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Terahertz Sensing, Communication, and Networking: A Survey

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***Abstract*—Terahertz has emerged as a pivotal technology that will enable next-generation wireless systems due to its unique properties. Over the past few years, numerous studies related to terahertz have been conducted, prompting us to undertake a comprehensive survey to summarize the sensing, communication, and networking technologies based on terahertz. In this survey, we first introduce the characteristics of terahertz and its associated hardware devices. Subsequently, we provide a comprehensive review of existing terahertz-based sensing, communication, and networking technologies. We analyze the key techniques, system design, and application scenarios. Finally, we discuss the challenges and future directions of terahertz technology.**

***Index Terms*—Terahertz wave, terahertz sensing, terahertz communication, terahertz networking**

I. Introduction

With the development of communication technologies, the growing demand for higher communication rates and network capacity will drive future 6G systems toward the terahertz frequency band (0.1-10 THz). Terahertz waves, defined as electromagnetic radiation within this specific frequency range, are characterized by high-frequency operation, substantial bandwidth, and unique physical properties. These distinctive attributes establish THz technology as a critical enabler for next-generation wireless communication systems. There has been a rising focus on terahertz sensing, communication, and networking technologies.

Terahertz sensing leverages the unique penetration and spectral identification capabilities of terahertz-band electromagnetic waves to achieve high-resolution imaging and material composition analysis of concealed objects in a non-ionizing and non-invasive manner. It is widely applied in fields such as security inspection, biomedical diagnosis, and non-destructive testing of materials. Compared to the currently popular millimeter waves, terahertz waves have a shorter wavelength, offering higher resolution and imaging accuracy. Additionally, terahertz waves resonate with the vibrational and rotational energy levels of material molecules, enabling specific identification of chemical substances and providing chemical composition analysis capabilities. Furthermore, the terahertz band covers a broader frequency range, supporting ultra-wideband signals and enhancing the information dimension of sensing systems.

Terahertz communication, occupying the gap frequency band between microwave communication and optical communication, combines the penetration capabilities of microwaves with the broadband characteristics of optical waves. Its bandwidth reaches up to tens of THz, far exceeding the GHz-level bandwidth of millimeter waves, with a theoretical communication rate that can reach the Tbps level. Due to the extremely short wavelength of terahertz waves, they can easily achieve highly directional transmission through narrow-beam antennas, reducing multipath interference and enhancing communication security and spectrum utilization efficiency, making them suitable for dense device environments. Terahertz communication technology is poised for application in areas such as 6G mobile communications, satellite and space communications, data center and short-range direct links, secure communications, and military applications, as well as biomedicine.

With the rapid development of terahertz communication and sensing technologies, terahertz networking technology is emerging as the core architecture supporting future 6G and ultra-high-speed wireless systems, attracting widespread attention from both academia and industry. Terahertz networks need to tackle key challenges such as resource allocation, network topology optimization, and protocol design in high-density and high-mobility scenarios. This paper systematically reviews the key technical framework of terahertz networks, with a focus on discussing the innovative applications of resource allocation, network protocols, Multiple Input Multiple Output (MIMO) systems, and ISAC (Integrated Sensing and Communication), aiming to provide a theoretical reference for the efficient and intelligent evolution of 6G networks.

THz surveys bridge critical gaps to accelerate next-generation communication technologies. While terahertz technology has witnessed substantial research progress in recent years, its practical implementation remains limited due to several unresolved challenges and a narrow scope of real-world applications. This survey serves as a systematic effort to identify and analyze the key bottlenecks impeding the widespread adoption of THz technology by thoroughly examining and synthesizing existing research findings. These insights are particularly crucial as they will inform future research directions and innovation strategies in the field of advanced communication systems. Given the transformative potential of THz-based sensing, communication, and network-

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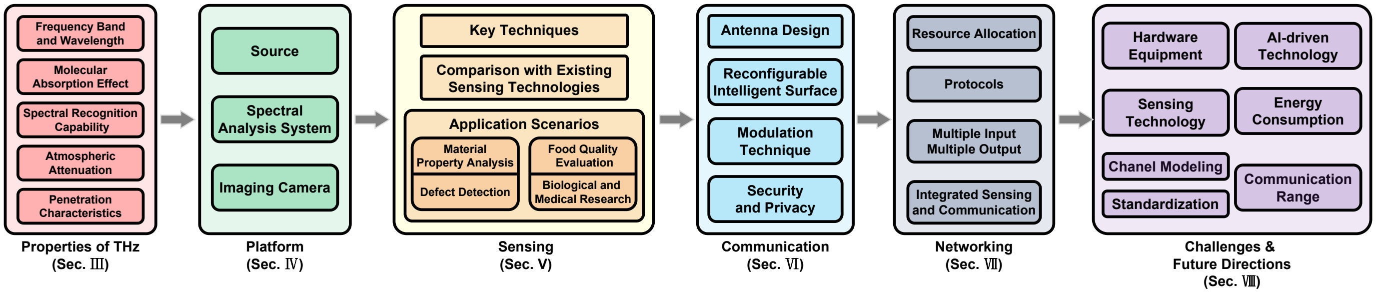

Fig. 1: Survey organization.

ing technologies, we believe this comprehensive investigation is not only timely but essential for shaping the trajectory of next-generation wireless technologies and their integration into practical applications.

