacks. Further, regulatory frameworks should address potential privacy concerns arising from the use of THz technology in various applications, such as imaging and surveillance.

TABLE 15. Key PLS THz techniques.

Technique	Technique	THz Applicability
Beamforming security	Dynamic null-steering to block eavesdroppers	UM-MIMO enables precise control
AN injection	Injects noise in non-user directions	High THz bandwidth allows wideband AN
Channel-based key generation	Uses THz channel randomness (e.g., phase) for keys	Fast fading at THz improves entropy
IRS	IRS scrambles signals for eavesdroppers	Graphene-based RIS enables rapid reconfiguration

C. RESEARCH DIRECTIONS AND POTENTIAL BREAKTHROUGHS

THz communication faces substantial path loss—up to 100 dB/m at 300 GHz—primarily due to free-space attenuation and molecular absorption. To mitigate this, advanced techniques such as UM-MIMO, dynamic beam steering, and IRS-based designs are essential. Ultra-dense antenna arrays, comprising hundreds to thousands of elements in compact configurations, enable high beamforming gains through strong directivity, helping to counteract severe propagation losses. Additionally, tunable reflection coefficients in IRSs—achieved via electrostatic biasing—can significantly enhance signal strength in THz systems. However, the development of efficient THz phase shifters remains a challenge due to their high insertion loss, underscoring the need for improved materials. For real-world deployments, hybrid solutions combining UM-MIMO, IRS, and AI-driven beam tracking appear to be the most promising pathway forward.

To address hardware limitations in THz system design, ongoing research is focused on several fronts. Efforts include developing high-performance THz transceivers using advanced semiconductor technologies such as InP, GaN, and SiGe, which offer better gain and thermal stability. Researchers are also exploring graphene-based components and photonic-integrated circuits (PICs) to overcome limitations in speed, integration density, and signal loss. Additionally, there is active work in co-designing antennas and front-end modules with low-noise amplifiers and efficient mixers to reduce power consumption. Thermal management solutions, such as micro-cooling systems and heat-spreading materials, are being integrated into compact THz devices. Moreover, hybrid integration strategies are being investigated to combine CMOS with novel materials for scalable and energy-efficient THz hardware platforms.

Doppler effects become significantly pronounced at THz frequencies due to the ultra-short wavelengths, leading to rapid channel variations and frequency shifts that degrade system performance, especially in high-mobility scenarios. Ongoing research focuses on developing Doppler-resilient waveforms such as OTFS modulation, which offers robustness against TF dispersion. Moreover, machine learning techniques are being explored for real-time Doppler estimation and compensation. Directional transmission via narrow beams, as used in UM-MIMO and beamforming architectures, also helps reduce Doppler spread by minimizing angular dispersion. Adaptive beam tracking algorithms and predictive mobility models are under active investigation to maintain beam alignment despite fast-moving users or platforms (e.g., UAVs or vehicles). Additionally, researchers are exploring the integration of radar and communication functions to jointly sense motion and adaptively mitigate Doppler-induced impairments in THz systems. Some THz challenges and research directions are highlighted in TABLE 16.

As THz technology continues to advance, researchers are exploring numerous avenues to address challenges and capitalize on opportunities. Addressing these research challenges through interdisciplinary innovations in materials science, AI/ML, signal processing, and hardware design will be critical to making THz communication a viable reality for 6G and beyond.

1) NEW MATERIALS EXPLORATION FOR THz DEVICES

The development of efficient and scalable THz devices hinges on the exploration of novel materials with exceptional electrical, optical, and thermal properties. Conventional semiconductor materials such as silicon (Si) and gallium arsenide (GaAs) face inherent limitations in mobility, breakdown voltage, and processing capabilities at THz frequencies. To address these challenges, researchers are investigating advanced materials like graphene and metamaterials, alongside innovative devices such as THz transistors and photonic crystals, to enhance the performance of THz sources and detectors.

Graphene, with its remarkable properties–including high carrier mobility, broadband absorption, and tunable conductivity–has emerged as a promising candidate for THz modulators, detectors, and transistors. However, its lack of an intrinsic bandgap poses challenges for active device applications. Additionally, artificially engineered structures like metamaterials offer precise control over THz wave propagation, enabling advancements in modulators, filters, and cloaking devices.

The integration of these next-generation materials into THz devices is expected to drive the development of high-performance, low-power, and compact THz communication, sensing, and imaging systems. Future research should focus on optimizing material synthesis, enhancing scalability, and refining device fabrication techniques to achieve practical, cost-effective, and energy-efficient THz technologies.

