IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 22 September 2024, accepted 14 October 2024, date of publication 17 October 2024, date of current version 29 November 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3482564

SURVEY

A Survey on RIS Advances in Terahertz Communications: Emerging Paradigms and Research Frontiers

MANZOOR AHMED[1], ABDUL WAHID[2], WALI ULLAH KHAN[3], (Member, IEEE), FEROZ KHAN[4], ASIM IHSAN[5], ZAIN ALI[6], KHALED M. RABIE[7], (Senior Member, IEEE), THOKOZANI SHONGWE[8], (Senior Member, IEEE), AND ZHU HAN[9,10], (Fellow, IEEE)

[1]School of Computer and Information Science, Institute for AI Industrial Technology Research, Hubei Engineering University, Xiaogan 432000, China
[2]College of Computer Science and Technology, Qingdao University, Qingdao 266071, China
[3]Interdisciplinary Centre for Security, Reliability, and Trust (SnT), University of Luxembourg, 1855 Luxembourg City, Luxembourg
[4]Electronics Engineering Department, Beijing University of Posts and Telecommunications, Beijing 100876, China
[5]Department of Engineering, University of Cambridge, CB2 1TN Cambridge, U.K.
[6]Department of Electrical and Computer Engineering, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
[7]Department of Computer Engineering and Center for Communication Systems and Sensing, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[8]Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2092, South Africa
[9]Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004, USA
[10]Department of Computer Science and Engineering, Kyung Hee University, Seoul 446-701, South Korea

Corresponding author: Feroz Khan (ferozkhan687@gmail.com)

This work was supported by the Ministry of Education of China (MOE) Project of Humanities and Social Sciences under Grant 23YJAZH169, and in part by the Hubei Provincial Department of Education Outstanding Youth Scientific Innovation Team Support Foundation under Grant T2020017.

ABSTRACT Communication at terahertz (THz) frequencies has emerged as a potential answer to the challenge of providing massive capacity and ultra-high data speeds for 6G wireless networks. However, THz waves are vulnerable to obstruction because of their attenuation during propagation and poor diffraction. The development of reconfigurable intelligent surfaces (RIS) technology has shown promise in addressing these issues. The RIS enables the development of smart radio settings with enhanced spectrum coverage and efficiency by regulating the phase shifts of passively reflecting elements. Amidst the vast potential of RIS-based THz communication, a noticeable void exists in comprehensive research, calling for a systematic survey to shed light on its principles, use cases, performance evaluation, challenges, and future trajectories. This review investigates the exciting field of RIS-based THz communication in fifth-generation (B5G), sixth-generation (6G), and beyond. Our study provides a comprehensive overview of this emerging technology, covering a variety of use cases, including channel estimation (CE), coverage, security, sum rate, and energy efficiency. We also investigate resource allocation strategies for THz communication using RIS. Additionally, the performance of RIS-based THz systems with multiple-input and multiple-output (MIMO) and massive MIMO and unmanned aerial vehicle (UAV) technologies is analyzed. By analyzing the existing literature, we illuminate the various approaches, methodologies, and future developments in this field. We also emphasize open issues and research opportunities in THz communication based on RIS. This survey is a valuable resource, contributing to understanding the emerging paradigms and research frontiers of RIS-based THz communication.

INDEX TERMS Reconfigurable intelligent surfaces (RIS), intelligent reflecting surfaces (IRS), terahertz (THz), simultaneous transmitting and reflecting RIS (STAR-RIS).

I. INTRODUCTION

The progression from the fifth-generation, the sixth-generation (6G), and beyond of wireless communications networks offers the potential for significant advances in communication technology [1]. The 6G networks are

The associate editor coordinating the review of this manuscript and approving it for publication was Miguel López-Benítez.

intended to support new applications, such as virtual reality, holographic communications, high-speed wireless data centers, quick kiosk downloads, and efficient backhaul connections [2]. In addition, they seek to provide increased data rates, bandwidth, spectrum efficiency, connection density, decreased latency, expanded coverage, and enhanced intelligence. Identifying additional spectrum resources is imperative in light of the limited bandwidth currently accessible within the microwave and millimeter wave (mmWave) frequency spectrums [3], [4]. A potential answer to the needs of the 6G wireless network is terahertz (THz) transmission [5]. The THz frequency range, which spans from 0.1 THz to 10 THz, offers a wide spectrum bandwidth that facilitates the communication of data at exceptionally high rates, reaching up to several terabits per second (Tbps) and hundreds of gigabits per second (Gbps). Moreover, the World Radio Communication Conference 2019 (WRC2019) has designated a frequency band between 0.275 and 0.47 THz for fixed and mobile communication services. Notwithstanding the advantages, the real-world implementation of THz communication encounters numerous challenges. The attenuation of THz waves at higher frequencies during their transmission is the main impediment to THz communication [6]. THz waves experience significant attenuation upon reflection from typical surfaces such as concrete, walls, and buildings, leading to diminished signal coverage and impaired communication efficiency. This limitation reduces the device's utility by restricting the communication range to a small area [7]. Moreover, the limited bandwidth of the THz frequency range presents obstacles to achieving accurate beam manipulation and tracking, thereby rendering the construction and operation of THz communication systems more arduous [8]. Additionally, the narrow beam of the THz frequency range makes it challenging to provide precise beam control and tracking, making it more challenging to develop and maintain THz communication systems [9].

One promising approach to overcoming these issues is the implementation of reconfigurable intelligent surfaces (RIS) [10]. In conventional wireless communication systems, the optimization of transmitters and receivers is typically limited to adjusting to the existing radio environment rather than proactively manipulating it. Programming radio environments has gained significant attention in the wake of recent progress in wireless research [11]. The ability mentioned above is enabled through the utilization of RISs, which provide accurate control over radio wave characteristics such as reflection (beamforming), refraction, and absorption. Integrating RISs within a network can transform the surrounding environment into a space that is intelligent and capable of adapting, thus introducing the concept of smart radio environment (SRE) [12], [13]. SREs can flexibly manipulate and personalize the radio frequency spectrum, resulting in exceptional opportunities for enhancing wireless systems and attaining communication efficiency customized to particular demands [14], [15]. The paradigm shift mentioned above offers new prospects for exploring advanced wireless technologies and their associated applications.

RIS, composed of multiple passively reflecting meta-atoms, can manipulate THz waves' amplitude and phase, enhancing wireless channel programmability [16]. This adaptability boosts system capacity, reliability, and power efficiency. RIS's passive nature reduces the need for active components, cutting deployment costs and power consumption [17]. Its extensive coverage enables THz communication over large areas, overcoming traditional surface limitations [9]. By altering THz wave propagation direction with minimal reflection loss, RIS facilitates extended transmission ranges and effective obstruction management, especially in non-line-of-sight networks [18]. RIS integration can facilitate THz communication adoption in practical 6G wireless networks as shown in Fig. 1.

A. MOTIVATION AND CONTRIBUTION

Prior academic literature has extensively explored various aspects of RIS from different perspectives. However, this study specifically focuses on the emerging applications of RIS in THz communication, addressing the critical need for updated research in this rapidly developing field. As THz communication plays an increasingly significant role in next-generation wireless systems, understanding how RIS can enhance these systems is essential for overcoming the challenges inherent in THz frequencies, such as high signal attenuation. For example, [19] analyzed the functionality of RIS as reflectors, comparing their performance with traditional reflecting relays and backscatter communication techniques. In a related study, [20] introduced RIS meta-surfaces as a vital enabler for SRE, offering an overview of RIS characteristics and the current state of research in the context of SRE. Expanding on these foundations, [21] explored the application of RIS for smart city development, highlighting potential advantages and identifying future research directions in this domain.

Building on these works, [22] and [23] addressed key challenges in RIS-assisted wireless communication systems, focusing on channel characteristics and deployment strategies. These studies set the stage for further exploration into the use of RIS across diverse environments, including Industry 4.0, underground Internet of Things (IoT), and underwater IoT, as discussed in [24] and [25]. Both studies also examined future research challenges, deployment strategies, and design considerations, with [24] additionally covering performance metrics, innovative signal models, and hardware architectures for RIS devices. Further expanding on the technical aspects of RIS integration, [26] identified three major challenges in incorporating RIS into wireless networks: passive information transfer, low-complexity phase shift optimization, and the collection of channel state information (CSI). Additionally, [27] explored the use of machine learning algorithms for optimizing resource allocation in RIS-assisted wireless systems, while [28]

TABLE 1. Summary of important acronyms.

Acronym	Definition	Acronym	Definition
6G	Sixth Generation	AN	Artificial Noise
AO	Alternating Optimization	AP	Access Point
AR	Augmented Reality	BCD	Block Coordinate Descent
B5G	Beyond Fifth-Generation	BER	Bit Error Rate
BLOS	Beyond-Line-of-Sight	BS	Base Station
CE	Channel Estimation	CSI	Channel State Information
CS	Compressed Sensing	DRL	Deep Reinforcement Learning
EE	Energy Efficiency	Eve	Eavesdropper
FD	Full-Duplex	FSPL	Free-Space Path Loss
Gbps	Gigabits per Second	HD	Half-Duplex
IOS	Intelligent Omni-Surface	IoT	Internet of Things
IRS	Intelligent Reflecting Surface	ISAC	Integrated Sensing and Communication System
MIMO	Multiple-Input Multiple-Output	MISO	Multiple-Input Single-Output
mmWave	Millimeter-Wave	NLOS	Non-Line-of-Sight
NOMA	Non-Orthogonal Multiple Access	OMA	Orthogonal Multiple Access
OP	Outage Probability	PLS	Physical Layer Security
PSO	Particle Swarm Optimization	QoS	Quality of Service
RIS	Reconfigurable Intelligent Surface	RSMA	Rate Division Multiple Access
SCA	Successive Convex Approximation	SDR	Semi Definite Relaxation
SE	Spectral Efficiency	SEE	Secrecy Energy Efficiency
SIC	Successive Interference Cancellation	SNR	Signal-to-Noise Ratio
SR	Secrecy Rate	SRE	Smart Radio Environment
STARS	Simultaneously Transmitting and Reflecting Surfaces	Tbps	Terabits per Second
THz	Terahertz	UAV	Unmanned Aerial Vehicle
umMIMO	Ultra-Massive Multiple-Input Multiple-Output	VLC	Visible Light Communication
VR	Virtual Reality		

provided a detailed tutorial on the use of RIS for wireless sensing and localization. Reference [29] contributed to this growing body of work by focusing on the signal processing aspects of RIS-enhanced wireless communications. Recent developments in the field have shifted attention toward intelligent omni-surfaces (IOS), which expand the capabilities of traditional RIS. Reference [30] introduced a hybrid beamforming technique based on IOS, which facilitates full-dimensional communication. Additionally, [31] analyzed IOS beamforming, channel modeling, and potential applications in future cellular networks, marking a significant advancement in RIS research. These studies underscore the ongoing evolution of RIS technologies, particularly in the context of 6G networks and beyond.

In terms of optimization techniques for RIS, [32] reviewed a variety of approaches, including model-based, heuristic, and machine learning methods. Their research highlighted key challenges, such as sum-rate maximization and power minimization, and proposed future directions for RIS in 6G networks. Building on this, [33] explored how RIS can be integrated with machine learning for intelligent spectrum allocation in IoT systems. Similarly, [34] compared the application of deep reinforcement learning (DRL) and multi-armed bandit techniques for configuring RIS in 6G networks, suggesting the growing role of artificial intelligence in enhancing RIS functionality.

As RIS becomes increasingly important for THz communication, recent studies have focused specifically on the challenges and opportunities within this spectrum. Reference [35] examined the role of RIS in improving THz communication for B5G and 6G networks, particularly in channel modeling and network reliability. Likewise, [36] provided a comprehensive overview of the technological advancements and challenges in RIS for THz systems, focusing on improving signal quality and overcoming propagation issues. This research offers insights into future directions for fully integrating RIS into 6G THz communication networks, enhancing both performance and coverage. Additional studies have investigated the role of RIS in addressing THz-specific challenges. For instance, [37] explored how RIS can mitigate high path loss and enhance system performance in terms of data rates and security. Moreover, [38] discussed the integration of compressive sensing with RIS to improve security and efficiency in THz communication networks by addressing signal propagation challenges and preventing eavesdropping. Finally, [39] examined how RIS can enhance 6G sub-THz communication systems, particularly through the use of advanced beamforming techniques to optimize network performance.

This comprehensive survey aims to provide a thorough understanding of the applications of RIS in THz communication. Our study covers theoretical foundations, practical applications, and performance evaluations, while also addressing future developments in this field. By systematically organizing and analyzing existing literature, identifying key challenges, and proposing relevant use cases,

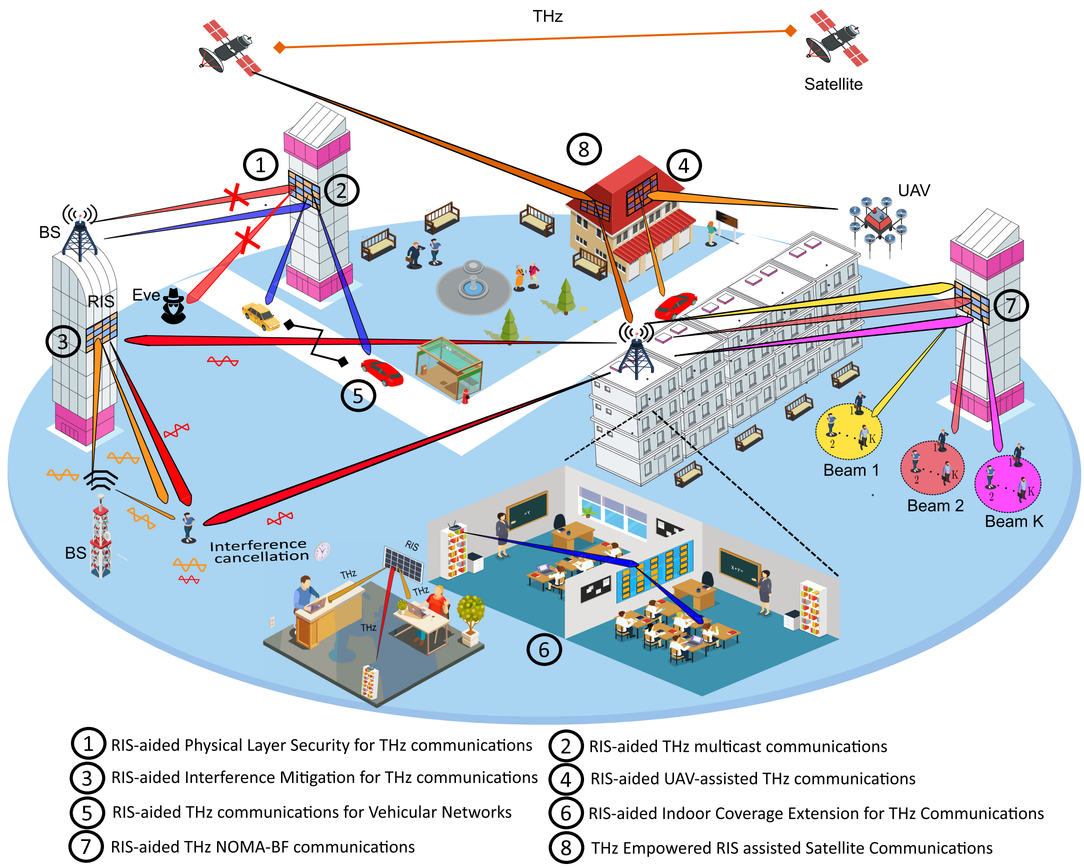


FIGURE 1. **RIS-based THz applications.**

this research serves as a valuable resource for practitioners and researchers seeking to advance RIS technology in the context of THz communication. Following are our survey's salient contributions:

- Comprehensive overview: This survey gives a thorough overview of RIS-based THz communication, covering its fundamentals, use cases, performance evaluation, challenges, and prospects for the future. Researchers and professionals seeking a complete picture of this developing technology will find this work invaluable.
- Coverage of use cases: The study looks at many use cases made conceivable by RIS-based THz communication, such as CE, higher THz transmission capacity, improved security, higher data rates, and increased energy efficiency (EE). These use cases demonstrate the technology's wide range of uses and advantages.
- Resource allocation strategies: This study examines resource-allocation techniques explicitly designed for THz communication with RIS. This includes examining effective resource allocation methods and optimizing system performance, helping create frameworks for efficient communication.
- Performance evaluation: The study evaluates the performance of multiple-input multiple-output (MIMO) and massive MIMO (mMIMO) and UAV technologies in combination with RIS-based THz systems. This analysis offers perceptions of the potential synergies and capacities of merging these technologies, motivating further investigation and system design.
- Open issues and research opportunities: The survey's conclusion identifies unresolved problems and areas for future research in THz communication based on RIS. Pointing out these gaps motivates future researchers to look into undiscovered areas of this discipline.

B. SURVEY STRUCTURE

The survey unfolds well-structured, allowing readers to delve into the intricacies of RIS-based THz communication. Section II sheds light on the RIS types, modes, and applications. In Section III, the fundamentals of THz communication, including its applications, challenges, and channel model are explored. Building upon this foundation, Section IV unveils the RIS-based use case strategies in THz communication. This captivating section covers essential aspects such as THz CE, expanding communication coverage, improving THz security, maximizing THz communication systems' sum rate, and enhancing EE. Moving forward, in Section V, we intricately examine diverse resource allocation and performance evaluation approaches. Section VI enumerates uncovered issues and possible directions for future research.

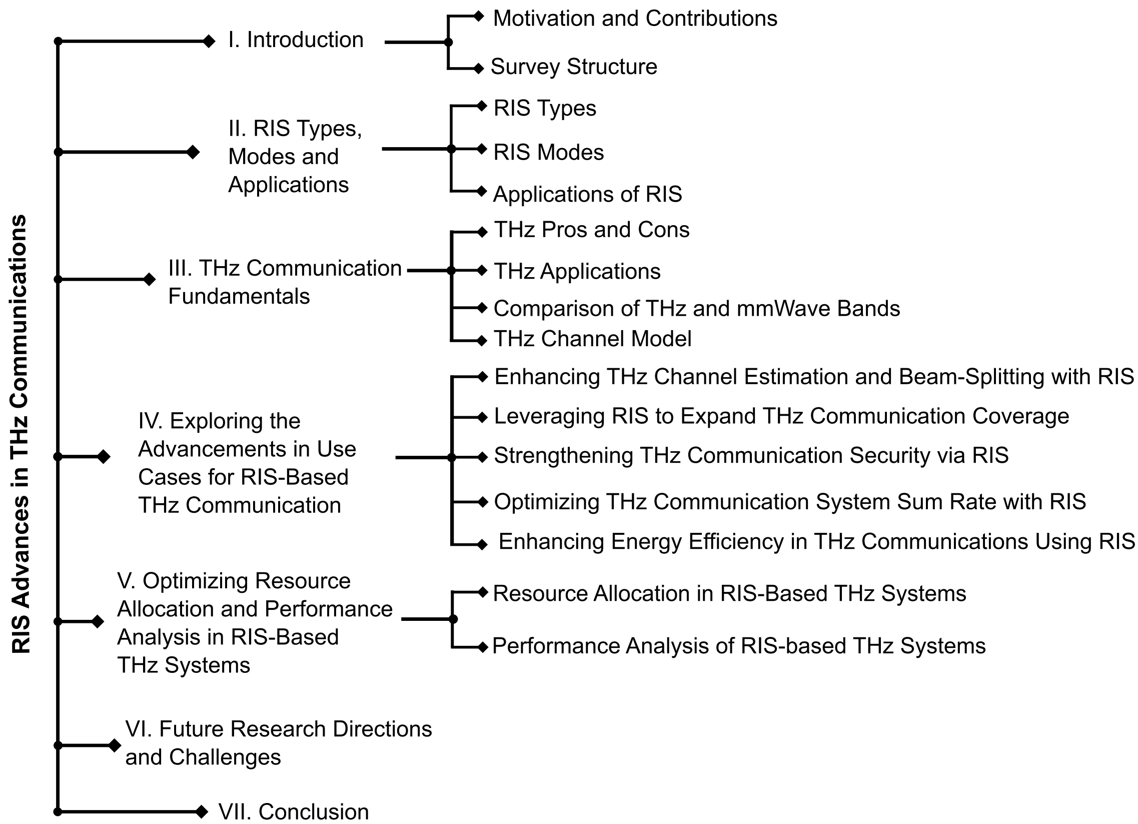


FIGURE 2. Structure of this paper.

Lastly, the survey concludes in Section VII. Fig. 2 presents the structure of this paper.

II. RIS TYPES, MODES, AND APPLICATIONS

In recent times, intelligent reflecting surfaces (IRS), also referred to as RIS, have emerged as a promising solution for addressing challenges in wireless communication [40]. These surfaces manipulate incoming signals using a planar configuration of inexpensive reflecting elements [27]. An intelligent controller, often implemented using FPGA technology, facilitates coordination between active base stations (BSs) and users, enabling real-time control and information exchange [41]. The deployment of RIS offers several benefits, including reduced hardware costs and energy consumption compared to traditional 5G solutions. Their passive scattering mechanism effectively enables full-duplex transmission without the noise and interference issues encountered by active relay systems, thus enhancing spectrum efficiency. Furthermore, the physical characteristics of RIS, such as their low-profile and lightweight design, allow for easy placement on various surfaces, making them suitable for deployment in diverse environments such as smart factories, stadiums, and airports [42]. Their compatibility with existing infrastructure and devices adds to their appeal. Additionally, the programmable nature of RIS enables customized wireless propagation settings, providing solutions to communication challenges while remaining accessible and backward compatible. In the following subsections, we will discuss RIS types, modes, and applications.

A. RIS TYPES

This subsection briefs the different types of RIS, including passive, active, and hybrid. Each type plays a unique role in manipulating electromagnetic waves to improve communication network performance.

1) PASSIVE RIS

Passive RIS leverages low-cost electromagnetic materials to merge seamlessly with our environment and transform wireless transmission [43]. These surfaces smartly modify incoming signals through passive reflection, creating virtual LoS paths while conserving EE [41]. Despite its significant advantages, passive RIS encounters optimization challenges in wireless communications. A major drawback is double fading, which intensifies signal degradation and limits capacity. The pathway involving the transmitter, RIS, and receiver suffers from compounded path loss—each segment's losses multiply, reducing passive RIS's effectiveness [27]. Such constraints lead to only incremental benefits over non-RIS systems. To overcome these issues, the innovative domain of active RIS has emerged, targeting the mitigation of double fading and enhancing the performance of wireless networks.

