A Survey on Terahertz Integrated Sensing and Communication: OFDM, Waveform Optimization, Spectral Efficiency, and Channel Modeling

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Abstract

Terahertz (THz) communication, with its promise of ultra-high data rates and low latency, is pivotal for the advancement of next-generation networks, particularly 6G. This survey explores the multifaceted domain of THz communication, focusing on Integrated Sensing and Communication (ISAC), Orthogonal Frequency Division Multiplexing (OFDM), waveform optimization, spectral efficiency, and channel modeling. Key advancements include the use of Reconfigurable Intelligent Surfaces (RIS) to enhance spectral efficiency and the integration of THz with Free-Space Optical (FSO) links for improved network performance. OFDM emerges as a critical technique for robust signal transmission and spectral efficiency. Recent developments in channel modeling, such as the Geometry-Based Stochastic Model (GBSM) and machine learning-based approaches, offer enhanced accuracy in simulating THz propagation characteristics. Waveform optimization, leveraging thin-film lithium niobate circuits, facilitates programmable and adaptive designs that bolster system robustness. Despite these advancements, challenges remain in modeling non-stationary effects and integrating THz systems into existing infrastructures. Future research should focus on refining channel models, optimizing waveforms, and enhancing spectral efficiency to fully harness THz potential. The development of hybrid nanocommunication systems and interdisciplinary approaches will be crucial for overcoming current limitations, driving innovation, and ensuring secure and efficient THz communication systems.

1 Introduction

1.1 Significance of Terahertz Frequencies

The terahertz (THz) frequency band, ranging from 0.1 to 10 THz, is crucial for advancing wireless communication technologies, particularly in the context of sixth-generation (6G) networks. The ultra-broad bandwidth of the THz spectrum enables high data rates essential for next-generation mobile communications and supports data-intensive applications, addressing the demands of an increasing number of connected devices and the anticipated surge in mobile traffic [1].

THz frequencies also facilitate integrated sensing capabilities, which are vital for high-resolution imaging and material identification [2]. This dual functionality is particularly beneficial in health monitoring applications, such as accurate breathing rate assessment in clinical settings [3]. Furthermore, THz frequencies are integral to developing hybrid communication systems that encompass molecular and nano communication, essential for realizing the full potential of the Internet of Things (IoT) and other advanced applications [4]. The transition to 6G networks necessitates addressing challenges like immersive throughput, hyper-reliability, and ultra-low latency, all of which THz frequencies are well-equipped to tackle [5]. Additionally, a hybrid sub-6GHz-mmWave-THz network framework is vital for meeting the increasing demand for high data rates in future mobile communications [6].

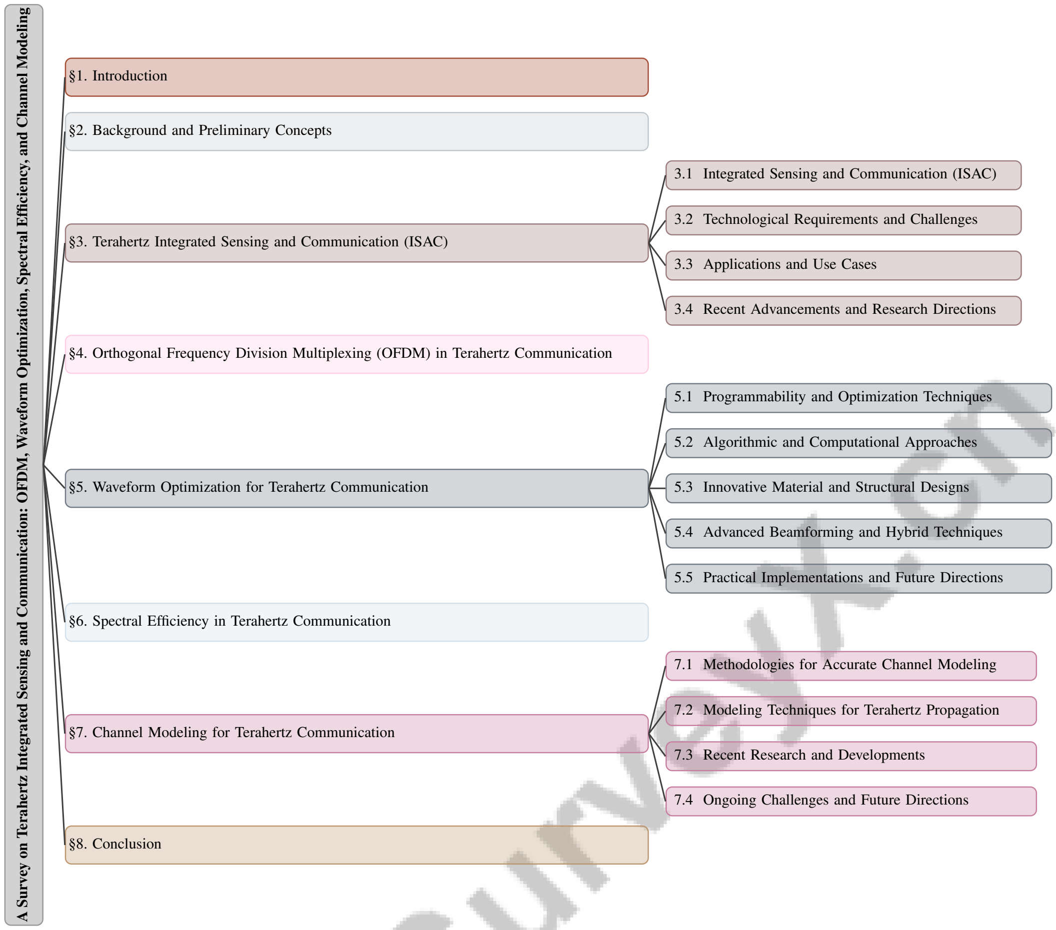


Figure 1: chapter structure

However, deploying THz frequencies poses challenges, including atmospheric absorption and the need for efficient generation and detection mechanisms, which require innovative solutions [7]. High-spectral-purity, frequency-agile sources at room temperature are foundational for applications in imaging, sensing, metrology, and communications [7]. Moreover, ensuring reliable information for augmented reality (AR) services in wireless THz networks is crucial for maintaining a high quality of physical experience (QoPE) [8].

1.2 Key Concepts in Terahertz Communication

Terahertz (THz) communication represents a significant advancement in wireless technology, driven by the need for terabit-level peak rates and improved energy efficiency in large-scale networks, which are essential for sixth-generation (6G) mobile communication systems [9]. A key aspect of THz communication is the generation of THz frequencies, necessitating innovative techniques to overcome challenges such as achieving high frequency resolution alongside broad bandwidth, a task current methods struggle to accomplish [7].

Channel modeling is critical in THz communication, addressing severe path loss and limited coverage typical of these frequencies. The integration of sensing and communication within THz Integrated Sensing and Communication (ISAC) systems offers unprecedented data rates and millimeter-level accurate sensing, enhancing both capabilities [10]. Additionally, exploring novel paradigms, such as molecular communication and electromagnetic (EM) interaction, is essential for advancing communication among nanomachines, bridging existing technological gaps.

The shift to terahertz frequencies is driven by the spectrum limitations of current wireless networks, necessitating exploration of THz communication technologies that can support the high bandwidth and low latency demands of future applications, especially as we develop sixth-generation (6G)

AI-generated, for reference only.

systems that require extensive use of the electromagnetic spectrum to meet growing data traffic and connectivity needs [11, 12, 13, 14]. This evolution in communication systems reflects a historical trend where increased bandwidth and hardware complexity have prompted a move to higher carrier frequencies. The integration of Ultra-Wideband (UWB) technology provides a framework for understanding THz communication characteristics and applications.

Standardization activities are vital for the widespread adoption of THz communication, establishing guidelines and frameworks for implementation across diverse environments. The complexity of deploying THz communication systems is underscored by challenges such as high path loss, restricted coverage areas, and the necessity for a comprehensive full-stack design. These issues arise from the unique characteristics of the THz frequency band (0.1-10 THz), offering ultra-high bandwidth and low latency ideal for high-speed data transmission while suffering from substantial path loss—approximately -100 dB for a 10-meter distance at 300 GHz. Furthermore, integrating THz technology into mobile networks requires meticulous design across all layers of the communication stack to address critical factors like network management, energy efficiency, and end-to-end connectivity. The deployment of THz access points (THz-APs) is especially sensitive, necessitating a higher density compared to current models to meet demands in ultra-dense environments, complicating coverage and escalating operational costs [15, 16, 17, 14, 11]. Addressing these challenges requires a multidisciplinary approach, integrating advancements in THz device technologies, channel modeling, and innovative communication paradigms to fully realize the potential of THz frequencies in future wireless networks.