2) MACHINE LEARNING AND AI

Applying AI/ML to THz communication presents several challenges, particularly in single-layer optimization (e.g., physical layer) and cross-layer optimization (e.g., joint physical and MAC layer). THz systems often employ large

TABLE 16. THz communication challenges & research directions.

Specific Challenges	Potential Solutions	Research Directions
Path loss and absorption: extreme free-space path loss (100 dB/m), molecular absorption (e.g., H_2O peaks at 350 GHz), etc.	UM-MIMO beamforming, IRS, high-power THz amplifiers (GaN, InP), etc.	Metasurface lenses for beam focusing, hybrid optical/electronic THz generation
Limited coverage and blockage : high directivity leads narrow beams (1°), penetration loss (e.g., walls attenuate 50 dB/cm)	Dynamic beam steering (AI-based tracking), multi-IRS cooperative networks, reconfigurable antennas (graphene-based)	NLoS relaying with UAVs, holographic beamforming
Hardware limitations: lack of efficient THz transceivers, high noise in CMOS above 100 GHz, power-hungry ADCs/DACs	Photonic-integrated circuits (PICs), Graphene plasmonic devices, Cryogenic CMOS for low-noise	Quantum cascade lasers (QCLs), Neuromorphic THz signal processing
Mobility and Doppler effects: beam misalignment due to mobility, high Doppler spread at THz frequencies	ML-based predictive beamforming, true-time-delay (TTD) networks	Federated learning for distributed beam tracking, OAM (orbital angular momentum) beams
Channel modeling complexity: hybrid deterministic-stochastic models are computationally expensive, lack of real-world measurements.	AI/ML-based surrogate models, federated learning for collaborative channel data	THz ray-tracing with molecular absorption, standardized datasets (e.g., 6G-SHINE).
Standardization gaps: no global THz spectrum allocation, fragmented PHY/MAC protocols	ITU/WRC harmonization (e.g., 275–450 GHz), IEEE 802.15.3d/3e extensions	3GPP 6G THz standardization (Post-Rel-20).

antenna arrays and wide bandwidths, resulting in high-dimensional state and action spaces. Consequently, training AI/ML models, such as RL-based algorithms, becomes computationally expensive and time-intensive. For instance, optimizing beamforming vectors for massive MIMO THz systems requires extensive computational resources.

Additionally, THz channels exhibit high dynamism due to mobility, blockages, and environmental factors like humidity. As a result, AI/ML models must quickly adapt to these changing conditions, necessitating frequent retraining or online learning. A key example is AI/ML-driven real-time beam tracking and alignment, which demands continuous model updates to maintain accuracy in dynamic environments.

Another major challenge is the limited availability of real-world THz communication data. Since THz technology is still in its early stages, AI/ML models trained primarily on simulated data may struggle to generalize effectively to real-world scenarios. This data scarcity hinders the development of robust and reliable AI/ML algorithms tailored for THz applications.

Moreover, THz communication relies on highly directional beams, making resource allocation—such as time slots and frequency bands—more complex. AI/ML models must not only optimize resource allocation but also account for beam alignment and interference. For example, efficient multi-user scheduling in THz networks requires AI-driven techniques that dynamically adjust to spatial and temporal variations in network demand.

Significant hurdles remain in optimizing AI/ML for THz communication, both at the single-layer and cross-layer levels. Overcoming these challenges will require innovative solutions, including hierarchical AI models, transfer learning, and hybrid AI-heuristic approaches. Additionally, collaboration between academia, industry, and standardization bodies is essential for developing scalable AI/ML frameworks for THz networks. By addressing these limitations, AI/ML can unlock the full potential of THz communication, paving the way for 6G and beyond.

Further, RL has emerged as a promising tool to address the dynamic and complex challenges of beam tracking and resource allocation in THz communication systems. Given the high directionality and narrow beamwidths in THz bands, maintaining beam alignment in mobile environments is critical [323], [326]. RL agents can learn optimal beam steering policies by interacting with the environment and receiving feedback on signal quality or throughput, enabling real-time adaptive beam tracking even under user mobility and blockage. Similarly, for resource allocation, RL-based frameworks can intelligently assign power, bandwidth, and spatial resources by learning to balance performance objectives such as throughput, energy efficiency, and latency. Deep RL variants like Deep Q-Networks (DQN) and proximal policy optimization (PPO) are particularly effective in high-dimensional THz environments, offering fast convergence and scalability.

Generative adversarial networks (GANs) have emerged as a powerful tool to address challenges in channel estimation [119]. By learning the distribution of the THz channel from limited pilot measurements, the generator in a GAN is trained to synthesize realistic CSI, while the discriminator refines the quality of generated channels

TABLE 17. Key RL applications in THz systems [25], [323], [324], [325].