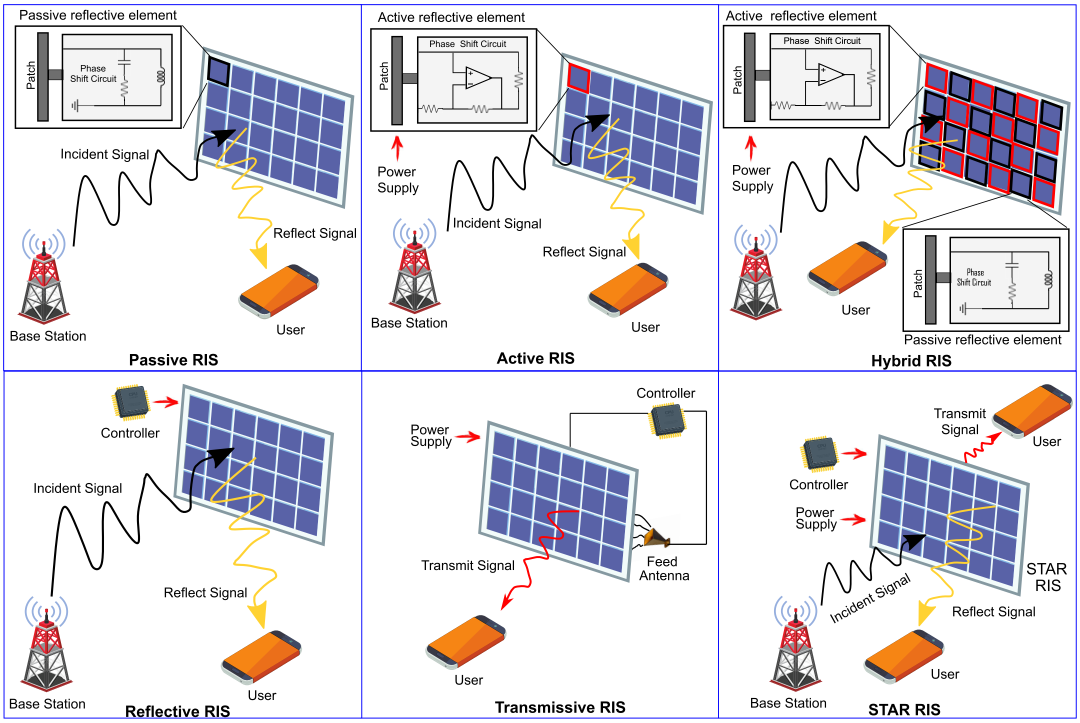


FIGURE 3. The upper three figures illustrate the different types of RIS: passive, active, and hybrid. The lower three figures demonstrate the RIS modes: reflective, transmissive, and STARS.

2) ACTIVE RIS

Active RIS was developed to mitigate the "multiplicative fading" effect observed with passive RIS, enhancing signal modulation and adding amplification [44]. Unlike passive RIS, which only reflects signals, active RIS boosts signal strength through its specialized hardware architecture, including phase shift circuits and reflection-type amplifiers [45]. However, this leads to significant power demands, potentially equating to those of base station amplifiers, and resulting in higher overall system power consumption [46]. Active RIS converts the channel loss from multiplicative to additive, providing a gain that exceeds simple reflection. Integrating active and passive elements in a hybrid RIS architecture could improve system optimization and analysis. Yet, the energy requirements of active RIS components pose challenges, particularly in off-grid setups [24].

3) HYBRID RIS

A hybrid RIS represents a versatile and advanced concept within the realm of RIS in wireless communication. As the name suggests, a hybrid RIS combines active and passive RIS features to offer a balanced, adaptable solution for signal optimization and wireless communication enhancement. Hybrid RIS represents a novel approach that integrates passive and active elements into a single reflective surface, combining their distinct functionalities to enhance wireless communication [47]. The hallmark of Hybrid RIS lies in its ability to strike a delicate equilibrium between passive and active capabilities [6]. On the one hand, it can actively control signals in real-time using its electronic components, allowing for adaptive signal processing, beamforming, and interference mitigation. Simultaneously, it leverages its passive elements to harness the benefits of reflection, making it a versatile and adaptable solution for various wireless communication scenarios. It's important to note that while the active components of Hybrid RIS consume power, incorporating passive elements contributes to a more energy-efficient system when compared to fully active alternatives [48]. This optimization of energy usage underscores the practicality and sustainability of Hybrid RIS in wireless communication networks. The versatility of Hybrid RIS further enhances its appeal. It can be seamlessly deployed across various scenarios, ranging from B5G networks to indoor wireless communication setups. This adaptability empowers network operators to fine-tune their communication infrastructure, offering a balanced, flexible solution catering to diverse communication requirements.

B. RIS MODES

This subsection overviews RIS's modes, which are primarily categorized into reflective, transmissive, and simultaneously transmitting and reflecting surfaces (STARS). These modes are fundamental in tailoring the propagation environment to improve signal quality and network performance.

1) REFLECTIVE RIS

Reflecting modern technologies, or reflecting RISs, use passive elements to control electromagnetic waves.

To individually manage the phase response of incident electromagnetic waves, these surfaces comprise various subwavelength-scale elements [49]. Wavefront manipulation and advanced signal control and shaping can be achieved by precisely adjusting the phase of the reflecting RIS. The concept of metasurface engineering underpins the functionality of RIS reflection [50]. Each subwavelength element introduces a phase change to the electromagnetic wave when it contacts the surface of an RIS. It is possible to achieve a high degree of accuracy in shaping and regulating the reflected wavefront through meticulous manipulation of the components' geometry, orientation, and material characteristics [42]. This functionality enables the manipulation of beam steering, focusing, and polarization. The RIS technology exhibits great potential for upcoming communication networks due to its distinctive phase and amplitude control features, EE, and full duplex capability.

2) TRANSMISSIVE RIS

The transmissive RIS stands out as an innovative wireless communication technology due to its unique ability to dynamically adjust and optimize the direction of in-band RF signals as they traverse its aperture. This distinct characteristic allows the transmissive RIS to engage in dynamic beamforming, actively altering the phase and amplitude of transmitted signals in real-time [51]. A significant advantage of the transmissive RIS lies in its capability to greatly improve direct indoor coverage by leveraging outdoor cellular signals. By dynamically shaping and steering RF signals, it effectively enhances signal strength and quality within indoor environments, thereby overcoming typical challenges like signal attenuation and interference [52].

3) SIMULTANEOUS TRANSMITTING AND REFLECTING SURFACES (STARS)

The conventional reflecting/transmissive RIS exhibit intrinsic constraints, as they are capable of solely reflecting/transmitting wireless signals and necessitate the co-location of the transmitter and receiver in the case reflective RIS, thereby leading to the adoption of a half-space SRE [52], [53] [54]. Nevertheless, the adaptability and effectiveness of an RIS are significantly limited in situations where users are positioned on both ends. To overcome this constraint, STARS is proposed, as outlined in the research of [30] and [55]. Implementing the communication protocol for STARS necessitates the consideration of various factors, such as energy, mode, and time. STARS may not be the most cost-effective way to get full 360° wireless coverage because of its sophisticated hardware design and somewhat archaic appearance [56].

C. APPLICATIONS OF RIS

Applications of RIS in Wireless Communication:

1) **Wireless Communication Enhancement:** RIS optimizes wireless communication by strategically reflecting signals, improving signal strength, and extending coverage. It is particularly valuable in indoor environments, enhancing connectivity in homes, offices, and public spaces [21].
2) **5G and Beyond:** RIS technology is integrated into 5G networks, enhancing signal propagation, reducing interference, and increasing data rates. This is vital for achieving the full potential of 5G and future wireless standards [33], [57]
3) **Millimeter-Wave (mmWave) and THz Communication:** In mmWave and THz communication, RIS can overcome signal propagation challenges in urban areas by redirecting signals and improving connectivity in dense environments [36].
4) **Beyond-Line-of-Sight (BLOS) Communication:** RIS enables BLOS communication, ensuring signals reach their destinations even when obstructed. This is crucial in military communications and disaster response scenarios.
5) **Satellite Communication:** RIS enhances satellite communication by improving signal reception and transmission, making satellite-based services more efficient and reliable.
6) **IoT:** RIS optimizes communication in IoT networks, facilitating efficient data exchange among a multitude of devices. This supports the growth of smart cities and industrial IoT applications [58].
7) **Rural Connectivity:** RIS provides cost-effective solutions to extend wireless connectivity in remote and underserved areas, bridging the digital divide and bringing internet access to previously unconnected regions.
8) **Indoor Positioning and Navigation:** RIS improves indoor positioning systems by enhancing signal accuracy and reliability. This is valuable for indoor navigation in shopping malls, airports, and industrial facilities [58].
9) **Energy-Efficient Networks:** RIS contributes to the energy efficiency of wireless networks by optimizing signal paths and reducing the power consumption of active network elements.
10) **Security and Surveillance:** RIS enhances wireless communication in security and surveillance systems, improving real-time video streaming and data transmission in airport security and border monitoring applications [59].
11) **Vehicular Communication:** In connected vehicles and autonomous driving, RIS enhances vehicular communication by optimizing signal quality and reducing latency, ensuring safer and more efficient transportation [60].
12) **VLC:** RIS enhances VLC systems by optimizing the distribution of visible light signals for applications in smart buildings, retail, hospitality, and underwater communication [61].

13) **Aviation and Transportation:** RIS technology is applied in aviation for in-flight communication and entertainment and in transportation hubs to provide seamless connectivity to travelers [60].

III. THz COMMUNICATION FUNDAMENTALS

THz communication operates within the THz frequency spectrum, offering exceptional capabilities such as ultra-high data rates and suitability for short-range transmissions. This section covers the key elements of THz communication, including its frequency range, propagation behavior, antenna design requirements, and its immense potential for data transmission [35], [36].

Beyond its theoretical foundations, THz communication holds significant promise in practical applications across various fields. The following section explores these applications in detail, highlighting its use in wireless communications, short-range indoor connectivity, medical imaging, security, surveillance, and scientific research [36]. In each of these areas, THz waves are applied to overcome specific technical challenges and harness emerging opportunities. Despite its potential, THz communication also presents unique challenges stemming from its place within the electromagnetic spectrum. These challenges include signal attenuation due to atmospheric absorption and the complexity involved in designing highly specialized THz antennas. Additionally, issues related to security, privacy, and the evolving regulatory landscape further complicate its implementation [36].

A. THz PROS AND CONS

THz communication, operating within the 0.1 THz to 10 THz frequency range, represents an emerging technology poised to revolutionize wireless communication and sensing [5]. By utilizing electromagnetic waves at frequencies beyond those of conventional microwaves and radio waves, THz communication offers a unique combination of opportunities and challenges across various applications. On the advantageous side, THz communication boasts exceptional data throughput capabilities, potentially reaching Tbps transmission rates. The THz spectrum provides an abundance of spectral resources, enabling simultaneous multi-stream data transmission and alleviating network congestion. Furthermore, THz waves exhibit sub-millimeter wavelengths, allowing for highly focused, directional communication beams that enhance security and minimize interference. Additionally, the ability of THz waves to penetrate certain materials makes them invaluable for non-invasive imaging in medical diagnostics and security screening. Moreover, operating in the relatively unexplored frequency band reduces electromagnetic interference, enhancing signal quality.

However, THz communication presents several challenges. For instance, THz waves have a limited propagation range as they are prone to absorption by atmospheric gases, particularly water vapor, which restricts their use to short-distance applications [7]. Additionally, THz signals can be absorbed by various materials such as water and certain plastics, impeding signal penetration. The short wavelengths of THz waves necessitate intricate and expensive antenna designs for communication systems. Furthermore, concerns about security and privacy arise due to the ability of THz waves to penetrate materials, prompting worries about unauthorized surveillance or data interception. Moreover, the lack of standardized protocols and equipment in THz communication poses challenges for interoperability and widespread adoption in commercial applications. Overcoming these challenges will be pivotal in realizing the full potential of THz technology in wireless communication and sensing applications [35], [62], [63]. Based on different THz characteristics pros and cons are given in Table 2

B. THz APPLICATIONS

THz wireless communication operates within the THz frequency range, spanning approximately 0.1 THz to 10 THz, situated between the microwave and infrared bands of the electromagnetic spectrum. This technology is characterized by its potential for extremely high data transmission rates and suitability for short-range, high-speed communications. We provide a detailed exploration of both current and emerging applications of THz wireless communication, as shown in Fig. 4.

1) **Ultra-High-Speed Data Transfer:** At the forefront of THz communication applications is its remarkable potential to redefine data transfer speeds. With the capacity to attain data rates approaching Tbps levels, THz communication is poised to revolutionize the way we exchange large datasets, multimedia files, and engage in data-intensive computational tasks [64]. This capability is of paramount significance in fields ranging from scientific research to cloud computing.
2) **6G Wireless Networks:** THz communication is slated to play a central role in the realization of 6G wireless networks, which represent the next evolutionary step in wireless technology [65]. The promise of ultra-high data rates and minimal latency positions THz as the backbone of future wireless systems, enabling augmented reality, virtual reality, and massive-scale IoT connectivity.
3) **Short-Range Indoor Communication:** THz waves exhibit limited propagation range due to their susceptibility to absorption by atmospheric gases and water vapor [66]. Paradoxically, this limitation becomes an asset in short-range indoor communication scenarios. Within smart homes, offices, and industrial settings, THz communication can supply high-speed connectivity for devices within close proximity, underpinning the IoT and enabling efficient data exchange.
4) **Wireless Virtual Reality (VR) and Augmented Reality (AR):** The realm of immersive experiences, encompassing wireless VR and AR applications, stands to benefit immensely from THz communication [67].

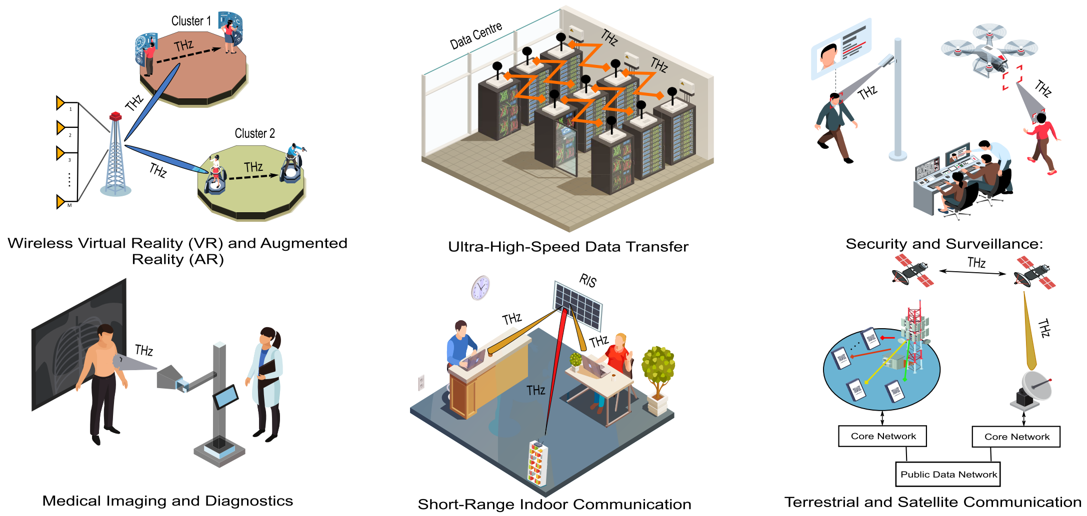


FIGURE 4. Emerging applications of THz technology in wireless communication and beyond.

TABLE 2. THz communication characteristics, Pros, and Cons.

Characteristic	Pros	Cons
Wide Bandwidth	Ultra-fast data transfer rates	Limited range due to atmospheric absorption and signal attenuation
High Frequency	Supports dense data transmission	Susceptible to obstacles and buildings that block THz waves
Short Wavelength	Compact device designs	Requires precise alignment and line-of-sight communication
Low Interference	Utilizes less congested frequency spectrum	Limited availability of THz devices and infrastructure
Unexplored Spectrum	Potential for new applications and innovations	Limited standardization and commercialization
Enhanced Security	Difficult to intercept THz signals	Challenges in implementing secure encryption methods
Non-Ionizing Radiation	Generally safe for human exposure	Long-term health effects not extensively studied
Sensing and Imaging	Non-destructive testing and imaging	Limited depth penetration for imaging applications
Terrestrial and Space Applications	High-bandwidth and low-latency communication	Limited availability of space-based THz communication infrastructure
Wireless VR	Extremely high data rates and capacity	Technical challenges in THz device development and signal propagation
Future Wireless Networks	Potential for transformative wireless communication	Technical Challenges in THz device development and signal propagation

Its ultra-high data rates and minimal latency support real-time streaming of high-resolution VR content and interactive AR applications, ushering in a new era of immersive digital experiences.

5) **Security and Surveillance:** THz communication has the potential to elevate security and surveillance systems to new heights. Airports and critical infrastructure facilities can deploy THz-based scanners for enhanced detection of concealed weapons, dangerous substances, or illicit objects carried by individuals [68]. In addition, perimeter security can benefit from the ability of THz waves to penetrate clothing, providing a comprehensive security solution.
6) **Environmental Sensing:** Environmental monitoring and sensing can leverage THz communication's capacity to detect and analyze gases in the atmosphere [69]. Applications include real-time pollution monitoring, atmospheric research, and environmental protection efforts.
7) **Terrestrial and Satellite Communication:** THz communication holds potential for integration into terrestrial and satellite-based communication systems [70]. Particularly in remote and underserved regions, THz communication can deliver high-speed, low-latency connectivity, bridging digital divides and enabling global connectivity.

C. COMPARISON OF THz AND mmWave BANDS

The THz band offers significant advantages over existing wireless technologies, particularly mmWave, due to its potential for ultra-high data rates over short distances. However, both THz and mmWave face similar challenges, such as path loss, molecular absorption, and atmospheric attenuation, though THz has unique strengths that make it a promising candidate for future high-speed communication systems.

MmWave frequencies (30-300 GHz) are susceptible to significant attenuation, especially from oxygen absorption. Some frequencies, like 35 GHz, 94 GHz, 140 GHz, and 220 GHz, experience lower attenuation and can support longer-range communication [71]. Conversely, bands such as 60 GHz and 180 GHz face higher attenuation (up to 15 dB/km) and poor diffraction when obstructed. Although both mmWave and THz communications suffer from path loss and atmospheric conditions, the use of highly directional antennas helps mitigate these effects. mmWave antenna technology is more advanced, allowing for better beamforming and signal tracking, while THz antennas are still in earlier stages of development [72], [73].

The most significant difference between the two technologies lies in their bandwidth capabilities. mmWave offers up to 10 GHz of bandwidth, which limits its ability to support ultra-high data rates [9], [71], [74], [75]. In contrast, THz bands provide broader transmission windows, allowing for data rates in the Tbps range. To achieve high throughput, such as 100 Gbps, THz requires advanced transmission schemes with high spectral efficiency (14 bits/s/Hz) [76], [77], [78]. While mmWave is already deployed in WLAN and cellular networks, THz is better suited for scenarios requiring extremely high data rates and low latency, particularly in fixed infrastructure settings. However, THz technology still requires advancements in power generation and receiver sensitivity before it can be widely adopted.

THz also offers better security compared to mmWave due to its highly directional beams, which make eavesdropping more difficult. Unauthorized users would need to align precisely with the narrow beam to intercept data, reducing the risk of interference [9], [72], [73]. Although mmWave remains more practical for broader coverage and mobile applications, such as cellular and backhaul communications, THz excels in high-data-rate, low-latency use cases. Nonetheless, mmWave benefits from well-established channel models and more developed infrastructure, while THz technology is still evolving, particularly in terms of device readiness and real-world performance measurements [9]. While mmWave is currently more mature and widely deployed, particularly for large-scale, mobile communications, THz holds greater potential for applications requiring ultra-high-speed data transmission and low latency. As the technology matures, THz is likely to play an increasingly important role in future wireless communication systems.

D. THz CHANNEL MODEL

The THz frequency range, particularly between 100 and 300 GHz, presents significant opportunities for 6G systems due to its large available bandwidth, enabling ultra-high data rates. However, the unique propagation characteristics at these frequencies introduce specific challenges that require specialized channel models, especially in indoor environments [79]. This subsection provides an overview of the key aspects of the THz channel model.

1) FREE-SPACE PATH LOSS (FSPL)

FSPL is a critical factor in THz communications, where higher frequencies result in greater attenuation. The path loss in LOS scenarios, typical in indoor environments [79], is often modeled using the close-in reference distance model:

$$PL(fc, d)[\text{dB}] = FSPL(fc, 1\,\text{m}) + 10n\log_{10}\left(\frac{d}{1\,\text{m}}\right) + X_\sigma$$

In this model:

- fc represents the carrier frequency in GHz,
- d is the distance between transmitter and receiver in meters,
- n is the path loss exponent, and
- X_σ accounts for shadow fading, which follows a log-normal distribution.

The free-space path loss for a reference distance of 1 meter is given by:

$$FSPL(fc, 1\,\text{m}) = 20\log_{10}\left(\frac{4\pi fc}{c}\right)$$

As frequency increases, path loss becomes more severe due to shorter wavelengths, with additional attenuation from atmospheric absorption, particularly from water vapor.

2) SHADOW FADING

Shadow fading in THz communications is caused by obstacles in the environment blocking the direct line of sight [79], [80]. Due to the shorter wavelengths of THz waves, diffraction around obstacles is limited. As a result, shadow fading effects are less pronounced compared to lower frequencies. The standard deviation of shadow fading, represented by X_σ, is typically smaller in THz channels, leading to a reduced shadow fading margin.

3) DELAY SPREAD

Delay spread is a key parameter that describes the dispersion of signal arrival times due to multiple propagation paths [79], [80]. In THz systems, delay spreads are generally shorter than in lower-frequency systems because longer paths are attenuated more heavily. For example, at 140 GHz, the delay spread in LOS scenarios is typically around 3.16 ns. This reduction in delay spread improves temporal resolution, making it easier to resolve individual multipath components and enabling higher data rates.

4) ANGULAR SPREAD

Angular spread refers to the variation in signal arrival and departure angles at the transmitter and receiver [79], [80]. Due to the high directivity of THz signals, the angular spread is smaller compared to lower-frequency systems. This narrower angular spread facilitates more efficient beamforming and focused signal transmission, which is essential for overcoming the high path loss in THz communication.

Measurements at frequencies like 140 GHz show reduced angular spread, which enhances beamforming performance but can slightly reduce spatial diversity [81].

5) RICIAN K-FACTOR

The Rician K-factor measures the ratio of the power in the direct LOS path to the power in scattered or reflected non-line-of-sight (NLOS) paths [79], [80]. In THz communications, the K-factor is typically higher than in lower-frequency systems, indicating a stronger LOS component. For example, at 140 GHz, the K-factor is around 12.67 dB, much higher than the 7 dB observed at sub-100 GHz frequencies. This highlights the reliance on LOS propagation in THz communication, where scattered paths contribute less to the overall signal strength [81].

6) LINK BUDGET ANALYSIS

Link budget analysis is essential for predicting the performance of THz communication systems in terms of capacity, coverage, and antenna configuration [79], [80]. High path loss at THz frequencies necessitates the use of beamforming and large antenna arrays to maintain adequate signal-to-noise ratio (SNR) over short distances. In typical indoor environments, a system operating at 140 GHz with a 2.16 GHz bandwidth can achieve data rates between 10 and 100 Gbps, depending on the number of antenna elements used [81]. Optimizing the balance between antenna size, transmit power, and bandwidth is critical for maximizing system performance in 6G THz networks.

