A Survey on Terahertz ISAC Waveform Design and Optimization for Integrated Sensing and Communications

Abstract

Terahertz (THz) Integrated Sensing and Communication (ISAC) systems represent a transformative advancement in next-generation wireless networks, offering ultra-high bandwidth and low latency essential for modern communication environments. This survey explores the integration of sensing and communication functionalities in THz systems, emphasizing their role in achieving significant improvements in data transmission and environmental sensing capabilities. Notable advancements include innovative fabrication methods, such as hybrid THz photoconductive antennas (PCAs), which have demonstrated a more than fivefold increase in THz signal generation. The survey addresses challenges in THz signal propagation and attenuation, highlighting the importance of robust models and interdisciplinary approaches to optimize channel performance. Advanced waveform design and optimization techniques, including cooperative beam training and hybrid beamforming, significantly enhance the performance of THz multi-user massive MIMO systems. The survey also underscores the potential of metasurfaces and metamaterials in enhancing waveform design and optimization, providing unparalleled control over electromagnetic waves. Future research directions include the integration of advanced machine learning techniques, hybrid and multi-band systems, and advanced fabrication methods to further optimize THz ISAC systems. By addressing existing challenges and leveraging opportunities presented by advanced technologies, THz communications can realize their full potential, driving innovation and connectivity across diverse sectors. The ongoing exploration of these areas will be pivotal in shaping the future landscape of wireless communications.

1 Introduction

1.1 Significance of Terahertz (THz) Frequency Communications

The terahertz (THz) frequency band, spanning 0.1 to 10 THz, is increasingly acknowledged for its transformative potential in wireless communications, providing ultra-high bandwidth and rapid data transmission essential for the evolution of beyond 5G networks [1]. THz frequencies address the limitations of current data transfer methods, enabling data rates reaching terabits per second, thereby alleviating baseband computation bottlenecks and enhancing network coverage [2]. This positions THz technology as pivotal for next-generation wireless systems.

THz transmission offers significant advantages over traditional radio frequency (RF) networks by enhancing coverage and providing the bandwidth necessary to meet future data demands [2]. The capability of THz frequencies to synthesize arbitrary waveforms is crucial for narrow band sources in sensing and few-cycle drives for classical and quantum objects [3]. Additionally, the brightness of THz radiation, with peak fields and intensities in the low-frequency THz range, enhances its applicability to nonlinear phenomena in science [4].

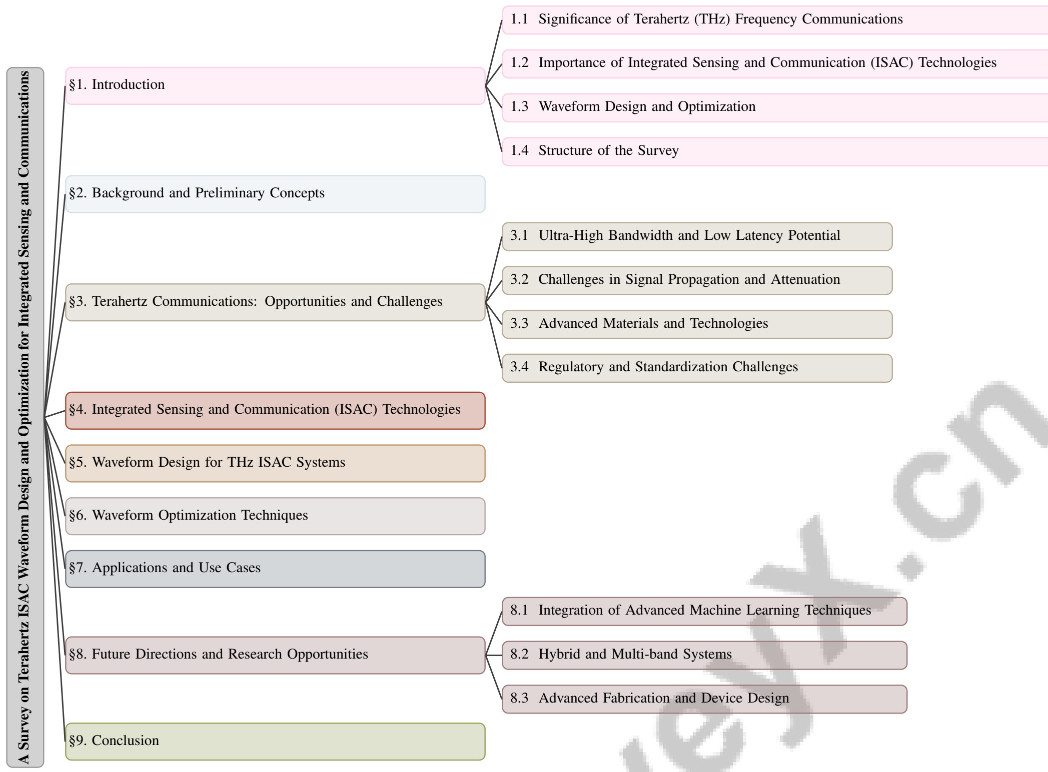


Figure 1: chapter structure

Recent advancements in THz technology include THz acceleration technology, which utilizes short pulses of terahertz radiation to accelerate electrons over short distances, achieving high gradients and compact accelerator designs [5]. This underscores the importance of THz frequencies in modern communications, particularly in sensing and telecommunications applications [6]. Moreover, spintronic terahertz emitters (STEs) demonstrate efficiency in generating terahertz radiation, addressing challenges in waveform and receiver design for THz integrated sensing and communication (ISAC) systems.

The development of compact sources of energetic, phase-locked multi-terahertz pulses addresses limitations of previous methods, which restricted repetition rates to a few kHz [7]. Advancements in measuring high-frequency complex conductivity of correlated-electron materials at low temperatures and high magnetic fields further support the integration of THz technology into mobile networks, overcoming conventional 'table-top' terahertz spectrometer limitations [8].

As research progresses, THz frequencies are set to become a cornerstone of future wireless communication technologies, meeting high-speed data transmission demands while offering innovative solutions across various sectors. Enhanced modulation techniques at THz frequencies promise to revolutionize data transmission, ensuring the continued growth of communication systems [9].

1.2 Importance of Integrated Sensing and Communication (ISAC) Technologies

Integrated Sensing and Communication (ISAC) technologies are crucial for advancing 6G mobile communications, enabling the use of communication signals for dynamic target sensing, particularly within the THz band. This dual functionality is essential for THz systems, where simultaneous data transmission and precise sensing are critical for applications such as autonomous navigation and smart infrastructure development. The integration of ISAC technologies in THz systems optimizes resource use, enhancing performance in both communication and sensing tasks [10].

The deployment of ISAC technologies is exemplified by compact terahertz dual-comb spectroscopy systems utilizing quantum cascade lasers for real-time spectral detection, showcasing the dual benefits of sensing and communication in THz systems [11]. Furthermore, the integration of super-resolution

AI-generated, for reference only.

sensing and communication (ISSAC) enables high precision in parameter estimation, enhancing the accuracy and reliability of THz systems [12].

However, implementing ISAC technologies in mmWave/THz multi-user MIMO systems presents challenges related to resource competition and interference management, necessitating advanced optimization techniques for efficient system performance [13]. Despite these challenges, ISAC technologies have vast potential applications in fields such as biology, pharmaceuticals, and security, where continuous-wave terahertz systems have been successfully applied [14].

As the demand for high-speed and reliable communication grows, ISAC technologies are poised to play a critical role in the evolution of wireless systems, particularly in the transition to 6G and beyond. By integrating sensing and communication capabilities, ISAC technologies enhance the operational efficiency of THz systems, achieving unprecedented data rates and millimeter-level accuracy in sensing. This integration addresses challenges in waveform and receiver design in THz channels and paves the way for innovative applications across diverse sectors, including advanced wireless communications, radar systems, and real-time environmental monitoring. Consequently, these technologies are well-positioned to adapt to the evolving demands of future communication environments, ensuring robust performance in complex scenarios such as multi-target estimation and Doppler effect mitigation [13, 15, 16, 17, 18].