This paper provides a comprehensive review of terahertz sensing, communication, and networking. The main contributions of this paper are summarized as follows:

- This paper presents a comprehensive literature review in the field of terahertz sensing, communication, and networking.
- We provide a detailed introduction to the hardware platforms and key technologies associated with terahertz, followed by a comparative analysis of these components.
- Depending on the variations in application scenarios and key technologies, we categorize and comprehensively compare the research on terahertz sensing, communication, and networking to gain a more intuitive understanding of the current research status, as well as future challenges and opportunities for each category of work.
- We comprehensively discuss the key challenges and future directions associated with terahertz sensing, communication, and networking, encompassing hardware, channel modeling, and sensing technologies.

Previous research efforts have produced several survey papers addressing specific aspects of terahertz technology, including terahertz sensing, communication systems, and networking applications, which will be thoroughly analyzed and discussed in the subsequent chapter. However, we reveal a significant gap in the existing literature: the absence of a comprehensive survey that systematically integrates terahertz sensing, communication, and networking technologies while providing insightful perspectives on future challenges and development trajectories. Recognizing the pivotal role of such a comprehensive survey in advancing terahertz research, this work aims to bridge this critical gap by offering a holistic overview and serving as a valuable reference for researchers.

Roadmap. As shown in Fig. 1, the structure of the survey is as follows: In Sec.II, we will summarize the related surveys and point out the innovation of our paper. Sec.III presents a detailed introduction to the properties of terahertz. Sec.IV provides a summary of terahertz-related hardware devices. Sec.V and Sec.VI introduce terahertz sensing and communication technologies separately. Sec.VII introduces THz networking focusing on ISAC. We propose future challenges, development prospects, and directions in Sec.VIII.

II. RELATED WORK

In this section, we introduce these related surveys and summarize them in Table I. The related works can be divided into three groups.

• **THz Communication.** Chen *et al.* [1] provided a detailed introduction to the applications of terahertz technology in Earth observation, plasma fusion diagnostics, gas spectroscopy, and other domains, while discussing the current development status of terahertz components such as sensors and sources. Thomas *et al.* [2] primarily summarized the application potential, system considerations, current research status of components, and future development trends of terahertz technology in the field of high-speed wireless communications. However, their research is confined solely to terahertz communications. He *et al.* [3] primarily summarized the research background, fundamental concepts, typical antenna types, and fabrication techniques of THz antennas, and pointed out the current challenges faced by THz antennas as well as future research directions. However, this paper is limited to a review of the improvements in THz antenna performance. Han *et al.* [4] comprehensively overviewed the research on THz wireless channels, introduced and compared three of the most prevalent THz channel measurement methods, and classified existing channel modeling approaches. But their efforts are restricted exclusively to the exploration of THz wireless channels.

• **THz Sensing.** Gezimati *et al.* and Anitha *et al.* [5, 6] summarized the recent advancements and technologies related to terahertz sensing and imaging, and presented their perspectives on the key challenges and difficulties of future terahertz sensing technologies. Their research is confined to terahertz imaging and sensing technologies, and the introduction of terahertz-related technologies remains incomplete.

• **THz networking.** Integrated sensing and communication (ISAC) is one of the key technologies in THz networks. By jointly optimizing time, frequency, and spatial resources, integrated scheduling of sensing and communication functions can be achieved, thus avoiding spectrum fragmentation, such as intelligent multiplexing of communication channels and radar beams. Liu *et al.* [7] primarily summarized the current status and research progress of ISAC technology. Liu *et al.* [8] conducted a comprehensive review of the background, key application areas, and state-of-the-art methodologies of ISAC. However, they do not closely associate ISAC with terahertz technology. And the closest work to ours is [9–12]. They integrated THz with ISAC, analyzing and summarizing some