IV. EXPLORING THE ADVANCEMENTS IN USE CASES FOR RIS-BASED THz COMMUNICATION

This section provides an in-depth exploration of RIS-based THz communication use cases. The literature is categorized according to various use cases, addressing the critical factors influencing communication in the THz frequency range. This section delves into the enhancements that RIS technology brings to THz communication systems, segmented into five detailed subsections. Subsection IV-A examines how RIS improves CE and beam-splitting, enhancing accuracy and efficiency in data transmission. Subsection IV-B discusses the expansion of THz communication coverage through RIS, which facilitates broader and more dependable networks. Subsection IV-C highlights the role of RIS in bolstering security within THz systems, providing enhanced safeguards against disruptions. Subsection IV-D analyzes how RIS optimizes the sum rate, boosting overall system throughput. Finally, Subsection IV-E focuses on the increased energy efficiency achievable with RIS, contributing to more sustainable communication operations. These subsections collectively underscore the pivotal enhancements RIS introduces to the performance and reliability of THz communications.

A. ENHANCING THz CHANNEL ESTIMATION AND BEAM-SPLITTING WITH RIS

This subsection examines CE in THz communication systems employing RIS. The research articles explore various approaches and strategies for precise channel estimates in diverse THz communication contexts. These papers encompass indoor THz communication, THz MIMO systems utilizing lens antenna arrays, and THz communication systems incorporating RIS to improve signal coverage and transmission. The following papers offer significant contributions to the field of THz communication systems by presenting CE techniques customized to specific scenarios. These insights are valuable in enhancing the reliability and effectiveness of THz communication systems. Additionally, a summary Table 3 is provided to compare different schemes and offer deeper insights into their applications and performance.

The authors in this work [82] examine the issue of CE in a multiple-input single-output (MISO) system operating in the THz frequency range, assisted by an RIS, and employing a lens antenna array. The aim is to calculate the values of numerous consecutive channels. A proposed solution to tackle this issue involves the implementation of a two-stage CE scheme. During the initial phase, the communication pathway linking the BS and the user is evaluated without RIS involvement by implementing an absorbing mode. During the second phase, the estimation of the channel involving the RIS is conducted by configuring it to operate in a state of perfect reflection. According to the research findings, the channel utilized by the RIS is cascaded, and the overall issue of CE is divided into separate and independent problems. The least squares method is utilized to estimate each channel component.

Unlike the THz MISO ssytem [82], the authors of this study [83] have tackled the difficulties associated with channel acquisition in THz MIMO systems that are enabled with RIS. The proposal suggests employing an RIS to establish a manageable propagation environment to address coverage constraints. The absence of signal processing capability within the RIS impedes channel acquisition. The research endeavors to address the issue by formulating the CE problem as a sparse recovery problem, utilizing the sparsity characteristics of the THz channel. The present study proposes a novel approach, namely the deep learning-based channel estimation (DL-CE), which aims to address the issue of sparse recovery. This is achieved by establishing a correlation between the received signals and the path gains. The simulation findings indicate that the DL-CE technique exhibits superior recovery performance compared to traditional compressed sensing-based methods while simultaneously reducing computational complexity.

Recently, in [84], the authors introduce a new CE approach called regularized sensing beam-split based orthogonal matching pursuit (RSBS-OMP) specifically for RIS THz systems to tackle the beam split effect. This technique reformulates the CE challenge into a sparse recovery issue, utilizing the RSBS-OMP algorithm to precisely estimate the cascaded channel. The results reveal that the RSBS-OMP approach surpasses current algorithms in reducing normalized mean-square-error, providing a substantial performance improvement, particularly under conditions of high SNR. Similarly in study [85], a novel approach using a nested tensor algorithm is introduced for simultaneous sensing and communication in THz MIMO systems enhanced by RIS. This method leverages a KRST coding mechanism at the transmitter and RIS phase alterations to represent the received signal as a nested tensor, incorporating both outer PARAFAC and inner PARATUCK tensors. A specialized LS-KRF algorithm is utilized for simultaneous CE and symbol detection, while an OF-ALS algorithm estimates sensing details like AoDs, AoAs, and delay times. This technique shows enhanced performance over current methods, adaptable to scenarios with unknown path numbers.

The authors of the paper [86] investigate the potential use of RIS in THz communication for indoor settings. The study addresses the difficulties of significant path attenuation and susceptibility to blockage. The research presents a novel architecture for an RIS utilizing graphene-based tunable elements. Additionally, a model for the THz MIMO system, assisted by the RIS, is being developed. The authors proposed an iterative atom pruning-based subspace pursuit (IAP-SP) scheme to obtain CSI. The study presents an approach to maximizing the communication rate, framed as a phase shift search problem. The research explores three techniques to address this problem: exhaustive search, local search, and a deep neural network- based approach. The research endeavors encompassed examining the characteristics of graphene, the proposition of a hardware structure, the implementation of the IAP-SP approach, and the investigation of phase shift search techniques.

Different from the studies MISO and MIMO-based systems in [82], [83], [84], [85], and [86], respectively, this study [87], examines the integration of ultra-massive multiple-input multiple-output (umMIMO) and RIS for THz communications in 6G networks. It addresses coverage and line-of-sight issues by introducing a hybrid spherical-and-planar-wave channel model (HSPM) and employs a compressive-sensing framework with separate-side estimation (SSE) and dictionary-shrinkage estimation (DSE) to enhance CE accuracy in noisy environments. The results show the accuracy of the HSPM and the enhanced precision of SSE and DSE in CE, particularly in noisy environments. These findings advance THz communication technologies for upcoming generations. In another study [88], the authors introduce a novel CE approach called polar-domain frequency-dependent RIS-assisted channel estimation (PF-RCE), which addresses the shortcomings of conventional methods that rely on planar wavefront assumptions. By harnessing the sparsity and common support features of the polar domain, PF-RCE efficiently estimates near-field THz channels characterized by spherical wavefronts. Numerical results demonstrate that this method significantly improves CE accuracy, markedly reducing the normalized mean square error compared to traditional techniques.

In [89], the research examines the use of RIS in THz communications to address blocked LoS propagation. As the size of both the BS antenna array and the RIS panel increase, the THz channel transitions from a far-field to a near-field model, challenging traditional channel training methods and affecting performance. The study focuses on near-field channel training in a THz communication system with close proximity between the THz BS, RIS, and UE in an indoor environment. A unified near-field channel model and a particle swarm optimization (PSO)-based channel training method are proposed. The effectiveness of this approach is confirmed by simulations, which also show that RIS illumination can significantly enhance the UE-received SNR, even in imperfect channel conditions and localization. In another paper [90], the authors investigated the implications of ultra-large RIS in localization and communication systems, underscoring their affordability and difficulties. The introduction of near-field propagation channels by ultra-large RIS, particularly in THz communication systems, dramatically increases the difficulty of localization and channel estimate. This paper emphasizes near-field propagation in THz systems aided by RIS, precisely spherical wavefront propagation. The algorithm uses a second-order Fresnel approximation of the near-field channel model and meticulously designs a downsampled Toeplitz covariance matrix to facilitate separate estimation of UE distances and angles of arrival (AoAs). The algorithm estimates the AoAs and UE distances using sub-space-based methods and a one-dimensional search, whereas the channel attenuation coefficients are obtained using least squares. Through simulations, the superiority of the NF-JCEL algorithm over conventional far-field algorithms is demonstrated, demonstrating its ability to accomplish a higher level of localization resolution accuracy.

RIS provides significant performance improvements for THz MIMO-OFDM systems, but CE in high-dimensional RIS channels remains challenging. This paper [91] introduces a compressed sensing (CS)-based CE method that separates angle and gain estimation, reducing both pilot overhead and computational complexity. By leveraging spatial path selection through tailored beam and reflection patterns, the dimensionality is reduced. The proposed method achieves over a 35% reduction in pilot overhead and significantly enhances computational efficiency, while maintaining accuracy comparable to existing approaches.

RIS passivity makes CE challenging, as channels can only be measured at the transceiver, not the RIS. This paper [92] introduces a novel two-stage CE method for RIS-enabled mmWave/THz systems, leveraging cascaded sparsity in the angular domain. The cascaded channel is separated into BS-RIS and RIS-UE components, exploiting sparsity in hybrid angular domains for multi-user systems. The CE problem is formulated using atomic norm minimization (ANM) to strengthen the sparsity structure, and a

TABLE 3. Summary of CE and beam splitting schemes for RIS-Based THz communication in different scenarios.

Ref	Year	System Setup	Direct Link	CSI	Solving Techniques	Proposed Solution
[83]	2020	UL MISO, BS (MA), RIS, UEs (SA)	Severe propagation loss	To be estimated	Two-Stage CE	With the help of lens antenna array, channel were estimated for RIS-THz multi-user MISO.
[84]	2020	DL MIMO, BS (MA), RIS-THz, Mobile BS (MA).	Blocked	To be estimated	DL-CE.	The DL-CE system was developed to solve the CE problem.
[85]	2020	DL THz MIMO, BS (MA), RIS, mobile UEs (MA)	Blocked	To be estimated	IAP-SP	For CE an IAP-SP design was developed which decreases the computational complexity while maintaining accurate channel recovery and also data rate was maximized by these estimated channels.
[86]	2024	DL THz MIMO, BS (ULA), RIS, UEs (SA)	Blocked	To be estimated	RSBS-OMP	RSBS-OMP novel scheme is proposed to mitigate the beam split effect and enhance CE accuracy.
[87]	2024	THz MIMO, BS (UPA), RIS, Vehicle Terminal (UPA)	Blocked	To be estimated	LS-KRF, OF-ALS	LS-KRF, OF-ALS algorithm is proposed for precise CE and sensing parameter estimation.
[88]	2023	THz umMIMO, BS (MA), RIS, UE (MA)	Blocked	To be estimated	SSE & DSE	HSPM was presented as an actual representation of the cascaded channel in a THz integrated system consisting of umMIMO and RIS.
[89]	2023	Wideband THz, BS (MA), RIS, UE (SA)	Blocked	To be estimated	PF-RCE	Proposed PF-RCE technique that efficiently estimates sparse multipath components (angles, distances, and path gains) in near-field THz systems by leveraging polar-domain sparsity and common support properties.
[90]	2023	Indoor DL THz, BS (MA), RIS, UE (SA)	Blockage	To be estimated	PSO	For indoor THz channel a PSO-aimed channel training method is proposed to reduce the CE complexity.
[91]	2023	UL THz scenario, AP (ULA), RIS, UEs (SA)	Blocked	To be estimated	NF-JCEL	Introduced a novel NF-JCEL algorithm that combines spherical wavefront propagation modeling with advanced signal processing techniques to improve accuracy and decrease complexity.
[92]	2024	MIMO, BS (ULA), RIS, UE (ULA)	Blocked	To be estimated	Compressed Sensing	Proposed a compressed sensing-based CE method that separates angle and gain estimation, reducing pilot overhead by over 35%.
[93]	2024	BS (MA), MU, RIS, UEs (SA)	Blocked	To be estimated	ADMM, Atomic Norm Minimization (ANM)	Proposed a two-stage CE method leveraging RIS to enhance CE accuracy in multi-user mmWave/THz systems.
[94]	2023	Wideband THz, BS (MA), RISs, UEs (SA)	Blocked	known	Iterative algorithm	A wideband THz RIS communication system was examined to explore the normalized array gain so as the beam split effect considering different RIS sizes, shapes and deployments.
[95]	2023	DL THz, BS (MA), RIS, UE (SA)	Blockages	Perfect	Joint Wideband Precoding	A study on the joint optimization of phase and delay in wideband precoding was conducted by specifically focusing on the investigation of the beam split effect and the subsequent array gain loss at the RIS.
[96]	2024	mMIMO, APs (ULA), RISs, UE (SA)	Blockages	Perfect	Joint precoding optimization	Proposed a joint precoding framework with time delay (TD) layers at both APs and RISs to mitigate beam split effect and enhance system capacity in THz mMIMO.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex, UPA-Uniform planar arrays, ULA-Uniform linear array

low-complexity estimator based on the Alternating Direction Method of Multipliers (ADMM) is developed. Simulation results demonstrate that the proposed estimator surpasses existing methods in performance.

The authors in [93] develop an extensive wideband THz RIS channel model, enabling detailed analysis of the impacts of array gain loss and variations in RIS sizes, configurations, and placements. A key contribution of the work is the introduction of a fully connected time delay phase shifter hybrid beamforming (FC-TD-PS-HB) architecture designed to mitigate the effects of beam splitting associated with the BS and distributed RISs. It achieves this through a sum rate maximization strategy that integrates the optimization of analog/digital beamforming, BS time delays, and RIS reflection coefficients. To tackle the non-convexity of this problem, an iterative algorithm based on minimum mean square error is employed, refined further with Lagrangian dual reformulation and a complex quadratic transform. This transforms the challenge into a quadratically constrained program, effectively addressed using the alternating direction multiplier method. Simulation results confirm that this approach significantly reduces beam splitting effects and enhances the communication capacity of THz RIS networks.

The authors in [94] examine the beam split effect in RIS-assisted THz communication systems. To counter this effect, they introduce a sub-connected RIS architecture equipped with time-delay modules and phase shifters. The authors develop a wideband precoding strategy designed to offset the array gain loss caused by the beam split effect. Moreover, they further explore scenarios involving large antenna arrays at the BS and the double-beam split effect's challenges. Simulation results demonstrate that the proposed sub-connected RIS architecture effectively mitigates the beam split effect and achieves near-optimal rates, while maintaining reasonable hardware costs and power consumption.

THz cell-free mMIMO networks are a promising technology for boosting system capacity, performance, and reliability in 6G networks. However, challenges such as signal attenuation, limited scattering, and high power consumption due to multiple APs hinder further improvements. RIS offer a low-cost solution to reduce AP deployment and enhance data transmission, but the beam split effect caused by ultra-wide bandwidth remains a major issue. To address this, the authors [95] introduce additional time delay (TD) layers at APs and RIS to mitigate performance degradation. A joint precoding framework is proposed to optimize beam alignment. The non-convex optimization problem is decoupled into three subproblems: baseband beamforming, RIS optimization, and RIS TD adjustment. Using a multidimensional quadratic transformation and alternating optimization, the method effectively mitigates beam split and significantly improves the achievable rate over conventional mMIMO networks.

Discussion: This subsection reviews key CE and beam-splitting techniques for RIS-assisted THz systems, summarized in Table 3. The two-stage CE for MISO systems [82] and deep learning-based CE for MIMO [83] show potential but lack real-world validation. The IAP-SP algorithm [86] reduces computational complexity, though scalability remains a challenge. Beam-splitting mitigation techniques like RSBS-OMP [84] and tensor-based methods [85] offer high accuracy but struggle with computational demands in dynamic scenarios like UAV-based systems. The HSPM model [87] improves accuracy in umMIMO systems, though it needs further testing in complex environments. Parametric CE approaches like PF-RCE [88] enhance near-field estimation but require scaling for practical use. PSO-based training [89] and NF-JCEL [90] boost performance in near-field and localization but need further investigation into hardware resilience. Reference [91] proposes innovative solutions for RIS-enabled THz and mmWave systems and introduces a compressed sensing-based method to reduce pilot overhead and computational complexity while maintaining accuracy, but lacks discussion on real-world deployment in dynamic environments. Another paper [92] presents a two-stage CE method for multi-user systems, yet falls short in addressing scalability in dense networks and real-time processing. Wideband THz RIS systems [93] and joint wideband precoding [94] address beam-splitting but face challenges with energy efficiency and cost-effective implementation. Reference [95] tackles the beam split issue in THz cell-free mMIMO networks with time delay layers and joint precoding, though it does not sufficiently address the high complexity of joint optimization or the EE needed for power-intensive THz systems. Addressing these gaps in scalability, computational efficiency, and hardware resilience is essential for advancing RIS-assisted THz communication systems in real-world applications.

B. LEVERAGING RIS TO EXPAND THz COMMUNICATION COVERAGE

This particular subsection is centered on augmenting the coverage of THz communication through the utilization of the RIS. The research articles in this specific subsection focus on the challenge of extending coverage in communication systems operating in the THz frequency range, as shown in Fig. 5. The researchers investigate diverse methodologies and approaches to enhance the scope of cellular network coverage and optimize users' efficiency within and beyond the cell coverage area, as shown in summary Table 4.

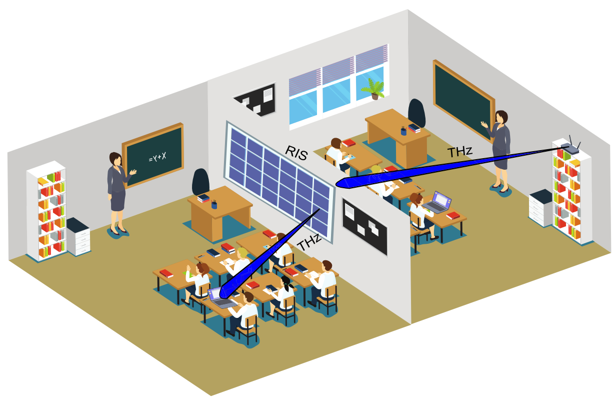


FIGURE 5. RIS THz coverage extension.

The research articles explore various scenarios on indoor THz communication and suggest possible solutions, such as implementing RIS and optimizing resource allocation. These studies utilize RIS technology to gain insights into efficacious techniques for expanding THz communication coverage and enhancing capacity, thereby contributing to the progression of THz wireless networks. The authors in [96] conducted a study aimed at enhancing the coverage performance of indoor THz communication systems by leveraging RIS. The study's contributions encompass examining graphene properties, comprehensive modeling of the THz communication system utilizing RIS, and creating a suboptimal search scheme with low complexity. This research examines the electrical characteristics of graphene and proposes a hardware configuration for an infrared sensor utilizing graphene technology that

TABLE 4. Summary of communication coverage schemes for RIS-Based THz communication in different scenarios.

Ref	Year	System Setup	Direct Link	CSI	Solving Techniques	Proposed Solution
[97]	2020	DL MISO, BS (MA), RIS, Users (SA)	LoS	Known	Exhaustive Search & Suboptimal Search Algorithm	The coverage problem is analyzed for RIS-THz communication, i.e. phase response and demonstrated that graphene-assisted RIS is good for the indoor THz scenarios
[98]	2021	DL scenario, AP (MA), RIS-THz, UEs (MA)	Blockage	Known	End-to-end (e2e) channel attenuation formula	A novel e2e channel attenuation formula was applied that returns the optimal phase shifting of each reflection unit (RU) of the RIS and analyzed the RIS-THz wireless scenario performance.
[99]	2021	Multihop THz, BS (MA), RISs, Users (SA)	Weak	Perfect	DDPG & DRL based HB.	To mitigate propagation loss, the joint design of digital beamforming at the BS and analog beamforming at the RISs incorporates DRL technique.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex

can effectively operate within the THz frequency range. A model of the THz communication system incorporating an RIS has been developed. The optimization problem has been reformulated as a discrete phase shift search problem. The suboptimal search strategy under consideration involves the selection of phase shift combinations that are partially superior to attain nearly optimal performance. This approach results in a reduction in computational complexity when compared to the exhaustive search method.

The authors in [97] have endeavored to bridge the knowledge gap surrounding the utilization of RIS in THz wireless systems. They have accomplished this by developing a channel model that is both low in complexity and accounts for the distinctive features of the THz band and RIS. The research paper introduces a theoretical framework for RIS technology to enhance THz wireless communication. The article also formulates a general formula for the overall channel attenuation, which considers various parameters such as the distance between devices, the dimensions of the RIS, the radiation patterns, and the surrounding environmental conditions. An analytical expression is formulated to calculate the optimal phase shift for individual elements of an RIS. The paper presents a feasible approximation of the channel coefficient to analyze the system's performance. The authors establish a theoretical framework to quantify the coverage probability of RIS-assisted THz wireless systems. The framework incorporates the random positions of user equipment within a circular cluster. This study addresses a significant research gap by offering valuable insights into channel modeling and coverage analysis, considering the unique propagation characteristics of THz waves and the properties of RIS.

Unlike the single-hop works in [96] and [97], the authors in [98] leverage multi-hop communication networks and present a novel approach to HB that utilize RIS in the THz frequency band. The objective is to address the constraints posed by high propagation attenuations and molecular absorptions in the THz frequency band, which impede signal transmission distance and coverage area. To enhance coverage, the suggested approach implements numerous passive and controllable RISs between the BS and individual users with single antennas. This study explores the application of deep reinforcement learning (DRL) to optimize the joint design of digital beamforming at the BS and analog beamforming at the RISs for mitigating propagation loss. This paper presents a pair of algorithms designed to facilitate the initialization of beamforming matrices and improve their convergence. The simulation findings indicate that the suggested approach enhances the coverage range by 50 percent compared to the established standards.

Discussion: This subsection explores RIS-based solutions to extend THz communication coverage, with a summary in Table 4. In [96], graphene-based RIS enhances indoor coverage using a low-complexity phase shift search, reducing computational demands. The study in [97] introduces a low-complexity channel model considering RIS size, distance, and environment, providing a theoretical framework for optimal phase shifts and coverage probability. Moving beyond single-hop designs, [98] uses multi-hop RIS networks with DRL to optimize beamforming, extending coverage by 50%. Similarly, [99] proposes a hybrid 3D beamforming scheme for multi-user mMIMO, improving beamforming accuracy and spectral efficiency through RIS and ultra-wideband sensors. These studies show how RIS effectively enhances THz coverage by optimizing beamforming, reducing path loss, and improving resource use in various scenarios.

C. STRENGTHENING THz COMMUNICATION SECURITY VIA RIS

The secure and covert communication in THz systems employing RIS is covered in this subsection. The research articles under discussion look into several ways to improve security and privacy in THz networks. They offer creative solutions that use RIS technology to increase the secrecy rate (SR) and prevent eavesdropping, as shown in

Fig. 6. The experiments encompass a variety of scenarios, such as multi-UAV covert communication, downlink THz communication with wiretap channels, secure transmission in RIS-assisted mmWave and THz systems, and secure communication in the THz frequency band. These papers present essential insights and techniques for accomplishing secure and covert communication in THz networks, paving the way for advanced applications in the IoT, wireless networks, and beyond, as summarized in Table 5.

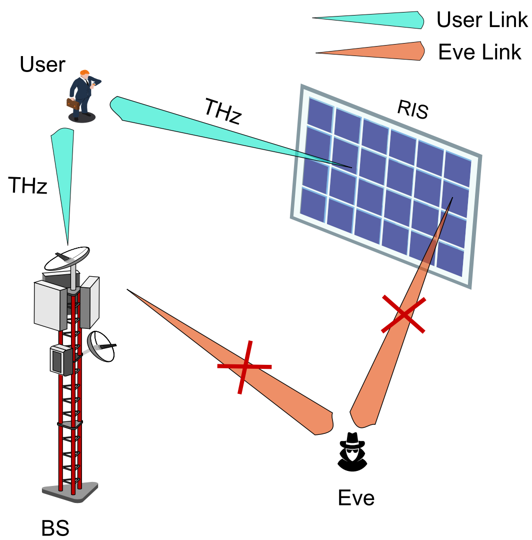


FIGURE 6. THz RIS security.

In [100], the study addresses enhancing security in downlink THz communications within a MISO wiretap channel by designing beamforming and RIS systems. The problem is framed as a mixed integer nonconvex optimization issue and introduce a low-complexity successive and a high-security-performance joint design, both delivering suboptimal but improved secrecy performance. Initially, the successive design derives a closed-form solution for the beamformer by optimizing RIS phase shifters (PSs) based on the LoS matching principle. The joint design then iteratively optimizes the PSs and beamformer using an alternating optimization approach. Numerical results demonstrate that these methods notably surpass existing secure communication strategies, both RIS-assisted and non-RIS-assisted in terms of secrecy rate.