1.3 Waveform Design and Optimization

Waveform design and optimization are pivotal in Terahertz (THz) Integrated Sensing and Communication (ISAC) systems, enhancing both communication and sensing functionalities. The integration of THz systems within photonic structures, as demonstrated by Lampert et al. [19], illustrates the potential of nonlinear optical mixing for efficient THz generation and detection, crucial for practical deployment.

The development of multifunctional terahertz metadevices, discussed by Pitchappa et al. [20], underscores the significance of waveform design in enabling devices to respond to various stimuli, enhancing adaptability and functionality across applications. Additionally, tunable THz radiation generation through optical rectification of a temporally modulated laser beam in organic crystals, explored by Vicario et al. [21], significantly improves tunability and efficiency.

Optimization frameworks aimed at enhancing throughput and trajectory for THz-enabled UAVs, incorporating UAV-GU association and transmit power management, further exemplify the necessity of waveform optimization in dynamic environments [22]. In THz pulse generation, driving large amplitude electron plasma waves in a plasma slab using ultrashort laser pulses produces single-cycle THz pulses [23], essential for achieving high-intensity THz fields.

The use of 3D Dirac semimetals for optical-to-terahertz conversion, investigated by Wang et al. [24], emphasizes material innovation's role in waveform design, enhancing THz system efficiency. Advanced techniques, such as side-absorbers in quantum cascade lasers (QCLs) for ultra-short pulse generation, are critical in waveform design [25]. Furthermore, managing THz noise is vital for device performance, as highlighted by Colom et al. [26], reinforcing the need for meticulous waveform design.

Waveform design also enhances imaging capabilities in THz systems, addressing low contrast and blurred images [27]. The use of flat liquid jets for terahertz generation, focusing on optimizing medium parameters to enhance energy conversion efficiency, exemplifies innovative approaches in this field [28].

These advancements in waveform design and optimization drive innovations that expand THz technology's potential applications, ensuring THz ISAC systems can meet the diverse needs of future communication environments [29].

1.4 Structure of the Survey

This survey is structured to provide a comprehensive overview of Terahertz (THz) Integrated Sensing and Communication (ISAC) systems, emphasizing critical aspects of waveform design and optimization, including techniques such as time-frequency-space transmit design, hybrid beamforming architectures, and advanced receiver processing methods that enhance data transmission rates—potentially reaching Terabit-per-second levels—and millimeter-level sensing accuracy [13, 17, 18].

The survey begins with an **Introduction** that establishes the significance of THz frequency communications and the importance of ISAC technologies, delving into the critical role of waveform design in enhancing the dual functionalities of communication and sensing.

The subsequent section, **Background and Preliminary Concepts**, lays the foundational knowledge necessary for understanding THz communications, ISAC technologies, and waveform design principles, contextualizing the advancements discussed later.

In the survey titled , the transformative potential of terahertz (THz) frequencies is examined, highlighting their capacity to deliver ultra-high bandwidth and minimal latency for next-generation communication systems, particularly in the context of 6G networks. The survey addresses the advantages of THz communication in meeting increasing data traffic demands while thoroughly examining significant challenges, including signal propagation issues, the need for advanced materials, and regulatory complexities. It emphasizes the necessity for robust design strategies to facilitate THz technology integration into complex mobile networks, ensuring efficient and reliable communication across diverse applications [30, 15, 29, 31, 32].

The section on **Integrated Sensing and Communication (ISAC) Technologies** explores the dual functionality of ISAC systems, highlighting how integrated sensing can enhance communication capabilities and provide innovative solutions across various applications.

The survey delves into , discussing the innovative integration of electronic and photonic technologies. It presents various frameworks and methodologies employed in waveform design, including advanced techniques like sensing integrated discrete Fourier transform spread orthogonal frequency division multiplexing (SI-DFT-s-OFDM) and dynamic array-of-subarray (DAoSA) hybrid beamforming architectures. The challenges of high path loss in the THz band are addressed, along with solutions for optimizing communication and sensing performance, illustrating how these approaches can enhance data transmission rates and sensing accuracy in next-generation wireless systems [13, 15, 33, 17, 18].

are extensively examined, focusing on the integration of machine learning and adaptive algorithms to enhance waveform performance. The role of advanced materials such as metasurfaces and metamaterials is emphasized, particularly in applications like terahertz (THz) wave manipulation and reconfigurable intelligent surfaces (RIS). These technologies enable precise control over electromagnetic properties, allowing for significant improvements in imaging, spectroscopy, and wireless communication through optimized transmission, reflection, and polarization of THz waves [34, 35, 36].

The section on **Applications and Use Cases** provides real-world examples of THz ISAC systems, illustrating their applications in biomedical sensing, environmental monitoring, and communication scenarios.

The section titled outlines emerging trends and potential research areas, focusing on integrating advanced machine learning techniques and developing hybrid systems, driven by the evolving demands of high-data-rate communications and radar sensing in next-generation technologies. This includes a shift towards unified vehicular communications and radar systems operating in millimeter-wave and terahertz bands, necessitating a reevaluation of traditional models and exploration of new methodologies to address the complexities introduced by higher frequency operations. It emphasizes the importance of real-world measurements in guiding research and the need for collaborative efforts across academia and industry to foster innovation in physical-layer communications [37, 38].

The survey concludes by summarizing critical insights discussed throughout, emphasizing the necessity for ongoing research and development in Terahertz (THz) Integrated Sensing and Communication (ISAC) waveform design and optimization. This effort is essential to harness THz communications' full potential, particularly in addressing challenges such as high path loss, the beam squint effect in sub-THz systems, and the need for advanced algorithms to improve performance in both communication and sensing tasks. The findings underscore the importance of innovative approaches, such as hybrid analog/digital beamforming and deep learning-powered receiver designs, to enhance the dual functionalities of THz ISAC systems and ensure their practical implementation in future wireless networks [13, 15, 16, 17, 18].The following sections are organized as shown in Figure 1.

2 Background and Preliminary Concepts

2.1 Fundamentals of Terahertz Communications

Terahertz (THz) communications, covering 0.1 to 10 THz, are integral to addressing the surging demand for high-speed data transfer driven by the exponential growth in wireless data traffic [39]. The THz band's vast bandwidth enables terabit-per-second (Tbps) data rates, marking it as a cornerstone for future ultra-high-speed wireless networks.

A primary challenge in THz communications is the efficient generation and detection of THz waves, as many materials exhibit high absorption in this frequency range [40]. Spintronic THz emitters, which convert spin into charge currents in magnetic heterostructures, offer a promising approach to overcoming these challenges [41]. However, current methods for generating structured THz pulses often lack spatial structure, limiting their use in sophisticated spectroscopy [42].

Ultra-massive multiple-input multiple-output (UM-MIMO) systems within THz-band non-orthogonal multiple access (NOMA) setups face significant signal losses, necessitating advanced data detection techniques [43]. Moreover, traditional photoconductive detectors in terahertz imaging and spectroscopy are limited by narrow operational bandwidth and low responsivity, primarily due to parasitic effects [44].

Enhancing sensing capabilities at terahertz frequencies can be achieved using perfect metamaterial absorbers (PMAs), which provide superior sensitivity compared to previous planar metamaterial sensors [45]. Despite advancements, challenges like severe insertion losses at THz wavelengths and the limited flexibility of bulk crystal methods for synthesizing arbitrary waveforms remain [46, 3].

Generating multi-terahertz pulses with high peak electric fields and suitable repetition rates is crucial for advanced applications in lightwave electronics [7]. As THz communications progress, innovations in substrate technologies, device architectures, and system designs will be pivotal in enhancing next-generation wireless networks' capabilities, paving the way for novel applications across various sectors.

2.2 Integrated Sensing and Communication (ISAC) Overview

Integrated Sensing and Communication (ISAC) technologies are essential for advancing modern wireless networks, particularly as we transition to 6G systems. ISAC merges communication and sensing functionalities, optimizing resource use and enhancing next-generation wireless systems' efficiency [47]. This integration supports diverse applications, from autonomous vehicles to smart cities, by enabling simultaneous data transmission and environmental sensing [10].