Use Case	Challenge	RL Solution	Algorithm Examples
Beam alignment	High overhead in beam training (ms latency)	RL predicts optimal beams using past observations.	DQN, PPO, soft actor-critic (SAC)
Dynamic IRS control	Real-time IRS phase-shift optimization.	RL adjusts IRS reflection coefficients	multi-agent deep deterministic policy gradient (MADDPG), twin delayed deep deterministic policy gradient (TD3)
Mobility management	Doppler shifts and beam misalignment	RL anticipates user movement for beam steering	LSTM-based deep RL (DRL), Meta-RL
Power allocation	Energy-constrained THz transceivers	RL optimizes transmit power per link	Q-learning, Actor-critic
Spectrum sharing	Coexistence with mmWave/sensing systems	RL learns interference patterns for dynamic access	Multi-agent RL (MARL)

by distinguishing them from actual CSI. This adversarial learning framework enables data-driven reconstruction of high-dimensional, sparse THz channels with significantly reduced pilot overhead, making it highly efficient for UM-MIMO and IRS-aided systems [327]. Possible applications of RL in THz system design are highlighted in TABLE 17.

3) ADVANCED MODULATION AND SIGNAL PROCESSING TECHNIQUES

Developing adaptive modulation schemes and error correction codes tailored for THz communication is crucial to achieving higher data rates and enhanced reliability. These techniques must dynamically adjust to varying channel conditions and atmospheric effects. Environmental factors such as humidity, temperature, and obstacles can cause rapid fluctuations in THz channel quality, potentially degrading signal strength by up to 40 dB. Additionally, the high-frequency nature of THz waves increases susceptibility to noise and interference, resulting in a significant and variable probability of errors.

To address these challenges, researchers should explore non-coherent and low-power detection techniques to minimize complexity and energy consumption. Enhancing spectral efficiency through novel multi-carrier waveforms and advanced multiplexing strategies is also essential. Hybrid analog-digital signal processing techniques can be particularly effective in managing the high-dimensional nature of THz systems, while sparse signal processing frameworks leverage the inherent sparsity of THz multipath channels to improve detection performance. Furthermore, both single-carrier and multi-carrier system designs should be evaluated for different applications. For instance, in OFDM-based THz systems, high peak-to-average power ratio (PAPR) can be a concern due to the wide bandwidth and gain variations across frequency bands.

Security is another critical aspect, requiring the integration of AI-based anomaly detection and intrusion prevention mechanisms to safeguard THz networks. Additionally, solutions must be proposed to mitigate the high computational complexity arising from large bandwidths and massive antenna arrays, as well as to improve dynamic channel estimation and tracking for robust communication performance.

4) BEAMFORMING AND ANTENNA DESIGN

The design of advanced beamforming techniques is essential for THz communication to maximize signal strength, counteract severe path loss and beam-split effects, and mitigate spatial fading. Achieving these goals requires innovative antenna designs that provide higher directivity and efficiency in THz transceivers. Additionally, wideband antennas are crucial to supporting the large bandwidth available in the THz spectrum.

To ensure practical implementation, beamforming algorithms in THz systems must be simple and energy-efficient. Deploying UM-MIMO antenna configurations for THz networks necessitates a distinct approach compared to conventional MIMO systems. AI/ML-driven hybrid beamforming techniques offer promising solutions by enabling dynamic adaptation to rapid THz channel variations. Furthermore, exploring massive MIMO architectures can significantly enhance high-directivity beamforming and mitigate interference in dense THz networks.

A key research direction involves joint beamforming and localization techniques tailored for mobile THz networks, including UAV-assisted and satellite-based THz systems. Addressing critical challenges such as the high power consumption of large antenna arrays and ensuring precise beam alignment and tracking in dynamic environments is crucial for the successful deployment of THz communication systems.

5) CHANNEL MODELING AND PROPAGATION STUDIES

Accurate channel models are essential for capturing the effects of atmospheric absorption, scattering, and interference in THz propagation. A precise propagation model enables better system design and enhances performance predictions. Additionally, understanding the impact of various environmental conditions on THz channel characteristics is crucial for optimizing THz communication across different applications.

THz propagation measurement and channel modeling remain key research areas, particularly in characterizing multipath effects due to the small wavelength of THz signals and the roughness of surfaces. Developing data-driven and AI-enhanced THz channel models can provide more accurate representations of diverse scenarios, including indoor, outdoor, and space-based applications.

Furthermore, investigating reconfigurable intelligent surface (RIS)-assisted propagation offers a promising approach to mitigating path loss and beam misalignment, thereby improving signal coverage and reliability in THz communication systems.