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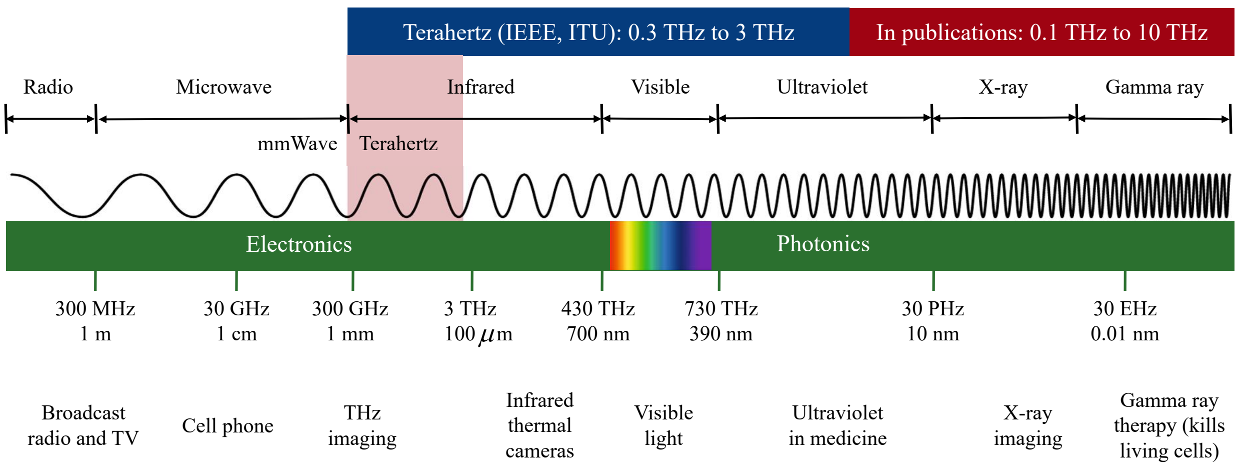

Fig. 2: Terahertz spectrum range.

TABLE I: Summary of Related Surveys on THz and ISAC

Category	Reference	Year	Content Coverage							
			Imaging	Antenna Design	Beamforming	Channel	Transmission Loss	Hardware Limitation	Performance Tradeoff	Algorithm & Framework
THz Communication	Chen et al.[1]	2019			✓	✓		✓		
	Thomas et al.[2]	2011					✓			
	He et al.[3]	2020					✓	✓		
	Han et al.[4]	2022			✓		✓			
THz Sensing	Gezimati et al.[5]	2023	✓							
	Anitha et al.[6]	2023	✓	✓						✓
THz Networking	Han et al.[9]	2024			✓	✓				
	Elbir et al.[10]	2024		✓	✓					
	Jiang et al.[11]	2024			✓	✓				✓
	Liu et al.[12]	2024							✓	✓
This Survey			✓	✓	✓		✓			✓

research findings related to ISAC in the THz domain. Their content exhibits differences from our paper.

Compared with these works, our paper presents new results in the following aspects: (1) Our paper is more inclusive and contains the latest advances in the field of THz studies. (2) We propose a comprehensive taxonomy of mmWave-based techniques. Our paper classifies the existing works into three categories: THz-based sensing, communication, and networking. (3) We conduct a comprehensive comparison and summary of the existing works. Specifically, the hardware platform, signal processing technique, and performance of these works are compared in detail. (4) The scope of our paper is more broader. In addition to summarizing the existing THz research works, we also discuss the key challenges and future directions, which may motivate more follow-up research in THz studies.

III. Properties of Terahertz

Terahertz waves possess unique properties that enable diverse applications in high-speed communication, precision sensing, and imaging. While these characteristics offer significant potential for technological advancement, they also present implementation challenges. In this section, we introduce the THz wave properties.

A. *Terahertz Frequency Band and Wavelength*

Terahertz represents electromagnetic waves with frequencies ranging from 0.1 to 10 THz, and the frequency band within the range of 100 to 300 GHz is commonly known as the sub-terahertz band, which can be more intuitively observed from Fig. 2. It provides very small wavelengths which fall within the range of 0.03 to 3 millimeters. THz waves are important for next-generation communications and sensing. Their high frequency and wide bandwidth enable high-speed, high-capacity communication. It also bridges electronics and photonics, allowing integration of communication and sensing.

B. *Molecular Absorption Effect*

THz waves exhibit molecular absorption, allowing them to penetrate non-polar materials while being absorbed by polar materials. This absorption occurs because specific frequencies of THz waves resonate with molecules, causing them to transition to higher energy levels [13]. This property enables THz waves to detect metal and moisture content in objects and enhances wireless communication security by preventing signal penetration through certain materials. However, it also introduces molecular absorption noise, causing additional attenuation and path loss peaks in the THz spectrum, which impacts system design [14], which is shown in Fig. 3 (a).