This research in [101] focuses on a THz-communication system using an RIS to enhance security. It involves transmitting secure signals from a BS to a user, with an eavesdropper present, aiming to boost the SR by optimizing the RIS's discrete phase shifts and the BS's precoder. This involves solving a complex nonconvex optimization problem. The authors employ an iterative method that uses the Rayleigh-Ritz theorem to optimize the precoder, followed by a cross-entropy-based approach to refine the phase-shift matrix. Numerical results show that this method significantly improves the SR over systems without an RIS.

In [102], the authors investigate secure transmission in an RIS-assisted mmWave and THz system, aiming to optimize the SR. They jointly optimize transmit beamforming at the BS and the reflecting matrix at the RIS under power and phase-shift constraints. The study addresses the rank-one channel assumption, showing that beamforming decisions are independent of phase shift designs. They propose techniques such as closed-form beamforming, semidefinite programming (SDP), and element-wise block coordinate descent (BCD) to solve the non-convex problem. Simulation results demonstrate significant SR improvements irrespective of Eve's location.

This paper [103] put forward a multi-RIS-assisted secure transmission strategy in THz systems, considering the blockage-prone nature of THz waves and the presence of potential Eves. A joint optimization problem for HB and reflecting phase shifts is described, and the worst-case SR is obtained. The research describes an iterative technique for RIS-user link eavesdropping and suggests methods for BS-RIS link eavesdropping, such as ZF-based HB and closed-form phase shifts. A robust approach for multi-eve systems is also investigated. The analysis of blocking effects, the formulation of optimization issues, and the suggestion of effective, secure transmission algorithms are all contributions. The efficiency of the plan in reducing the blockage propensity of THz waves and enhancing THz communications secrecy performance is supported by simulation findings.

To improve covert communication and maximize EE in IoT networks, the authors in [104] describe a novel communication system that combines UAVs with RIS equipped with THz technology. The system introduces a multi-UAV covert communication technique that combines an aerial cooperative jammer (UCJ) with an RIS installed on a UAV (URIS) to preserve privacy and enhance communication covertness. The trade-off between covert throughput and UAV propulsion energy consumption is considered when formulating the optimization problem based on minimum average energy efficiency. The nonconvex nature of the problem is addressed by a computationally practical approach employing block-coordinated successive convex approximation (BSCA), which resolves a series of subproblems for user scheduling, power allocation, beamforming optimization, and trajectory planning. Numerical results show considerable improvements in covert communication.

The authors of [105] examine RIS in a THz-MIMO-NOMA system with an Eve. The emphasis is on using two sparse RF chain antenna configurations for hybrid precoding. The system entails the selection of cluster heads, analog precoding design, and user clustering based on channel correlation with NOMA technology. To eliminate inter-cluster interference, digital precoding uses a low-complexity forced-zero technique. A secure transmission method that maximizes the sum SR is suggested by optimizing power distribution, RIS phase shifts, total transmit power, minimal attainable rates, and RIS RCs. The non-convex problem is transformed into a convex one using Taylor series expansion and semidefinite programming. An alternating optimization algorithm is developed to get a viable solution. Simulation results confirm the algorithm's convergence and highlight the improved beamforming gains achieved by deploying RIS, enhancing security against eavesdropping.

This article [106] examines the effects of various variables on the physical layer security (PLS) of a THz communication system helped by the RIS. The system considers phase shift quantization errors, pointing errors, and statistical CSI of the Eves, which also considers the existence of both colluding and non-colluding Eves. Through simulations, new expressions for secrecy capacity are developed and validated. Understanding how these elements affect the security of RIS-assisted THz systems is the primary goal of the analysis. This paper [107] explores the secure transmission challenge in a THz-integrated sensing and communication system (ISAC) enhanced by active RIS, where delay alignment modulation is employed at the BS. In this system, the target is considered a potential eavesdropper. The goal is to maximize the SR while ensuring the target receives a minimum level of illumination power. The authors formulate a non-convex optimization problem, which poses difficulties for direct resolution. To address this, they propose an alternative optimization algorithm that iteratively adjusts the BS transmit beamforming and the active RIS reflection coefficients. This is achieved using majorization-minimization and SDR techniques. Simulation results confirm the effectiveness of the proposed scheme, demonstrating its potential to enhance secure communication.

Discussion: This subsection critically reviews methods for enhancing security in RIS-assisted THz communication systems, as summarized in Table 5. Several key studies have made significant contributions, but notable gaps remain. In [100], the authors propose low-complexity beamforming and phase-shifting designs to boost the SR in MISO systems. However, this approach primarily focuses on theoretical models, lacking real-world validation and scalability to larger, dynamic networks. Similarly, [101] uses iterative algorithms to optimize SR in THz MISO systems, but the high computational complexity could be a limitation in practical implementations with resource constraints. The study in [102] addresses SR optimization for RIS-assisted mmWave/THz systems via SDP and BCD, but it assumes ideal CSI and perfect eavesdropper location knowledge, which may not hold in real-world scenarios. The multi-RIS strategy proposed in [103] tackles signal blockages, but the approach's scalability and adaptability to highly dynamic environments such as mobile or UAV-based systems are not fully explored. In [104], the combination of UAVs and RIS enhances covert communication in IoT networks, but the energy consumption and trajectory optimization for UAVs remain under-explored, which could impact the system's efficiency. The power allocation and phase-shift optimization approach in [105] for THz MIMO-NOMA systems improves SR, but the study does not address the impact of hardware impairments or imperfect CSI. Reference [106] offers new secrecy capacity expressions that account for eavesdroppers and phase shift errors, but the analysis focuses on theoretical models, and practical deployment challenges, such as handling real-time channel variations, are not addressed. This paper [107] proposes an optimization algorithm for secure transmission in a THz ISAC system with active RIS, improving secrecy rate through beamforming and reflection adjustments.

D. OPTIMIZING THz COMMUNICATION SYSTEM SUM RATE WITH RIS

This section emphasizes using RIS to increase the sum rate of THz communication systems. The research articles examined various methods for improving the data transmission rate while ensuring THz communication networks adhere to specific rate constraints. These techniques address the nonconvex characteristics of the sum rate maximization problem, including RIS phase shift optimization, sub-band allocation, and power control. Furthermore, to account for THz path loss attenuation and provide stable sub-band allocation, the articles present cutting-edge algorithms, including the long-distance priority (LDP) and blocking pair elimination (BPE). The suggested methods exhibit considerable improvements in the sum-rate efficiency of RIS-aided THz networks. Additionally, using RIS in interior settings is investigated to address the reliability issues with LoS communication links. The RIS's adjustable reflecting elements' phase shifts can be optimized to increase the sum rate performance of THz communication systems. Local search (LS) and cross-entropy approaches are introduced to achieve the best phase-shift values, reducing complexity compared to exhaustive search methods while retaining sum-rate performance. These papers offer insightful techniques for enhancing the sum rate in THz communication systems using RIS technology, as summarized in Table 6.

The use of RIS is examined in this work [108] to improve the effectiveness of THz communication systems in indoor scenarios. Potential obstructions jeopardize the dependability of LoS lines for indoor THz communication. The RIS, which is made up of phase-shift-adjustable reflecting elements, enables the modification of the propagation direction of THz signals. The system's sum-rate performance can be enhanced by optimizing these phase shifts. In contrast to exhaustive search techniques, a LS approach is suggested to locate the ideal phase-shift values, significantly lowering complexity. The LS approach, though, suffers from some performance loss. To improve the sum-rate performance over the LS approach, a cross-entropy method is presented. Numerical findings have demonstrated the efficiency of the RIS-enhanced THz communication system.

In a wireless VR network, the issue of connecting RISs with VR users is addressed in this research [109]. The emphasis is on a cellular network that uses THz-controlled

TABLE 5. Summary of improving security for RIS-Based THz communication in different scenarios.

Ref	Year	System Setup	Direct Link	CSI	Solving Techniques	Proposed Solution
[101]	2019	Wiretap MISO, Alice (MA), RIS-THz, Bob & Eve (SA).	Saleh Valenzuela model	Known	Low-computational complexity successive and a high secure performance joint design.	The active beamformer at the BS and the passive reflecting phase shifters (PSs) at the RIS were designed to maximize the SR.
[102]	2020	DL THz MISO BS (MA), RIS, User & Eve (SA).	Geometric channel model	Known	Rayleigh-Ritz theorem cross entropy-based algorithm	The SR maximized by designing the precoder at the BS and the discrete phase-shifts at the RIS.
[103]	2020	DL mmWave / THz, BS (MA), RIS, Bob (SA), Eve (SA).	Blockage	Perfect	SDP, Element-wise BCD.	With discrete phase shift and transmit power constraints, the transmit beamforming at the BS and the reflecting matrix at the RIS are jointly optimized to maximize the system SR.
[104]	2022	Multi RIS asisted THz, BS (MA), Bob (SA), Eves (SA).	Blocked	Perfect (bob), imperfect (Eves).	Alternative algorithm, iterative algorithm.	The SR performance was maximized by jointly optimizing the HB at the BS and reflecting phase shifts at multiple RISs.
[105]	2022	URIS-UCJ-aided THz, AP, Bobs & (Willies) (SA) .	Blocked	Known	Block-successive convex approximation (BSCA),	A URIS-THz bands system was proposed where URIS is used for the passive covert data relaying from the AP to the scheduled UE, and UCJ is used for efficient AN, reducing unscheduled UEs' detection performance.
[106]	2023	Multi cluster, THz MIMO NOMA, BS (MA), RIS, Users & Eve (SA)	Blocked	Perfect	AO	Jointly optimising power allocation and phase shifts of RIS to boost the sum SR considering total transmit power budget, minimal achievable rate requirement of each user, and RIS reflection coefficients.
[107]	2023	DL THz, Alice, RIS, Bob, Eves	Blockages	Instantaneous (Bob) Statistical (Eves)	New Expression for Secrecy Capacity	Considering the presence of colluding and non-colluding Eves, a new formula for the secrecy capacity was derived.
[108]	2024	BS (ULA), RIS, ISAC, User (SA), Eve	Blocked	Perfect	AO, majorization-minimization, SDR	Proposed a secure transmission scheme using DAM for active RIS-assisted THz ISAC systems to enhance secrecy rate.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex

RISs as BSs. For a flawless VR experience, it is essential to guarantee high data speeds and low latency. A unique risk-based paradigm based on entropic value-at-risk is proposed for rate optimization and reliability performance. To keep higher-order statistics of the queue length below a certain threshold, the problem is stated as a linear weighted function using Lyapunov optimization. To address the challenge of a large state space, a policy-based RL algorithm is presented, with the policy being learned by a deep-RL algorithm utilizing a recurrent neural network (RNN) framework. Simulation results demonstrate the effectiveness of the proposed method, with the maximal queue length deviating from the optimal solution by less than 1 percent and exhibiting high accuracy and rapid convergence.

In this paper [110], deploying an RIS for THz communications is investigated to maximize the aggregate rate of user equipments (UEs) while ensuring the rate requirements of each UE are satisfied. To jointly optimize the coordinates, phase shifts, allocation of THz sub-bands, and power regulation of the RIS, a block coordinate searching (BCS) technique is presented. To get workable RIS coordinates and guarantee the monotonicity of the objective value, a relaxation with a penalties-based (RPB) technique is developed to handle the problem's nonconvexity. Closed-form equations with price components are also developed for the RIS phase shifts. Simulation results show the substantial performance gain brought about by the suggested approach.

This study [111] focuses on enhancing the sum rate in THz non-orthogonal multiple access (NOMA) communication systems supported by the RIS. The suggested technique approaches the nonconvex problem by alternatingly optimizing the RIS phase shift, sub-band allocation, and power control. A workable initialization solution and individual rate needs are both guaranteed by the use of auxiliary variables. The RIS phase is changed to increase the sum rate, and the decoding order for successive interference cancellation

(SIC) is chosen based on channel gain maximization. The paper offers a blocking pair elimination (BPE) technique to create a stable sub-band allocation and a long-distance priority (LDP) approach to account for distance-dependent THz path-loss attenuation. The simulation results clearly show the improvement of the sum-rate performance in RIS-assisted THz NOMA networks.

This work in [112] examines the usage of cascaded RISs for uplink multiple access with correlated channels in THz communication. The goals are to maximize the received rate of a desired user while minimizing interference from another user and to maximize the combined rate of the two users. The optimization problems are non-convex, and diverse methods are investigated. Suboptimal analytical solutions, approximation approaches, and an exhaustive search are applied. DRL is also employed to solve intricate optimization problems. The findings demonstrate the scheme's effectiveness, outperforming other compared approaches and achieving high sum rates. The DRL-based technique operates more effectively when channel correlation is present.

This paper, [113], presents a novel STAR-RIS-based framework for near-field MIMO communication. The framework enables a BS to support numerous users in the STAR-RIS's near-field area. To maximize the active beamforming at the BS and the transmission/reflection coefficients at the STAR-RIS, a weighted sum rate maximization problem is devised. An approach known as BCD is used to overcome the issue. The STAR-RIS coefficients can be optimized using the penalty-based iterative (PEN) and the low-complexity element-wise iterative (ELE) algorithms. The findings demonstrate that STAR-RIS near-field beamforming enhances the sum rate compared to far-field beamforming. The near-field channels made available by STAR-RIS provide the multiuser MIMO system with more degrees of freedom and accessibility. While the BCD-ELE algorithm has a lower computational cost, it performs worse than the BCD-PEN approach.

The authors in [114] discuss enhancing THz communication networks using RIS amid challenges like high pathloss and molecular absorption. It introduces an angle-based trigonometric channel model and formulates the transmitter-receiver matching as a mixed-integer nonlinear programming problem, addressing it with a Gale-Shapley algorithm for stable matching. The algorithm's efficiency, complexity, and performance improvements over conventional methods are demonstrated through numerical results. This research contributes to optimizing user association and improving sum rates in THz networks with imperfect CSI.

THz wireless systems promise ultra-high data rates but are limited by severe path loss due to molecular absorption over long distances. RIS can enhance coverage, while adaptive sub-band bandwidth (ASB) allocation mitigates absorption by dynamically assigning variable bandwidths. However, the unknown bandwidths of sub-bands complicate accurate CE. To address this, in [115], a metapath-based heterogeneous graph-transformer network (MHGphormer) is proposed to bypass CE. The sum-rate maximization problem is formulated with quality of service (QoS) constraints in a RIS-aided multiuser MIMO THz system, optimizing precoding, phase shifts, and ASB allocation. MHGphormer uses unsupervised learning to map inputs like user locations and data rates to optimized system parameters and can adapt to varying user counts. Simulation results demonstrate that MHGphormer achieves higher system sum-rates compared to baseline algorithms, including homogeneous graph neural networks and deep learning methods.

In another paper [116], the authors introduce a novel RIS-assisted spatial modulation (SM)-CNOMA system for THz communication, termed RSM-CNOMA. In this system, a base station transmits information to two distinct users through the RIS using SM, with a nearby user acting as a relay to forward data to a distant user via an index modulation (IM) scheme. The BER and sum-rate for RSM-CNOMA are derived, showing improved performance over conventional RIS-CNOMA systems. A detailed comparison of achievable sum-rates across various systems, including RIS-SM-NOMA, RIS-CNOMA, and RIS-supported orthogonal multiple access (OMA), highlights the advantages of the proposed approach.

The evolution of 6G systems aims to deliver high-speed data services with minimal latency over higher spectrum bands. This research in [117] presents a framework that enhances wireless communication networks by addressing dynamic information access and blockage issues through the integration of caching strategies and RIS in the sub-THz band. The achievable system rate is derived, showing that caching popular content maximizes performance. A closed-form solution is introduced to determine the optimal user distance, utilizing a specialized r-Lambert W function. In another study [118], the authors explore the problem of downlink aggregated sum-rate maximization in a MIMO system supported by RIS for NOMA transmission within the THz spectrum. The authors propose an optimization algorithm that iteratively optimizes the transmit power at the AP and the phase-shift settings of RIS elements. Simulation results indicate that the proposed method significantly outperforms conventional benchmark schemes in terms of aggregated throughput.

As multi-hop, high-bandwidth indoor THz wireless communication systems gain traction, the integration of RIS and relay devices within emerging 6G networks offers a promising solution for establishing flexible, cell-less, and on-demand indoor mesh networks. RIS devices, composed of arrays of reflecting elements, enable the adjustment of phase shifts to steer, focus, and amplify signals toward the intended receiver. This paper [119] provides an analytical exploration of how path allocation influences interference in such networks. It introduces a novel model that examines interference based on the geometric characteristics of beams (conic, cylindrical) as they interact with RIS, UE, and relays.

Additionally, a transmission scheduling heuristic is proposed to minimize interference, along with an optimization method to maximize throughput. Performance results shed light on how interference affects communication path quality and offer strategies for optimizing path selection to enhance throughput.

Discussion: This subsection reviews methods for optimizing the sum rate in RIS-assisted THz communication systems, highlighting key techniques and identifying existing gaps, as summarized in Table 6. While these studies present innovative solutions, several limitations need to be addressed for practical deployment. In [108], phase shift optimization using LS and cross-entropy improves sum rate performance in indoor settings, but the LS method incurs performance loss and may be impractical for real-time scenarios due to computational complexity. In [109], a risk-based framework for VR networks using RIS-controlled base stations ensures high data rates, but its scalability to larger, more dynamic networks is not fully explored. In [110], BCS and RPB techniques jointly optimize RIS placement, phase shifts, and sub-band allocation to maximize the sum rate, but the assumption of perfect CSI limits the method's real-world applicability in fluctuating environments. Similarly, [111] proposes LDP and BPE methods to optimize power control and sub-band allocation in NOMA-THz systems, but their scalability to more complex and larger-scale networks remains a challenge. The study in [112] explores multi-hop RIS systems for uplink access and uses DRL-based optimization to maximize the sum rate, but the high computational demands of DRL present concerns for real-time application. In [113], a STAR-RIS framework enhances the sum rate in near-field MIMO systems, yet its effectiveness in far-field or larger-scale deployments is underexplored. Finally, [114] addresses the sum rate problem in multi-RIS THz networks with imperfect CSI, providing a promising low-complexity solution. However, further research is needed to validate its scalability and performance in more dynamic and mobile network conditions.

The paper [115] introduces MHGphormer, a graph-transformer network that optimizes system parameters in RIS-aided MIMO THz systems, improving sum rates but lacking real-time adaptability. Similarly, [116] proposes RSM-CNOMA, enhancing BER and sum rate but not addressing scalability or RIS imperfections. Reference [117] integrates caching with RIS in sub-THz bands to boost performance but overlooks dynamic user demands and mobility. Reference [118] presents an algorithm for RIS-NOMA MIMO systems, increasing throughput but failing to address EE challenges. Finally, [119] tackles interference in RIS-relay-based THz mesh networks, yet does not fully consider environmental effects on beams.

E. ENHANCING ENERGY EFFICIENCY IN THz COMMUNICATIONS USING RIS

This section delves into using RIS to improve the EE of THz communication systems. Maximizing EE in communication at THz, the research articles presented in this domain provide novel methodologies and algorithms. These approaches include sequential convex approximation, BCD, and the Salp swarm algorithm. The studies show these strategies' measurable system performance and EE enhancements. The articles aid in developing and deploying energy-efficient RIS systems for THz communications through in-depth analysis, hardware design considerations, and practical insights, as summarized in Table 7.

This study [120] optimizes the EE of multiuser rate division multiple access (RSMA) downlink systems using RIS in the THz frequency range. This paper presents a new paradigm for RIS-assisted THz RSMA and uses the Salp swarm algorithm (SSA) to optimize the EE objective function. Comparing SSA to successive convex approximation (SCA), the results indicate that SSA outperforms SCA in boosting EE and reducing computational time, thereby enhancing the overall system performance.

This paper concentrates on the problem of EE optimization in a THz communication system with an RIS. The system consists of a BS with multiple antennas and an RIS with various reflecting elements to accommodate numerous users. Considering transmit power and RIS phase shift constraints, the authors propose an energy-efficient design that maximizes system EE. Using a covariance matrix adaptation evolution strategy (CMA-ES) and Dinkelbach's method, the RIS phase shift, transmit power and precoding matrix are jointly optimized. Simulation results demonstrate that the proposed algorithm is more energy efficient than existing baseline algorithms. This is the first study to maximize EE in an RIS-assisted THz network to achieve green and sustainable indoor communications.

This paper [121] introduces a simultaneous THz information and power transfer (STIPT) system employing RIS for data and power transmission. The objective is to optimize the total data rate for information users (IUs) while also satisfying the needs of energy users (EUs) and the RIS's power harvesting requirements. The nonconvex optimization issue is solved using the BCD technique by iteratively optimizing the transmit precoding of IUs, the RIS's reflecting coefficients, and the RIS's position. Moreover, a penalty-constrained convex approximation (PCCA) algorithm is proposed to optimize the RIS deployment while maintaining feasibility. Simulation findings show that the suggested solution is superior to benchmark schemes, and the BCD algorithm considerably improves the STIPT system's performance.

The authors in [122] offer a THz communication system augmented by a STARS and introduce a novel power consumption model. Joint optimization of HB at the BS and passive beamforming at the STARS is performed to maximize spectral efficiency (SE) and EE in narrowband and wideband THz systems. Independent phase-shift STARS was the first type of STAR the authors explored using for narrowband systems. Low-complexity element-wise algorithms are proposed to optimize the analog beamforming

TABLE 6. Summary of sum rate maximization schemes for RIS-Based THz communication in different scenarios.