1.3 Structure of the Survey

This survey is systematically organized to comprehensively explore terahertz (THz) integrated sensing and communication systems, focusing on key technological innovations and challenges. It begins with an introduction that emphasizes the critical role of THz frequencies in modern communication systems, detailing their capacity to deliver ultra-high data rates and facilitate integrated sensing applications. The THz frequency band (0.1-10 THz) is positioned to revolutionize wireless communication by bridging the gap between millimeter wave and optical frequencies, addressing escalating demands for bandwidth and connectivity amid increasing wireless data traffic. The introduction also highlights ongoing advancements, such as the establishment of IEEE standards aimed at optimizing THz communication architectures and the potential for joint THz communications and sensing, which could significantly enhance future wireless system functionality [11, 12, 18, 14]. It is followed by a detailed discussion of foundational concepts essential for understanding THz communication, including ISAC, OFDM, waveform optimization, spectral efficiency, and channel modeling.

The survey is structured into several key sections. Section 2 delves into background and preliminary concepts, offering an overview of fundamental technologies involved in THz communication systems, potential applications, future prospects, and identifying challenges and existing knowledge gaps in the field.

Section 3 focuses on Terahertz Integrated Sensing and Communication (ISAC), highlighting the innovative integration of sensing and communication functionalities at THz frequencies. It discusses the use of ultra-massive antenna arrays and advanced beamforming techniques to achieve simultaneous data transmission at Terabit-per-second rates while ensuring millimeter-level accuracy in sensing. This section addresses challenges posed by high path loss in the THz band and presents solutions such as dynamic subarray architectures and deep learning-based receiver designs that enhance both communication and sensing capabilities. Additionally, it reviews the latest advancements in signal processing techniques tailored for THz applications, emphasizing their significance in optimizing performance and addressing the unique characteristics of the THz channel [19, 20, 18, 10, 11]. It explores the benefits, challenges, and potential applications of ISAC, along with recent advancements and future research directions.

In Section 4, we examine the critical role of Orthogonal Frequency Division Multiplexing (OFDM) in Terahertz (THz) communication systems, emphasizing its advantages such as high data throughput and resilience to multipath fading. We also explore the unique challenges posed by THz frequencies, including atmospheric absorption and limited range, as well as recent advancements in OFDM technology tailored for THz applications, which are essential for supporting the anticipated high-speed transmission requirements of future 6G networks. This examination highlights OFDM's potential to enhance THz communication while identifying key areas for further research and development in this rapidly evolving field [21, 14].

Section 5 addresses waveform optimization for THz communication, discussing various optimization techniques and their impact on system efficiency and reliability. This section explores programmability, algorithmic approaches, innovative material designs, and advanced beamforming techniques.

Spectral efficiency in THz communication is analyzed in Section 6, focusing on methods to enhance spectral efficiency and the associated trade-offs. This section discusses technological advancements and applications, alongside challenges and future research directions.

Section 7 provides an in-depth analysis of channel modeling for terahertz (THz) communication, detailing essential characteristics of THz propagation channels necessary for successful implementation in 6G networks. It elaborates on methodologies for developing realistic, measurement-based THz channel models and reviews existing literature on THz channel measurements. Additionally, the section explores various modeling techniques, including machine learning algorithms for channel estimation, highlighting the effectiveness of the projected gradient ascent algorithm in achieving superior performance metrics [22, 23]. It highlights recent research developments and ongoing challenges, suggesting future directions for channel modeling research.

The paper concludes by synthesizing central themes, including advancements in Terahertz (THz) Integrated Sensing and Communication (ISAC), intricacies of Orthogonal Frequency Division Multiplexing (OFDM), and the significance of waveform optimization for enhancing spectral efficiency. It identifies the critical need for innovative channel modeling techniques to address unique challenges posed by higher frequency bands and highlights promising avenues for future research, emphasizing the necessity for comprehensive investigations into THz technologies, the development of Full-Spectrum Wireless Communications (FSWC) strategies, and refinement of channel characteristics to support the evolving demands of 6G and beyond [24, 13, 16, 14, 25].The following sections are organized as shown in Figure 1.

2 Background and Preliminary Concepts

2.1 Applications and Prospects of Terahertz Communication

The terahertz (THz) frequency band, ranging from 100 GHz to 10 THz, is poised to revolutionize wireless communication systems by providing exceptional data rates and ultra-low latency, essential for next-generation mobile networks [26]. Integrating THz technologies with optical systems enhances both communication and sensing capabilities, paving the way for innovative applications, particularly in extended reality (XR) systems where high data rates and low latency are crucial for immersive experiences [5, 27]. THz communication also holds significant potential for e-health and nanonetworks, supporting advanced healthcare delivery and facilitating complex interactions within nanonetworks [3].

The expanding scope of THz technologies is unlocking applications across sectors such as security monitoring, medical imaging, and quality control [2]. Terahertz imaging, a recognized nondestructive examination (NDE) method, is increasingly used for material inspection and defect detection in industrial and medical contexts [28]. Terahertz Time Domain Spectroscopy (THz-TDS) systems have emerged as established technologies for non-destructive testing and material inspection, underscoring the relevance of THz frequencies [29]. The integration of THz communication with millimeter-wave (mmWave) and free-space optical (FSO) transmission for IoT data collection in remote areas illustrates the adaptability of THz communication in diverse environments [30].

In environmental monitoring, THz communication systems can significantly enhance public health responses by detecting airborne pollutants [13]. The potential of THz-enabled unmanned aerial vehicles (UAVs) to provide communication services to ground users further exemplifies the versatility of THz communication in addressing various technological and societal needs [5]. Advances in materials, such as metallic borophene nanosheets, offer promising solutions for THz shielding, reducing electromagnetic interference and ensuring human safety [31].

The increasing demand for high-speed data transfer highlights the importance of the THz spectral range for next-generation wireless communication systems [12]. As research progresses, integrating THz communication into various technological frameworks is expected to unlock new possibilities and foster innovation across multiple sectors. This includes potential applications of extremely large-scale (XL) arrays and sparse arrays (SAs) in near-field sensing and communications, which could further enhance THz system capabilities [5]. Additionally, advancements in beam management techniques for mmWave and THz communications, such as initial beam training and recovery from beam failures, are crucial for optimizing THz communication system performance [32]. Emerging technologies, including spintronic THz emitters and DebriSense-THz systems, illustrate the expanding scope of THz applications, ranging from communication to space debris detection.

2.2 Challenges and Knowledge Gaps

The development of terahertz (THz) communication systems encounters several challenges and knowledge gaps that must be addressed for effective integration into future wireless networks. A primary challenge is the high free-space path loss and molecular absorption loss associated with THz frequencies, complicating cell association and necessitating advanced solutions [6]. The computational overhead of current algorithms exacerbates these issues, leading to delays and inefficiencies when processing large datasets [33].

Another significant hurdle is the requirement for complete instantaneous channel state information (CSI) for all network nodes, which is impractical and limits the efficacy of existing relay selection strategies [34]. Uncertainty in the THz channel can result in outdated information being transmitted, jeopardizing the performance of augmented reality (AR) services [8].

The non-convex nature of optimization problems, due to unit-modulus constraints on reconfigurable intelligent surfaces (RIS), complicates the design of THz communication systems. This complexity is further compounded by the absence of explicit expressions for the ergodic achievable rate, posing significant challenges for system optimization [35]. Furthermore, existing THz wavelength division multiplexers and demultiplexers exhibit design features that hinder on-chip integration, limiting their practical applications [27].

Addressing these complex challenges requires an interdisciplinary approach, integrating advancements in metamaterials, which enable tailored electromagnetic properties for improved signal transmission, alongside cutting-edge detection technologies and sophisticated computational methods. By tackling limitations such as high path loss and the necessity for highly directional beams, this integrated methodology aims to maximize THz system capabilities, poised to revolutionize high-speed wireless communication, enhance data transfer in data centers, and facilitate new applications across various domains. Leveraging insights from established standards like the IEEE 802.15 suite will support the development of regulatory frameworks that foster innovation and interoperability in next-generation communication infrastructures [36, 2, 37, 14, 11].

The advancements in Terahertz Integrated Sensing and Communication (ISAC) present a compelling case for the integration of various technological components to enhance system performance and application scope. Figure 2 illustrates the hierarchical structure of ISAC, detailing its key features, technological requirements, applications, and recent advancements. This figure highlights not only the integration of sensing and communication but also the challenges and solutions encountered in technology deployment. Furthermore, it showcases the diverse applications of ISAC across various sectors and underscores the ongoing research and standardization efforts aimed at enhancing ISAC systems. By examining these elements, we gain a comprehensive understanding of the potential and complexities associated with ISAC technologies.

3 Terahertz Integrated Sensing and Communication (ISAC)

3.1 Integrated Sensing and Communication (ISAC)

Integrated Sensing and Communication (ISAC) at terahertz (THz) frequencies marks a pivotal advancement in wireless technology, enabling simultaneous sensing and communication with high precision and efficiency. The THz spectrum's broad bandwidth and high-frequency attributes are particularly suited for applications demanding precision and low latency, such as immersive reality systems [5]. ISAC enhances detection accuracy over traditional methods, improving reliability in dynamic settings [10].