A key feature of ISAC technologies is their capability to enhance system performance through methods like Diversity Electro-Optic Sampling (DEOS), which improves resolution by employing phase diversity in dual-output electro-optic sampling systems, particularly beneficial in sub-terahertz systems where beam squint is a major challenge [33]. Optimizing hybrid precoding in these systems ensures the effective maintenance of both communication and sensing functionalities [16].

ISAC also addresses challenges related to charge transport mechanisms in emerging materials critical for efficient terahertz systems [48]. Accurate measurement of electrical properties is vital for deploying high-performance terahertz communication systems [49]. Furthermore, ISAC plays a crucial role in detecting and classifying space debris in Low Earth Orbit (LEO), enhancing situational awareness and ensuring the safety of space operations [10].

Research in ISAC spans various domains, including AI-based methods, sensing-based techniques, and reconfigurable intelligent surface (RIS)-assisted approaches, each addressing specific challenges and opportunities [50]. These methodologies are essential for optimizing the balance between communication and sensing, ensuring ISAC technologies can meet the diverse demands of future wireless networks [13].

Moreover, ISAC technologies enhance the sensitivity and performance of terahertz applications, particularly in detecting analytes with unique spectral signatures. The application of PMAs improves sensitivity compared to traditional planar metamaterial sensors, addressing limitations in existing sensor technologies [45]. Corrective algorithms are also vital for mitigating noise from non-uniform sampling in terahertz time-domain spectroscopy (TDTS), thereby enhancing ISAC systems' accuracy and reliability [51].

By integrating advanced techniques such as joint transceiver optimization and hybrid analog/digital beamforming, while addressing challenges like maximizing communication rates and minimizing signal interference, ISAC technologies are poised to significantly improve wireless networks' efficiency and performance. These advancements are crucial for adapting to a rapidly evolving technological landscape, particularly as we move to higher frequency bands, including millimeter wave and terahertz, which demand sophisticated modeling and system design to accommodate increased data rates and complex channel conditions [37, 13].

3 Terahertz Communications: Opportunities and Challenges

Terahertz (THz) communications promise transformative advantages through ultra-high bandwidth and low latency, crucial for next-generation wireless networks. These features enhance spectral efficiency and data transmission rates, addressing current limitations and enabling broader applications in future infrastructures. Figure 2 illustrates the hierarchical structure of THz communications, highlighting the opportunities presented by ultra-high bandwidth and low latency potential. It also depicts the challenges related to signal propagation and attenuation, as well as advancements in materials and technologies. Furthermore, the figure addresses regulatory and standardization challenges, breaking each category down into specific aspects such as technological innovations and regulatory issues. This comprehensive overview reflects the complexity and potential of THz communications in the context of next-generation wireless networks, thereby reinforcing the significance of these features in overcoming existing barriers.

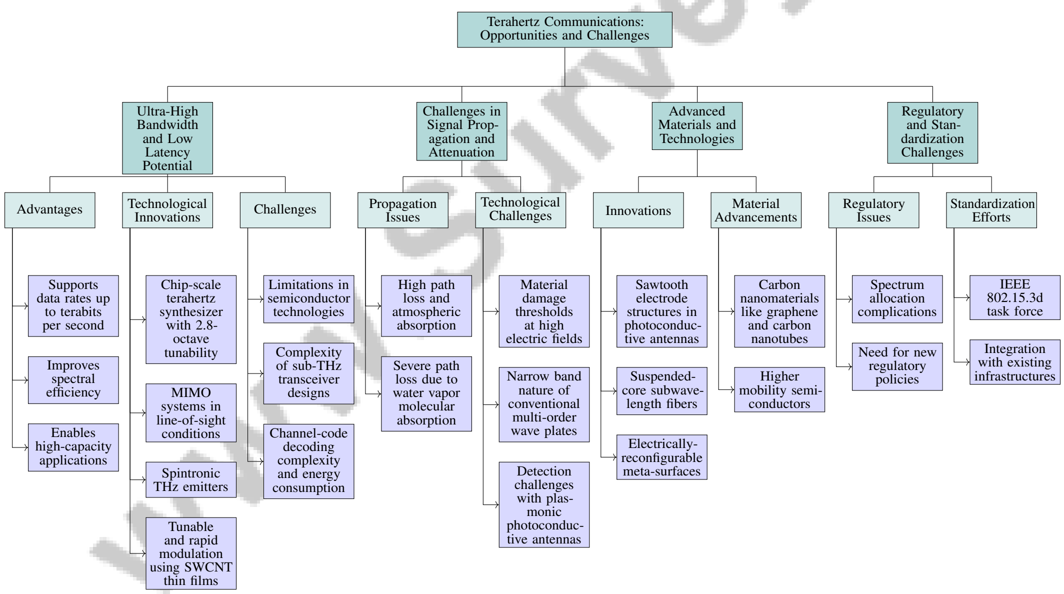


Figure 2: This figure illustrates the hierarchical structure of Terahertz (THz) communications, highlighting the opportunities in ultra-high bandwidth and low latency potential, challenges in signal propagation and attenuation, advancements in materials and technologies, and regulatory and standardization challenges. Each category is further broken down into specific aspects, such as technological innovations and regulatory issues, reflecting the complexity and potential of THz communications in next-generation wireless networks.

3.1 Ultra-High Bandwidth and Low Latency Potential

The THz frequency band is essential for future wireless systems, supporting data rates up to terabits per second (Tbps) and improving spectral efficiency, particularly in the congested sub-6GHz range [52]. This positions THz communications as a solution to spectrum scarcity, enabling high-capacity applications [52]. Recent advancements include a chip-scale terahertz synthesizer with 2.8-octave tunability and sub-100 Hz linewidths, crucial for metrology, sensing, and communications [53]. These innovations exemplify THz frequencies' potential for high-accuracy data transmission and diverse applications, such as monitoring breathing rates [54].

Integrating multiple-input multiple-output (MIMO) systems, especially in line-of-sight (LOS) conditions, is vital for realizing THz's high data rate potential. Spintronic THz emitters demonstrate high efficiency and broad bandwidth, surpassing traditional sources [41]. Furthermore, innovative modulation techniques, including tunable and rapid modulation using stretchable single-walled carbon nanotube (SWCNT) thin films, enhance data rates and reduce latency [9]. THz acceleration technology uses short pulses for high acceleration gradients, overcoming material damage thresholds and enhancing system performance [5]. Miniature fiber-coupled THz emitters and receivers facilitate effective conductivity measurements in high-field magnets, advancing THz communications [8].

Challenges persist, including limitations in semiconductor technologies and the complexity of sub-THz transceiver designs [55]. Ensuring backward compatibility with existing 5G and 4G systems complicates THz deployment [55]. Additionally, channel-code decoding complexity and energy consumption impede THz communication systems' efficiency [1]. Achieving high repetition rates and peak electric fields, as shown by methods increasing repetition rates to 190 kHz and peak fields exceeding 13 MV/cm, is vital for advancing THz applications [7].

Addressing these challenges through ongoing research is crucial for fully harnessing THz frequencies' potential in ultra-high bandwidth and low latency communication. This effort will facilitate THz technology integration into high-speed data transmission and seamless connectivity while supporting regulatory frameworks like the IEEE 802.15 suite of standards. As the THz band evolves, it promises to revolutionize information creation, distribution, and consumption, bridging millimeter wave and optical frequencies [15, 30].

3.2 Challenges in Signal Propagation and Attenuation

THz communications face challenges in signal propagation and attenuation due to high path loss and atmospheric absorption. Severe path loss, exacerbated by water vapor molecular absorption, degrades signal quality, necessitating dense THz access point deployment, increasing costs and inefficiency [2]. The limited effective communication distance, primarily due to deep fading from large free space path-loss and atmospheric absorption, is a critical obstacle [2]. Current methods struggle to generate THz radiation with sufficient intensity, with peak fields limited to 0.12-0.5 GV/m, insufficient for overcoming propagation challenges [4].

Material damage thresholds at high electric fields further complicate THz systems, limiting achievable acceleration gradients [5]. The narrow band nature of conventional multi-order wave plates complicates THz radiation manipulation [56], while THz interconnects suffer from losses and defects that hinder signal integrity [57]. Detection challenges arise from the limited operational bandwidth of current plasmonic photoconductive antennas, requiring precise optical alignment for acceptable sensitivity [44]. Additionally, the complexity of spin current dynamics complicates THz emission optimization [41].