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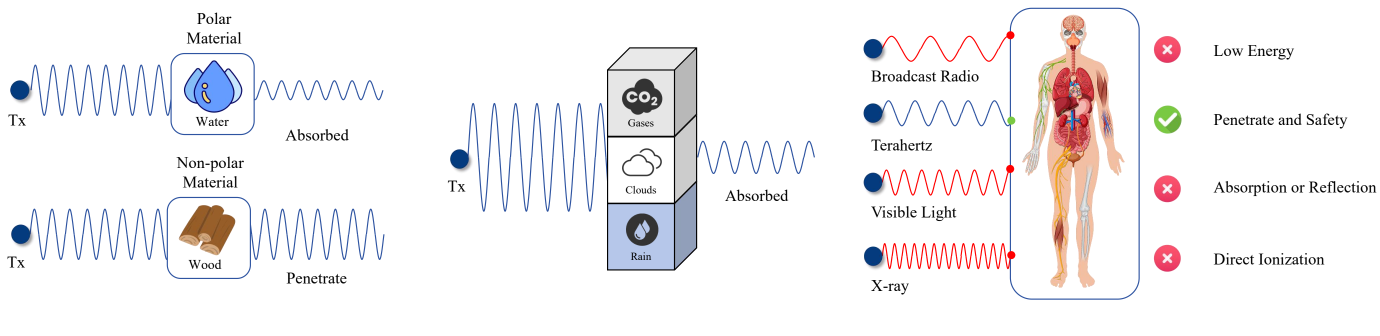

(a) Molecular absorption effect (b) Atmospheric attenuation (c) Penetration characteristics

Fig. 3: The properties of terahertz.

C. Spectral Recognition Capability

THz waves enable material identification through unique spectral fingerprints, capturing molecular rotations, vibrations, and intraband transitions. This makes them valuable in remote sensing (e.g., atmospheric and interstellar analysis), security (explosives/chemical detection), and industrial inspections (coating defects, paint thickness). Their coherence allows direct electric field and phase measurements, improving material characterization via refractive index and absorption analysis.

D. Atmospheric Attenuation

Atmospheric attenuation in the terahertz band results from interactions between THz waves and atmospheric gases, clouds, rain, and aerosols. Rain attenuation is most significant below 90 GHz but stabilizes above this frequency, while water vapor and clouds become more impactful [15]. Higher THz frequencies experience greater attenuation, reducing transmission distance [16]. Current challenges include limited transmission power and the need for high-gain antennas. However, THz can still be useful for long-distance communication in specific scenarios, such as air-to-air or air-to-space links, especially by utilizing narrow atmospheric windows below 1.6 THz and above 10 THz, as observed in Fig. 3 (b).

E. Penetration Characteristics

THz waves have strong penetration capabilities through non-polar materials like clothing, paper, and wood, but their ability decreases with increasing frequency. This makes THz technology useful for security inspections and non-destructive testing. For example, compared with X-rays and millimeter waves, THz waves can detect hidden items like knives and guns through clothing without harming humans and offer higher spatial resolution, making them ideal for security inspection, ass shown in Fig. 3 (c). However, THz waves cannot penetrate metals or water, which can be used to measure metal and moisture content.

IV. PLATFORM

In the realm of terahertz research and applications, THz hardware equipment is indispensable. In the following, we will enumerate some common THz-related devices and experimental setups, along with their performance characteristics and comparisons, to facilitate scholars and researchers in conducting THz-related studies and experiments.

A. Terahertz Source

Currently, there are primarily two methods for generating terahertz signals: the *bottom-up* approach using electronic mixing to produce THz carriers and the *top-down* approach utilizing photonic beat frequencies to generate THz carriers. The two methods are shown in Fig. 4.

We have enumerated several terahertz signal generation hardware devices sourced from different companies in Table II to facilitate relevant researchers in conducting THz-related studies. Some devices generate THz signals through electronic mixing methods, while others utilize photonic beating techniques. Different THz signal generators are also capable of producing THz waves at various frequencies. For instance, the Tera-AX is an advanced terahertz source, notable for its high pulse energy and broad spectral range from 0.5 to 2.5 THz. It features a pulse duration of 0.5-1 ps, making it suitable for high-resolution applications. The device also offers a frequency resolution of 30 GHz and operates within a comfortable temperature range of 20-25°C.

B. Terahertz Spectral Analysis System

A terahertz spectral analysis system is an instrument capable of measuring the electromagnetic radiation of materials within the terahertz frequency range. These systems are designed to analyze the spectral characteristics of materials, encompassing transmission, reflection, absorption, polarization, and other properties. They find applications in security inspection, material analysis, medical imaging, and others.

We enumerate several terahertz spectral analysis system products, which are shown in Table. III. Critical operational parameters of the devices are comprehensively profiled, empowering researchers with quantitative evaluation frameworks for optimal selection tailored to heterogeneous application requirements.