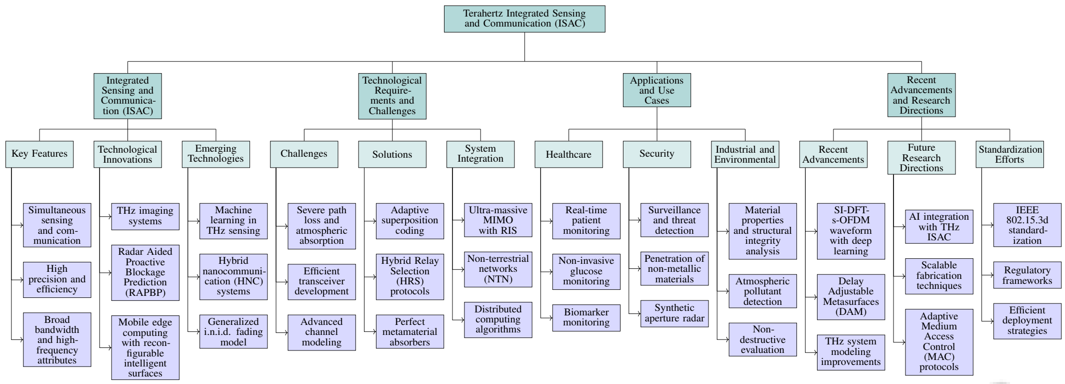


Figure 2: This figure illustrates the hierarchical structure of Terahertz Integrated Sensing and Communication (ISAC), detailing its key features, technological requirements, applications, and recent advancements. It highlights the integration of sensing and communication, the challenges and solutions in technology deployment, diverse applications across various sectors, and ongoing research and standardization efforts to enhance ISAC systems.

Frameworks for THz imaging systems, like frequency-domain and time-domain imaging, underscore ISAC's potential by providing structured design approaches [2]. Unifying communication and radar subsystems through shared channel access methods reduces interference and boosts performance, enhancing communication reliability and efficiency [26]. Integrating radar sensing with advanced tracking algorithms, such as the Radar Aided Proactive Blockage Prediction (RAPBP) method, further bolsters mmWave communication systems, adaptable to THz frequencies [32].

The synergy of mobile edge computing (MEC) with reconfigurable intelligent surfaces (RIS) exemplifies ISAC's practical applications, notably in enhancing THz communication for virtual reality [1]. Innovations in materials, such as anti-reflection coatings, improve interactions with metallic structures, boosting THz sensing and communication [38]. Ultrathin, broadband metamaterial structures enhance polarization conversion, elevating THz application performance [2]. Nonparaxial diffractive optics for lensless photonic systems in THz imaging also highlight ISAC's relevance by improving resolution and contrast [27].

Emerging technologies, such as machine learning in THz sensing, offer novel frameworks for methodology categorization, emphasizing signal processing advances [1]. The hybrid nanocommunication (HNC) system leverages THz communication for faster, more reliable information transfer than traditional molecular methods [39]. The proposed generalized i.n.i.d. fading model for analyzing THz-RF relay systems illustrates ISAC's potential, providing detailed metrics like outage probability and average bit error rate (BER) [1].

ISAC at THz frequencies promises transformative potential for next-generation wireless systems, offering unprecedented integration and functionality. Continued research is crucial for addressing challenges and seizing opportunities within the THz band, paving the way for advanced communication technologies. ISAC's applicability is further demonstrated in healthcare through THz technology integration for patient monitoring, underscoring its relevance in health applications [8].

3.2 Technological Requirements and Challenges

Implementing Integrated Sensing and Communication (ISAC) systems at terahertz (THz) frequencies requires overcoming several technological hurdles. The severe path loss and atmospheric absorption at THz frequencies necessitate innovative solutions to enhance sensing and communication. Developing efficient transceivers for sub-THz frequencies is vital, addressing challenges like power consumption and integration [12].

Advanced channel modeling techniques, such as the modified alpha-beta path loss model for Non-Line-of-Sight (NLoS) scenarios and ray-tracing (RT)-statistical hybrid models, are crucial for optimizing THz communication systems [40]. Electronically controlled optical sampling (ECOPS) in THz-TDS spectrometers, combined with mini-coil pulsed magnets, enhances measurement capabilities, particularly in high magnetic fields, improving THz sensing accuracy [41].

Adaptive superposition coding and subspace detection techniques are essential for dynamically adapting to channel conditions, enhancing data recovery in THz Non-Orthogonal Multiple Access (NOMA) systems [42]. These methods facilitate efficient spectrum use and improve communication link robustness. Hybrid Relay Selection (HRS) protocols, prioritizing THz relays for short distances and RF relays for longer ones, optimize coverage and system performance [34].

Perfect metamaterial absorbers for THz sensing require optimized designs to enhance sensitivity through resonance frequency shifts, improving detection accuracy [2]. Addressing beam squint effects, which cause beam gain loss in far-field and near-field scenarios, is crucial for maintaining high beamforming performance and efficient resource allocation [43].

Integrating ultra-massive Multiple Input Multiple Output (umMIMO) systems with reconfigurable intelligent surfaces (RIS) and non-terrestrial networks (NTN) within ISAC frameworks is essential for optimizing resource allocation and system performance. Developing new beamforming techniques that exploit near-field effects can enhance communication capacity and sensing accuracy, addressing fundamental ISAC challenges at THz frequencies. Distributed computing algorithms that boost data processing speeds while maintaining accuracy are vital for managing ISAC systems' computational demands [33].

3.3 Applications and Use Cases

Terahertz (THz) Integrated Sensing and Communication (ISAC) systems offer transformative potential across various applications by enabling simultaneous high-precision sensing and ultra-fast communication. A key application is electromagnetic interference (EMI) shielding, where polymer composites with low graphene loading serve as effective THz absorbers, enhancing EMI shielding and enabling practical applications in environments needing robust electromagnetic compatibility [44].

In healthcare, ISAC systems can revolutionize patient monitoring with real-time, high-resolution imaging. THz sensing technologies' high sensitivity and specificity are advantageous for non-invasive glucose monitoring and breath analysis, improving diagnostic accuracy and patient outcomes. Advances in THz spectroscopy and signal processing enable precise material and gaseous component identification, facilitating biomarker monitoring. Metamaterial absorbers at THz frequencies significantly shift resonance frequency and amplitude, enhancing detection capabilities [2, 18, 45]. Integrating ISAC with mobile health platforms can support continuous monitoring, enabling timely interventions and personalized healthcare solutions.

The security sector benefits from THz ISAC systems in surveillance and threat detection. THz ISAC's ability to penetrate non-metallic materials while providing high-resolution imaging suits security screening, such as concealed weapons or explosives detection in critical environments like airports. Techniques like synthetic aperture radar at THz frequencies and innovative optical components improve imaging quality and efficiency, enhancing surveillance and threat detection [46, 47, 20]. Integrating advanced THz sensing with machine learning algorithms can enhance threat detection accuracy and reduce false positives, improving security measures.

In industrial automation and quality control, THz ISAC systems offer insights into material properties and structural integrity. The non-destructive nature of THz imaging enables comprehensive composite material analysis, facilitating subsurface defect identification with high precision, essential for maintaining product quality and safety. Recent THz technology advancements have increased imaging throughput, making it practical for non-destructive evaluation, biomedical diagnostics, and security screening [46, 48, 49]. Integrating THz ISAC with automated inspection systems can streamline quality control, reduce downtime, and enhance production efficiency.

In environmental monitoring, THz ISAC technologies can detect and analyze atmospheric pollutants. THz sensing technologies' exceptional sensitivity enables precise real-time air quality monitoring by detecting specific materials and gaseous components, crucial for enhancing environmental management strategies and public health responses. Advanced signal processing and machine learning techniques optimize detection and classification based on unique THz spectral signatures [2, 18]. Deploying THz-enabled unmanned aerial vehicles (UAVs) for environmental monitoring can provide comprehensive data collection over large areas, supporting sustainable practices.

The diverse applications and use cases of THz ISAC systems demonstrate their potential to foster innovation and enhance operational efficiencies across sectors, including telecommunications, data centers, and IoT environments. These systems leverage ultra-broad bandwidths and advanced technologies, such as analog precoder optimization and deep learning-based receivers, to achieve high data rates and precise sensing capabilities. The IEEE has made strides in standardizing THz frequency bands, paving the way for new applications in Earth exploration and radio astronomy. Challenges like high path loss and efficient deployment strategies in dense networks must be addressed through ongoing research and development efforts, emphasizing THz ISAC technology's critical role in shaping future wireless communication and sensing [16, 50, 20, 10, 11].

3.4 Recent Advancements and Research Directions

Recent advancements in terahertz (THz) Integrated Sensing and Communication (ISAC) have enhanced performance and broadened application domains. A significant development is the SI-DFT-s-OFDM waveform with a deep learning-powered receiver, achieving a 5 dB gain at the 10^{-3} BER level over conventional OFDM systems [10]. This highlights the potential of integrating advanced signal processing with THz communications for superior performance.

The deployment of Delay Adjustable Metasurfaces (DAM) in Intelligent Reflecting Surface (IRS) communications marks another innovation. DAM enables dynamic delay and phase shift adjustments, enhancing beam focusing capabilities compared to traditional methods [43]. This advancement is vital for addressing beam squint issues and optimizing beamforming performance, improving THz ISAC systems' overall efficiency.