Ref	Year	System Setup	Direct Link	CSI	Solving Techniques	Proposed Solution
[109]	2019	RIS aided MIMO, BS (MA), RIS, Users (SA)	Severe propagation loss	Perfect	Local search (LS), & cross-entropy (CE)	Sum-rate performance was enhanced by selecting the optimal values of the phase-shift of RIS.
[110]	2020	DL RIS-THz, RISs act as BSs, VR Users.	Blocked	Perfect	Lyapunov optimization and RNN RL	For rate optimization and reliable performance of the system, a risk-based framework based on the entropic value-at-risk was proposed.
[111]	2022	AP, RIS, UEs.	Blocked	Known	Block coordinate searching (BCS) & relaxation with penalties based (RPB)	Maximized UEs' sum rate while ensuring each UE's rate requirement by jointly optimizing RIS's coordinates, phase shifts, THz sub-bands allocation and power control.
[112]	2022	DL NOMA THz AP, RIS Users.	Single NLoS	Perfect	long-distance-priority (LDP), blocking-pair eliminating (BPE).	To increase the sum-rate, an algorithm was proposed that alternatively optimize the RIS phase shift, power control, and the sub-band allocation.
[113]	2023	UL Multi-hop RIS, Tx1, & Tx2 (MA), RISs, Rx (MA)	No Direct Link	Perfect	Block Solution based framework & DDPG based framework	UL multiple access scenario of cascaded RIS system was developed to resist the short-range communications in THz networks to expand the rate of the desired user under second's user interference and to expand the sum rate for both users.
[114]	2023	DL MU-MIMO, BS (MA), STAR-RIS, Users (MA)	Blocked	Known	BCD-PEN & BCD-ELE	Sum rate maximization problem was studied and improved by active beamforming at the BS and the TRCs at the STAR-RIS.
[115]	2024	Transmitters, RISs, Receivers	Blocked	Imperfect	Gale-Shapley algorithm	Proposed Gale-Shapley algorithm based low-complexity matching approach for Tx-RIS-Rx pairing in multi-RIS-aided THz networks to maximize the sum rate with imperfect CSI.
[116]	2024	DL MU-MIMO, BS (UPA), RIS, Users (ULA)	Blocked	Imperfect	MHGphormer	The proposed algorithm jointly optimizes spectrum allocation, precoding, and RIS phase shifts to maximize the system's sum-rate without CE.
[117]	2024	BS, RIS, Near User and Far User	Blocked	Perfect	Spatial modulation with cooperative NOMA	Joint optimization of spatial modulation and cooperative NOMA is proposed to improve bit error rate (BER) and sum-rate performance compared to conventional RIS-NOMA systems.
[118]	2024	Main BS (ULA), RIS, Sub BS and User	Blocked	Perfect	Optimization algorithm	Proposed joint optimization of caching strategies and RIS to maximize the system rate, using r-Lambert W function to determine the optimal user distance.
[119]	2024	DL MIMO, AP (MA), RIS, UEs (SA)	Blocked	Perfect	Iterative algorithm	Proposed an optimization algorithm that jointly optimizes transmitting power and phase-shift coefficients at the RIS to maximize system throughput.
[120]	2024	BSs, RISs, and UEs	Blocked	Known	Transmission scheduling and routing optimization	Proposed a scheduling heuristic for interference avoidance and a throughput maximization method for RIS-assisted THz networks with mesh relay nodes.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex

at the BS and the passive beamforming at the STARS, and dual penalty decomposition is used to break down the joint optimization problem into its parts. Then, the case of coupled phase-shift STARS is tackled using this method. Due to the beam split problem, wideband systems compensate for the drop in performance brought on by the spatial wideband effect at the BS and STARS. To address this issue, effective wideband beamforming is made possible by adding true time delayers (TTDs) to the standard HB architecture. A quasi-Newton-based iterative methodology is provided for designing the TTDs' coefficients. The numerical findings prove that STARS are better than regular RISs in this regard. In addition, coupled phase shifts of the STARS have negligible effects on the SE and EE performance of both narrowband and wideband systems. Additionally, conventional HB in narrowband systems achieves SE performance on par with full-digital beamforming and much superior EE performance. However, wideband systems cannot avoid the wideband beam split and perform at their best without TTD-based HB.

This paper [123] introduces a novel communication scheme that enhances spectrum and energy efficiency in multi-user MIMO systems through index modulation (IM). This method, termed RIS-SA-IM, utilizes the structure of subarrays in a RIS to convey additional information bits without extra power consumption. The system model described involves splitting a large RIS array into subarrays, each directing beams to a unique UE. The key technique involves a distributed mapping rule that ensures index information for each UE is determined by its allocated subarray, allowing for localized demodulation without inter-UE data exchange. Performance is evaluated using bit-error-rate analysis, showing that RIS-SA-IM outperforms traditional non-IM methods in terms of throughput and energy efficiency.

Discussion: This subsection reviews methods to enhance EE in RIS-assisted THz communication systems, as outlined in Table 7. Various strategies are proposed for optimizing EE, but some limitations prevent broader practical use. In [120], SSA is applied to optimize EE in multi-user RSMA systems. Although SSA improves both EE and computational time, the study lacks real-world testing, particularly in dynamic networks, limiting its scalability. In [121], a STIPT system is introduced to optimize data rates for IUs while meeting EUs' power needs. The BCD and PCCA algorithms show promising results, but they don't fully address challenges like handling real-time CSI fluctuations. The study in [122] explores joint optimization of hybrid and passive beamforming in STARS-based systems to enhance EE. However, while it improves EE and SE, the wideband beam-split issue is only partially addressed, and phase-shift coupling in wideband systems needs further investigation. In [123], RIS-SA-IM enhances EE through subarray index modulation, reducing power consumption. This paper [107] proposes an optimization algorithm for secure transmission in a THz ISAC system with active RIS, improving secrecy rate through beamforming and reflection adjustments. Yet, its scalability to larger, multi-user systems and performance with imperfect CSI are not sufficiently explored.

V. OPTIMIZING RESOURCE ALLOCATION AND PERFORMANCE ANALYSIS IN RIS-BASED THz SYSTEMS

This section addresses optimizing resource allocation and performance analysis in RIS-based THz systems, divided into two main subsections. The first Subsection V-A discusses methods for effectively allocating resources to improve system performance. The second Subsection V-B is further split into two parts. The first Subsubsection V-B1 evaluates performance metrics specific to MIMO andmMIMO setups utilizing RIS in the THz spectrum. The second Subsubsection V-B2 investigates the effectiveness and challenges of integrating UAVs in RIS-enhanced THz communications. These sections collectively offer a detailed perspective on the management and evaluation of performance in THz communication technologies, as summarized in Table 8.

A. RESOURCE ALLOCATION IN RIS-BASED THz SYSTEMS

This subsection explores the strategies and techniques used to allocate resources efficiently in THz communications, considering the unique capabilities and challenges associated with the RIS.

This paper [124] presents a study on energy-efficient resource optimization in the THz band, a promising frequency band for future high-frequency communication. The authors propose a network system that combines mMIMO technology and RIS to improve capacity and EE. They established an RIS-assisted THz-MIMO downlink wireless network system and decomposed the original EE problem into phase-shift matrix optimization and power allocation. To tackle this problem, the authors develop a distributed EE optimization algorithm that transforms the original nonlinear problem into a convex optimization problem. The algorithm achieves rapid convergence and maximizes EE. The simulation results demonstrate the effectiveness of the proposed approach and validate the feasibility of integrating both RIS and mMIMO technology into THz communication networks.

This paper [125]introduces a RIS-aided wideband THz communication system to enable the coexistence of enhanced mobile broadband (eMBB) and ultra-reliable low-latency communication (URLLC) services in B5G networks. The authors formulate a resource management problem and propose a supervised learning approach that combines optimization, deep learning, and ensemble learning methods. Simulation results demonstrate up to 49 percent SE gain for eMBB services compared to existing methods while satisfying URLLC service requirements. The proposed solution utilizes an alternative decomposition technique, trains a long short-term memory (LSTM) for future parameter prediction, and employs an ensemble model for improved precision. The study provides a practical approach for supporting coexistence in THz communication systems.

THz communications and RISs have facilitated the development of VR and other indoor wireless applications. THz path allocation must be optimized to maximize the VR user experience. This study [126] examines the effect of RIS hardware failure on path allocation in a THz network employing THz-operated RIS BSs for VR users. A path allocation model based on the Semi-Markov Decision Process (SMDP) is proposed to ensure reliable THz connections and maximize long-term system benefits. The state space, action space, reward model, and transition probability distribution for the RIS system are formulated by the SMDP-based model. An optimal path allocation iterative method is devised to decide what should be done next at each system state. The results shed light on the average reward and probability of VR service obstruction by considering various scenarios, VR service arrivals, and RIS failure rates. This research is the first step towards implementing reliable VR services over THz RIS by highlighting the challenges and performance considerations associated with RIS hardware failures.

Discussion: This subsection examines resource allocation strategies in RIS-assisted THz systems, highlighting key methods for optimizing performance. Several approaches show promise but face challenges in practical applications, as summarized in Table 8. In [124], the authors propose an energy-efficient optimization for THz-MIMO systems by

TABLE 7. Summary of energy efficient approaches for RIS-Based THz communication in different scenarios.

Ref	Year	System Setup	Direct Link	CSI	Solving Techniques	Proposed Solution
[121]	2022	DL MISO, BS (MA), RIS, Users (SA)	Attenuated	Perfect and Imperfect	Salp-swarm-algorithm (SSA)	The Salp swarm algorithm (SSA) was introduced to optimize system EE and reduce the time to improve overall performance.
[122]	2022	DL THz, AP (MA) , RIS, EUs (MA), IUs (MA)	Attenuated	Imperfect	BCD & PCCA	Proposed a scheme to maximize IUs' sum data rate while ensuring the power requirements of EUs and RIS.
[123]	2023	STARS based THz, BS (MA), STARs, Users (SA)	Blocked	Known	Quasi-Newton	SE and EE were maximized in narrowband and wideband THz systems via joint optimizing BS-based beamforming and the passive beamforming at the STARS.
[124]	2024	Transmitter, RIS, UEs	Blocked	Known	RIS Subarray Index Modulation	RIS-SA-IM scheme is proposed, which utilizes index modulation on subarray structures for efficient and robust communication without the need for extra power consumption.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex

breaking down the problem into phase-shift matrix optimization and power allocation. While the method improves EE and shows rapid convergence, its real-time scalability and application in dynamic networks remain untested. In [125], a RIS-aided THz system supports eMBB and URLLC services using a supervised learning approach. The method enhances SE by 49% for eMBB but may face issues in dynamic environments due to its reliance on LSTM for parameter prediction. The study in [126] explores RIS hardware failures in path allocation for VR services, using an SMDP model. While the model provides insights into VR service reliability, the impact of hardware failures in large-scale networks needs further exploration.

B. PERFORMANCE ANALYSIS OF RIS-BASED THz SYSTEMS

This subsection delves into performance analysis methodologies for mMIMO and UAV systems to evaluate the effectiveness and efficiency of RIS-based THz systems.

1) MIMO/MMIMO-BASED RIS-ASSISTED THz SYSTEMS

This subsection compiles a series of academic works evaluating the performance of THz systems that utilize MIMO/Massive MIMO and RIS technology. The following papers employ diverse methodologies and approaches to tackle the challenges related to THz communication. The techniques used encompass cooperative beam training, holographic RIS designs, efficient beamforming algorithms, hybrid precoding architectures, optimization frameworks, and DL-based approaches. The THz papers aim to augment the precision of CE, elevate the range of coverage, optimize SE, and attain energy-efficient operation through these techniques. The usefulness of these techniques is proven by comprehensive simulations and analysis, offering insightful information on the design and optimization of MIMO/mMIMO-based RIS-assisted THz systems.

The authors in [127] examine THz communication, which has high data transmission rates but is impeded by path attenuation and indoor barriers. To address the barriers mentioned above, the authors suggest the utilization of RIS to regulate the propagation direction of the THz beam and augment its coverage efficacy. To determine the desired phase shift combination of RIS elements in a THz MIMO system, they devise an effective Taylor expansion-aided gradient descent (TE-GD) scheme. The TE-GD algorithm employs a dynamic step size adjustment strategy that adapts during the iterative procedure, utilizing the coefficients derived from a second-order Taylor expansion formulation. The simulation outcomes indicate that the TE-GD approach attains a level of SE akin to the exhaustive search technique, albeit with substantially reduced complexity. The TE-GD method exhibits a 4.3 bps/Hz increase in SE and an 80.17 percent reduction in complexity compared to conventional gradient descent utilizing a fixed step size.

The study conducted by the authors in [128] explores the utilization of RIS in THz communication. The research addresses the difficulties arising from the growing dimensions of the RIS and the requirement to accommodate the spherical wavefront of the transmitted waves. Concerning power gain and EE at THz frequencies, the study seeks to investigate the performance of MIMO systems assisted by RIS thoroughly. A comprehensive evaluation of power amplification in beam focusing and beamforming is undertaken to accomplish this objective. Unexpectedly, the findings show that beamforming, typically considered ideal, is poor even at great distances from the RIS. A precise estimation of the reduction in power gain resulting from beamforming is obtained by formulating an accurate and approximate closed-form expression. The research findings indicate that MIMO systems' EE can be substantially improved by utilizing RIS operation within the radiating near-field and beam focusing. This research presents significant results regarding the optimization and efficacy of THz communication systems utilizing RIS technology. Specifically, the study introduces a novel near-field channel model that incorporates the dimensions of RIS components and the spherical wavefront of transmitted signals. The research exposes the scaling principles driving EE by calculating the ideal number of RIS elements needed to match the rate of MIMO while minimizing power consumption.

The article in [129] suggests a solution by introducing an RIS-assisted multiuser THz MIMO system that utilizes OFDMA. To conserve energy, the system employs a sparse radio frequency chain structure. The aim is to optimize the hybrid analog/digital beamforming at the BS and the reflection matrix at the RIS jointly to maximize the weighted sum rate. A proposed approach for addressing the complexity of the problem is to utilize an iterative optimization algorithm. The design of analog beamforming is formulated as a capacity maximization problem, whereas digital beamforming and reflection matrix optimization are addressed through semidefinite relaxation (SDR) techniques. The article additionally examines the scenario where CSI is imperfect and proposes a robust beamforming and reflection matrix.

In [130], the authors studied the THz communications that have surfaced as a promising technology for achieving ultra-high data transmission rates in the context of 6G wireless networks. A nanoscale reconfigurable intelligent surface (NRIS) has been developed as a potential solution to the challenges posed by blockage vulnerability in THz waves. The NRIS is designed to manipulate the propagation directions of THz waves. The present study examines the electrical characteristics of graphene and devises an effective hardware architecture for electrically manipulated non-reciprocal interlayer switching (NRIS). It is possible to program the phase response of NRIS to a maximum of 306.82 degrees. The article additionally presents an adaptive gradient descent (A-GD) algorithm for optimizing the phase shift matrix of NRIS in a THz communication system. The efficacy of the hardware architecture and algorithm was demonstrated through the simulation results.

The study by [131] centers on using RIS in THz communication within indoor environments. This communication encounters difficulties arising from path attenuation and obstacles, which can potentially hamper the communication links. The study presents a model for a MIMO system utilizing THz technology, which the RIS assists. The present study introduces an iterative atom pruning-based subspace pursuit (IAP-SP) scheme, which uses compressed sensing techniques to estimate CSI in a low-complexity manner. The IAP-SP method alleviates the computational load by removing redundant columns of the sensing matrix in each iterative step. Simulation results demonstrate that the IAP-SP scheme obtains channel recovery performance comparable to conventional subspace pursuit while reducing complexity by 99.51 percent.

The authors in [132] investigate the difficulties encountered in THz communications, characterized by significant path attenuation and inadequate diffraction. The proposed solution put forth by the authors involves integrating mMIMO and RIS to address the challenges mentioned earlier. Nonetheless, the integration of CE and beamforming presents particular challenges. The authors propose a collaborative beam training strategy to enhance CE efficiency using an RIS, thereby addressing the constraints above. The proposal outlines HB designs that are cost-effective and suitable for both single-user and multi-user scenarios. The primary contributions of the paper consist of a comprehensive technique for beam training, a cooperative low-complexity beam training method, innovative codebooks for training, and the identification of RIS-PS as well as analog/digital precoders/combiners. The simulation results demonstrate that the joint beam training and HB scheme proposed in this investigation achieves performance comparable to fully digital beamforming, even in scenarios where CSI is perfect.

The paper [133] introduces a holographic iteration of an RIS designed for employment in mMIMO THz systems. With the adoption of tightly packed sub-wavelength unit cells made possible by the reduction in the size of THz electronic components, holographic communications can now be carried out through continuous or nearly continuous apertures in RISs. The authors derive the beam pattern of a holographic RIS and suggest a closed-loop CE method for effectively estimating MIMO THz channels with the assistance of holographic RISs. The CE scheme comprises a downlink coarse CE stage and an uplink finer-grained CE stage. The pilot signals are well-considered, and a compressive sensing-based CE algorithm minimizes pilot overhead. The results obtained from the simulation indicate that the holographic RISs exhibit a higher performance level than other baseline methods.

In this study [134], the authors investigate THz multiuser mMIMO systems to improve coverage in forthcoming wireless networks. The significant reduction in signal strength experienced by THz channels, known as path attenuation, presents a formidable obstacle to achieving comprehensive wireless coverage. To solve this problem, the authors suggest a THz multiuser mMIMO technique that an RIS helps. A low-cost sub-connected hybrid precoding architecture is devised for uplink and downlink data transmission while considering the constraints imposed by physical devices and environments. The uplink and downlink spectral efficiencies are derived as closed-form equations, and the effects of system characteristics are examined. The primary contributions are the framework design for RIS-assisted THz multiuser large MIMO systems, taking precoding errors into account, and analyzing system performance and parameter impacts.

In this paper [135], a novel hybrid precoding architecture for THz communication is presented. The proposed architecture employs a RIS to achieve analog beamforming and address the energy consumption challenges associated with mMIMO systems. The RIS-based hybrid precoding architecture poses a challenge in formulating a sum-rate maximization problem, primarily due to the discrete phase shifts that the RIS implements. To address this issue optimally, the proposal involves implementing a deep learning-based

TABLE 8. Summary of resource allocation schemes and performance analysis for RIS-Based THz communications.

Ref	Year	System Setup	Direct Link	CSI	Solving Techniques	Proposed Solution
[125]	2021	DL THz-MIMO, BS (MA), RIS, UEs (SA)	Blocked	Known	Distributed EE optimization algorithm	The capacity and EE were enhanced in mMIMO and RIS-THz system through a distributed EE optimization algorithm.
[126]	2023	DL wideband THz, BS (MA), RIS, eMBB & URLLC UEs.	Short range coverage	Known	supervised learning deep learning & ensemble learning	The joint optimization of RIS reflection coefficients, BS transmit power, and wideband THz resource block allocation was conducted to address the resource management challenge.
[127]	2023	Small BS (MA), RISs, VR UEs.	Blocked	Statistical	SMDP	SMDP-based path allocation model was proposed to enhance THz connection reliability. The model aims to maximize overall long-term rewards, considering gains, link utilization costs, and penalties for RIS failure.
[128]	2020	DL THz MIMO, BS (MA), RIS, UEs (MA)	Blocked	Known	Taylor expansion aided gradient descent (TE-GD)	RIS intelligently phase shifts in its reflecting elements to direct THz beam propagation and enhance coverage performance.
[129]	2021	THz-MIMO based RIS, Tx (SA), Rx (SA).	LoS	Perfect	Beamfocusing & bean-forming.	Performed comprehensive analysis of power gain and EE in RIS-based MIMO systems utilizing a spherical wave channel model.
[130]	2021	THz MIMO OFDMA, BS (MA), RIS, UEs	Blocked	Imperfect	Alternatively iterative optimization algorithm	The power consumption is reduced by implementing a sparse radio frequency chain antenna structure in RIS-aided multiuser THz MIMO system with OFDM access.
[131]	2022	DL THz MIMO, BS (MA), NRIS, MS (MA)	Blocked	Known	Adaptive gradient descent (A-GD) algorithm	A method of disclosure the connection between conductivity and applied voltages is used to research the electric properties of the graphene, then Fabry-Perot resonance model is used as a base of systematic hardware structure of electrically-controlled NRIS.
[132]	2020	Narrowband DL mMIMO, BS (MA), RIS	Blocked	Perfect	Hierarchical codebook.	Studied Beam training and the quantization error to evaluate the performance for CE and transmission solutions for mMIMO RIS-based THz system.
[133]	2021	DL mMIMO, BS (MA), RISs, UEs (MA)	LoS	To be estimated	Cooperative beam training	A cooperative beam training design was proposed to facilitate the CE with RIS, and HB design was also proposed for single user and multi-user based on training outputs.
[134]	2021	DL THz mMIMO, BS (MA), RIS, UEs (MA)	Blocked	Perfect	Closed-loop CE	The beam pattern of a holographic RIS was analyzed, demonstrating that an ideal holographic RIS closely approximates the beam pattern of an ultra-dense RIS with a more efficient hardware architecture.
[135]	2021	THz mMIMO, BS (MA), RIS, Devices (SA)	Blocked	Known	Hybrid Precoding	An uplink and downlink data transmission framework is developed for RIS-assisted THz multiuser mMIMO systems. The impact of phase-shifting errors in analog recording on SE was analyzed.
[136]	2022	DL THz mMIMO, BS (MA), RIS, UEs (SA)	Blocked	Known	Deep Learning based Multiple Discrete Classification (DL-MDC)	For hybrid precoding, the energy-intensive phased array is replaced by an energy-efficient RIS to facilitate analog beamforming. Additionally, the optimization of sum-rate maximization for hybrid precoding is investigated.
[100]	2022	THz-mMIMO RIS, BS (MA), UEs (MA)	Blocked	To be estimated	Precise Beamforming Algorithm (PBA)	A hybrid 3D beamforming architecture, coupled with a sensor-based training scheme, enhances THz multi-user mMIMO systems using RIS technology.
[137]	2022	umMIMO, BS (MA), RISs, UEs (MA).	Blocked	Imperfect	Accelerated proximal gradient-(APG) method	To overcome the challenges of large-scale RIS-aided umMIMO systems, a low-complexity accelerated proximal gradient algorithm is employed to optimize the achievable rate by efficiently adjusting the phase shifts of the RIS elements.
[138]	2023	Multi-RIS-aided THz, Source (MA), RISs, Destination (MA)	LoS	Known	Adaptive coordinated direct and multi-RIS links	The multi-RIS link plays the role of a backup link to develop the accuracy of the direct communication in THz band as a main concept of an adaptive coordinated direct and multi-RIS communication system.
[139]	2023	RTHz-NOMA, BS (MA), RIS, UEs (SA).	Blocked	Known	RTHz-NOMA	RTHz-NOMA is proposed and analyzed that aims to enhance sum-rate performance and reduce BER for THz communications, overcoming the challenges of severe propagation losses and improving massive connectivity for future 6G networks.
[140]	2024	Transmitter, RIS, Receiver	Blocked	Fixed	mPPP	To analyze the performance of indoor network environments utilizing RIS to counteract the path loss and attenuation challenges in THz communications, by introducing a novel analysis method based on a mPPP for bounded areas.
[141]	2024	Transmitter, RISs, Receiver	Blocked	Perfect	Maximal ratio combining and selection combining	Proposed a hybrid RIS-assisted FSO/THz system that combines diversity combining schemes to improve reliability and performance in challenging conditions.
[142]	2024	AP (MA), RISs, UE	Blocked	Partial	Lyapunov-CLT, Optimization	Proposed a distributed hybrid active-passive RIS system for THz communications to improve SNR and energy efficiency, optimizing transmit power with partial CSI.
[143]	2024	Source, Multiple RIS, Destination	Blocked	Known	Statistical analysis, Fox-H function	Proposed a multihop relaying system combined with multiple RIS to address multiplicative channel effects, improving performance for THz communications.
[144]	2021	BS (MA), Drone RIS, UE (SA)	Blockage	To be estimated	Gated Recurrent Unit (GRU)	GRU based on a recurrent neural network is introduced to integrate RISs into THz drone communications. Based on past drone location and beam trajectory data, the system predictively forecasts each drone's appropriate BS/RIS and beam.
[145]	2022	THz band ISL LEO, Sat-S (source), Sat-R (RIS), Sat-D (Destination)	Misalignment fading	Known	Numerical Analysis	To address the significant path loss inherent in high carrier frequencies and enhance the SNR, employed neighboring satellites equipped with RISs to facilitate signal propagation.
[146]	2021	DL UAV THz, RIS, UEs.	Frequency selective fading	Known	SCA	To maximize the minimum average rate of UEs by optimizing the UAV's trajectory, RIS phase shift, the THz sub-band allocation, and power control

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex multiple discrete classifications (DL-MDC) approach characterized by low complexity. The DL-MDC approach involves the conversion of the problem of maximizing the sum rate into a classification problem that utilizes a parallel DNN. The DL-MDC scheme's efficacy is assessed via simulations in theoretical and practical channel models, showcasing accurate classification outcomes and nearly optimal sum-rate performance with minimal complexity.