C. Terahertz Imaging Camera

Terahertz imaging cameras play a crucial role in technologies such as imaging recognition. A Terahertz imaging camera

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TABLE II: COMPARISON OF TERAHERTZ SOURCE DEVICES

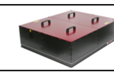
Name	Frequency range	Principle	Size $mm^3 : (W \times L \times H)$	Image
Tera-AX	0.5 - 2.5 THz	Photon beat mode	$600 \times 300 \times 200$	
IMPATT	100, 140, 180, 300 GHz	Electronic mixing mode	-	
TAS1130	0.5 - 7 THz	Photon beat mode	$43 \times 24 \times 21$	
TAS1110	0.1 - 4 THz	Electronic mixing mode	$55 \times 20 \times 20$	

TABLE III: COMPARISON OF TERAHERTZ SPECTRAL ANALYSIS SYSTEM DEVICES

Device name		Frequency range	Frequency resolution	Dynamic range	Image
TAS7500	**TAS7500SL**	0.03-2THz	30.4GHz	>60dB	
	TAS7500SP	0.1-4THz	7.6GHz	>70dB	
	TAS7500SU	0.5-7THz	7.6GHz	>70dB	
Z3		0.1-3.5THz	<5GHz	>70dB	
TearSmart		>5THz	<1.2GHz	>90dB	

is a device capable of capturing and analyzing electromagnetic radiation within the terahertz frequency band (0.05 – 0.7 THz). Even in the terahertz spectroscopic analysis system mentioned earlier, the terahertz imaging camera constitutes a vital component. Consequently, they have broad applications in fields such as security inspection, material analysis, and medical imaging. We enumerate in detail several terahertz imaging camera products as shown in Table. IV.

We conduct a detailed analysis of two selected terahertz camera products: the Tera-256 and the Tera-4096. By conducting a comparative analysis of the performance parameters of the two products, we find that The Tera-256 camera is well-suited for applications requiring portability and rapid imaging, such as security surveillance and defect identification. On the other hand, the Tera-4096 camera offers a higher resolution and is ideal for applications demanding high detail in imaging, including medical diagnosis and material analysis.

V. SENSING

Sensing plays a crucial role that enables precise and reliable data acquisition across various applications [17–22]. Terahertz sensing technology has emerged as a rapidly developing field, garnering significant attention from both academia and industry due to its unique capabilities.

A. *Key Techniques*

The main THz sensing technology can be generally categorized into pulsed and continuous-wave (CW) techniques based on the signal source types. Here, we briefly introduce the main techniques for THz generation and detection, as well as the basic principle and typical applications of THz spectroscopy and imaging.

1) THz Radiation Generation and Detection: THz radiation sources can be categorized into three main types: pulsed THz sources, continuous wave (CW) THz sources, and incoherent thermal THz sources [23]. The first two types are the most prominent, each with distinct advantages and disadvantages. Pulsed THz sources offer a broad frequency range, providing richer and more informative data compared to CW sources [24]. They allow for comprehensive data collection in a single measurement using one detector, although this increases the demand for advanced processing techniques [25]. In contrast, CW THz sources excel in terms of compactness, cost-effectiveness, spectral resolution, real-time capabilities, and potential for monolithic integration, all without the need for additional optical detection elements.

Pulsed THz radiation is commonly generated using methods such as biased photoconductive antennas (PCAs) [26], optical rectification (OR) with nonlinear optical (NLO) crystals [27], carrier tunneling in coupled double quantum well structures [28], and plasma generation in air [29]. On the other hand, CW THz emitters often rely on NLO, photonic, or electronic sources [23], including optically pumped THz gas lasers [30], quantum cascade lasers (QCL) [31], diodes, and high-speed transistors [32]. For tunable CW THz radiation, techniques such as photo-mixing, frequency multiplication [33], backward wave oscillators (BWO) [34], and parametric conversion are employed.