Despite these advancements, challenges and knowledge gaps remain. Current models often inadequately reflect the physical processes in terahertz lasers, necessitating precise modeling approaches that capture THz generation and propagation complexities [51]. Future research should focus on developing models that accurately represent these processes, facilitating more efficient THz system design.

Beyond modeling improvements, future research should explore integrating artificial intelligence (AI) with THz ISAC technologies to enhance adaptability and performance in dynamic environments. Prioritizing scalable fabrication techniques and hybrid devices that integrate carbon nanomaterials—such as single-wall carbon nanotubes and graphene—with advanced materials like two-dimensional beta12-borophene nanosheets is essential. These materials exhibit exceptional properties in terahertz applications and electromagnetic interference shielding, enabling innovative solutions across various fields, including communication, healthcare, and IoT sensor technology [52, 53, 54, 55]. Exploring adaptive Medium Access Control (MAC) protocols tailored for the THz band's unique challenges, like energy management and robust channel access mechanisms, is crucial for advancing THz ISAC systems.

Ongoing investigation into THz ISAC technologies is essential for fully realizing their capabilities, including ultra-high bandwidth and minimal latency, facilitating advanced communication systems development. These systems are expected to meet future wireless networks' increasing demands by leveraging the THz frequency band (0.1-10 THz) for high-speed data transmission and improved connectivity. The IEEE 802.15.3d standardization efforts are pivotal in establishing regulatory frameworks that enhance interoperability and innovation across applications, such as indoor environments and IoT deployments. However, significant challenges remain, including high path loss, hardware limitations, and efficient deployment strategies for THz access points. Overcoming these hurdles will be critical for creating robust and effective communication infrastructures capable of meeting future data traffic requirements [16, 20, 14, 10, 11].

4 Orthogonal Frequency Division Multiplexing (OFDM) in Terahertz Communication

4.1 Advantages of OFDM in Terahertz Communication

Orthogonal Frequency Division Multiplexing (OFDM) is a key modulation technique in terahertz (THz) communication, enhancing spectral efficiency and signal robustness. By dividing bandwidth into narrow sub-channels, OFDM maximizes THz spectrum utilization, crucial for high data rates and low latency in future wireless networks [5]. Its integration with advanced spatial modulation in cell-free massive MIMO (CFmMIMO) systems boosts spectral and energy efficiency by minimizing user distance [56]. OFDM's compatibility with hybrid THz/free-space optical (FSO) networks further leverages THz and FSO strengths for robust communication [39]. It mitigates multipath fading, ensuring high data throughput [12], and supports molecular and neural communication modes for versatile solutions [42]. In multi-user MIMO systems, OFDM enhances signal transmission by extracting multipath components, improving reliability [32]. It also supports innovative technologies like 3D-Printed Terahertz Topological Waveguides, increasing bandwidth and reducing costs [27]. OFDM's manifold advantages in THz communication systems include enhanced spectral efficiency, improved detection capabilities, and robust performance across environments, underscoring its role in advancing next-generation wireless systems. As research progresses, OFDM's capacity for high-speed transmission and efficient resource management is vital for bridging millimeter-wave and optical frequencies. IEEE 802.15 standards further bolster this advancement, promoting communication capable of achieving data rates up to 100 Gbps. However, challenges like high path loss and the need for directional THz beams highlight the need for scalable, low-cost technologies [11, 14].

4.2 Challenges Specific to Terahertz Frequencies

Implementing OFDM at terahertz (THz) frequencies presents challenges due to the THz band's properties and technological limitations. High propagation loss complicates reliable communication links, necessitating advanced beamforming techniques despite traditional methods' overheads in beam training [57]. Detector sensitivity and robustness are challenged by current technologies' lack of speed or resilience, risking performance degradation [58]. Limited nanoscale energy supply constrains continuous wave wireless communication [53]. Efficient optical components and high-sensitivity detectors are essential for preserving image quality [46]. Blockage effects and antenna misalignment necessitate relay-based strategies [59]. Beam squint effects in THz IRS communications introduce challenges as beams may not focus correctly [43]. ISAC enables efficient channel estimation schemes, outperforming traditional methods [60], yet optimizing both communication link ends remains challenging [61]. Advancements in channel modeling, beamforming strategies, and new transmission mediums are crucial for high-speed, low-latency communication, meeting future bandwidth and connectivity demands [57, 14, 62, 11].

4.3 Recent Developments in OFDM Technology for Terahertz Applications

Recent advancements in OFDM technology for terahertz (THz) applications focus on enhancing communication and sensing capabilities, addressing THz band challenges. The development of dual-functional Frequency Modulated Continuous Wave (DF-FMCW) waveforms demonstrates significant potential in detecting hypervelocity space debris while ensuring reliable inter-satellite communication [63]. Enhancing laser absorption through interference effects in metal-dielectric photonic crystal structures improves THz emission [64], supporting more effective OFDM systems by providing higher power and stable signal generation. These advancements emphasize ongoing efforts to enhance OFDM technology for THz applications, focusing on emission efficiency and integrating multifunctional capabilities. The THz frequency band supports ultra-high bandwidth communication, vital for future 6G networks and addressing high path loss challenges. Advanced techniques like highly directional THz beams and large-scale phased arrays are essential for overcoming these challenges and realizing efficient, scalable communication systems bridging millimeter-wave and optical frequencies [11, 16, 13, 14].

4.4 Frameworks and Methodologies for OFDM in Terahertz Systems

Implementing OFDM in terahertz (THz) communication systems requires sophisticated frameworks and methodologies addressing THz band challenges. Positioning THz Access Points (THz-APs) strategically optimizes efficiency and minimizes energy consumption, enhancing network performance [16]. Plasmonic terahertz detectors with double grating gates offer a responsive solution for THz signal detection and processing [65]. Adapting beamforming strategies to exploit near-field effects improves communication and sensing capabilities [66]. In multi-user THz networks, formulating the transmitter-IRS-receiver (Tx-IRS-Rx) allocation as a matching problem maximizes performance [26]. The Hybrid Relay Selection (HRS) protocol optimizes coverage and data rates based on source-destination distance [34]. Performance analysis of hybrid sub-6GHz-mmWave-THz networks provides insights into OFDM integration [6]. Developing advanced frameworks and methodologies is crucial for enhancing OFDM performance in Terahertz communication systems, pivotal for meeting ultra-high bandwidth and low-latency connectivity demands in future wireless networks [11, 12, 13, 14].

5 Waveform Optimization for Terahertz Communication

Category	Feature	Method
Programmability and Optimization Techniques	Adaptive Design Strategies	ASCD[42], PB-BRMS[3], ECOPS-THz-TDS[41]
	Computational Efficiency Techniques	PPODRL[67], FDSS[68]
	Security and Transmission Optimization	HARQ-IR[32]
	Dynamic Material and Component Design	WDM[27]
Algorithmic and Computational Approaches	Channel Estimation Methods	CCETD[69], SBCE[70]
	Signal Processing Techniques	WGP[71]
	Ensemble Learning Approaches	DEL-F[72]
Innovative Material and Structural Designs	Magnetic and Electric Field Enhancement	ASM[73], DTHM[29]
	Advanced Metamaterial Designs	MLPC[74]
	Signal Transmission Optimization	HTW[75], 3D-THz-WG[76]
Advanced Beamforming and Hybrid Techniques	Mode and Interference Management	SIBW[77]
	Signal Optimization	STM-TC[78]
Practical Implementations and Future Directions	Optimization and Tuning	ECTT[79], MTPB[80], HHS-Lens[81], PMA[2], PSI-CCD[1], EARM[35]
	Adaptive and Robust Communication	IRSMO[82], C@TDS[45], DR-MLPCE[83], GS-IRS[26]
	Integration and Fusion	kR-Net[84]
	Coverage and Synthesis	CBF[85], TFLN-WS[86]

Table 1: This table provides a comprehensive overview of various methodologies and techniques employed in terahertz (THz) communication systems. It categorizes these methods into programmability and optimization techniques, algorithmic and computational approaches, innovative material and structural designs, advanced beamforming and hybrid techniques, and practical implementations and future directions. Each category highlights specific features and methods, along with relevant references, underscoring the advancements in waveform optimization for THz communications.

In the realm of terahertz (THz) communication, waveform optimization is a critical component that influences the overall performance and efficiency of communication systems. As the demand for higher data rates and improved reliability continues to grow, it becomes imperative to explore various methodologies that enhance waveform design and adaptability. Table 1 presents a detailed categorization of the methodologies and techniques integral to waveform optimization in terahertz communication systems, emphasizing their significance in enhancing system performance and adaptability. Additionally, Table 5 provides a comprehensive categorization of methodologies integral to waveform optimization in terahertz communication systems, emphasizing their critical role in improving system performance and adaptability. This section delves into the programmability and optimization techniques that serve as foundational elements in the development of advanced THz communication systems. By leveraging innovative strategies and technologies, researchers aim to address the unique challenges posed by high-frequency environments and to facilitate the creation of adaptive waveforms tailored for specific applications.