6) INTEGRATED TRANSCEIVER AND CHIP DESIGN

Research in compact, low-power THz transceiver chips and integrated circuits is essential for enabling practical THz communication systems. This includes the design and analysis of photonic and electronic integration for efficient THz signal generation, modulation, and detection.

Advancements in chip-scale THz technologies and semiconductor materials, such as InP, GaAs, SiGe, and CMOS, are crucial for achieving high-performance THz transceivers. However, designing high-gain power amplifiers at THz frequencies remains a significant challenge due to the wide bandwidth and extremely high carrier frequencies. Additionally, nonlinear device effects can be leveraged for harmonic power generation and signal detection.

Future research should focus on developing high-performance THz transistors, photonic-based THz devices, and energy-efficient power amplifiers. Addressing key hardware impairments, such as PN, IQ imbalance, and nonlinear distortions, will be critical for ensuring reliable and efficient THz communication systems.

Graphene-based THz devices are emerging as key enablers for next-generation high-frequency communication systems due to graphene's exceptional electrical, thermal, and optical properties. With its ultra-high electron mobility and tunable conductivity, graphene supports the development of ultra-fast THz transistors, modulators, detectors, and antennas. These devices are particularly suited for compact, energy-efficient THz systems operating at room temperature. Graphene plasmonics also enable sub-wavelength confinement and dynamic beam control, making them ideal for applications such as IRS and high-speed wireless links.

Photonic-Integrated Circuits (PICs) for THz communication offer a compact, energy-efficient, and high-bandwidth solution for generating, modulating, and detecting THz signals [200]. PICs integrate multiple optical components—such as lasers, modulators, and photodetectors—on a single chip using platforms like silicon photonics or indium phosphide. For THz applications, they enable the conversion of optical signals into THz waves through photomixing techniques, supporting ultra-high data rates and low latency. PICs also facilitate beam steering, frequency tunability, and coherent detection, making them ideal for short-range, high-throughput scenarios in 6G networks, such as indoor ultra-fast access, wireless backhaul, and holographic communications.

TABLE 18. Recent advancements in THz hardware [200].

Technology	Key Advancement	System-Level Impact
Graphene transistors	100+ GHz modulation	Ultra-fast, energy-efficient THz transceivers
Photonic ICs	Optical THz generation	High-power, wideband THz sources
InP/GaN HEMTs	Amplification up to 1 THz	Longer-range THz links
CMOS/SiGe	Low-cost THz ICs	Mass-market THz sensors

Advanced semiconductor technologies play a pivotal role in enabling THz communications by addressing the challenges of high-frequency signal generation, amplification, and detection. Emerging materials such as Indium Phosphide (InP), Gallium Nitride (GaN), and Gallium Arsenide (GaAs) offer superior electron mobility and breakdown voltages, making them ideal for high-speed, low-noise THz components. Furthermore, practical and scalable THz systems require improvements in bandwidth scalability, thermal management, noise figure, and integration density. However, achieving high power efficiency in THz devices remains a significant challenge, as they generally consume more power than mmWave systems. Integrating graphene, photonics, and CMOS technologies on a single chip also poses substantial difficulties. Moreover, thermal management at THz frequencies is critical, as components like GaN amplifiers generate considerable heat, which must be effectively dissipated, especially in compact device designs. Table 18 highlights the THz hardware design approach.

Most existing THz testbeds are based on SISO configurations and depend on external high-gain directional antennas, such as horn or dish antennas. The development of fully digital antenna arrays with 16 or more channels remains a significant challenge due to hardware complexity and power constraints. Furthermore, the design of reliable and dynamic wavefront controllers for conformal electromagnetic metasurfaces holds great promise for future 6G wireless communications, particularly in enabling advanced beamforming and spatial signal manipulation.

7) THz COMMUNICATION FOR SATELLITE AND SPACE COMMUNICATION

THz communication enables extremely high data rates, which are crucial for space applications such as Earth observation, deep-space communication, inter-satellite links, and space exploration. However, it also presents unique challenges due to the harsh space environment, long transmission distances—resulting in significant delays and Doppler effects—and the need for highly reliable and

efficient systems. Channel modeling and signal propagation are essential for understanding the behavior of THz waves in space, considering factors such as vacuum conditions, cosmic radiation, and solar flares. Additionally, it is important to investigate the impact of Earth's atmosphere, including tropospheric absorption and rain fade, on THz signals for satellite-to-ground communication. To enhance the feasibility of THz communication in space, research should focus on developing high-gain, lightweight, and deployable THz antennas for satellite communication. Furthermore, designing and exploring delay-tolerant networking protocols for THz-based deep-space communication is crucial, as such environments experience long propagation delays and intermittent connectivity. Integrating THz communication with lower-frequency RF systems will ensure robust and flexible space communication. Additionally, hybrid laser-THz communication systems should be explored for high-capacity and long-distance space links. The development of miniaturized THz communication systems for small satellites and CubeSats is another important aspect. Finally, applying AI and machine learning techniques to optimize THz communication parameters in dynamic space environments will further enhance system performance and reliability.