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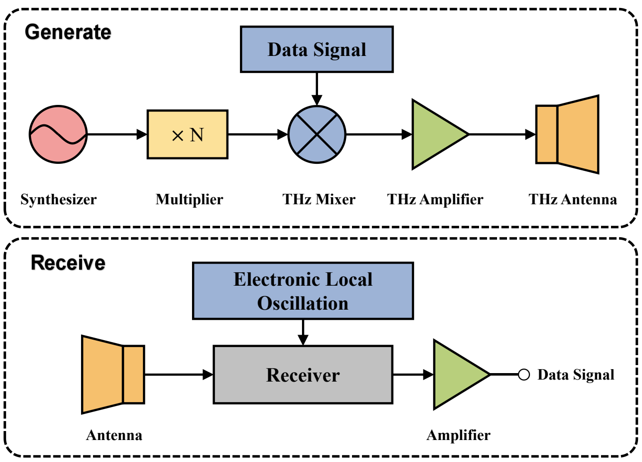
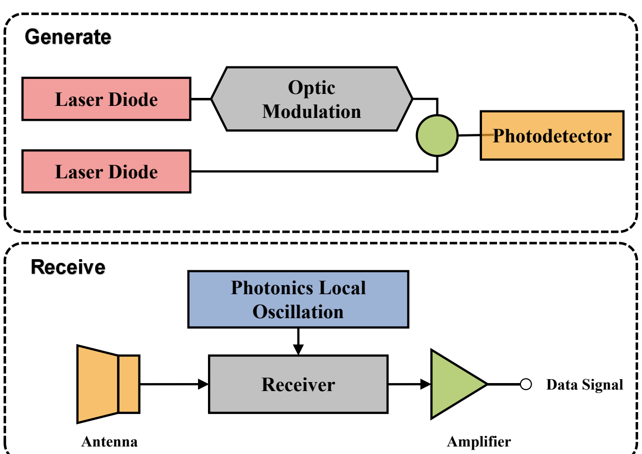
TABLE IV: COMPARISON OF TERAHERTZ CAMERA DEVICES

Camera name	Pixel count	Pixel size	Responsivity	Size $cm^3 : (W \times L \times H)$	Image
Tera-256	256 pixels (16 × 16 array)	1.5 × 1.5 mm	50 kV/W	10 × 10 × 5.5	
Tera-1024	1024 pixels (32 × 32 array)	1.5 × 1.5 mm	50 kV/W	10 × 10 × 5.5	
Tera-4096	4096 pixels (64 × 64 array)	1.5 × 1.5 mm	50 kV/W	16.5 × 16.5 × 4.5	
Linear Tera-1024	1024 pixels (256 × 4 array)	1.5 × 1.5 mm	50 kV/W	44 × 4.3 × 8.9	
TeraFAST-256	256 pixels (256 × 1 array)	3 × 1.5 mm	8000 V/M	-	



(a) Electronic mixing mode



(b) Photon beat mode

Fig. 4: Two distinct methodologies exist for the generation of terahertz signals.

THz detectors convert THz-frequency electromagnetic radiation into electrical signals that can be stored digitally. Detection methods are generally classified into incoherent and coherent techniques. Incoherent methods utilize power-to-signal transducers [35], such as uncooled or Li-He cooled bolometers [36], Golay cells [37], pyroelectric detectors [38], thermopiles [39], and Schottky diodes [40]. In contrast, coherent detectors, including NLO crystals [41], electro-optic crystals [42], and PCAs [43], can provide detailed information about phase, power, and frequency spectra.

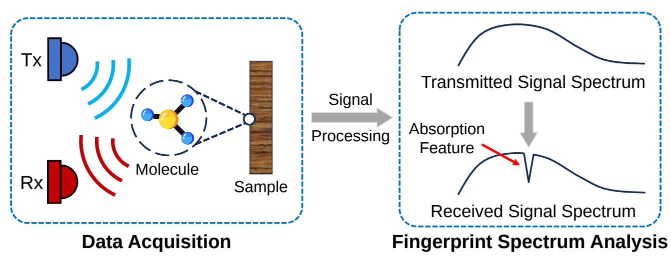
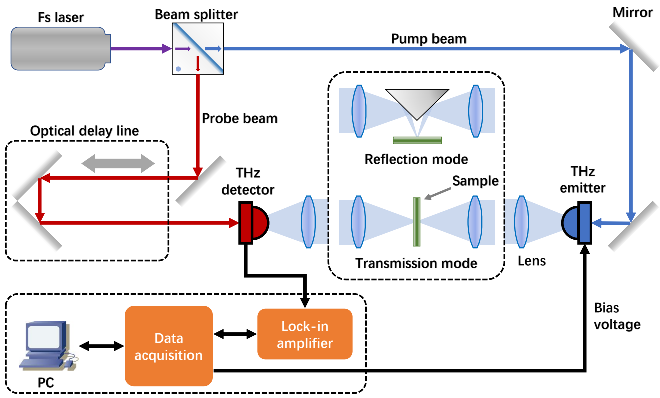


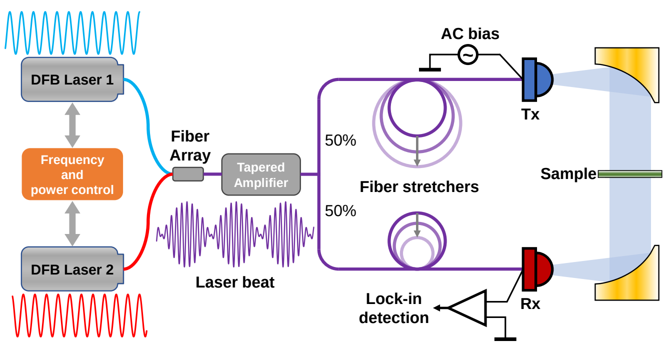
Fig. 5: The formation process of the molecular fingerprint spectrum.