5.1 Programmability and Optimization Techniques

Method Name	Programmability	Optimization Techniques	Adaptive Signal Processing
TFLN-WS[86]	Waveform Synthesis Adaptability	Antenna Design Parameters	Dynamic Phase Matching
PB-BRMS[3]	Multiple Antenna Beam	Reflective Intelligent Surfaces	Phase Shifts Monitoring
FDSS[68]	-	Preconditioned Integral Equation	-
HARQ-IR[32]	Rate Adaptation Policy	Robust Rate Adaptation	Dynamic Adjustments
ECOPS-THz-TDS[41]	Electronically Controlled Optical	Optimize Ecops Setup	Dynamic Adjustments Synchronization
ASCD[42]	Adaptive Spatial Tuning	Channel Matrix Puncturing	Adaptive Superposition Coding
PMA[2]	-	Optimized Designs	Dynamic Adjustments
EARM[35]	Optimize Signal Transmission	Alternating Optimization	Dynamic Adjustments
WDM[27]	Inverse Design Topology	Topology Optimization Applied	Signal Manipulation Routing
PPODRL[67]	Dynamic Network Conditions	Joint Optimization Approach	Dynamic Network Conditions

Table 2: Summary of various programmability and optimization techniques applied in terahertz (THz) communication systems. The table presents a comparison of different methods, highlighting their programmability, optimization techniques, and adaptive signal processing capabilities. These methods contribute to the advancement of THz technologies by enhancing waveform adaptability, improving signal transmission, and optimizing system performance.

Programmability and optimization techniques are central to advancing terahertz (THz) communication systems, enabling the development of adaptive waveforms that address the unique challenges of high-frequency domains. A significant innovation in this area is the use of thin-film lithium niobate (TFLN) circuits to facilitate versatile THz waveform synthesis, effectively overcoming the limitations associated with bulk systems [86]. This advancement allows for greater control and flexibility in waveform design, which is crucial for optimizing signal transmission in THz communication.

The strategic use of phase shifts in THz signals for accurate monitoring of breathing rates exemplifies the potential of programmability in enhancing performance through adaptive signal processing [3]. This adaptability is further supported by the integration of fast direct solver strategies, which improve modeling efficiency at THz frequencies via preconditioned combined field integral equations [68].

In secure HARQ-IR aided THz communications, the insertion of dummy messages during retransmissions highlights the importance of optimizing retransmission strategies to enhance system robustness [32]. Additionally, the rapid scanning capability of THz time-domain systems allows for precise material measurements under strong magnetic influences, showcasing the programmability of THz systems in capturing dynamic waveforms [41].

Adaptive superposition coding techniques in THz-band MIMO-NOMA systems reduce complexity in data detection and improve performance in high-loss environments, facilitating efficient resource allocation [42]. This is complemented by the design of perfect metamaterial absorbers, which enhance performance through programmable configurations tailored for THz communication [2].

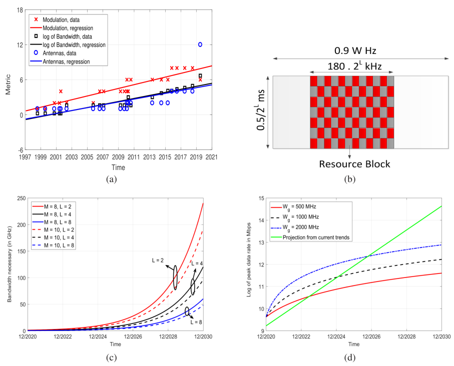
The integration of reconfigurable intelligent surfaces (RIS) in communication systems, inspired by their potential to enhance performance in mmWave systems, utilizes statistical channel state information (CSI) to optimize waveform design without relying solely on instantaneous CSI [35]. This approach underscores the importance of programmability in achieving efficient resource utilization and enhanced system performance.

Furthermore, the active nature of on-chip inverse-designed wavelength division multiplexers (WDM) allows for gain compensation and fine-tuning, providing performance enhancements over passive designs [27]. These programmable elements are crucial for optimizing waveform propagation and interaction with the environment.

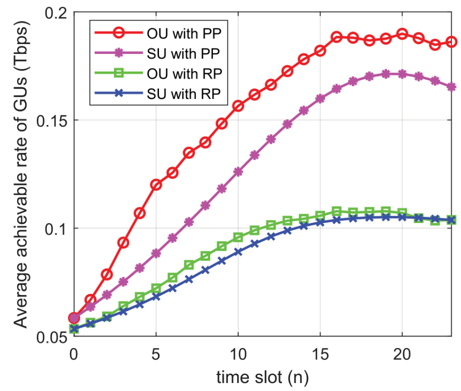
The integration of programmable elements and advanced optimization techniques is crucial for improving the performance and adaptability of terahertz (THz) communication systems. This enhancement is vital for addressing the challenges posed by high path loss, antenna misalignment, and atmospheric influences, which are significant obstacles in THz communications. By leveraging techniques such as hybrid automatic repeat request (HARQ) and implementing relay-based solutions for blockage mitigation, researchers are paving the way for more efficient and reliable next-generation wireless networks. Furthermore, the establishment of standards like IEEE 802.15.3d facilitates the development of scalable, low-cost THz systems, which are essential for meeting the increasing demands for ultra-high bandwidth and low-latency communication in future applications, including the Internet of Things (IoT) and ultra-dense networks [16, 17, 14, 59, 11].

Table 2 provides a comprehensive overview of key programmability and optimization methods employed in terahertz communication systems, detailing their specific techniques and applications in adaptive signal processing.

As shown in Figure 3, in the rapidly evolving field of terahertz communication, waveform optimization plays a crucial role in enhancing the programmability and efficiency of communication systems. The illustrative examples depicted in Figure 3 provide insights into the advancements and optimization techniques employed in this domain. The first subfigure, "Progress in Modulation and Antenna Metrics Over Time," showcases a series of four graphs that collectively illustrate the historical progression of modulation metrics and antenna capabilities. These graphs highlight key data points and regression models, capturing the technological advancements from 1997 to 2021. This visualization underscores the continuous improvements in modulation techniques, which are fundamental to achieving higher data rates and more efficient spectrum utilization in terahertz communications. The second subfigure, "Comparison of Average Achievable Rates of GUs in Different Time Slots," presents a comparative analysis of average achievable rates of Generalized Utility (GUs) across different time slots under two scenarios: Point-to-Point (PP) and Random Point (RP). By examining the variations in achievable rates depicted by distinct lines, this analysis emphasizes the impact of different optimization strategies on communication performance. Together, these examples



(a) Progress in Modulation and Antenna Metrics Over Time[25]



(b) Comparison of Average Achievable Rates of GUs in Different Time Slots[67]

Figure 3: Examples of Programmability and Optimization Techniques

highlight the critical role of programmability and optimization in advancing terahertz communication technologies, paving the way for more robust and efficient wireless communication systems. [25, 67]

5.2 Algorithmic and Computational Approaches

Method Name	Optimization Techniques	Channel Estimation	Adaptive Schemes
kR-Net[84]	Complex-valued Cnn	-	Deep Learning
CCETD[69]	Beam Training	Hierarchical Search Codebook	Adaptive Methods
ITXRX[87]	Neural Networks	Coefficient Estimation	Adaptive Training Processes
SBCE[70]	Sparse Recovery Techniques	Sparse Bayesian Learning	Machine Learning Techniques
WGP[71]	Spatial Modulation Refractive	-	-
DEL-F[72]	-	-	Dynamic Weighting Mechanism

Table 3: Overview of various algorithmic and computational methods employed in terahertz (THz) communication systems, highlighting their optimization techniques, channel estimation strategies, and adaptive schemes. The table provides a comparative analysis of methods such as kR-Net, CCETD, ITXRX, SBCE, WGP, and DEL-F, illustrating their unique contributions to enhancing THz waveform design and reliability.

The optimization of waveforms in terahertz (THz) communication systems requires advanced algorithmic and computational approaches to address the unique challenges posed by the high-frequency domain. Table 3 summarizes the diverse algorithmic and computational approaches utilized in optimizing waveforms within terahertz communication systems, underscoring the significance of these methods in improving system performance and reliability. A prominent method in this context is the kR-Net, a deep learning-based algorithm designed for multiband signal fusion, employing a hybrid, dual-domain complex-valued convolutional neural network architecture to enhance 3-D Synthetic Aperture Radar (SAR) imaging [84]. This approach leverages the power of deep learning to optimize waveform characteristics, offering significant improvements in imaging resolution and accuracy.

In IRS-assisted THz systems, beam training and hierarchical search codebooks are utilized to estimate the channel and design transmission strategies based on the acquired channel information, as demonstrated by Ning et al. [69]. This method enhances the efficiency of channel estimation and transmission, thereby optimizing waveform propagation and interaction with the environment.

Machine learning techniques are further employed to design constellation and detection schemes that adaptively mitigate the effects of in-phase and quadrature-phase imbalance (IQI) in terahertz wireless systems [87]. These adaptive schemes are crucial for ensuring robust communication in the presence of hardware imperfections, enhancing the reliability of THz systems.