Simailarly, this paper [99] proposes a novel joint hybrid 3D beamforming scheme for THz multi-user mMIMO systems assisted by RIS. The system under consideration aims to tackle the significant path loss encountered in THz communication using high-gain beamforming methodologies. The architectural design comprises subarray-based THz BS and sub-RISs, wherein UPAs are implemented at the BS, RIS, and user receivers. The employed methodology involves the integration of ultrawideband sensors into the RIS for and the derivation of optimal active and passive beamforming schemes. Introducing the precise beamforming algorithm (PBA) aims to enhance beamforming accuracy by reducing positioning errors. The suggested system is suitable for delay-sensitive applications, as shown by simulation results showing notable gains in SE compared to existing methods.

The present study in [136] centers on a THz communication system that employs MIMO technology on an ultra-massive scale. The system is designed to operate indoors, where direct links are obstructed. The communication establishment of the system is facilitated by utilizing a nearby RIS. The adjustment of the phase shifts of the elements of the RIS achieves this. The issue of configuring the RIS phase shifts is expressed as maximizing the constrained achievable rate, and a proposed solution involves using an accelerated proximal gradient (APG) algorithm. The algorithm's efficacy is evidenced by the numerical outcomes, despite practical phase shift quantization and imprecise channel knowledge. Comparing the suggested technique with a constrained set of RIS elements to available options reveals considerable range gains, ranging from 30 to 120 percent. The suggested technique offers a way to maximize the rate achieved in THz umMIMO systems, get around physical constraints, and improve communication efficiency.

This paper [137] focuses on increasing the reliability of THz communication systems leveraging adaptive coordinated direct and multi-RIS transmission. The objective is to eliminate connection loss by pointing errors and severe attenuation in the THz frequency. Cooperative RIS (CR) and opportunistic RIS (OR) schemes are proposed to improve the system's reliability by employing multi-RIS communication as a backup link. The paper derives exact and asymptotic outage probabilities, considering small-scale fading and nonzero boresight pointing errors. Monte Carlo simulations are conducted to validate the analytical results. When carefully constructed, the suggested system offers advantages over traditional isolated direct THz lines, making it a promising strategy for ensuring adequate coverage in 6G networks. In another paper [138], the authors introduce RTHz-NOMA, which integrates RIS, THz communication, and user pairing NOMA. The proposed system optimizes user pairing based on distance and power allocation, resulting in better sum-rate performance and a lower BER than conventional THz NOMA and orthogonal multiple access (OMA) without RIS. The system is applicable throughout the entire THz frequency range, and the effect of user coupling distance and the number of reflecting elements is analyzed.

This paper [139] introduces a modified Poisson point process (mPPP) for analyzing indoor network performance in THz communications with RIS assistance. It focuses on deriving probability density functions (PDFs) for distances between transmitters, RIS, and receivers to calculate coverage probability. The method accurately predicts coverage probability variations with room size, transmitter location, room shape, and RIS density, showing optimal transmitter placements and the impact of RIS density on network performance.

The authors in [140] propose a hybrid backhaul network combining FSO and THz technologies, enhanced by RIS. The system uses maximal ratio combining (MRC) or selection combining at the receiver to merge FSO and THz links. Performance is evaluated under various impairments, with closed-form expressions derived for the PDF, CDF, and moment-generating function (MGF) of the output SNR. Outage probability and average symbol error rate (SER) are calculated based on these SNR statistics. An asymptotic analysis at high SNR levels simplifies the outage and SER expressions, reducing complexity and revealing the system's diversity gain. Numerical results compare the proposed system with existing setups, including direct FSO without RIS, RIS-enhanced FSO, and hybrid FSO/THz systems without RIS.

In another paper [141], the authors introduce distributed hybrid active-passive RIS (H-RIS) for THz communication systems, considering hardware impairments and small-scale fading. The end-to-end channel is modeled using a gamma distribution via the Lyapunov-central limit theorem. Closed-form expressions for outage probability and ergodic capacity are derived, and the scaling law for the received SNR is examined, comparing H-RIS with fully active and fully passive RIS systems. Transmit power optimization is performed to maximize energy efficiency with partial CSI. The impact of hardware impairments, phase-shift errors, and the number of active and passive RIS elements on system performance is also analyzed. Simulations validate the theoretical findings.

Research on multiple RIS-assisted wireless systems often faces challenges due to multiplicative channel effects. To address this, the authors in [142] propose an MRIS-MH to enhance THz communication performance. Exact expressions for the SNR are derived, considering double - fading, THz pointing errors, and phase errors. The system's outage probability and average BER are analyzed using these results. The diversity order is shown to depend on fading parameters and, as well as the TPE parameter, but remains unaffected by phase errors. The proposed MRIS-MH approach effectively extends the range of THz transmission with multiple RIS.

2) RIS-BASED THz COMMUNICATIONS USING UAV

The performance evaluation of RIS-based THz communications utilizing UAVs is the main topic of this subsection. The research focuses on optimizing UAV trajectory, RIS phase shift, THz sub-band allocation, and power control, as well as tackling the difficulties of proactive handoff and beam selection in THz drone communication networks and using the THz band for inter-satellite links in low Earth orbit (LEO) satellite systems. Several approaches are used, such as those based on deep learning, evaluation of THz band use, mathematical modeling of error performance, and iterative optimization algorithms. Extensive simulations show that these techniques improve coverage, reliability, achievable rates, and error rate performance in RIS-based THz communications employing UAVs, as shown in the studies.

In this study [143], the authors use RISs to address the difficulties of proactive handoff and beam selection in THz drone communication networks. In the next generation of wireless networks, drones are essential, and their use in the THz band allows significant data speeds. However, THz communications are vulnerable to channel imperfections and blockage effects when considering drone mobility. The authors suggest a deep learning approach based on the Gated Recurrent Unit (GRU), which predicts each drone's serving BS/RIS and the serving beam based on previous observations of drone location and beam trajectories. This approach integrates RISs into THz drone communications. This strategy improves wireless communications' coverage and dependability by lowering beam training overhead and delay. The numerical results from 3D ray-tracing simulations demonstrate the usefulness of the proposed deep learning solution, which achieves near-optimal proactive handoff performance and greater than 90 percent accuracy for beam prediction. In another study [144], the use of the THz band for inter-satellite links in LEO satellite systems is investigated. The THz band enables wideband communication, and multi-antenna systems can improve system performance. However, the implementation of multi-antenna systems needs to be rethought due to size, weight, and power restrictions. RISs, an opportunity to loosen these restrictions, may cause beam misalignment because of differences in reflection properties. The research evaluates the use of the THz spectrum and quantifies the effect of misalignment fading on error performance. RISs mounted on nearby satellites are suggested for signal propagation to reduce excessive path loss and enhance the SNR. Mathematical formulas for error rates in RIS-aided ISLs under misalignment fading are derived, and numerical results show that RISs can improve error rate performance and achievable capacity in THz ISLs.

The authors in [145] examine how UAVs and RIS can be used for THz communications. To increase the minimum feasible rate for all users, the joint optimization of UAV trajectory, RIS phase shift, THz sub-band allocation, and power regulation is examined. An SCA with the rate constraint penalty iteration algorithm is developed to handle the problem's non-convexity. The program divides the optimization problem into three subproblems: THz sub-band allocation with power management, RIS phase shift, and UAV trajectory. According to simulation results, the proposed strategy dramatically improves the system's overall rate performance.

Discussion: This subsection delves into performance analysis for RIS-assisted THz systems, particularly in mMIMO and UAV applications, to enhance system capacity, EE, beamforming, and reliability. The following references provide insights into various approaches, as summarized in Table 8.

MIMO/mMIMO-based RIS-Assisted THz Systems: In [127], a TE-GD algorithm optimizes RIS phase shifts in MIMO systems, significantly boosting SE by 4.3 bps/Hz and reducing complexity by 80%. However, real-world dynamic condition validation is needed. Reference [128] investigates power gain and EE in RIS-assisted MIMO systems, demonstrating better performance with beam focusing than traditional beamforming. However, testing in diverse environments is essential for broader optimization. Reference [129] presents an RIS-aided multiuser THz MIMO system with hybrid analog/digital beamforming to optimize energy consumption and address CSI imperfections. The approach is effective, but larger network scalability and real-time performance need further validation. Reference [130] introduces an NRIS and an A-GD algorithm for optimizing phase shifts. While the study showcases improvements in phase response and EE, further testing is required in dynamic and larger networks. [131] introduces an IAP-SP scheme for CSI estimation using compressed sensing, achieving a 99.5% reduction in complexity while maintaining performance. The method's adaptability to real-time communications needs further exploration. Reference [132] introduces a cooperative beam training strategy to enhance CE efficiency for RIS-assisted mMIMO systems. While the technique shows potential, it requires broader testing in multi-user, complex environments.

In [134], a hybrid precoding architecture for RIS-assisted THz multi-user mMIMO systems is developed to mitigate phase-shifting errors and improve SE. While the framework is promising, further real-world trials are needed to assess performance under practical conditions. Reference [135] proposes an DL-MDC algorithm for hybrid precoding, optimizing SE in THz mMIMO systems with low complexity. This method showcases high performance but lacks real-time adaptive trials in large-scale deployments. Reference [136] focuses on optimizing RIS phase shifts in THz umMIMO systems using an APG method. This method shows strong performance gains but needs broader validation for larger RIS deployments and more complex scenarios. Reference [137] examines coordinated multi-RIS systems to improve reliability in THz communications. While the system's robustness against pointing errors is demonstrated, further tests are needed for full scalability in 6G applications. Reference [138] introduces RTHz-NOMA to enhance sum-rate performance in THz communications using RIS and NOMA techniques. While it shows promise for reducing BER, further real-world validation is required for large-scale 6G networks. The paper [140] proposes a RIS-enhanced hybrid FSO-THz network, improving outage probability and SER but overlooking real-world issues like FSO misalignment and weather effects. In [141], a H-RIS system for THz communication improves EE, but scalability challenges in large deployments are not addressed. The study [142] presents a multihop RIS-assisted scheme that extends THz transmission range, though it lacks consideration of real-world factors like mobility and interference.

UAV-based RIS-Assisted THz Systems: [143] proposes a GRU-based deep learning approach to predict optimal beam selection and handoff in THz drone networks, achieving over 90% beam prediction accuracy. However, real-time testing in highly dynamic environments is necessary. Reference [144] investigates RIS usage for THz inter-satellite links in LEO satellite systems, addressing path loss and beam misalignment. The study is promising, but further research is needed to scale the solution across larger satellite constellations. Reference [145] optimizes UAV trajectory, RIS phase shifts, and sub-band allocation, improving the minimum achievable rate in THz communications. While effective, real-time testing under various environmental challenges is required for broader validation. Reference [39] explores the use of RIS for beamforming in sub-THz bands, achieving significant improvements in high data rate transmission. However, more extensive studies are needed to validate its performance in real-world 6G environments.

VI. FUTURE RESEARCH DIRECTIONS AND CHALLENGES

This section explores the open challenges and potential avenues for future research in RIS-based THz communications. It aims to shed light on unresolved questions and explore new opportunities for advancement.

- CE and Transmission Optimization: Securing precise CSI is pivotal for achieving optimal beamforming, enabling the nuanced adjustment of amplitude and phase weights across each antenna element to facilitate multifaceted beamforming rather than mere beam direction. However, this process faces several hurdles. Traditional pilot signals often lack sufficient beam gain, leading to their reception at suboptimal SNR or complete non-detection due to THz communication's pronounced propagation losses [146]. This scenario complicates CSI estimation, necessitating more robust beamforming algorithms. Additionally, the sheer scale of umMIMO systems in the THz range, with their thousands of elements, significantly amplifies the burden of estimation, demanding rapid CE methods that balance latency demands with accuracy. Furthermore, the inability of the RIS to process or emit THz signals independently complicates the direct estimation of the channel between the transmitter-RIS and RIS-receiver. Consequently, transceivers and RIS must collaboratively ascertain the characteristics of the cascaded reflective link, presenting a unique challenge to the CE process.
- New Materials Exploration for RIS: The unique electromagnetic properties of RIS have sparked significant interest in creating a controllable wireless environment beyond what traditional materials can achieve, especially in terms of THz beam manipulation. RIS, essentially a two-dimensional metamaterial with minimal thickness, can modulate incoming electromagnetic waves by creating a phase gradient across its surface, allowing for the precise control of the THz beam's propagation direction, polarization, and waveform. The challenge in RIS design lies in optimizing dynamic sub-wavelength reflectors, utilizing materials like vanadium dioxide [147], [148], liquid crystal [149], [150], and graphene [151], with a notable design for a graphene-based RIS presented in [96]. VO2-based RISs adjust their conductivity and, consequently, the phase response of reflectors through thermal and laser pumping. Despite advancements, the development of RIS hardware for practical use in upcoming 6G networks remains in early stages. Future research must tackle issues around the theoretical and practical integration of RIS, including material exploration and device engineering. Current commercial semiconductor devices, such as PIN diodes, varactor diodes, and micro motors, are too large for THz applications. Although materials like vanadium dioxide and liquid crystal offer some solutions, they suffer from slow modulation speeds. High Electron Mobility Transistors (HEMT) have been proposed [152] for their nanoscale dimensions and rapid electron mobility, making them suitable for active THz devices, though their high power consumption poses new challenges. This underscores the urgent need for developing new RIS materials and designs that balance performance and power efficiency.
- Channel Measurements and Modeling: Optimizing THz wireless communication systems enhanced by RIS technology necessitates the creation of precise and realistic communication models that highlight the propagation characteristics of THz waves and the physical attributes of RIS, crucial for the evolution of 6G networks. Researchers have put forward three path loss models rooted in electromagnetic theory, focusing on scenarios like far-field and near-field beamforming, as well as near-field broadcasting, all of which consider the RIS's size and element radiation patterns and are validated through experiments. These models emphasize the impact of RIS dimensions and proximity on path loss, especially in near-field conditions. Additionally, a phase shift model introduced in [153] addresses

the amplitude variations relative to phase shifts in RIS elements, suggesting a superior beamforming approach over traditional models that assume constant amplitude. Despite progress, THz wave propagation's unique challenges, such as significant path loss and molecular absorption, are addressed by proposing a multi-hop RIS configuration to enhance coverage and signal integrity [154]. Experimental efforts, particularly leveraging graphene's tunable properties for THz frequency applications [155], demonstrate its feasibility, though the gap between theoretical models and practical implementation highlights the need for further empirical research and channel model development.

- Deployment and Networking: The deployment and networking of RIS technology are critical areas of study for enhancing THz wireless communication systems, addressing the significant challenge of propagation attenuation due to THz's short transmission range. To ensure viable communication distances, extensive RIS deployment is necessary within the wireless environment, calling for optimized deployment strategies across various locations to improve link quality and system performance [156]. Practical considerations such as cost, environmental conditions, urban architecture, RIS quantity, maintenance, and aesthetics play a significant role in deployment decisions. Despite ongoing research into RIS's capacity enhancement through phase shift and precoding matrix optimization for user scenarios, the specific strategies for RIS placement and density in THz communications remain underexplored. Unlike active relay systems [157], RIS operates passively, reflecting signals without processing them, suggesting proximity to transmitters or receivers can mitigate THz signal loss. RIS's simple, lightweight, and low-energy design allows for denser network deployment, enhancing coverage and addressing THz's propagation limitations. Unlike active relays, RIS avoids mutual interference, simplifying network design by allowing signal separation from multiple RIS units. Research using stochastic geometry has shown significant network performance gains from RIS deployment, and machine learning approaches have been proposed to optimize energy efficiency and system design in RIS-assisted NOMA systems [158]. Various deployment strategies, including distributed and centralized RIS configurations, have been analyzed [159], emphasizing the need to integrate RIS deployment with traditional network architectures and design MAC protocols that consider THz's narrow beamwidth for optimal network performance.
- Transceivers and RIS Hardware Design: The advancement of THz technology in umMIMO systems presents several challenges. Currently, THz antennas and RIS typically support single carrier modulation with small arrays of fewer than 20 elements. As these systems evolve towards wideband communication, the design complexity of antenna arrays increases due to sophisticated wiring and the need for effective heat dissipation. Additionally, the nonlinear behavior of THz devices complicates signal amplification, leading to higher energy consumption and reduced transmission power. The short wavelength of THz waves requires a denser arrangement of reflective elements, up to 1024 per 1 mm^2 at 1 THz, making integration with semiconductor devices difficult. The use of tunable materials in RIS, like vanadium dioxide, liquid crystal, and graphene, also adds variability that complicates passive beamforming for wideband communication. RIS-activated reflectarray antennas are emerging as a potential solution, enhancing waveform control, modulation, and beamforming capabilities.
- Beam Management: Ultra-massive MIMO systems in the THz spectrum use tightly focused beams to mitigate significant propagation losses, necessitating precise beam alignment toward the receiver. In applications like RIS-enhanced drone and vehicular networks, there's a crucial need for beams that can dynamically adjust in three dimensions to match the rapid movements of these platforms. This introduces complex beam management challenges. Key requirements include developing advanced 3D codebook configurations tailored for THz transceivers and RIS setups, possibly incorporating hybrid beamforming or low-bit quantized phase shifters to boost efficiency. Additionally, co-developing beam training and tracking methods between transmitters and RIS is essential to maintain seamless communication with fast-moving entities. In multi-user scenarios, crafting strategies for beam scheduling and interference suppression is critical to improve system performance and minimize interference risks.
- AI/ML-Empowered Techniques: AI and ML technologies offer promising solutions to the complex challenges in THz RIS communications, particularly in acquiring CSI and managing the nuances of joint beamforming [33]. The use of ultra-high frequency bands and large antenna arrays complicates these tasks significantly. AI/ML methods, by leveraging the sparse nature of THz communication channels, can simplify CSI acquisition and enable more efficient beamforming and antenna selection strategies. This approach reduces the computational burden and addresses the complexity inherent in designing beamforming strategies for THz communications. Despite the potential, the application of AI/ML in this field is still in early development stages, indicating a substantial scope for future research to optimize their use in THz RIS systems and enhance overall communication efficiency.
- Sensing and Localization: The THz frequency band, renowned for its ultra-high data transmission capabilities, also holds significant promise for advanced sensing and localization applications. Its transmission properties enable fast tracking and millimeter-level precision in wireless positioning. The integration of RIS further

enhances these capabilities, offering new avenues for merging communication with high-resolution sensing and localization. This integration within THz RIS communications presents a complex yet valuable research opportunity.

VII. CONCLUSION

This survey has provided a comprehensive and detailed review of the RIS-based THz communication technology in the context of 6G networks. We have explored distinct use cases, resource allocation strategies, and performance evaluation criteria by examining RIS-based THz systems' most recent schemes and advancements. The survey has offered a cohesive and connected overview of the RIS and its variants, including reflective RIS, transmissive RIS, and STAR-RIS. We have highlighted the versatility and potential of RIS-based THz technology by categorizing schemes based on specific use cases, such as CE, coverage, security, sum rate maximization, and EE. The survey has also investigated various resource allocation strategies and performance evaluation metrics, providing valuable insights into system optimization and performance assessment. By delving into the literature and comparing different approaches, we have contributed to a deeper understanding of this field's system model settings, solving techniques, and optimization objectives. Finally, we have identified outstanding research challenges and proposed new directions for future investigations.

REFERENCES

[1] C.-X. Wang, X. You, X. Gao, X. Zhu, Z. Li, C. Zhang, H. Wang, Y. Huang, Y. Chen, H. Haas, J. S. Thompson, E. G. Larsson, M. D. Renzo, W. Tong, P. Zhu, X. Shen, H. V. Poor, and L. Hanzo, "On the road to 6G: Visions, requirements, key technologies and testbeds," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 2, pp. 905–974, Feb. 2023.

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

[3] D. Serghiou, M. Khalily, T. W. C. Brown, and R. Tafazolli, "Terahertz channel propagation phenomena, measurement techniques and modeling for 6G wireless communication applications: A survey, open challenges and future research directions," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 1957–1996, 4th Quart., 2022.

[4] D. G. S. Pivoto, T. T. Rezende, M. S. P. Facina, R. Moreira, F. de Oliveira Silva, K. V. Cardoso, S. L. Correa, A. V. D. Araujo, R. S. E. Silva, H. S. Neto, G. R. de Lima Tejerina, and A. M. Alberti, "A detailed relevance analysis of enabling technologies for 6G architectures," *IEEE Access*, vol. 11, pp. 89644–89684, 2023.

[5] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Phys. Commun.*, vol. 12, pp. 16–32, Sep. 2014.

[6] W. U. Khan, A. Mahmood, M. A. Jamshed, E. Lagunas, M. Ahmed, and S. Chatzinotas, "Beyond diagonal RIS for 6G non-terrestrial networks: Potentials and challenges," 2024, *arXiv:2406.10691*.

[7] A. A. A. Solyman and I. A. Elhaty, "Potential key challenges for terahertz communication systems," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 4, p. 3403, Aug. 2021.

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

[9] Q. Xue, C. Ji, S. Ma, J. Guo, Y. Xu, Q. Chen, and W. Zhang, "A survey of beam management for mmWave and THz communications towards 6G," *IEEE Commun. Surveys Tuts.*, vol. 26, no. 3, pp. 1520–1559, 2024, doi: 10.1109/COMST.2024.3361991.

[10] K. Rasilainen, T. D. Phan, M. Berg, A. Pärssinen, and P. J. Soh, "Hardware aspects of sub-THz antennas and reconfigurable intelligent surfaces for 6G communications," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2530–2546, Jun. 2023.

[11] S. Gong, X. Lu, D. T. Hoang, D. Niyato, L. Shu, D. I. Kim, and Y.-C. Liang, "Toward smart wireless communications via intelligent reflecting surfaces: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2283–2314, 4th Quart., 2020.

[12] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. de Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2450–2525, Nov. 2020.

[13] C. Pan, G. Zhou, K. Zhi, S. Hong, T. Wu, Y. Pan, H. Ren, M. D. Renzo, A. L. Swindlehurst, R. Zhang, and A. Y. Zhang, "An overview of signal processing techniques for RIS/IRS-aided wireless systems," *IEEE J. Sel. Topics Signal Process.*, vol. 16, no. 5, pp. 883–917, Aug. 2022.

[14] M. Ahmed, S. Raza, A. A. Soofi, F. Khan, W. U. Khan, F. Xu, S. Chatzinotas, O. A. Dobre, and Z. Han, "A survey on reconfigurable intelligent surfaces assisted multi-access edge computing networks: State of the art and future challenges," *Comput. Sci. Rev.*, vol. 54, Nov. 2024, Art. no. 100668.

[15] M. Ahmed, S. Raza, A. A. Soofi, F. Khan, W. U. Khan, S. Z. U. Abideen, F. Xu, and Z. Han, "Active reconfigurable intelligent surfaces: Expanding the frontiers of wireless communication—A survey," *IEEE Commun. Surveys Tuts.*, early access, Jul. 4, 2024, doi: 10.1109/COMST.2024.3423460.