2) THz Spectroscopy and Imaging: The THz spectroscopy system typically comprises a THz emitter, a THz detector, and various optical components, including a beam splitter, optical delay line, and beam guiding elements such as mirrors and lenses. The fundamental principle of this system is that when THz radiation interacts with a sample—either transmitted through or reflected by it—the sample imparts unique characteristics in both the time and frequency domains. By analyzing the transmitted or reflected signals, valuable information about the sample can be extracted, including insights into its surface or internal structure and the identification of specific molecules that absorb energy at frequencies corresponding to their rotational or vibrational modes, resulting in a distinct fingerprint spectrum, as shown in Fig. 5.

THz imaging systems build upon the principles of spectroscopy, focusing on collecting spectral data across a larger



(a) Schematic of a typical THz-TDS system.



(b) Schematic of a typical CW THz system.

Fig. 6: Examples of THz systems.

sample area rather than at a single point. This is achieved through a point-by-point raster scanning mechanism, which can involve moving either the beam or the sample holder in conjunction with coherent detection [44]. The sample is sampled on a discrete grid, and temporal data at each pixel is recorded, allowing for the extraction of frequency data. The collected time or frequency domain data is then processed to derive the desired physical values and generate an image [41].

Two typical THz systems are illustrated in Fig. 6. Terahertz pulsed spectroscopy (TPS), also known as terahertz time-domain spectroscopy (THz-TDS), is depicted in Fig. 6a. In a standard THz-TDS setup, a femtosecond laser beam is split into two parts by a beam splitter: the pump beam directed toward the THz emitter and the probe beam toward the THz detector. An optical delay line adjusts the optical path difference between these beams, enabling the sampling of the entire temporal profile of the THz pulse rather than just a single moment. The generated THz pulsed radiation is focused onto the sample, interacting with its interfaces through reflection or transmission. The resulting THz pulses are converted into electrical signals by the detector, which are then digitized and transmitted to a computer for further analysis via a lock-in amplifier and data acquisition card.

In CW THz systems that utilize photo-mixing, variations in phase difference are crucial for determining the amplitude and phase information of the signal [25]. While a delay line can be used to adjust the phase difference, fiber stretchers offer a more rapid and precise method of phase modulation, as shown in Fig. 6b. In this setup, a laser beat is generated by superimposing a pair of slightly detuned distributed feedback (DFB) lasers, which are then fed into a tapered amplifier and a fiber-optical 50:50 splitter. Two fiber stretchers operate in opposite directions to finely tune the optical path difference.

B. Comparison with Existing Sensing Technologies

In this section, we conduct a comparative analysis between THz technology and other existing sensing technologies, including mmWave, acoustic, and LiDAR systems.

1) Sensing Capability: Due to the submillimeter wavelength and penetrating ability, THz technology achieves high-precision internal detection. Besides, the molecular fingerprint spectrum enables it to analyze certain characteristics of the sample. Other technologies, such as millimeter wave (mmWave) and acoustic sensing, primarily target macroscopic structures and motions (e.g., hand gestures) instead, with a slightly lower resolution. Meanwhile, although light detection and ranging (LiDAR) performs better in resolution than THz, its sensing range is narrow and confined to the surface, which limits its application scenarios.

2) Safety Profiles: The safety advantages of THz radiation derive from its low photon energy (4 meV for 1 THz), which is about one-millionth of that of X-rays. Unlike LiDAR systems, where high-intensity laser pulses can cause retinal damage or skin burn, THz does not lead to photoionization radiation damage to the biological tissues. While millimeter waves and acoustic waves share similar non-ionizing safety profiles, they cannot retrieve as much information as THz waves when interacting with the sample.

3) Environmental Adaptability: Currently, THz technology is usually applied indoors or in controlled environments. It faces challenges in humid environments (e.g., rain and fog) with limited effective range, similar to LiDAR, while mmWave and ultrasonic-based technologies exhibit strong resistance to these conditions and still support long-range detection in them.

C. Application Scenarios

We introduce four typical application scenarios of terahertz sensing, including material property analysis, defect detection, food quality evaluation, and biological & medical research.

1) Material Property Analysis: Terahertz spectroscopy provides rich information about the physical state and chemical processes of materials, especially molecular-level changes that are difficult to observe. By analyzing spectral characteristics like absorption coefficient and refractive index, relevant properties of the material can be determined, and their transformation process can be further monitored online, which is particularly useful in material selection, industrial production, and equipment maintenance.