The Sparse Bayesian Channel Estimation (SBCE) method employs sparse Bayesian learning to reconstruct the channel from underdetermined observations while accounting for beam-split effects

[70]. This approach provides a robust framework for channel estimation, crucial for optimizing waveform design and enhancing communication reliability.

The concept of sub-cycle control of THz waveforms through transient metamaterials, such as the Waveform Generating Platform (WGP), illustrates the potential of manipulating THz waveforms by creating a spatially varying refractive index using femtosecond laser pulses [71]. This technique offers precise control over waveform properties, facilitating the development of tailored waveforms for specific applications.

In high-dimensional settings, ensemble learning approaches like DEL-F dynamically adjust the weight of each algorithm based on its predictive performance, improving accuracy [72]. This flexibility is essential for optimizing waveform characteristics in complex communication environments.

Furthermore, novel re-gridding algorithms, such as cubic spline and Shannon interpolation, provide better estimates of the waveform at uniformly spaced positions, enhancing the accuracy of waveform modeling and optimization [88]. These computational techniques are vital for refining waveform properties and ensuring efficient signal transmission.

The integration of advanced algorithmic and computational methods is essential for optimizing waveform design in terahertz (THz) communication systems, as it enhances the efficiency and reliability of next-generation wireless networks. This is particularly important given the challenges posed by high path loss, antenna misalignment, and atmospheric effects in THz communications. Techniques such as hybrid automatic repeat request (HARQ) can significantly improve reliability, while the development of large-scale THz arrays and highly directional beams can mitigate signal degradation. Furthermore, the establishment of regulatory frameworks, such as the IEEE 802.15 suite of standards, is critical for facilitating innovation and ensuring seamless connectivity across diverse applications, from mobile backhaul links to high-speed data transfer in wireless communication networks. [14, 17, 11]

5.3 Innovative Material and Structural Designs

Innovative material and structural designs play a pivotal role in optimizing waveforms for terahertz (THz) communication systems, offering significant advancements in performance and efficiency. A notable development in this area is the use of metamaterials that generate a uniform magnetic field enhancement, approximately 20 times greater in the central region, which significantly boosts the effectiveness of THz applications [73]. This enhancement is crucial for achieving high precision in THz sensing and communication.

The integration of low-loading graphene composites introduces a novel approach to THz absorption, leveraging their lightweight and electrically insulating properties to achieve significant absorption in the THz range [44]. These composites provide an efficient solution for electromagnetic interference (EMI) shielding, crucial for maintaining signal integrity in THz systems.

Ultrathin metamaterials with high efficiency and broad bandwidth capabilities represent another key advancement, offering substantial improvements over traditional methods [74]. These materials facilitate the development of compact and efficient THz devices, enhancing both communication and sensing capabilities.

The microfabrication process enables the creation of compact, substrate-free waveguide structures, which are essential for minimizing losses and enhancing signal transmission in THz systems [75]. Furthermore, the fabrication of air-channel metallic waveguides, which support topologically protected modes, demonstrates the potential of innovative structural designs to optimize performance in THz communication [76].

The structural tunability of metamaterials, allowing for a fourfold increase in oscillator strength and a 40

Additionally, the unique geometry of indium arsenide (InAs) nanowires contributes to enhanced THz emission efficiency, highlighting the importance of material design in achieving high-performance THz systems [31]. These innovations in material and structural design are essential for advancing waveform optimization in THz communication, paving the way for more efficient and reliable next-generation wireless networks.

5.4 Advanced Beamforming and Hybrid Techniques

Method Name	Technological Innovations	Waveform Optimization	Application Scenarios
DAM[43]	Delay Adjustable Metasurfaces	Reflection Phase Shifts	6G Networks
SIBW[77]	Bragg Waveguides	-	Thz Applications
TFLN-WS[86]	Tfln Circuits	Phase Matching	Quantum Technologies
DRCSD[89]	-	Sequence Parameters Optimization	Autonomous Driving
STM-TC[78]	Diffuse Reflectors	Group Delay Dispersion	Terahertz Communication Systems

Table 4: Overview of advanced beamforming and hybrid techniques for optimizing waveform performance in terahertz (THz) communication systems. The table details various methods, highlighting their technological innovations, waveform optimization strategies, and application scenarios, demonstrating their relevance to emerging communication technologies. These methods are pivotal for addressing challenges associated with high-frequency domains and enhancing communication quality and coverage.

Table 4 presents a comprehensive analysis of advanced beamforming and hybrid techniques, showcasing their contributions to waveform optimization in terahertz (THz) communication systems and their applicability across various technological domains. Advanced beamforming and hybrid techniques are pivotal in optimizing waveforms for terahertz (THz) communication systems, addressing the unique challenges posed by high-frequency domains. Recent advancements in beamforming technologies, particularly through the integration of Intelligent Reflecting Surfaces (IRS), have significantly enhanced communication quality and coverage in THz networks [90]. IRS technology enables dynamic adjustments of signal delays and phases, leading to improved beam focusing across all subcarriers, which is essential for maintaining robust communication links in diverse environments [43].

The development of Substrate Integrated Bragg Waveguides (SIBW) offers several advantages, including lower propagation losses and single-mode operation across a wide frequency range, which are crucial for efficient THz communication [77]. These waveguides facilitate ease of fabrication compared to conventional waveguides, making them an attractive option for implementing advanced beamforming techniques.

In addition to structural innovations, the use of TFLN waveguides in synthesizing THz waveforms with tailored temporal, spectral, phase, and coherence properties has demonstrated significant potential in enhancing beamforming capabilities [86]. This method allows for precise control over waveform characteristics, optimizing signal transmission and reception in THz systems.

The application of Doppler-resilient design techniques, such as the modification of CAZAC sequences, effectively maintains a high Peak-to-Sidelobe Level Ratio (PSLR) and reduces false alarm rates by strategically shifting sidelobes away from the main peak [89]. This approach is particularly beneficial in dynamic environments where Doppler effects can significantly impact waveform performance.

Furthermore, the quantitative modeling of spintronic terahertz emitters, including the effects of detector shape and the energy dependence of the spin Hall effect, provides insights into optimizing waveform techniques for enhanced performance [91]. The simulation of group delay dispersion and its impact on symbol error rates in THz wireless communication underscores the importance of waveform optimization in improving system performance [78].

The integration of advanced beamforming and hybrid techniques is crucial for optimizing waveform performance in terahertz (THz) communication systems, as it enhances spectral efficiency and energy efficiency by addressing the significant propagation losses associated with THz frequencies. This approach is particularly vital for the development of next-generation wireless networks, such as 6G, which require ultra-massive multiple-input multiple-output (UM-MIMO) architectures that can effectively utilize both inter-path and intra-path multiplexing to improve data transmission capabilities in spatially sparse THz channels. By leveraging innovations such as widely-spaced multi-subarray configurations, these techniques promise to overcome challenges associated with high path loss and enable efficient, reliable communication across a range of applications, including mobile front and backhaul links and data center connectivity [92, 11]. These innovations pave the way for more robust communication strategies, addressing the complex challenges associated with THz frequencies.

5.5 Practical Implementations and Future Directions

The practical implementation of waveform optimization in terahertz (THz) communication systems is critical for advancing high-frequency domains, offering significant improvements in both communication and sensing capabilities. A promising approach involves the development of Doppler-robust channel estimation methods, which enhance parameter estimation accuracy in high mobility environments, crucial for joint sensing and communication applications within OFDM systems [83]. Future research should focus on refining these algorithms to improve performance under varied conditions, thereby increasing system robustness.

The optimization of the geometry and doping concentration in electronic THz devices presents another avenue for enhancing device performance, impacting the efficiency and reliability of THz communication systems [79]. Mechanical tuning of photonic structures offers significant potential for enhancing tuning capabilities in THz applications, with future research focusing on optimizing geometrical configurations to further improve performance [80].

The integration of THz communication in Internet of Things (IoT) networks highlights the need for hybrid approaches that address computational demands and enhance system robustness against environmental factors [93]. Future research should focus on optimizing these hybrid methods for real-world applications, ensuring effective management of complexities in dynamic environments.

In the context of Intelligent Reflecting Surfaces (IRS), robust design and sophisticated channel estimation techniques are crucial for supporting THz communication systems [82]. Future research could explore the scalability of these methods in larger and more dynamic environments, ensuring they can effectively support the growing demands of next-generation networks.

Deep learning-based approaches for multiband signal fusion, such as kR-Net, offer significant potential for optimizing waveforms in THz communication systems [84]. Future research should focus on developing more diverse datasets and exploring additional architectures to address limitations related to frequency dependence in scattering properties.

The design and implementation of Conjugate Beamforming (CBF) in various antenna architectures hold promise for enhancing THz communication systems [85]. Future research could investigate the performance of CBF in more complex channel conditions, optimizing its design for diverse environments.

Optimizing dielectric materials and exploring alternative lens designs in superstrate lenses for patch antennas can further enhance coupling efficiency and detector performance in THz systems [81]. Future research should focus on these aspects to improve the overall effectiveness of THz communication technologies.