To integrate THz communications into next-generation networks effectively, innovative approaches in advanced materials, signal processing techniques, and system designs are essential. These advancements will address high path loss and the need for highly directional THz beams while enabling scalable, low-cost interfaces and robust network architectures to support high data rates and low latencies required for 6G systems. Leveraging insights from existing millimeter-wave systems and designing a comprehensive communication stack will ensure efficient management within complex mobile networks [58, 15, 30, 55, 32]. Overcoming these obstacles will unlock new applications and innovations across sectors, paving the way for a more connected and efficient future.

3.3 Advanced Materials and Technologies

Advanced materials and technologies are crucial for addressing THz communications challenges in signal propagation, attenuation, and device efficiency. Innovations such as sawtooth electrode structures with elliptical beam illumination in photoconductive antennas (PCAs) enhance carrier collection efficiency compared to conventional strip-line PCAs [59], significantly improving THz device performance. Suspended-core subwavelength fibers, with propagation losses as low as

0.02 cm^{-1}, minimize signal loss and enhance transmission efficiency [60]. Relay-based strategies that address blockage and antenna misalignment improve THz communication performance under challenging conditions [61].

Electrically-reconfigurable meta-surfaces dynamically alter structural configurations to achieve desired electromagnetic properties, enabling adaptive THz devices capable of real-time optimization [62]. A new blockage model that considers obstacle size and density enhances the understanding of THz networks, providing insights for deploying intelligent reconfigurable surfaces (IRSs) to improve efficiency and coverage [63]. Simulating and optimizing THz emission in higher mobility semiconductors, as opposed to traditional GaAs systems, significantly enhances THz radiation efficiency [64]. Identifying novel materials with superior electronic properties is vital for improving THz device performance.

Recent advancements in materials and technologies are essential for addressing unique challenges in THz communications, including high path loss and the need for highly directional beams. These innovations pave the way for efficient and versatile THz systems that meet the demands of next-generation wireless networks. The establishment of the IEEE 802.15.3d standard facilitates spectral allocations and standardizations in the 252–325 GHz range, essential for high-speed transmission applications. Furthermore, integrating carbon nanomaterials, such as graphene and carbon nanotubes, enhances THz technology by improving radiation generation, manipulation, and detection. Collectively, these developments are poised to transform communication systems, enabling ultra-high bandwidth, negligible latency, and seamless connectivity across diverse applications [15, 65, 30].

3.4 Regulatory and Standardization Challenges

The deployment of THz communications is significantly influenced by regulatory and standardization challenges essential for efficient adoption of THz technologies. Current limitations in bulk crystal methods for THz waveform generation restrict the synthesis of arbitrary waveforms necessary for various applications [3]. This necessitates developing new standards that accommodate THz frequencies' unique requirements, ensuring compatibility and interoperability across systems.

THz communications' unique characteristics, including high frequency and wide bandwidth, complicate spectrum allocation, as existing regulatory frameworks primarily cater to lower frequency bands. Despite the THz band's (0.1-10 THz) potential for ultra-high bandwidth and negligible latency, it remains one of the least explored frequency ranges. The IEEE has initiated efforts, such as forming the IEEE 802.15.3d task force, to address standardization and spectral allocation beyond 0.3 THz, yet significant technological hurdles persist, including high path loss and the need for highly directional beams for effective communication [15, 66, 30]. Establishing new regulatory policies is essential for managing spectrum resources, preventing interference, and ensuring fair access for stakeholders. The absence of standardized protocols complicates deployment, hindering the development of compatible systems.

Integrating THz technologies into existing infrastructures requires evaluating backward compatibility and coexistence with current wireless standards, especially in light of the IEEE 802.15.3d task force's efforts to standardize spectral allocations and medium access control (MAC) layers in the 252–325 GHz range. This integration aims to meet the increasing demand for ultra-high bandwidth and low latency, drawing lessons from millimeter-wave bands while addressing high path loss challenges at THz frequencies [15, 30]. Ensuring seamless communication across heterogeneous infrastructures while fostering innovation in wired and wireless domains is crucial for a smooth transition to THz systems without disrupting existing services. The complexity of THz communication systems and the need for high precision in waveform synthesis and detection highlight the importance of developing comprehensive standards addressing both technical and regulatory aspects.

International collaboration and coordination are vital for overcoming these challenges, enabling harmonization of regulatory policies and establishment of global standards. This approach facilitates efficient deployment of THz technologies across regions, promoting widespread adoption and seamless integration into next-generation wireless networks. By leveraging insights from IEEE 802.15 standards and addressing challenges like high path loss and directional THz beams, this strategy enhances communication capacities and supports diverse applications—from mobile backhaul links to indoor Internet-of-Things (IoT) environments—ultimately paving the way for ultra-high bandwidth networks that meet growing data transmission and connectivity demands [67, 68, 30, 15, 32].

Effectively addressing regulatory and standardization challenges associated with THz communications unlocks its full potential, paving the way for innovative applications such as high-speed data transmission, wireless communication in data centers, and advanced mobile backhaul links. This enhances wireless infrastructure efficiency and meets the growing demand for ultra-high bandwidth and low-latency communication, ultimately fostering substantial growth in the wireless communication sector. Establishing frameworks like the IEEE 802.15.3d standard is crucial for achieving these goals, yet ongoing technological hurdles related to scalable, cost-effective systems and high path loss in THz links must be overcome to fully realize these opportunities [15, 30].

4 Integrated Sensing and Communication (ISAC) Technologies

Exploring advancements in Integrated Sensing and Communication (ISAC) technologies reveals their dual functionality, enhancing both communication and environmental sensing capabilities. This versatility is crucial for optimizing performance across various applications. The following subsection examines specific aspects of this dual functionality, demonstrating how ISAC technologies operate across multiple frequency bands to facilitate Full-Spectrum Wireless Communications and improve system efficiency in diverse environments.

4.1 Dual Functionality of ISAC Technologies

ISAC technologies are pivotal in advancing terahertz (THz) communication systems by integrating communication and environmental sensing, enabling Full-Spectrum Wireless Communications across all feasible frequency bands [52]. This integration is essential for deploying THz communications in environments demanding high adaptability and efficiency. The SHINE framework illustrates this dual role by optimizing THz-AP deployment strategies to enhance indoor system performance, thereby improving both communication quality and environmental sensing [68]. The hybrid relay selection protocol further exemplifies ISAC's dual functionality by selecting between RF and THz relays based on data rates and distances [2]. Innovations like nanowire utilization significantly enhance THz emission efficiency, optimizing nanoscale THz emitter and detector applications [69]. Integrating ISAC technologies into 6G systems ensures seamless coexistence with existing 4G and 5G networks, addressing backward compatibility challenges [55]. This integration underscores ISAC technologies' transformative potential in optimizing THz systems' performance and functionality, paving the way for their widespread adoption in next-generation wireless networks.

4.2 Enhancing Communication Systems with ISAC

ISAC technologies significantly enhance communication systems by leveraging the dual functionality of sensing and data transmission, optimizing resource utilization and improving performance. Their integration addresses challenges such as high path loss and atmospheric absorption at THz frequencies [2]. By sharing resources for communication and sensing, ISAC technologies enable efficient and reliable THz system operation. Hybrid beamforming techniques exemplify ISAC's impact, optimizing resource allocation between communication and sensing tasks to enhance system efficiency [16]. These techniques are particularly advantageous in scenarios where spectrum scarcity and high data rate demands necessitate efficient bandwidth use. Furthermore, ISAC technologies facilitate advanced channel estimation methods in mmWave and THz multi-user MIMO systems, improving communication link accuracy and reliability [13]. By integrating sensing capabilities, ISAC technologies enable real-time adaptation to changing environmental conditions, enhancing communication network robustness. The deployment of ISAC technologies in space environments illustrates their potential to enhance communication systems. Accurate detection and classification of space debris using ISAC contribute to the safety and reliability of satellite communication systems, ensuring uninterrupted data transmission in LEO environments [10]. Moreover, ISAC technologies applied in smart city infrastructure optimize communication systems by providing real-time environmental monitoring and data transmission capabilities. This integration supports the development of intelligent transportation systems and autonomous vehicles, which rely on precise sensing and communication to function effectively in dynamic urban settings [47]. By enhancing the functionality and performance of communication systems, ISAC technologies are pivotal for advancing next-generation wireless networks. These innovations facilitate the development of cutting-edge applications and enhance connectivity across diverse sectors by leveraging millimeter wave and terahertz frequencies, addressing spectrum shortage challenges, and enabling a more integrated and efficient wireless ecosystem [37, 52, 13, 16].