[16] D. T. Phan, J. Palosaari, D. Kong, T. Siponkoski, S. Myllymäki, M. E. Leinonen, A. Pärssinen, J. Juuti, and P. J. Soh, "Sub-THz spatially modulated beam splitting reflectors for potential RIS implementations," in *Proc. 18th Eur. Conf. Antennas Propag. (EuCAP)*, Glasgow, U.K., Mar. 2024, pp. 1–4.

[17] M. Deng, M. Ahmed, A. Wahid, A. A. Soofi, W. U. Khan, F. Xu, M. Asif, and Z. Han, "Reconfigurable intelligent surfaces enabled vehicular communications: A comprehensive survey of recent advances and future challenges," *IEEE Trans. Intell. Vehicles*, early access, Oct. 14, 2024, doi: 10.1109/TIV.2024.3476934.

[18] C. K. Sheemar, S. Solanki, W. U. Khan, Z. Abdullah, E. Lagunas, and S. Chatzinotas, "Reflecting intelligent surfaces assisted high-rank ultra massive MIMO terahertz channels," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2024, pp. 1–6.

[19] Y.-C. Liang, R. Long, Q. Zhang, J. Chen, H. V. Cheng, and H. Guo, "Large intelligent surface/antennas (LISA): Making reflective radios smart," *J. Commun. Inf. Netw.*, vol. 4, no. 2, pp. 40–50, Jun. 2019.

[20] M. D. Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, H. Gacanin, J. D. Rosny, A. Bounceur, G. Lerosey, and M. Fink, "Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, pp. 1–20, May 2019.

[21] S. Kisseleff, W. A. Martins, H. Al-Hraishawi, S. Chatzinotas, and B. Ottersten, "Reconfigurable intelligent surfaces for smart cities: Research challenges and opportunities," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 1781–1797, 2020.

[22] M. A. ElMossallamy, H. Zhang, L. Song, K. G. Seddik, Z. Han, and G. Y. Li, "Reconfigurable intelligent surfaces for wireless communications: Principles, challenges, and opportunities," *IEEE Trans. Cognit. Commun. Netw.*, vol. 6, no. 3, pp. 990–1002, Sep. 2020.

[23] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," *IEEE Trans. Commun.*, vol. 69, no. 5, pp. 3313–3351, May 2021.

[24] W. Long, R. Chen, M. Moretti, W. Zhang, and J. Li, "A promising technology for 6G wireless networks: Intelligent reflecting surface," *J. Commun. Inf. Netw.*, vol. 6, no. 1, pp. 1–16, Mar. 2021.

[25] S. Kisseleff, S. Chatzinotas, and B. Ottersten, "Reconfigurable intelligent surfaces in challenging environments: Underwater, underground, industrial and disaster," *IEEE Access*, vol. 9, pp. 150214–150233, 2021.

[26] X. Yuan, Y. A. Zhang, Y. Shi, W. Yan, and H. Liu, "Reconfigurable-Intelligent-Surface empowered wireless communications: Challenges and opportunities," *IEEE Wireless Commun.*, vol. 28, no. 2, pp. 136–143, Apr. 2021.

[27] Y. Liu, X. Liu, X. Mu, T. Hou, J. Xu, M. D. Renzo, and N. Al-Dhahir, "Reconfigurable intelligent surfaces: Principles and opportunities," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1546–1577, 3rd Quart., 2021.

[28] H. Zhang, B. Di, K. Bian, Z. Han, H. V. Poor, and L. Song, "Toward ubiquitous sensing and localization with reconfigurable intelligent surfaces," *Proc. IEEE*, vol. 110, no. 9, pp. 1401–1422, Sep. 2022.

[29] E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti, and E. de Carvalho, "Reconfigurable intelligent surfaces: A signal processing perspective with wireless applications," *IEEE Signal Process. Mag.*, vol. 39, no. 2, pp. 135–158, Mar. 2022.

[30] H. Zhang, S. Zeng, B. Di, Y. Tan, M. D. Renzo, M. Debbah, Z. Han, H. V. Poor, and L. Song, "Intelligent omni-surfaces for full-dimensional wireless communications: Principles, technology, and implementation," *IEEE Commun. Mag.*, vol. 60, no. 2, pp. 39–45, Feb. 2022.

[31] H. Zhang and B. Di, "Intelligent omni-surfaces: Simultaneous refraction and reflection for full-dimensional wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 1997–2028, 4th Quart., 2022.

[32] H. Zhou, M. Erol-Kantarci, Y. Liu, and H. V. Poor, "A survey on model-based, heuristic, and machine learning optimization approaches in RIS-aided wireless networks," *IEEE Commun. Surveys Tuts.*, vol. 26, no. 2, pp. 781–823, 2nd Quart., 2024.

[33] S. K. Das, F. Benkhelifa, Y. Sun, H. Abumarshoud, Q. H. Abbasi, M. A. Imran, and L. Mohjazi, "Comprehensive review on ML-based RIS-enhanced IoT systems: Basics, research progress and future challenges," *Comput. Netw.*, vol. 224, Apr. 2023, Art. no. 109581.

[34] G. C. Alexandropoulos, K. Stylianopoulos, C. Huang, C. Yuen, M. Bennis, and M. Debbah, "Pervasive machine learning for smart radio environments enabled by reconfigurable intelligent surfaces," *Proc. IEEE*, vol. 110, no. 9, pp. 1494–1525, Sep. 2022.

[35] A. Raza, U. Ijaz, M. K. Ishfaq, S. Ahmad, M. Liaqat, F. Anwar, A. Iqbal, and M. S. Sharif, "Intelligent reflecting surface-assisted terahertz communication towards B5G and 6G: State-of-the-art," *Microw. Opt. Technol. Lett.*, vol. 64, no. 5, pp. 858–866, Feb. 2022.

[36] Z. Chen, X. Ma, C. Han, and Q. Wen, "Towards intelligent reflecting surface empowered 6G terahertz communications: A survey," *China Commun.*, vol. 18, no. 5, pp. 93–119, May 2021.

[37] A. Patel and A. Shukla, "A review on intelligent reflecting surface-based terahertz communication," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 25, no. 3, pp. 1580–1588, Mar. 2022.

[38] S. Gopinath, "An overview of compressive sensing for IRS assisted secure terahertz communication," *Open J. Sci. Technol.*, vol. 4, no. 4, pp. 184–194, Apr. 2022. [Online]. Available: https://api.semanticscholar.org/CorpusID:235497499

[39] Y. Ogawa, S. Tadokoro, S. Suyama, M. Iwabuchi, T. Nishimura, T. Sato, J. Hagiwara, and T. Ohgane, "Smart radio environments with intelligent reflecting surfaces for 6G sub-terahertz-band communications," *IEICE Trans. Commun.*, vol. E106.B, no. 9, pp. 735–747, Sep. 2023.

[40] M. Ahmed, F. Xu, A. Wahid, K. Ali, M. A. Mirza, W. Khan, K. Dev, S. A. Hassan, and Z. Han, "A comprehensive survey of artificial intelligence advances in ris-assisted wireless networks," *TechRxiv*, Aug. 2024.

[41] E. Basar, M. D. Renzo, J. D. Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753–116773, 2019.

[42] W. U. Khan, E. Lagunas, A. Mahmood, S. Chatzinotas, and B. Ottersten, "RIS-assisted energy-efficient LEO satellite communications with NOMA," *IEEE Trans. Green Commun. Netw.*, vol. 8, no. 2, pp. 780–790, Jun. 2024.

[43] W. U. Khan, A. Mahmood, A. Bozorgchenani, M. A. Jamshed, A. Ranjha, E. Lagunas, H. Pervaiz, S. Chatzinotas, B. Ottersten, and P. Popovski, "Opportunities for intelligent reflecting surfaces in 6G empowered V2X communications," *IEEE Internet Things Mag.*, vol. 7, no. 6, pp. 72–79, Nov. 2024.

[44] Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. V. Poor, "Active RIS vs. passive RIS: Which will prevail in 6G?" *IEEE Trans. Commun.*, vol. 71, no. 3, pp. 1707–1725, Mar. 2023.

[45] J. Loncar and Z. Šipuš, "Challenges in design of power-amplifying active metasurfaces," in *Proc. Int. Symp. ELMAR*, Zadar, Croatia, Sep. 2020, pp. 9–12.

[46] K. Zhi, C. Pan, H. Ren, K. K. Chai, and M. Elkashlan, "Active RIS versus passive RIS: Which is superior with the same power budget?" *IEEE Commun. Lett.*, vol. 26, no. 5, pp. 1150–1154, May 2022.

[47] I. Yildirim, F. Kilinc, E. Basar, and G. C. Alexandropoulos, "Hybrid RIS-empowered reflection and decode-and-forward relaying for coverage extension," *IEEE Commun. Lett.*, vol. 25, no. 5, pp. 1692–1696, May 2021.

[48] R. Schroeder, J. He, and M. Juntti, "Passive RIS vs. hybrid RIS: A comparative study on channel estimation," in *Proc. IEEE 93rd Veh. Technol. Conf. (VTC-Spring)*, Helsinki, Finland, Apr. 2021, pp. 1–7.

[49] W. U. Khan, E. Lagunas, Z. Ali, M. A. Javed, M. Ahmed, S. Chatzinotas, B. Ottersten, and P. Popovski, "Opportunities for physical layer security in UAV communication enhanced with intelligent reflective surfaces," *IEEE Wireless Commun.*, vol. 29, no. 6, pp. 22–28, Dec. 2022.

[50] M. Najafi, V. Jamali, R. Schober, and H. V. Poor, "Physics-based modeling and scalable optimization of large intelligent reflecting surfaces," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2673–2691, Apr. 2020.

[51] J. Tang, S. Xu, F. Yang, and M. Li, "Recent developments of transmissive reconfigurable intelligent surfaces: A review," *ZTE Commun.*, vol. 20, no. 1, pp. 21–27, Mar. 2022.

[52] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394–5409, Nov. 2019.

[53] B. Zheng, Q. Wu, and R. Zhang, "Intelligent reflecting surface-assisted multiple access with user pairing: NOMA or OMA?" *IEEE Commun. Lett.*, vol. 24, no. 4, pp. 753–757, Apr. 2020.

[54] X. Mu, Y. Liu, L. Guo, J. Lin, and N. Al-Dhahir, "Exploiting intelligent reflecting surfaces in NOMA networks: Joint beamforming optimization," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6884–6898, Oct. 2020.

[55] Y. Liu, X. Mu, J. Xu, R. Schober, Y. Hao, H. V. Poor, and L. Hanzo, "STAR: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces," *IEEE Wireless Commun.*, vol. 28, no. 6, pp. 102–109, Dec. 2021.

[56] M. Asif, X. Bao, A. Ihsan, W. U. Khan, M. Ahmed, and X. Li, "Securing NOMA 6G communications leveraging intelligent omni-surfaces under residual hardware impairments," *IEEE Internet Things J.*, vol. 11, no. 14, pp. 25326–25336, Jul. 2024.

[57] M. Ahmed, A. Wahid, S. S. Laique, W. U. Khan, A. Ihsan, F. Xu, S. Chatzinotas, and Z. Han, "A survey on STAR-RIS: Use cases, recent advances, and future research challenges," *IEEE Internet Things J.*, vol. 10, no. 16, pp. 14689–14711, May 2023.

[58] R. Chen, M. Liu, Y. Hui, N. Cheng, and J. Li, "Reconfigurable intelligent surfaces for 6G IoT wireless positioning: A contemporary survey," *IEEE Internet Things J.*, vol. 9, no. 23, pp. 23570–23582, Dec. 2022.

[59] R. Kaur, B. Bansal, S. Majhi, S. Jain, C. Huang, and C. Yuen, "A survey on reconfigurable intelligent surface for physical layer security of next-generation wireless communications," *IEEE Open J. Veh. Technol.*, vol. 5, pp. 172–199, 2024.

[60] A. C. Pogaku, D.-T. Do, B. M. Lee, and N. D. Nguyen, "UAV-assisted RIS for future wireless communications: A survey on optimization and performance analysis," *IEEE Access*, vol. 10, pp. 16320–16336, 2022.

[61] S. Aboagye, A. R. Ndjiongue, T. M. N. Ngatched, O. A. Dobre, and H. V. Poor, "RIS-assisted visible light communication systems: A tutorial," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 1, pp. 251–288, 1st Quart., 2023.

[62] Q. Hou and J. Dong, "Dynamic event-triggered fixed-time tracking control for state-constrained nonlinear systems with dead zone based on fast fixed-time filters," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 54, no. 1, pp. 634–643, Jan. 2024.

[63] Q. Hou and J. Dong, "Fully distributed cooperative fault-tolerant output regulation of linear heterogeneous MASs: A dynamic memory event-triggered distributed observer approach," *IEEE Trans. Autom. Sci. Eng.*, vol. 21, no. 3, pp. 4548–4560, Jul. 2024.

[64] N. Yafune, K. Yano, K. Mori, and T. Sakano, "Evaluation of RoCE protocol in backhaul systems for ultra-high-speed THz wireless LAN," in *Proc. IEEE 21st Consum. Commun. Netw. Conf. (CCNC)*, Las Vegas, NV, USA, Jan. 2024, pp. 811–814.

[65] W. Jiang, Q. Zhou, J. He, M. A. Habibi, S. Melnyk, M. El-Absi, B. Han, M. D. Renzo, H. D. Schotten, F.-L. Luo, T. S. El-Bawab, M. Juntti, M. Debbah, and V. C. M. Leung, "Terahertz communications and sensing for 6G and beyond: A comprehensive review," *IEEE Commun. Surveys Tuts.*, early access, Apr. 8, 2024, doi: 10.1109/COMST.2024.3385908.

[66] X. Cai, X. Cheng, and F. Tufvesson, "Toward 6G with terahertz communications: Understanding the propagation channels," *IEEE Commun. Mag.*, vol. 62, no. 2, pp. 32–38, Feb. 2024.

[67] Y. Ma, K. Ota, and M. Dong, "QoE optimization for virtual reality services in multi-RIS-assisted terahertz wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 538–551, Mar. 2024.

[68] A. Mayuri, J. Chauhan, A. Gadgil, O. Rajani, and S. Rajadhyaksha, ''6G systems in secure data transmission,'' in *Wireless Communication for Cybersecurity*. Wiley, Oct. 2023, ch. 10, pp. 217–238. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119910619.ch10

[69] C. Han, Y. Wu, Z. Chen, Y. Chen, and G. Wang, ''THz ISAC: A physical-layer perspective of terahertz integrated sensing and communication,'' *IEEE Commun. Mag.*, vol. 62, no. 2, pp. 102–108, Feb. 2024.

[70] A. J. Alqaraghuli, J. V. Siles, and J. M. Jornet, ''The road to high data rates in space: Terahertz versus optical wireless communication,'' *IEEE Aerosp. Electron. Syst. Mag.*, vol. 38, no. 6, pp. 4–13, Jun. 2023.

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

[72] C. Han, X. Zhang, and X. Wang, ''On medium access control schemes for wireless networks in the millimeter-wave and terahertz bands,'' *Nano Commun. Netw.*, vol. 19, pp. 67–80, Mar. 2019.

[73] T. Kürner and S. Priebe, ''Towards THz communications—Status in research, standardization and regulation,'' *J. Infr., Millim., THz Waves*, vol. 35, no. 1, pp. 53–62, Jan. 2014.

[74] A. S. Cacciapuoti, K. Sankhe, M. Caleffi, and K. R. Chowdhury, ''Beyond 5G: THz-based medium access protocol for mobile heterogeneous networks,'' *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 110–115, Jun. 2018.

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

[76] M. Polese, F. Restuccia, A. Gosain, J. Jornet, S. Bhardwaj, V. Ariyarathna, S. Mandal, K. Zheng, A. Dhananjay, M. Mezzavilla, J. Buckwalter, M. Rodwell, X. Wang, M. Zorzi, A. Madanayake, and T. Melodia, ''MillimeTera: Toward a large-scale open-source mmWave and terahertz experimental testbed,'' in *Proc. 3rd ACM Workshop Millimeter-Wave Netw. Sens. Syst.*, Oct. 2019, pp. 27–32.

[77] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, ''Millimeter wave communication: A comprehensive survey,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1616–1653, 3rd Quart., 2018.

[78] J. Ma, ''Terahertz wireless communication through atmospheric turbulence and rain,'' Ph.D. dissertation, New Jersey Inst. Technol., Newark, NJ, USA, 2016. [Online]. Available: https://digitalcommons.njit.edu/dissertations/61

[79] C. Han, Y. Wang, Y. Li, Y. Chen, N. A. Abbasi, T. Kürner, and A. F. Molisch, ''Terahertz wireless channels: A holistic survey on measurement, modeling, and analysis,'' *IEEE Commun. Surveys Tuts.*, vol. 24, no. 3, pp. 1670–1707, 3rd Quart., 2022.

[80] S. Liu, X. Yu, R. Guo, Y. Tang, and Z. Zhao, ''THz channel modeling: Consolidating the road to THz communications,'' *China Commun.*, vol. 18, no. 5, pp. 33–49, May 2021.

[81] C. Han and Y. Chen, ''Propagation modeling for wireless communications in the terahertz band,'' *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 96–101, Jun. 2018.

[82] W. Chen, Z. Chen, and X. Ma, ''Channel estimation for intelligent reflecting surface aided multi-user MISO terahertz system,'' *THz Sci. Technol.*, vol. 13, no. 2, pp. 51–60, Jun. 2020.

[83] Z. Li, Z. Chen, X. Ma, and W. Chen, ''Channel estimation for intelligent reflecting surface enabled terahertz MIMO systems: A deep learning perspective,'' in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC Workshops)*. Chongqing, China: IEEE, Aug. 2020, pp. 75–79.

[84] X. Su, R. He, B. Ai, Y. Niu, and G. Wang, ''Channel estimation for RIS assisted THz systems with beam split,'' *IEEE Commun. Lett.*, vol. 28, no. 3, pp. 637–641, Mar. 2024.

[85] J. Du, Y. Cheng, L. Jin, S. Li, and F. Gao, ''Nested tensor-based integrated sensing and communication in RIS-assisted THz MIMO systems,'' *IEEE Trans. Signal Process.*, vol. 72, pp. 1141–1157, 2024.

[86] X. Ma, Z. Chen, W. Chen, Z. Li, Y. Chi, C. Han, and S. Li, ''Joint channel estimation and data rate maximization for intelligent reflecting surface assisted terahertz MIMO communication systems,'' *IEEE Access*, vol. 8, pp. 99565–99581, 2020.

[87] Y. Chen, R. Li, C. Han, S. Sun, and M. Tao, ''Hybrid spherical- and planar-wave channel modeling and estimation for terahertz integrated UM-MIMO and IRS systems,'' *IEEE Trans. Wireless Commun.*, vol. 22, no. 12, pp. 9746–9761, May 2023.

[88] J. Wu, S. Kim, and B. Shim, ''Parametric sparse channel estimation for RIS-assisted terahertz systems,'' *IEEE Trans. Commun.*, vol. 71, no. 9, pp. 5503–5518, Jun. 2023.

[89] W. Zhang, W. Wang, and W. Zhang, ''Channel training for RIS-aided indoor terahertz MIMO systems,'' *IEEE Wireless Commun. Lett.*, vol. 12, no. 8, pp. 1384–1388, Aug. 2023.

[90] Y. Pan, C. Pan, S. Jin, and J. Wang, ''RIS-aided near-field localization and channel estimation for the terahertz system,'' *IEEE J. Sel. Topics Signal Process.*, vol. 17, no. 4, pp. 878–892, Jun. 2023.

[91] Y. Dai, W. Zhao, Y. You, Y. Huang, and C. Zhang, ''Local subdivisional channel estimation in RIS-assisted THz MIMO-OFDM systems,'' in *Proc. 5th Inf. Commun. Technol. Conf. (ICTC)*. Nanjing, China: IEEE, May 2024, pp. 234–238.

[92] C. Hongyun, P. Xue, and L. Baijiang, ''Channel estimation for reconfigurable intelligent surface aided multiuser millimeter-wave/THz systems,'' *China Commun.*, vol. 21, no. 3, pp. 91–103, Mar. 2024.

[93] W. Yan, W. Hao, C. Huang, G. Sun, O. Muta, H. Gacanin, and C. Yuen, ''Beamforming analysis and design for wideband THz reconfigurable intelligent surface communications,'' *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2306–2320, Aug. 2023.

[94] R. Su, L. Dai, and D. W. K. Ng, ''Wideband precoding for RIS-aided THz communications,'' *IEEE Trans. Commun.*, vol. 71, no. 6, pp. 3592–3604, Jun. 2023.

[95] X. Su, R. He, P. Zhang, and B. Ai, ''Joint precoding for RIS-assisted wideband THz cell-free massive MIMO systems,'' 2024, *arXiv:2405.07830*.

[96] X. Ma, Z. Chen, W. Chen, Y. Chi, Z. Li, C. Han, and Q. Wen, ''Intelligent reflecting surface enhanced indoor terahertz communication systems,'' *Nano Commun. Netw.*, vol. 24, May 2020, Art. no. 100284.

[97] A. A. Boulogeorgos and A. Alexiou, ''Coverage analysis of reconfigurable intelligent surface assisted THz wireless systems,'' *IEEE Open J. Veh. Technol.*, vol. 2, pp. 94–110, 2021.

[98] C. Huang, Z. Yang, G. C. Alexandropoulos, K. Xiong, L. Wei, C. Yuen, Z. Zhang, and M. Debbah, ''Multi-hop RIS-empowered terahertz communications: A DRL-based hybrid beamforming design,'' *IEEE J. Sel. Areas Commun.*, vol. 39, no. 6, pp. 1663–1677, Jun. 2021.

[99] X. Wang, Z. Lin, F. Lin, and L. Hanzo, ''Joint hybrid 3D beamforming relying on sensor-based training for reconfigurable intelligent surface aided TeraHertz-based multiuser massive MIMO systems,'' *IEEE Sensors J.*, vol. 22, no. 14, pp. 14540–14552, Jul. 2022.

[100] B. Ning, Z. Chen, W. Chen, and L. Li, ''Improving security of THz communication with intelligent reflecting surface,'' in *Proc. IEEE Globecom Workshops (GC Wkshps)*. Waikoloa, HI, USA: IEEE, Dec. 2019, pp. 1–6.

[101] W. Chen, Z. Chen, X. Ma, Y. Chi, and Z. Li, ''Secrecy rate optimization for intelligent reflecting surface aided multi-input-single-output terahertz communication,'' *Microw. Opt. Technol. Lett.*, vol. 62, no. 8, pp. 2760–2765, Mar. 2020.

[102] J. Qiao and M.-S. Alouini, ''Secure transmission for intelligent reflecting surface-assisted mmWave and terahertz systems,'' *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1743–1747, Oct. 2020.

[103] J. Qiao, C. Zhang, A. Dong, J. Bian, and M.-S. Alouini, ''Securing intelligent reflecting surface assisted terahertz systems,'' *IEEE Trans. Veh. Technol.*, vol. 71, no. 8, pp. 8519–8533, Aug. 2022.

[104] M. Tatar Mamaghani and Y. Hong, ''Aerial intelligent reflecting surface-enabled terahertz covert communications in beyond-5G Internet of Things,'' *IEEE Internet Things J.*, vol. 9, no. 19, pp. 19012–19033, Oct. 2022.

[105] J. Xu, Z. Zhu, Z. Chu, H. Niu, P. Xiao, and I. Lee, ''Sum secrecy rate maximization for IRS-aided multi-cluster MIMO-NOMA terahertz systems,'' *IEEE Trans. Inf. Forensics Security*, vol. 18, pp. 4463–4474, 2023.