The integration of noise correction techniques with existing data analysis tools offers a practical approach to enhancing the usability of THz communication systems [45]. Future research should focus on refining these techniques to ensure accurate signal estimation and robust performance in diverse environments.

Exploring the integration of THz and FSO technologies, advanced relaying techniques, and addressing regulatory challenges are crucial for practical implementations [39]. Additionally, optimizing the designs of perfect metamaterial absorbers and exploring additional applications in various sensing scenarios can significantly enhance system capabilities [2].

Future research should also focus on optimizing the balance between code length and performance, exploring alternative decoding methods, and investigating the integration of Parallel Sensing and Information (PSI) in different communication scenarios [1]. Furthermore, exploring mobility support in IRS-aided networks, enhancing the practical implementation of IRS reflecting elements, and investigating near-field communication scenarios could provide significant advancements [26].

The development of adaptive relay selection strategies that dynamically adjust based on network conditions and user demands, as well as the integration of machine learning techniques to enhance relay selection efficiency, represent promising research directions [34]. Additionally, exploring adaptive algorithms that dynamically adjust to changing channel conditions and investigating the trade-offs between computational complexity and performance are essential for future advancements [35].

Enhancing the generation efficiency and spectral bandwidth of THz signals, exploring advanced techniques for arbitrary waveform synthesis, and integrating detection capabilities into the TFLN platform are promising areas for future research [86]. These efforts will be crucial for advancing the practical implementation and optimization of waveforms in THz communication systems, paving the way for more efficient and reliable next-generation wireless networks.

Feature	Programmability and Optimization Techniques	Algorithmic and Computational Approaches	Innovative Material and Structural Designs
Optimization Technique	Tfln Circuits	Kr-Net Algorithm	Metamaterials
Application Domain	Adaptive Waveforms	Signal Fusion	Thz Absorption
Unique Feature	Phase Shifts	Deep Learning	Magnetic Enhancement

Table 5: This table presents a comparative analysis of key methodologies employed in waveform optimization for terahertz (THz) communication systems. It categorizes the techniques into programmability and optimization techniques, algorithmic and computational approaches, and innovative material and structural designs, highlighting their unique features and application domains. The table underscores the significance of these methodologies in enhancing the adaptability and performance of THz communication systems.

6 Spectral Efficiency in Terahertz Communication

6.1 Conceptual Framework of Spectral Efficiency

The conceptual framework of spectral efficiency in terahertz (THz) communication is pivotal for optimizing bandwidth usage and maximizing data throughput. Spectral efficiency, defined as the rate of information transfer per unit bandwidth, serves as a crucial metric for assessing communication systems, especially in the high-frequency THz domain. This framework incorporates advanced technologies such as visible light and full-spectrum wireless communications to enhance capabilities and address challenges in future mobile networks, particularly in the context of anticipated 6G developments for the 2030s [25, 8, 13, 9, 11].

A fundamental strategy for enhancing spectral efficiency involves employing spatial multiplexing in line-of-sight (LOS) MIMO systems, demonstrating feasibility in achieving high efficiency despite traditional LOS limitations [32]. Additionally, integrating triple-band scheduling schemes optimizes resource utilization and bandwidth efficiency by selecting optimal bands based on quality of service (QoS) requirements [13].

System spectral efficiency is further evaluated through energy efficiency trade-offs, balancing bandwidth and power consumption to optimize performance. This involves simulating spectral efficiency and calculating total circuit power to balance energy consumption with communication efficiency, crucial for sustainable THz systems [53]. Advanced channel estimation techniques maintain spectral efficiency by reducing reliance on extensive pilot sequences, enabling accurate channel estimation while conserving bandwidth [35].

Innovative materials and structural designs, such as InAs-based photoconductive switches, enhance propagation over specific frequency ranges, improving bandwidth and supporting spectral efficiency [28]. Time reversal techniques in THz links create multipath channels for efficient signal transmission, exemplifying advanced methodologies that enhance spectral efficiency [10].

The stochastic characterization of the THz channel, treating reconfigurable intelligent surfaces (RIS) as continuous surfaces and analyzing misalignment effects on signal-to-noise ratio (SNR), provides a theoretical foundation for optimizing spectral efficiency [32]. This approach emphasizes precise channel modeling and adaptive modulation techniques to maximize bandwidth utilization and system performance.

The framework integrates advanced modeling, sensing, and modulation techniques to optimize bandwidth utilization and enhance system performance. It addresses challenges like high path loss and antenna misalignment through strategies like hybrid automatic repeat request (HARQ) for improved reliability. Insights from standards such as IEEE 802.15 promote innovation in high-speed transmission scenarios, facilitating scalable, low-cost THz networks supporting diverse applications, including wireless communication in data centers and mobile backhaul links [11, 17, 14]. These efforts are crucial for advancing next-generation wireless networks and meeting the high data rate and low latency demands of future communication applications.

6.2 Methods to Enhance Spectral Efficiency

Enhancing spectral efficiency in THz communication systems is essential for optimizing bandwidth utilization and improving performance. A promising method involves optimizing subarray configurations and spacing, significantly impacting spectral efficiency by leveraging the spatial properties of THz signals to maximize throughput [92].

Index modulation (IM) offers another effective strategy, dynamically adjusting pilot signal positions within data frames to transmit additional information alongside pilots without increasing bandwidth requirements [94]. This technique is particularly advantageous in bandwidth-limited scenarios.

Advanced signal processing techniques, such as the CRNet framework, leverage local spectral correlation and structured sensing to reconstruct the spectrum from under-sampled data, ensuring efficient bandwidth utilization [95]. Learning-based prediction and rendering transmission methods significantly improve quality of experience (QoE), achieving a two-fold enhancement compared to random phase shift selection [96].

Phase-based techniques, like reconstructing breathing motion from THz signals, enhance spectral efficiency by optimizing spectral resource usage while improving health monitoring accuracy [3]. Additionally, the transient WGP method enables precise control over THz waveform polarization, further enhancing spectral efficiency [71].

Assessing spectral efficiency concerning outage probability under varying signal-to-noise ratios (SNRs) provides valuable insights for optimizing system performance [97]. This evaluation is essential for developing robust communication strategies that maximize spectral efficiency while minimizing outage risks.

These methods highlight diverse strategies for enhancing spectral efficiency in THz communication systems. By incorporating advanced modulation techniques, sophisticated signal processing methods, and adaptive communication strategies, these approaches facilitate the development of next-generation wireless networks promising enhanced efficiency and reliability, particularly in the context of evolving 6G technology. This evolution necessitates utilizing a broader spectrum of frequencies, including millimeter waves and terahertz bands, to meet increasing bandwidth requirements and support innovative applications such as intelligent connectivity and ubiquitous communication [9, 13, 25].

6.3 Technological Advancements and Applications

Recent technological advancements have significantly enhanced the spectral efficiency of THz communication systems, enabling diverse applications across multiple sectors. Carbon nanomaterials have the potential to revolutionize THz technology by creating compact and efficient sources and detectors that operate at room temperature, promising for communications, biomedical imaging, and security applications where high efficiency and compactness are crucial [54].

The integration of Reconfigurable Intelligent Surfaces (RIS) in THz communication systems has also improved spectral efficiency. Studies comparing the FR3 frequency range with others have shown that FR3 offers enhanced spatial channel information and spectral efficiency in RIS-assisted scenarios [98]. This improvement optimizes available bandwidth and enhances overall system performance.

These technological advancements facilitate the development of high-performance THz communication systems capable of supporting a wide range of applications. In biomedical imaging, enhanced spectral efficiency enables more precise imaging, essential for accurate diagnostics and treatment planning. In security applications, efficient THz spectrum utilization enhances the detection of concealed objects and materials, bolstering threat detection capabilities and public safety measures. THz-specific signal processing techniques, including signal pre-processing, feature extraction, and classification, enable the identification of materials and gases of interest. The high-frequency, narrow-angle broadcasts characteristic of THz communications present a challenging environment for potential eavesdroppers, increasing the overall security of wireless systems operating in this frequency range [99, 18].

Ongoing advancements in THz technology, fueled by innovations in materials and system design, underscore the critical role of spectral efficiency in unlocking the capabilities of next-generation wireless networks. As wireless data traffic surges, the THz frequency band (0.1-10 THz) emerges as a promising solution for high-speed transmission, bridging the gap between millimeter wave and optical frequencies. This evolution supports ultra-high bandwidth and minimal latency while addressing the increasing demand for massive capacity and connectivity in diverse infrastructures. Establishing regulatory frameworks, such as the IEEE 802.15 suite of standards, is essential for facilitating innovation and ensuring seamless integration across wired and wireless systems. Challenges remain, including high path loss and the need for highly directional THz beams to maintain effective communication. As research progresses, optimizing spectral efficiency becomes paramount for realizing the full potential of future wireless communication systems, particularly in the context of emerging 6G technologies [11, 13, 25, 14]. Further advancements are expected to expand the application domains of THz communication systems, enhancing their capabilities and impact across various sectors.