5 Waveform Design for THz ISAC Systems

The design of waveforms in Terahertz (THz) Integrated Sensing and Communication (ISAC) systems is crucial for optimizing performance. Central to this design is the integration of electronic and photonic approaches, enhancing THz system capabilities while addressing high-frequency operational challenges. This section explores the significance of these methodologies in advancing THz ISAC systems.

5.1 Integration of Electronic and Photonic Approaches

Integrating electronic and photonic methodologies is vital for achieving high performance in THz ISAC systems, enabling data transmission rates of Terabits per second (Tbps) and millimeter-level sensing accuracy. This integration addresses challenges such as high path loss and directional beamforming through techniques like sensing integrated discrete Fourier transform spread orthogonal frequency division multiplexing (SI-DFT-s-OFDM) and deep learning-powered receivers, which enhance communication and target estimation [15, 17, 18].

Electronic methodologies optimize THz wave generation and detection. The Adaptive Superposition Coding and Subspace Detection (ASCD) method, employing adaptive spatial tuning and low-complexity algorithms, enhances data recovery under challenging conditions [43]. The TFLN-THz method exemplifies synergy by using thin-film lithium niobate circuits for effective THz waveform generation [3].

Photonic techniques complement these innovations, utilizing collinear terahertz generation schemes based on optical rectification in small organic crystals, optimizing pump wavefronts to enhance THz brightness [4]. Inverse design approaches in wavelength division multiplexing (WDM) systems integrated with THz quantum cascade lasers facilitate efficient THz signal routing [46].

The integration of fiber-coupled THz emitters and receivers for coherent time-domain spectroscopy allows direct measurement of complex THz conductivity [8]. Moreover, generating multi-terahertz pulses through difference frequency mixing of femtosecond pulses underscores photonic techniques' role in enhancing THz capabilities [7].

By merging electronic and photonic methodologies, THz ISAC systems effectively address high-frequency challenges, facilitating ultra-broad bandwidth communication and precise sensing. The SI-DFT-s-OFDM systems demonstrate significant improvements in data transmission and range estimation accuracy, while deep learning-based receivers mitigate imperfections. Hybrid architectures integrating terahertz transmission lines with photonic circuits enable compact, low-loss, high-speed operations essential for telecommunications, paving the way for scalable solutions to support wireless network densification [15, 19, 17, 16].

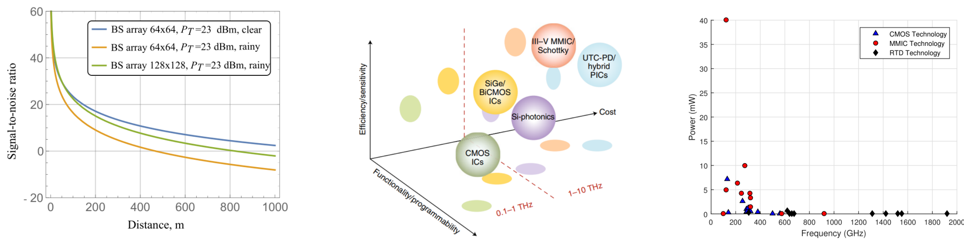
5.2 Frameworks and Methodologies

Sophisticated frameworks and methodologies are crucial for waveform design in THz ISAC systems, addressing the unique challenges of THz frequencies. Non-linear InAs metasurfaces with nanoscale resonators generate THz pulses with controlled spatial and temporal structures, enhancing communication and sensing capabilities [42].

Superposition coding combined with subspace detection optimizes data transmission and reception, maximizing spectral efficiency and improving signal quality in challenging environments [43]. The THz Photonic Light Cage (THzLC) introduces a novel waveguide design made from free-standing dielectric strands, facilitating efficient THz signal processing [6].

Compact planarized waveguide structures, as demonstrated in on-chip inverse-designed active wavelength systems, showcase high performance in THz signal processing [46]. These frameworks significantly enhance THz ISAC systems by optimizing performance and reliability across various applications, driven by innovations in analog precoder optimization and nonparaxial THz imaging systems.

Insights from millimeter-wave technologies inform resource management and network protocols, enabling highly directional THz links that mitigate path loss. Collectively, these efforts contribute to robust THz ISAC systems capable of supporting diverse use cases, from wireless communication in data centers to advanced imaging applications [15, 27, 16]. By leveraging these innovative approaches, researchers can overcome THz frequency challenges and develop next-generation wireless networks that seamlessly integrate sensing and communication.



(a) The image shows the signal-to-noise ratio (SNR) as a function of distance for three different BS array configurations: a 64x64 array with a transmit power of 23 dBm in clear conditions, a 64x64 array with the same transmit power in rainy conditions, and a 128x128 array with a transmit power of 23 dBm in rainy conditions.[70]

(b) Efficiency/Sensitivity vs. Functionality/Programmability vs. Cost: A Comparative Analysis of Different Photonic Integration Technologies[55]

(c) Comparison of Power Consumption in Different Technology Platforms at Various Frequencies[30]

Figure 3: Examples of Frameworks and Methodologies

As illustrated in Figure 3, understanding the frameworks and methodologies in THz ISAC systems is vital for advancing technology. The first aspect examines the signal-to-noise ratio (SNR) across various base station (BS) array configurations, revealing the impact of environmental conditions on communication performance. The second aspect presents a comparative analysis of photonic integration technologies through a 3D scatter plot, evaluating efficiency/sensitivity, functionality/programmability, and cost, which highlights the trade-offs in technology selection. Lastly, the comparison of power consumption across different technology platforms at various frequencies offers insights into the energy efficiency of CMOS and MMIC technologies in THz communication systems. These visual analyses underscore the complexities involved in designing effective waveforms for THz ISAC systems, guiding researchers in optimizing communication and sensing capabilities [70, 55, 30].

6 Waveform Optimization Techniques

Category	Feature	Method
Machine Learning and Adaptive Algorithms	Real-Time Optimization	ASCD[43], LP-PNA[44], FTHzS[8]
Algorithmic and Numerical Optimization	On-Chip Optimization	WDM[46]
Metasurfaces and Metamaterials	Geometric and Structural Enhancements Electrical and Mechanical Control Optical and Electromagnetic Effects	DM-THz[71], GPTE[72] MTP[73], ERMS[62] CTF[40], PMA[45]

Table 1: This table provides a comprehensive categorization of methods employed in the optimization of Terahertz (THz) Integrated Sensing and Communication (ISAC) systems. It delineates various features and corresponding methods across three primary categories: Machine Learning and Adaptive Algorithms, Algorithmic and Numerical Optimization, and Metasurfaces and Metamaterials. Each method is referenced with its respective citation, offering a detailed insight into the technological advancements in THz waveform optimization.

Exploring optimization techniques is essential to overcome challenges in Terahertz (THz) Integrated Sensing and Communication (ISAC) systems. Table 1 presents a detailed categorization of the methods and features utilized in the optimization of Terahertz (THz) Integrated Sensing and Communication (ISAC) systems, emphasizing the role of machine learning, numerical optimization, and metamaterials in enhancing system performance. Additionally, Table 3 offers a comprehensive comparison of the optimization approaches employed, illustrating the contributions of these techniques to system performance enhancement. This section reviews innovative approaches utilizing machine learning and adaptive algorithms, which are increasingly recognized for refining waveform parameters in dynamic environments. Understanding these techniques is crucial for improving communication efficiency and reliability in THz systems, setting the groundwork for subsequent discussions on machine learning and adaptive algorithms.