[106] A. M. Tota Khel and K. A. Hamdi, ''Secrecy capacity of IRS-assisted terahertz wireless communications with pointing errors,'' *IEEE Commun. Lett.*, vol. 27, no. 4, pp. 1090–1094, Apr. 2023.

[107] G. Sun, H. Shi, B. Shang, and W. Hao, ''Secure transmission for active RIS-assisted THz ISAC systems with delay alignment modulation,'' *IEEE Commun. Lett.*, vol. 28, no. 5, pp. 1019–1023, May 2024.

[108] W. Chen, X. Ma, Z. Li, and N. Kuang, ''Sum-rate maximization for intelligent reflecting surface based terahertz communication systems,'' in *Proc. IEEE/CIC Int. Conf. Commun. Workshops China (ICCC Workshops)*. Changchun, China: IEEE, Aug. 2019, pp. 153–157.

[109] C. Chaccour, M. N. Soorki, W. Saad, M. Bennis, and P. Popovski, ''Risk-based optimization of virtual reality over terahertz reconfigurable intelligent surfaces,'' in *Proc. IEEE Int. Conf. Commun. (ICC)*. Dublin, Ireland: IEEE, Jun. 2020, pp. 1–6.

[110] Y. Pan, K. Wang, C. Pan, H. Zhu, and J. Wang, "Sum-rate maximization for intelligent reflecting surface assisted terahertz communications," *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 3320–3325, Mar. 2022.
[111] Y. Pan, K. Wang, and C. Pan, "Intelligent reflecting surfaces-supported terahertz NOMA communications," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2022, pp. 1743–1748.
[112] M. Shehab, A. Almohamad, M. Elsayed, A. Badawy, T. Khattab, N. Zorba, M. Hasna, and D. Trinchero, "Terahertz multiple access: A deep reinforcement learning controlled multihop IRS topology," 2023, *arXiv:2303.09476*.
[113] H. Li, Y. Liu, X. Mu, Y. Chen, Z. Pan, and Y. C. Eldar, "Near-field beamforming for STAR-RIS networks," Jun. 2023, *arXiv:2306.14587*.
[114] M. Rahim, T. L. Nguyen, G. Kaddoum, and T. N. Do, "Multi-IRS-aided terahertz networks: Channel modeling and user association with imperfect CSI," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 836–855, 2024.
[115] A. Mehrabian and V. W. S. Wong, "Joint spectrum, precoding, and phase shifts design for RIS-aided multiuser MIMO THz systems," *IEEE Trans. Commun.*, vol. 72, no. 8, pp. 5087–5101, Aug. 2024.
[116] M. H. Kumar, S. Sharma, Y. Yoganandam, K. Deka, and A. Kherani, "Reconfigurable intelligent surfaces assisted SM-cooperative NOMA for THz communications," in *Proc. Nat. Conf. Commun. (NCC)*, Feb. 2024, pp. 1–6.
[117] H. Obaid, Y. Zhu, and B. Tan, "Collaborative caching and reconfigurable intelligent surface for the sub-THz mobile system," *IEEE Wireless Commun. Lett.*, vol. 13, no. 11, pp. 2995–2999, Nov. 2024.
[118] T. Do-Duy, A. Masaracchia, B. Canberk, L. D. Nguyen, and T. Q. Duong, "Throughput maximization in RIS-assisted NOMA-THz communication network," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 5706–5717, 2024.
[119] C. V. Phung, A. Drummond, and A. Jukan, "Maximizing throughput with routing interference avoidance in RIS-assisted relay mesh networks," 2024, *arXiv:2402.08825*.
[120] X. Chen, F. Yan, M. Hu, and Z. Lin, "Energy efficiency optimization of intelligent reflective surface-assisted terahertz-RSMA system," 2022, *arXiv:2211.11271*.
[121] Y. Pan, K. Wang, C. Pan, H. Zhu, and J. Wang, "Self-sustainable reconfigurable intelligent surface aided simultaneous terahertz information and power transfer (STIPT)," *IEEE Trans. Wireless Commun.*, vol. 21, no. 7, pp. 5420–5434, Jul. 2022.
[122] Z. Wang, X. Mu, J. Xu, and Y. Liu, "Simultaneously transmitting and reflecting surface (STARS) for terahertz communications," *IEEE J. Sel. Topics Signal Process.*, vol. 17, no. 4, pp. 861–877, Jul. 2023.
[123] T. Mao, Z. Zhou, Z. Xiao, C. Han, and Z. Wang, "Index-modulation-aided terahertz communications with reconfigurable intelligent surface," *IEEE Trans. Wireless Commun.*, vol. 23, no. 7, pp. 8059–8070, Jul. 2024.
[124] L. Ren, H. Zhang, Y. Zhu, and K. Long, "Resource management for intelligent reflecting surface assisted THz-MIMO network," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*. Madrid, Spain: IEEE, Dec. 2021, pp. 1–5.
[125] H. Zarini, N. Gholipoor, M. R. Mili, M. Rasti, H. Tabassum, and E. Hossain, "Resource management for multiplexing eMBB and URLLC services over RIS-aided THz communication," *IEEE Trans. Commun.*, vol. 71, no. 2, pp. 1207–1225, Feb. 2023.
[126] M. Bensalem, A. Engelmann, and A. Jukan, "Towards optimal path allocation for unreliable reconfigurable intelligent surfaces," in *Proc. 19th Int. Conf. Design Reliable Commun. Netw. (DRCN)*. Vilanova i la Geltru, Spain: IEEE, Apr. 2023, pp. 1–8.
[127] Z. Chen, W. Chen, X. Ma, Z. Li, Y. Chi, and C. Han, "Taylor expansion aided gradient descent schemes for IRS-enabled terahertz MIMO systems," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*. Seoul, South Korea: IEEE, Apr. 2020, pp. 1–7.
[128] K. Dovelos, S. D. Assimonis, H. Q. Ngo, B. Bellalta, and M. Matthaiou, "Intelligent reflecting surfaces at terahertz bands: Channel modeling and analysis," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*. Montreal, QC, Canada: IEEE, Jun. 2021, pp. 1–6.
[129] W. Hao, G. Sun, M. Zeng, Z. Chu, Z. Zhu, O. A. Dobre, and P. Xiao, "Robust design for intelligent reflecting surface-assisted MIMO-OFDMA terahertz IoT networks," *IEEE Internet Things J.*, vol. 8, no. 16, pp. 13052–13064, Aug. 2021.
[130] X. Ma, Z. Chen, and C. Huang, "Nanoscale reconfigurable intelligent surface design and performance analysis for terahertz communications," *IEEE Trans. Nanotechnol.*, vol. 21, pp. 629–637, 2022.
[131] B. Ning, Z. Chen, W. Chen, and Y. Du, "Channel estimation and transmission for intelligent reflecting surface assisted THz communications," in *Proc. IEEE Int. Conf. Commun. (ICC)*. Dublin, Ireland: IEEE, Jun. 2020, pp. 1–7.
[132] B. Ning, Z. Chen, W. Chen, Y. Du, and J. Fang, "Terahertz multi-user massive MIMO with intelligent reflecting surface: Beam training and hybrid beamforming," *IEEE Trans. Veh. Technol.*, vol. 70, no. 2, pp. 1376–1393, Feb. 2021.
[133] Z. Wan, Z. Gao, F. Gao, M. D. Renzo, and M.-S. Alouini, "Terahertz massive MIMO with holographic reconfigurable intelligent surfaces," *IEEE Trans. Commun.*, vol. 69, no. 7, pp. 4732–4750, Jul. 2021.
[134] G. Yu, X. Chen, X. Shao, and C. Zhong, "Low-cost intelligent reflecting surface aided terahertz multiuser massive MIMO: Design and analysis," *Sci. China Inf. Sci.*, vol. 64, no. 10, pp. 1–15, Sep. 2021.
[135] Y. Lu, M. Hao, and R. Mackenzie, "Reconfigurable intelligent surface based hybrid precoding for THz communications," *Intell. Converged Netw.*, vol. 3, no. 1, pp. 103–118, Mar. 2022.
[136] J. Praia, J. P. Pavia, N. Souto, and M. Ribeiro, "Phase shift optimization algorithm for achievable rate maximization in reconfigurable intelligent surface-assisted THz communications," *Electronics*, vol. 11, no. 1, p. 18, Dec. 2021.
[137] E. K. Agbogla, I. Trigui, K. Humadi, W. Ajib, and W.-P. Zhu, "Adaptive coordinated direct and multi-RIS transmissions for ultrareliable TeraHertz systems," *IEEE Trans. Veh. Technol.*, vol. 72, no. 8, pp. 10988–10993, Aug. 2023.
[138] M. H. Kumar, S. Sharma, K. Deka, and M. K. Sharma, "RIS-assisted user pairing NOMA system for THz communications," in *Proc. Nat. Conf. Commun. (NCC)*. Guwahati, India: IEEE, Feb. 2023, pp. 1–6.
[139] Z. Chai, J. Xu, S. Elston, S. Morris, M. Alouini, and J. Coon, "RIS-assisted indoor environment network: Performance analysis in terahertz communications," Univ. Oxford, Tech. Rep., 2024.
[140] N. Vishwakarma, R. Swaminathan, R. Premanand, S. Sharma, and A. S. Madhukumar, "RIS-assisted hybrid FSO/THz system with diversity combining schemes: A performance analysis," *IEEE Internet Things J.*, vol. 11, no. 17, pp. 28605–28622, Sep. 2024.
[141] N. P. Le and M.-S. Alouini, "Distributed hybrid active-passive RIS-assisted THz wireless systems: Performance analysis and optimization," *IEEE Trans. Commun.*, early access, Aug. 27, 2024, doi: 10.1109/TCOMM.2024.3450791.
[142] V. K. Chapala, O. R. Durgada, A. Sood, V. Gupta, R. Kapur, and S. M. Zafaruddin, "Multiple RIS transmissions with multihop relaying for THz wireless system," in *Proc. IEEE Int. Black Sea Conf. Commun. Netw. (BlackSeaCom)*. Tbilisi, Georgia: IEEE, Jun. 2024, pp. 7–12.
[143] N. Abuzainab, M. Alrabeiah, A. Alkhateeb, and Y. E. Sagduyu, "Deep learning for THz drones with flying intelligent surfaces: Beam and handoff prediction," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*. Montreal, QC, Canada: IEEE, Jun. 2021, pp. 1–6.
[144] K. Tekbiyik, G. K. Kurt, A. R. Ektı, and H. Yanikomeroglu, "Reconfigurable intelligent surfaces empowered THz communication in LEO satellite networks," *IEEE Access*, vol. 10, pp. 121957–121969, 2022.
[145] Y. Pan, K. Wang, C. Pan, H. Zhu, and J. Wang, "UAV-assisted and intelligent reflecting surfaces-supported terahertz communications," *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1256–1260, Jun. 2021.
[146] B. Zheng, C. You, W. Mei, and R. Zhang, "A survey on channel estimation and practical passive beamforming design for intelligent reflecting surface aided wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 2, pp. 1035–1071, 2nd Quart., 2022.
[147] J. Shabanpour, "Programmable anisotropic digital metasurface for independent manipulation of dual-polarized THz waves based on a voltage-controlled phase transition of VO_2 microwires," *J. Mater. Chem. C*, vol. 8, no. 21, pp. 7189–7199, Jun. 2020.
[148] A. Zimmers, L. Aigouy, M. Mortier, A. Sharoni, S. Wang, K. G. West, J. G. Ramirez, and I. K. Schuller, "Role of thermal heating on the voltage induced insulator-metal transition in VO_2," *Phys. Rev. Lett.*, vol. 110, no. 5, Jan. 2013, Art. no. 056601.
[149] R. Reese, E. Polat, H. Tesmer, J. Strobl, C. Schuster, M. Nickel, A. B. Granja, R. Jakoby, and H. Maune, "Liquid crystal based dielectric waveguide phase shifters for phased arrays at W-band," *IEEE Access*, vol. 7, pp. 127032–127041, 2019.
[150] H. Maune, M. Jost, R. Reese, E. Polat, M. Nickel, and R. Jakoby, "Microwave liquid crystal technology," *Crystals*, vol. 8, no. 9, p. 355, Sep. 2018.
[151] S. H. Lee, M. Choi, T.-T. Kim, S. Lee, M. Liu, X. Yin, H. K. Choi, S. S. Lee, C.-G. Choi, S.-Y. Choi, X. Zhang, and B. Min, "Switching terahertz waves with gate-controlled active graphene metamaterials," *Nature Mater.*, vol. 11, no. 11, pp. 936–941, Sep. 2012.

[152] Y. Zhang, S. Qiao, S. Liang, Z. Wu, Z. Yang, Z. Feng, H. Sun, Y. Zhou, L. Sun, Z. Chen, X. Zou, B. Zhang, J. Hu, S. Li, Q. Chen, L. Li, G. Xu, Y. Zhao, and S. Liu, "Gbps terahertz external modulator based on a composite metamaterial with a double-channel heterostructure," *Nano Lett.*, vol. 15, no. 5, pp. 3501–3506, Apr. 2015.

[153] S. Abeywickrama, R. Zhang, Q. Wu, and C. Yuen, "Intelligent reflecting surface: Practical phase shift model and beamforming optimization," *IEEE Trans. Commun.*, vol. 68, no. 9, pp. 5849–5863, Sep. 2020.

[154] C. Huang, Z. Yang, G. C. Alexandropoulos, K. Xiong, L. Wei, C. Yuen, and Z. Zhang, "Hybrid beamforming for RIS-empowered multi-hop terahertz communications: A DRL-based method," in *Proc. IEEE Globecom Workshops (GC Wkshps*. Taipei, Taiwan: IEEE, Dec. 2020, pp. 1–6.

[155] A. D. Koulouklidis, A. C. Tasolamprou, C. Daskalaki, C. P. Mavidis, G. Kenanakis, G. Deligeorgis, Z. Viskadourakis, P. Kuzhir, M. Kafesaki, E. N. Economou, C. M. Soukoulis, and S. Tzortzakis, "Experimental observation of ultrafast THz absorption modulation in a graphene-based metasurface," in *Proc. Conf. Lasers Electro-Opt. Eur. Eur. Quantum Electron. Conf. (CLEO/Eur.-EQEC)*, Jun. 2019, Art. no. cc_4_3.

[156] D. Sarkar, S. Mikki, and Y. Antar, "An electromagnetic framework for the deployment of reconfigurable intelligent surfaces to control massive MIMO channel characteristics," in *Proc. 14th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2020, pp. 1–4.

[157] A. Adinoyi and H. Yanikomeroglu, "Cooperative relaying in multi-antenna fixed relay networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 533–544, Feb. 2007.

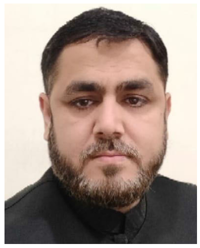
[158] X. Liu, Y. Liu, Y. Chen, and H. V. Poor, "RIS enhanced massive non-orthogonal multiple access networks: Deployment and passive beamforming design," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 4, pp. 1057–1071, Apr. 2021.

[159] S. Zhang and R. Zhang, "Intelligent reflecting surface aided multiple access: Capacity region and deployment strategy," in *Proc. IEEE 21st Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, May 2020, pp. 1–5.

MANZOOR AHMED received the Ph.D. degree in communication and information systems from Beijing University of Posts and Telecommunications, China, in 2015. From 1997 to 2000, he was a Lecturer with Balochistan Engineering University and a Telecomm Engineer with government-owned telecommunication service provider NTC, Pakistan, from 2000 to 2011. He was a Post-Doctoral Researcher with the Electrical Engineering Department, Tsinghua University, China, from 2015 to 2018. He worked as an Associate Professor with the Department of Computer Science and Technology, Qingdao University. He is currently working as a Professor with the School of Computer and Information Science and also with the Institute for AI Industrial Technology Research, Hubei Engineering University, Xiaogan. He has several research publications in IEEE top journals and conferences. His research interests include resource allocation and offloading in vehicular communications and networking, fog and edge computing, socially aware D2D communication, physical layer security, RIS, backscattering, and UAV communication. He received several awards, including the Distinction Award from the President of Pakistan, the Best Employee Award from NTC, and the excellent paper and Best paper awards from Intelligent and Converged Networks and the GameNets Conference in 2023 and 2014, respectively.

ABDUL WAHID received the B.S. degree in computer science from the University of Peshawar, Pakistan, in 2017, and the M.S. degree in computer science and technology from the Southwest University of Science and Technology (SWUST), Mianyang, Sichuan, China, in 2020. He is currently pursuing the Ph.D. degree with the College of Computer Science and Technology, Qingdao University, Qingdao, Shandong, China. His current research interests include wireless communications, physical layer security, reconfigurable intelligent surface, machine learning, and 6G technology.

WALI ULLAH KHAN (Member, IEEE) received the master's degree in electrical engineering from COMSATS University Islamabad, Pakistan, in 2017, and the Ph.D. degree in information and communication engineering from Shandong University, Qingdao, China, in 2020. He is currently with the Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg. He has authored/co-authored more than 100 publications, including international journals, peer-reviewed conferences, and book chapters. His research interests include convex/nonconvex optimizations, non-orthogonal multiple access, reflecting intelligent surfaces, ambient backscatter communications, the Internet of Things, intelligent transportation systems, satellite communications, unmanned aerial vehicles, physical layer security, and applications of machine learning.



FEROZ KHAN received the B.S. degree in electronics engineering and the M.S. degree in telecommunications engineering from the Balochistan University of Information Technology Engineering Management Sciences (BUITEMS), Quetta, Balochistan, Pakistan, in 2016 and 2018, respectively. He is currently looking to pursue Ph.D. degree. His current research interests include wireless communications, physical layer security, reconfigurable intelligent surface, machine learning, and 6G technologies.

ASIM IHSAN received the master's degree in information and communication engineering from Xi'an Jiaotong University, Xi'an, China, in 2018, and the Ph.D. degree in information and communication engineering from Shanghai Jiao Tong University, Shanghai, China, in 2022. Following the Ph.D. degree, he was a Postdoctoral Research Officer with Bangor University, Wales, and later as a Research Associate with the University of Strathclyde, Scotland, U.K. Currently, he holds the position of Postdoctoral Research Associate with the University of Cambridge, England, U.K. His research interests include energy-efficient resource allocations for beyond 5G wireless communication technologies, focusing on convex/non-convex optimizations and machine learning. He was a recipient of the U.K. Global Talent Visa.

ZAIN ALI received the Ph.D. degree in electrical engineering from COMSATS University, Islamabad, Pakistan, in 2021. Currently, he is a Postdoctoral Researcher with the Department of Electrical and Computer Engineering, University of California at Santa Cruz, USA. He received the HEC's Indigenous Talent Scholarship for M.S. and Ph.D. studies. His research interests include cognitive radio networks, energy harvesting, multihop relay networks, orthogonal frequency division multiple access (OFDMA), nonorthogonal multiple access (NOMA), machine learning, engineering optimization, and quantum communications.

KHALED M. RABIE (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from the University of Manchester, in 2011 and 2015, respectively. He is currently a Reader with the Department of Engineering, Manchester Metropolitan University (MMU), UK. He has worked as a part of several large-scale industrial projects and has published more than 200 journal and conference papers (mostly IEEE). His current research interests include designing and developing next-generation wireless communication systems. He is a fellow of the U.K. Higher Education Academy (FHEA) and the European Alliance for Innovation (EAI). He has received several awards over the past few years in recognition of his research contributions, including the Best Paper Awards at the 2021 IEEE CITS and the 2015 IEEE ISPLC and IEEE Access Editor of the Month Award for August 2019. He serves regularly on the Technical Program Committee (TPC) for several major IEEE conferences, such as GLOBECOM, ICC, and VTC. He is serving as an Editor for IEEE Communications Letters and *IEEE Internet of Things Magazine*.

THOKOZANI SHONGWE (Senior Member, IEEE) received the B.Eng. degree in electronic engineering from the University of Swaziland, Swaziland, in 2004, the M.Eng. degree in telecommunications engineering from the University of the Witwatersrand, South Africa, in 2006, and the D.Eng. degree from the University of Johannesburg, South Africa, in 2014. He is currently an Associate Professor of telecommunications and the Vice Dean for research, postgraduate studies and internationalization with the Faculty of Engineering and the Built Environment, University of Johannesburg. His research fields are in digital communications and error correcting coding. His research interests include power-line communications, cognitive radio, smart grids, visible light communications, machine learning, and artificial intelligence. He is the co-founder of a research group with the University of Johannesburg called Artificial Intelligence for Electrical Engineering Applications (AI for EE Applications). This research group is currently composed of, five staff members; two postdoctoral researchers working in the fields of communications and machine learning; five doctoral students and ten master's degree students working in the fields of power line communications, visible light communications, application of ML in PLC, power systems, agriculture, and object tracking. He was a recipient of the 2014 University of Johannesburg Global Excellence Stature (GES) Award, which was awarded to him to carry out his postdoctoral research with the University of Johannesburg. In 2016, he was a recipient of the TWAS-DFG Cooperation Visits Program funding to do research in Germany. He also received the Post-Graduate Merit Award Scholarship to pursue the master's degree with the University of the Witwatersrand, in 2005, which is awarded on a merit basis. In 2012, he and his co-authors received the Award of the Best Student Paper at the IEEE ISPLC 2012 (Power Line Communications Conference), Beijing, China.

ZHU HAN (Fellow, IEEE) received the B.S. degree in electronic engineering from Tsinghua University, in 1997, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Maryland, College Park, in 1999 and 2003, respectively.

From 2000 to 2002, he was an Research and Development Engineer of JDSU, Germantown, MD, USA. From 2003 to 2006, he was a Research Associate with the University of Maryland. From 2006 to 2008, he was an Assistant Professor with Boise State University, ID, USA. Currently, he is a John and Rebecca Moores Professor with the Electrical and Computer Engineering Department and the Computer Science Department, University of Houston, TX, USA. His main research targets on the novel game-theory related concepts critical to enabling efficient and distributive use of wireless networks with limited resources. His other research interests include wireless resource allocation and management, wireless communications and networking, quantum computing, data science, smart grids, carbon neutralization, security, and privacy. He has been an AAAS Fellow, since 2019, and an ACM Fellow, since 2024. He received the NSF Career Award, in 2010; the Fred W. Ellersick Prize of the IEEE Communication Society, in 2011; the EURASIP Best Paper Award for the *Journal on Advances in Signal Processing*, in 2015; the IEEE Leonard G. Abraham Prize in the field of communications systems (Best Paper Award in IEEE Journal on Selected Areas in Communications), in 2016; the IEEE Vehicular Technology Society 2022 Best Land Transportation Paper Award; and several best paper awards in IEEE conferences. Since 2017, he has been a 1% highly cited researcher according to Web of Science. He is also the winner of the 2021 IEEE Kiyo Tomiyasu Award (an IEEE Field Award), for outstanding early to mid-career contributions to technologies holding the promise of innovative applications, with the following citation: "for contributions to game theory and distributed management of autonomous communication networks." He was an IEEE Communications Society Distinguished Lecturer, from 2015 to 2018; and an ACM Distinguished Speaker, from 2022 to 2025.