6.4 Challenges and Future Research Directions

Enhancing spectral efficiency in THz communication systems presents several challenges that require ongoing research and innovation. A primary challenge is accurately modeling THz channel conditions, crucial for optimizing system design and performance. Current methodologies often rely on idealized channel models that fail to capture the complexities of real-world conditions and interference scenarios [6]. This underscores the need for more robust and adaptable sensing systems that can effectively translate laboratory findings to practical applications [65].

Integrating THz communication systems into existing network infrastructures raises questions about the long-term stability of THz links and optimizing channel models to accommodate various environmental conditions. Transitioning to higher carrier frequencies

7 Channel Modeling for Terahertz Communication

7.1 Methodologies for Accurate Channel Modeling

Accurate channel modeling in terahertz (THz) communication is crucial for optimizing system performance and understanding unique propagation characteristics. Recent advancements integrate empirical data with theoretical frameworks, notably through the Geometry-Based Stochastic Model (GBSM), which enhances wireless channel simulations by accounting for UAV dynamics and antenna characteristics [100]. Machine learning techniques, such as the NBA-OMP method, improve channel estimation by compensating for beam-split effects, significantly enhancing precision [101]. Hybrid approaches combining deterministic simulations with statistical models offer comprehensive solutions for complex environments [40].

Characterizing channel performance under adverse weather conditions is essential for developing robust 6G technologies, as demonstrated by Sen et al.'s benchmark [3]. The dual-hop relay system, employing THz for the first hop and RF for the second, exemplifies integrating diverse transmission technologies to enhance channel modeling [27]. Innovative scattering models assess surface roughness effects on temporal dispersion, impacting symbol error rates. The IEEE 802.15.3d task force's spectral allocations for 252–325 GHz frequencies facilitate applications like high-speed data transfer and mobile backhaul links. Despite THz technology's promise, challenges like high path loss require highly directional beams and large-scale phased arrays. Ongoing research into the sub-terahertz spectrum aims to unlock increased bandwidths and support ambitious 6G goals, including ultra-high data rates and minimal latency, while ensuring compatibility with existing infrastructure [12, 14, 11].

7.2 Modeling Techniques for Terahertz Propagation

Modeling techniques for THz propagation capture the unique characteristics of THz communication channels influenced by high frequencies and environmental factors. The Hybrid Spherical-Planar Wave Channel Model (HSPM) combines spherical-wave propagation for near-field scenarios with planar-wave propagation for far-field ones, ensuring accurate modeling across distances [102]. The General 3D Space-Time-Frequency Non-Stationary Model (GBSM) incorporates non-stationarities, allowing customization for various 6G applications by capturing dynamic aspects of THz channels [103].

In UAV scenarios, modeling THz channel conditions is crucial for optimizing signal propagation, necessitating techniques that consider dynamic environments and UAV mobility [67]. The LoS THz channel model reveals a complex relationship between SNR and distance, capturing interactions between THz waves and molecular structures [104]. A comprehensive dataset from 19,080 and 907,200 channel impulse responses provides insights into characteristics like path loss and delay spread, serving as a foundation for robust THz channel models [105]. Transfer learning-enabled transformer models enhance precision in THz channel modeling [62]. Principles of single-pixel THz imaging emphasize integrating optical system design with THz modeling for high-quality imaging and sensing [46]. Channel measurements from a 70 m link setup across various weather scenarios validate THz channel models, highlighting weather's impact on signal propagation [106].

In near-field THz systems, estimating channel parameters using widely-spaced multi-subarray configurations poses challenges, necessitating advanced techniques to manage complexities [107]. These techniques are integral to understanding and optimizing THz signal propagation, addressing high-frequency communication challenges, and paving the way for efficient next-generation wireless networks. The inability of existing methods to model near-field conditions effectively, leading to inaccuracies in DoA and range estimation, remains a core obstacle [108]. The scarcity of THz channel measurement data complicates conventional models' training, underscoring the need for innovative approaches like transfer learning [101].

7.3 Recent Research and Developments

Recent advancements in THz channel modeling focus on improving model accuracy and adaptability to capture unique propagation characteristics. Notable breakthroughs include four distinct estimation frameworks—PD-E, MAD-E, TS-PAD-E, and 2D-PAD-E—leveraging sparse recovery theory to enhance near-field channel estimation precision [107]. The NBA-OMP method effectively recovers channel parameters often missed by traditional methods, addressing beam-split effects [108].

Empirical studies, such as ground-to-UAV sub-terahertz channel measurements, reveal SNR's Weibull distribution under hovering conditions, highlighting THz channels' complex fading characteristics [109]. Integrating transfer learning with GANs, the T-GAN method improves power delay profile distributions for THz channels, even with limited data [101]. The RT-statistical hybrid channel model combines ray-tracing techniques with statistical methods, offering improved accuracy in capturing THz channels' dynamics in non-line-of-sight scenarios [40]. The 3D statistical indoor channel model demonstrates high fidelity by aligning simulated channel statistics with measured values, validating the integration of empirical data with theoretical models [100].

These advancements underscore the integration of advanced estimation frameworks, empirical studies, and machine learning techniques to enhance THz communication systems' precision and reliability. Such initiatives are crucial for advancing next-generation wireless networks, particularly in the THz frequency range, which presents challenges like high path loss and the need for highly directional beams. Addressing these issues is essential for achieving ultra-high bandwidth, minimal latency, and seamless communication, supporting advanced applications in mobile backhaul, data centers, and wireless communication systems. Developing scalable, low-cost interfaces and innovative transceiver designs will be vital for unlocking the sub-terahertz spectrum's potential and ensuring compatibility with existing technologies as we progress toward 6G deployment [12, 14, 11].

7.4 Ongoing Challenges and Future Directions

Ongoing challenges in THz channel modeling reflect the complexity of accurately capturing propagation characteristics across varied environments. A significant challenge is developing comprehensive models that account for non-stationary effects and spatial-temporal dynamics inherent in THz communication. Current models often lack adaptability for these dynamics, particularly in ultra-massive MIMO applications [40]. Future research should prioritize developing spatially consistent models to enhance THz communication systems' accuracy and reliability [40].

The scarcity of empirical data for THz channels, especially in non-line-of-sight scenarios, hinders robust model development. Future research should emphasize extensive measurement campaigns to gather data in underrepresented scenarios, informing more accurate model development [100]. Integrating advanced machine learning techniques into channel modeling presents opportunities and challenges. While enhancing accuracy, their complexity and hardware requirements pose barriers to real-world implementation. Future studies should explore additional machine learning algorithms, optimizing complexity for practical deployment [101]. Meta-learning techniques could further enhance model adaptability in diverse environments [108].

Novel THz channel sounders and low-complexity parameter estimation algorithms are critical for accurately characterizing THz channels and supporting joint communication and sensing applications [107]. Extending frameworks like NYUSIM to cover frequencies above 150 GHz will be crucial for advancing THz channel modeling [40]. Exploring advanced modulation techniques and MIMO channels for high-speed wireless communications is vital to address high data rate challenges and ensure robust performance in THz systems. Future studies should aim to extend current algorithms to manage near-field and nonstationary channels, broadening their applicability across diverse environments [100].

8 Conclusion

The investigation into terahertz (THz) communication systems underscores their pivotal role in advancing next-generation wireless networks. Integrating THz frequencies with Integrated Sensing and Communication (ISAC) systems has catalyzed substantial progress, notably through optimizing Reconfigurable Intelligent Surfaces (RIS) and enhancing spectral efficiency. These developments are vital for meeting the high data rate and low latency demands of 6G networks. The application of Orthogonal Frequency Division Multiplexing (OFDM) in THz communication has significantly bolstered spectral efficiency and signal transmission reliability. Furthermore, the hybrid deployment of THz and Free-Space Optical (FSO) links has notably improved backhaul network performance, illustrating the potential of integrated communication systems. Waveform optimization, particularly through thin-film lithium niobate circuits, has enabled programmable and adaptive designs, enhancing system robustness and efficiency.

Advancements in channel modeling have focused on the distinct propagation characteristics of THz frequencies, with models like the Geometry-Based Stochastic Model (GBSM) providing comprehensive frameworks for simulating wireless channel behavior. The integration of machine learning techniques, such as transfer learning-enabled transformer models, has further refined channel modeling accuracy, offering promising research pathways. Spectral efficiency continues to be a crucial focus, with ongoing research into optimizing bandwidth utilization and overall system performance. The deployment of THz MIMO systems has demonstrated that the unique properties of short wavelengths can significantly improve spectral efficiency when appropriate antenna architectures are utilized.

Future research should concentrate on refining channel modeling techniques, optimizing waveform designs, and enhancing spectral efficiency to fully harness the potential of THz frequencies in upcoming wireless networks. The development of hybrid nanocommunication systems and the integration of interdisciplinary approaches are essential to overcoming current limitations and fostering innovation in this transformative domain. Additionally, establishing new physical-layer security protocols is imperative to mitigate the threat of eavesdropping in THz communications. The conclusion underscores the need for further advancements in proposed systems to support diverse applications, suggesting future research directions in terahertz ISAC and communication.

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