6.1 Machine Learning and Adaptive Algorithms

Machine learning and adaptive algorithms are pivotal for optimizing waveforms in THz ISAC systems, enhancing adaptability and performance in complex environments. Strategic optimization of THz access points (APs) through machine learning techniques improves coverage and interference management, such as optimizing pump wavefront curvature to generate terahertz fields exceeding 5 GV/m [4]. Adaptive algorithms significantly enhance signal-to-noise ratios and minimize bit error rates, particularly in high signal-to-noise ratio conditions, using techniques like Adaptive Superposition Coding and Subspace Detection (ASCD) to reduce data detection complexity in MIMO-NOMA configurations [43].

Combining machine learning with advanced signal processing, such as phase-based breathing rate monitoring, illustrates the use of adaptive algorithms to recover lost motion components, optimizing waveform performance for precise motion detection [9]. Additionally, large-area plasmonic photoconductive nano-antenna arrays enhance terahertz fields by concentrating photo-generated carriers near the nano-antenna tips, improving photocurrent levels and waveform detection [44]. Fiber-coupled antennas maintain precise alignment and coherence in THz signals while minimizing losses, emphasizing the impact of machine learning and adaptive algorithms in optimizing THz ISAC systems [8]. Future research should explore optimizing algorithms for larger networks and integrating machine learning for real-time decision-making in IRS scheduling, enhancing adaptability and efficiency in THz communication systems.

Leveraging these computational techniques optimizes waveform performance, ensuring THz systems meet the demands of next-generation wireless networks. The integration of machine learning and adaptive algorithms represents a transformative leap in developing efficient and reliable THz communication systems, enhancing channel estimation and signal processing, and facilitating the convergence of THz communication and sensing applications, thereby enabling groundbreaking applications and improving connectivity across sectors, including telecommunications, materials science, and environmental monitoring [74, 58].

6.2 Algorithmic and Numerical Optimization

Algorithmic and numerical optimization techniques are vital for enhancing waveform performance in THz ISAC systems, addressing challenges such as high path loss, atmospheric absorption, and complex channel conditions. Implementing active wavelength division multiplexing (WDM) systems demonstrates the potential of on-chip inverse-designed active wavelength systems to extract coherent channels with low crosstalk, optimizing signal integrity and reducing interference [46]. In THz pulse generation, assessing performance through electro-optic sampling—focusing on pulse energy, peak electric field, and phase stability—highlights the importance of precise measurement and control in waveform optimization [7].

Multi-directional beam training sequences significantly enhance beam alignment processes by systematically scanning angular space to identify optimal alignments. This approach leverages the sparse structure of the channel in IRS-assisted mmWave and THz communication systems, employing compressive phaseless measurements for effective estimation with minimal training overhead. This improves performance in line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios, reducing training complexity and achieving results comparable to exhaustive beam search methods while decreasing training time by up to 95

Robust channel estimation techniques, such as the SBCE method, lower normalized mean-squared error (NMSE) and reduce hardware costs, enhancing the reliability and efficiency of THz communications. These methods are crucial for accurately characterizing the terahertz channel environment, essential for designing high-speed waveforms and establishing reliable communication links, particularly as the THz frequency band (0.1-10 THz) emerges as a key solution for ultra-high bandwidth and low-latency communication in next-generation systems like 6G [31, 30].

Numerical optimization techniques, especially basin-hopping Monte Carlo thermal annealing algorithms, meticulously adjust device parameters, such as the thicknesses and orientations of birefringent sapphire discs in terahertz range achromatic quarter-wave plates. This optimization reduces phase error to only 0.5

Active amplification in Reconfigurable Intelligent Surfaces (RIS) significantly enhances adaptive resource allocation strategies, crucial for optimizing waveform performance in THz communications. This integration mitigates issues like multiplicative fading and improves system capacity and energy efficiency by intelligently managing propagation characteristics [75, 76, 36, 77]. By improving signal quality and reducing path loss, these approaches maintain high-quality communication links and enhance overall system functionality.

Incorporating algorithmic and numerical optimization techniques enables THz ISAC systems to achieve improved performance and functionality, paving the way for innovative applications and enhanced connectivity in next-generation wireless networks. These advancements underscore the transformative potential of optimization methods in addressing challenges in THz communications, such as high path loss, antenna misalignment, and atmospheric interference. Techniques like hybrid automatic repeat request (HARQ) and advanced signal processing ensure THz communication systems effectively meet the demands of future environments characterized by ultra-high bandwidth, low latency, and diverse applications. As research progresses, particularly with standards like IEEE 802.15.3d and innovative THz signal generation technologies, the integration of optimization strategies will be critical for realizing the full capabilities of THz communications in next-generation wireless networks, including 6G [15, 58, 78, 30].

6.3 Metasurfaces and Metamaterials

Method Name	Wave Control	Material Properties	Technological Applications
ERMS[62]	Terahertz Waves	Diamagnetic Switching	Terahertz Modulation
DM-THz[71]	Beam Steering	Dielectric Materials	Ultrafast Beam Steering
MTP[73]	Dynamic Optical Control	Mechanical Compression Tuning	Dynamic Tuning Applications
GPTE[72]	Directional Emission Enhancement	Micro-scale Grooves	Imaging And Communications
PMA[45]	Enhance Light-matter	Customizable Electromagnetic Properties	Sensing Applications
CTF[40]	Thz Waveguides	Porous Dielectric Cladding	Terahertz Applications

Table 2: Overview of various methods for wave control, material properties, and technological applications in terahertz (THz) metasurfaces and metamaterials. The table highlights different techniques and their specific applications, showcasing the versatility and potential of these advanced materials in enhancing THz technologies.

Metasurfaces and metamaterials are pivotal in advancing THz ISAC systems, providing significant enhancements in waveform design and optimization. These engineered structures offer exceptional control over electromagnetic waves, enabling improvements in efficiency, tunability, and directivity crucial for THz technologies. Notably, metasurfaces achieve high modulation depth and speed at room temperature, outperforming existing terahertz modulators [62]. Dielectric metasurfaces, utilizing morphology-mediated resonances and inherent quadratic nonlinear responses, have demonstrated substantial efficiency improvements over unpatterned substrates [71]. This capability allows for precise control over waveform propagation. Additionally, metasurfaces surpass traditional methods in generating terahertz surface plasmon waves (SPWs), integral to waveform optimization [79]. Table 2 provides a comprehensive summary of the diverse methods employed in terahertz metasurfaces and metamaterials, detailing their wave control mechanisms, material properties, and technological applications.

Mechanical tuning of photonic bandgaps via metamaterials offers a novel approach for dynamic optical control in THz technologies, enabling significant adaptability to varying environmental conditions [73]. Enhanced lateral diffusion of photocarriers facilitates improved alignment of emitted THz waves along desired directions, showcasing the potential of these materials [72]. The integration of perfect metamaterial absorbers (PMAs) has led to improved sensitivity and a higher figure of merit (FoM) due to strong electromagnetic field interactions enabled by the Fabry-Perot cavity effect [45]. This enhancement is vital for sensing applications in THz systems. Furthermore, the assumption that

THz radiation arises from low-energy acoustic surface plasmon modes specific to high aspect ratio geometries highlights the optimization potential of these materials in THz emission [69].

Despite advancements, challenges such as low output power and efficiency in photomixing systems persist, limiting practical applications [14]. Future research should focus on AI-driven solutions and hybrid models to optimize THz systems for various applications, addressing digital bottlenecks [29]. The development of composite fibers that balance low-loss, low-dispersion, and efficient excitation properties exemplifies the potential of advanced materials in enhancing THz technologies [40].

Recent advancements in metasurfaces and metamaterials are crucial for the evolution of THz technology, enabling the development of highly efficient optical systems and innovative devices. With customizable electromagnetic properties, these materials can replace traditional bulky optics and serve as foundational components for next-generation applications in imaging, spectroscopy, and wireless communications. For instance, impedance-matched planar metamaterials achieve over 90

Feature	Machine Learning and Adaptive Algorithms	Algorithmic and Numerical Optimization	Metasurfaces and Metamaterials
Optimization Approach	Adaptive Algorithms	Numerical Techniques	Material Engineering
Key Benefit	Improved Adaptability	Enhanced Signal Integrity	Wave Control
Application Focus	Waveform Performance	Channel Estimation	Waveform Design

Table 3: This table provides a comparative overview of three key optimization approaches used in Terahertz (THz) Integrated Sensing and Communication (ISAC) systems: machine learning and adaptive algorithms, algorithmic and numerical optimization, and metasurfaces and metamaterials. It highlights the distinct optimization strategies, key benefits, and application focuses of each method, emphasizing their roles in enhancing waveform performance and system efficiency.