8) REAL-WORLD APPLICATIONS

Applying THz communication to practical applications like wireless sensing, indoor localization, healthcare diagnostics, and smart manufacturing, demonstrates its real-world impact. For example, THz localization is very accurate and may be suitable for security applications. Explore synergy between THz communication and next-generation technologies such as holographic MIMO, digital twins, and AI-native networks.

9) REGULATORY CONSIDERATIONS

Researching the regulatory implications of THz technology deployment is essential for health and safety regulations, privacy concerns, and international standards. Collaborative efforts between academia, industry, and regulatory bodies will be essential in driving these potential breakthroughs and realizing the full potential of THz communication.

Some of the mentioned THz challenges and research directions are also highlighted in Figure 16.

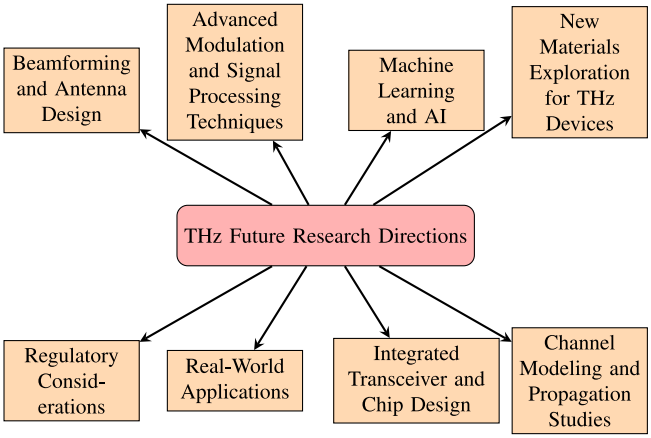

FIGURE 16. Possible research direction in THz communications.

XIII. CONCLUSION

The paper comprehensively covers the fundamentals of THz communication system design and discusses potential challenges. It includes a detailed examination of the THz spectrum and its characteristics such as path loss, attenuation, and fading effects—along with insights into THz channel properties. Channel models including deterministic, statistical, and hybrid approaches are discussed in detail, highlighting their practical accuracy and complexity. Various applications of THz bands across different fields are presented. Additionally, the paper explores THz wave generation sources and their corresponding detectors. Photonic, electronic, and hybrid THz sources are compared in terms of their potential advantages and disadvantages. Various THz waveform designs for single and multi-carrier systems are discussed. The impact of modulation schemes is analyzed considering the specific propagation characteristics of THz signals.

THz system design considerations such as OFDM, OTFS, massive MIMO, and RIS are prominently featured. RIS-based THz system design is shown to significantly enhance signal strength, as demonstrated through various configurations such as single RIS and multiple RIS scenarios. The effectiveness of OTFS in handling high Doppler shifts in frequency-selective channels is discussed and compared to conventional OFDM systems. 2D modulation schemes are introduced for delay-Doppler or time-frequency domain implementations in THz systems.

Different beamforming techniques, including hybrid and delay-phase approaches, are discussed along with their respective advantages and challenges. Hybrid beamforming with time-delay lines is found to be more suitable for THz system design due to its balanced implementation complexity, gain, and scalability. The phenomenon of beam split in THz systems and corresponding time-delay-based compensation schemes are also addressed, as beam split significantly degrades system performance. Wideband beamforming strategies, distinct from those used in sub-6 GHz narrowband systems, are also highlighted.

THz-based ISAC techniques are discussed, including their potential trade-offs. The paper explores various THz communication protocols and standards such as IEEE 802.15.3d, ITU-R, and 3GPP for 6G and beyond. Security aspects are also addressed, including cryptographic and physical-layer security (PLS) mechanisms tailored for THz communication. Furthermore, the role of AI/ML in THz system design and resource optimization is emphasized. Various deep learning algorithms, such as reinforcement learning and generative adversarial networks (GANs), are explored for beamforming and THz channel estimation. The paper discusses hardware design constraints in THz systems and provides possible solutions. Finally, the paper highlights

key research directions and potential solutions, concluding with the anticipated impact of THz communication on next-generation networks, particularly through the integration of advanced technologies and signal processing algorithms.

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