7 Applications and Use Cases

Terahertz (THz) Integrated Sensing and Communication (ISAC) systems are revolutionizing various fields through their diverse applications. This section underscores the transformative impact of THz technologies, particularly in biomedical sensing and environmental monitoring, highlighting the systems' potential to enhance accuracy, safety, and efficiency.

7.1 Biomedical Sensing and Environmental Monitoring

THz ISAC systems offer significant advancements in biomedical sensing and environmental monitoring due to their high-resolution imaging and precise sensing capabilities. The non-ionizing nature of THz radiation ensures safety in medical environments, while hybrid platform methods provide quasi-analytical solutions that enhance sensing accuracy and reliability [80]. In biomedical imaging, the generation of THz radiation through GHz-irradiated arrays of gold nanoparticles (GNPs) leverages both 'soft' and 'hard' THz ranges for high-resolution imaging, crucial for detailed analysis [81]. Achromatic quarter-wave plates with minimal phase error further enhance THz systems' potential in these applications [56].

Environmental monitoring benefits from Intelligent Reflecting Surfaces (IRS) in THz systems, which enable high-speed fronthaul/backhaul and improved indoor coverage via virtual Line-of-Sight (LoS) paths [82]. This is particularly advantageous in urban areas where physical obstructions challenge traditional monitoring methods. The adaptability of THz systems to dynamic environments, such as UAV operations, is highlighted by the significant impact of UAV hovering on channel performance, with SNR exhibiting a Weibull distribution [83].

These advancements highlight the transformative potential of THz ISAC systems in biomedical and environmental fields, offering innovative solutions that enhance precision, reliability, and efficiency. As THz technologies mature, they are expected to revolutionize applications in high-speed wireless communication, advanced imaging for medical diagnostics, and innovative environmental monitoring solutions. The IEEE's efforts to standardize THz frequency bands and breakthroughs in materials such as carbon nanotubes and graphene further enhance the efficiency and performance of THz devices, driving substantial improvements in data transmission, imaging resolution, and environmental sensing capabilities [65, 30, 15, 84, 79].

7.2 Indoor and Vehicular Communications

THz ISAC systems are poised to transform indoor and vehicular communication by enhancing connectivity and data transmission efficiency. In indoor environments, these systems deliver ultra-high data rates and low latency, ideal for high-capacity data transfer applications like augmented and virtual reality. The SHINE framework, optimizing THz-AP deployment, exemplifies the potential to improve communication quality and environmental sensing indoors [68].

In vehicular scenarios, THz ISAC systems significantly enhance communication performance, essential for autonomous vehicles reliant on real-time data exchange for navigation and safety [29]. Hybrid relay selection protocols optimize between RF and THz relays, ensuring reliable data transmission in challenging environments [2]. The adaptability to dynamic vehicular environments is further demonstrated by IRS deployment, creating virtual LoS paths to overcome obstructions and improve signal quality [82].

The integration of THz ISAC systems into communication networks promises to revolutionize connectivity by providing high-speed, reliable data transmission and advanced sensing capabilities. As THz technologies advance, their application in high-speed communication scenarios is expected to enhance efficiency and performance, facilitating the transition to next-generation wireless networks. The THz frequency band (0.1-10 THz) is crucial for meeting the demand for ultra-high bandwidth and low-latency communication, bridging the gap between millimeter-wave and optical frequencies. Despite challenges like high path loss and the need for highly directional beams, ongoing research aims to develop scalable, cost-effective solutions for widespread implementation [15, 30].

7.3 Terahertz Imaging and Sensing

THz ISAC systems are advancing imaging and sensing technologies, offering unparalleled capabilities in high-resolution imaging and precise environmental sensing. The unique properties of THz frequencies, such as their ability to penetrate materials and non-ionizing nature, make them ideal for imaging and spectroscopy applications [85]. These characteristics enable detailed imaging and comprehensive spectroscopic analyses, crucial for security screening, quality control, and biomedical diagnostics.

THz imaging systems provide high spatial resolution and sensitivity, allowing detection of minute structural details and material compositions. This is particularly advantageous in biomedical imaging, enabling non-invasive, high-resolution images of biological tissues, enhancing early disease detection and diagnosis. Recent advancements have improved imaging throughput and resolution, making THz systems increasingly applicable in clinical settings [27, 86, 87, 58]. Additionally, real-time imaging and sensing capabilities enhance applicability in dynamic environments, such as industrial process monitoring or construction material assessment.

THz ISAC systems' spectroscopy applications utilize the wide frequency range and high spectral resolution of THz waves to identify chemical compositions and detect molecular interactions, particularly useful in pharmaceutical quality control. The integration of imaging and spectroscopy fosters multifunctional devices capable of simultaneous imaging and analytical tasks, enhancing resource efficiency and effectiveness. This synergy is facilitated by advanced optical components, such as nonparaxial diffractive optics, optimizing imaging performance. The development of compact, user-friendly THz systems incorporating sensors and optical elements onto a single chip represents a significant leap forward, enabling diverse applications in communication, data processing, and environmental monitoring. Standardized protocols for THz communication, as seen in the IEEE 802.15.3d task force, underscore the potential for robust connectivity and scalable network solutions, paving the way for innovative advancements [15, 27].

The advancement of THz ISAC systems in imaging and sensing is poised to drive significant innovations across sectors, enhancing precision, reliability, and efficiency in applications from security and healthcare to industrial automation and environmental monitoring. As research progresses, their integration into practical applications is expected to significantly enhance THz ISAC systems' capabilities, facilitating next-generation imaging and sensing solutions. Innovations like lensless photonic systems, advanced signal processing, and deep learning-powered receivers will contribute to compact, efficient, and user-friendly THz imaging systems, addressing challenges like high path loss and improving data rates and sensing accuracy. Ultimately, these developments will pave the way for transformative applications in wireless communication and environmental monitoring, marking a new era in THz photonic technology [87, 58, 15, 27, 17].

8 Future Directions and Research Opportunities

The swift progress in Terahertz (THz) technologies prompts a need to explore future directions and research opportunities to enhance THz Integrated Sensing and Communication (ISAC) systems. A crucial area is the integration of advanced machine learning techniques to optimize system operations and address the unique challenges of THz communications. Machine learning can drive the development of adaptive algorithms that improve efficiency and offer innovative solutions to emerging problems in this evolving field.

8.1 Integration of Advanced Machine Learning Techniques

Incorporating advanced machine learning techniques into THz ISAC systems offers significant opportunities for performance enhancement. These algorithms can optimize waveform design, enabling adaptive, real-time performance improvements essential for efficient operations [1]. Future research should focus on developing models that dynamically adapt to varying environmental conditions, ensuring robust performance across diverse scenarios. Optimizing power allocation among distributed access points (APs) in cell-free massive MIMO (CFmMIMO) systems can enhance adaptability to environmental variations [2]. Additionally, machine learning-driven design processes can lead to the creation of transient metamaterials with complex functionalities, such as frequency shifting and spectral lensing, thereby advancing THz ISAC capabilities [3].

The deployment of Reconfigurable Intelligent Surfaces (RIS) can also benefit from machine learning to optimize their placement and transmitter locations, improving scalability in complex environments [88]. Future research should prioritize low-cost RIS development to enhance line-of-sight paths within THz ISAC systems [89]. Exploring integrated sensing and communications in the near-field, alongside developing holographic THz antennas, can significantly advance near-field applications. Machine learning can optimize spatial tuning processes, further enhanced by techniques such as IRS-assisted NOMA [9]. Additionally, refining simulation models to include complex interactions and investigating new semiconductor materials for THz emission will be crucial [8]. Leveraging machine learning will ensure the relevance and efficacy of THz ISAC systems in next-generation wireless networks, paving the way for innovative applications and improved connectivity.

8.2 Hybrid and Multi-band Systems

The development of hybrid and multi-band systems represents a promising direction in THz communications, addressing the limitations of single-band systems by leveraging multiple frequency bands. These systems maximize electromagnetic spectrum utilization, enhancing flexibility and performance in THz networks. By utilizing contiguous channels in the THz band (0.1-10 THz), they aim to meet demands for ultra-high throughput and low latency, crucial for applications like high-speed data transmission and wireless communication in mobile backhaul links. Advancements in hybrid automatic repeat request (HARQ) techniques are being explored to address challenges such as high path loss and atmospheric interference [15, 68, 78, 30].

Hybrid systems that integrate THz frequencies with RF and mmWave bands offer significant advantages in coverage and capacity. A novel hybrid relay selection (HRS) protocol optimizes performance by prioritizing THz relays for short-range, high-data-rate communications while utilizing RF relays for longer distances. This approach enhances coverage probability and maintains performance levels similar to optimal selection protocols based on complete channel state information. The IEEE 802.15.3d standard exemplifies how these hybrid systems address the high path loss associated with THz frequencies through highly directional beams and advanced phased array technologies [15, 2].

Multi-band systems further extend the capabilities of hybrid systems by operating across a wide range of frequency bands, from RF to optical frequencies. This significantly enhances spectral efficiency and increases communication network capacity, supporting high-capacity applications that demand ultra-high data rates and low latency. Leveraging higher frequency bands, particularly in the millimeter wave and THz ranges, addresses the growing bandwidth requirements of next-generation technologies like 6G, facilitating innovative communication paradigms for seamless connectivity and massive data transmission [37, 52, 30]. Multi-band systems also ensure backward compatibility with existing infrastructures.

Advancements in materials and technologies, such as metasurfaces and metamaterials, enhance control over electromagnetic waves across multiple frequency bands. These technologies enable the development of reconfigurable devices capable of dynamically adjusting their operating frequencies, optimizing performance. This adaptability is crucial in RIS and THz communications, where intelligent shaping of multipath propagation environments can improve connectivity and energy efficiency [68, 36, 30, 62, 77].

Future research should prioritize advanced algorithms and protocols for dynamic spectrum management, essential for optimal resource allocation and effective interference mitigation across frequency bands. As bandwidth demand escalates with 6G technologies, innovative spectrum sharing and resource management approaches will be crucial to support diverse applications and performance requirements [30, 15, 52, 37, 70]. Exploring novel materials and device architectures will further enhance performance and scalability, paving the way for widespread adoption in next-generation THz networks.

By harnessing hybrid and multi-band systems, THz communications can achieve exceptional performance levels, effectively addressing spectrum scarcity. This advancement supports innovative applications across sectors, such as high-speed data transmission and wireless communication in data centers, while facilitating the transition to sixth-generation (6G) cellular technology. The IEEE 802.15.3d standard plays a vital role in this evolution by addressing spectral allocations in the 252–325 GHz range, enhancing bandwidth and connectivity. Nonetheless, challenges like high path loss at THz frequencies necessitate highly directional beams and large-scale THz arrays for practical implementation [15, 52, 30]. These advancements will shape the future of wireless communications, driving the evolution of next-generation networks and supporting the growing demand for reliable connectivity.

8.3 Advanced Fabrication and Device Design

Advancements in fabrication and device design are crucial for optimizing THz ISAC systems, enhancing efficiency and broadening application potential. This includes developing scalable, low-cost interfaces and highly directional THz beams to mitigate high path loss, alongside innovative analog precoder optimization techniques tailored to sub-THz channels. Integrating advanced waveform designs, such as sensing integrated discrete Fourier transform spread orthogonal frequency division multiplexing (SI-DFT-s-OFDM), and deep learning-powered receivers can improve communication capabilities and sensing accuracy, addressing challenges posed by THz environments. These improvements are vital for applications in high-speed wireless communication, precise range estimation, and real-time velocity tracking [15, 17, 16]. A key focus area is optimizing dielectric materials and lens configurations to enhance electromagnetic wave control, improving both sensing and communication functionalities. The development of Tunable Antenna-Coupled Intersubband Terahertz (TACIT) detectors underscores the importance of refining fabrication processes to boost sensitivity and functionality.

Mechanical tuning of THz photonic crystals offers a promising avenue for enhancing material properties, broadening the application range of THz technologies [73]. This approach may lead to adaptable THz systems capable of meeting diverse environmental and operational demands. In waveguiding, silicon-core fibers demonstrate potential for improved THz capabilities, suggesting future research should explore alternative materials and optimize fiber design to reduce losses [90].

Future research should concentrate on optimizing porous structures in two-wire THz fibers to enhance performance and explore additional applications in sensing [40]. Investigating groove designs and alternative structures to improve THz emission directionality highlights the significance of innovative device architectures in optimizing THz systems [91]. Refining manufacturing processes to enhance tolerance levels and exploring new materials or configurations may further boost performance [56].

The scalability of all-dielectric digitized metasurfaces represents a key research area, with potential improvements in structure and materials enhancing overall system performance. Flexible quasi-three-dimensional THz metamaterials offer additional innovative avenues, with optimizations in fabrication processes impacting future THz ISAC systems [92]. Future research should also refine metasurface designs for different wavelengths and investigate the mechanisms of THz generation in these structures [42].

Future directions include optimizing metamaterial designs for broader bandwidth applications, which could significantly impact THz ISAC systems [93]. Additionally, refining models for dynamic blockage and exploring the integration of diverse traffic types and advanced service mechanisms will be essential for developing efficient THz systems [70]. Enhancing the ATJ design for better impedance matching and broader bandwidth applications signifies advancements in fabrication and device design [94].

Exploring additional liquid mediums and optimizing parameters for enhanced THz generation efficiency represents another promising area [28]. Further refinement of the SBCE method for practical applications and deeper exploration of near-field effects are crucial for advancing THz ISAC systems [95]. Optimizing FET detector designs to improve performance, particularly in responsivity and saturation power, presents additional opportunities for advanced fabrication and device design [96].

Addressing these aspects will enable researchers to overcome existing challenges and unlock new applications in next-generation wireless networks, ensuring THz ISAC systems meet the diverse demands of future communication environments. Future research could also enhance fabrication techniques for the Valley-Hall Photonic Crystal method and explore the integration of topological structures in larger-scale THz communication systems [57].

9 Conclusion

Terahertz (THz) Integrated Sensing and Communication (ISAC) systems represent a pivotal advancement in the evolution of wireless networks, particularly for next-generation applications. These systems merge sensing and communication functionalities, delivering unprecedented bandwidth and minimal latency, which are essential for modern communication ecosystems. The demonstrated success of hybrid THz photoconductive antennas (PCAs) underscores the potential of innovative fabrication techniques, significantly boosting THz signal generation capabilities.

Addressing the inherent challenges of THz signal propagation and attenuation necessitates the development of robust models and interdisciplinary methodologies. A comprehensive understanding of how THz waves interact with various environmental factors is critical for optimizing channel performance and mitigating power loss. The progress in near-field sensing and communications further highlights the applicability of THz technologies in future 6G networks.

Advanced techniques in waveform design and optimization, such as cooperative beam training and hybrid beamforming, are crucial for enhancing the performance of THz multi-user massive MIMO systems. The improvements observed in network sum-rate and resource allocation efficiency through molecular absorption-aware strategies emphasize the importance of such approaches in dense THz networks. The integration of promising sensor technologies and sophisticated computational methods is vital for the continued development of terahertz imaging systems.

Effective beamforming frameworks are essential for the efficient transmission of semantic information in multi-user wireless networks. The DS-FPS architecture exemplifies enhanced energy efficiency while maintaining spectral efficiency, highlighting the potential of innovative architectural designs in THz systems. Furthermore, the role of distributed reconfigurable intelligent surfaces (DRF) in improving the quality of THz wireless communications, particularly in indoor environments, is crucial for optimizing system performance.

A unified strategy is imperative for enhancing the reliability and scalability of vehicular communications and radar systems, setting the stage for future innovations in this field. The successful acceleration of electron bunches beyond 30 keV validates the feasibility of THz acceleration technology for compact light sources, indicating its potential for wide-ranging applications.

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