Contactless Tactile Sensing. As shown in Fig. 7, **airTac** [45] is a novel contactless digital tactile receptor taking advantage of the broad THz bandwidth to simultaneously extract material type and surface roughness in a fine-grained resolution. Its core innovation lies in resolving the complicated intertwined effects of these two properties on reflected THz signals through a custom-designed deep neural network model,

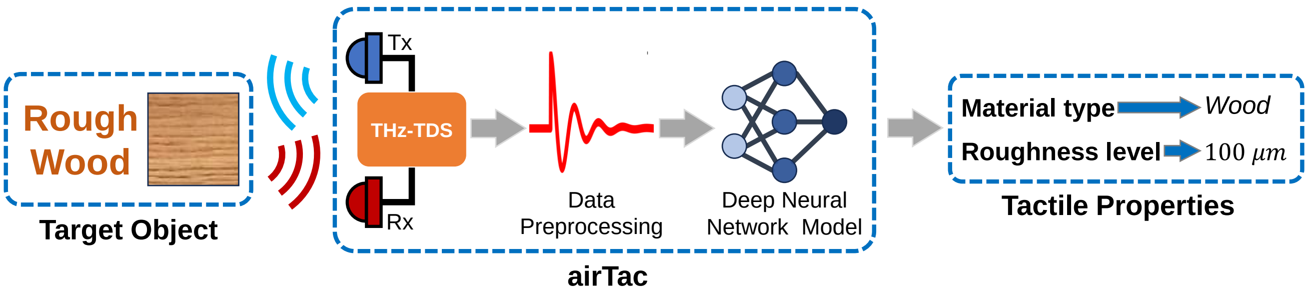


Fig. 7: Schematic of airTac.

achieving 97.43% material identification accuracy within 9 material types and 91.46% roughness classification accuracy on 39 rough surfaces. Notably, it attains 3-μm resolution in surface roughness detection, demonstrating superior performance in contactless tactile sensing.

Oil-Paper Insulation Monitoring. To achieve an online assessment of the degradation status of oil-paper insulation without equipment shutdowns, **He et al.** [46] correlated the degradation with THz-TDS features. Their experiments demonstrated a progressive increase in THz absorption spectra during thermal aging, and the calculated dissipation factor in the terahertz frequency range showed a great correlation with that under macroscopic power frequency (50 Hz). This indicates that the THz dielectric spectrum is capable of reflecting the aging condition of oil-paper insulation.

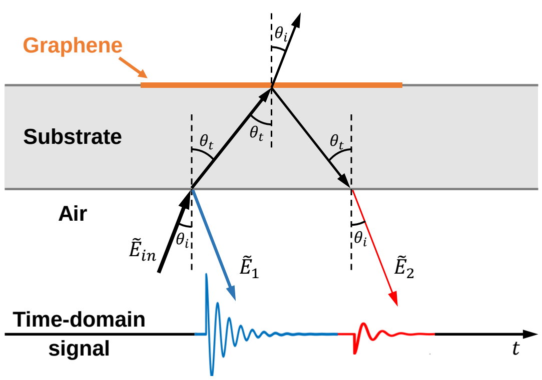


Fig. 8: Ray diagram for THz light incident on the graphene-on-substrate system and the corresponding measured THz pulse. The measured time-domain signal contains two pulses, corresponding to the reflection from respective interfaces.

Other Applications. (1) As Fig. 8 shows, **Vandrevala et al.** [47] employed THz-TDS to extract complex optical properties of graphene. From these its complex conductivity and complex dielectric function were determined, providing critical data for plasmonic antenna design. (2) To monitor the structural state of contact lenses as they dehydrate, **Jayasree et al.** [48] proposed a novel method for measuring their thickness and refractive index using a combined THz imaging and optical coherence tomography (OCT) system. (3) Industrial monitoring of the curing process of polyurethane materials was enhanced by **Han et al.**'s [49] work by correlating refractive index with material loss factor via reflection-mode THz-TDS.

2) Defect Detection: Since terahertz radiation exhibits excellent penetration capability through certain non-polar media, and is strongly absorbed by water, it can be used for nondestructive defect detection of non-metallic materials, such as paper, timbers, concrete, power cables, and tablets. Besides, compared with the conventional microwave, X-ray, and γ-ray methods, its advantages include higher spatial resolution and non-toxicity to human tissues.

Building Material Inspection. Oyama et al. [50] applied sub-THz imaging at 0.2 THz to the detection of defects in building blocks. Their system successfully identified different kinds of invisible defects in three key materials: (1) Timbers: Internal holes, knot defects, and moisture distribution patterns; (2) Concrete: Inner cracks and visualizes water diffusion; (3) Ceramic tiles: Adhesion defects of tiles on concrete walls. Additionally, they proposed an effective method to enhance the sensitivity of crack detection by filling the crack with water, as Fig. 9 shows.

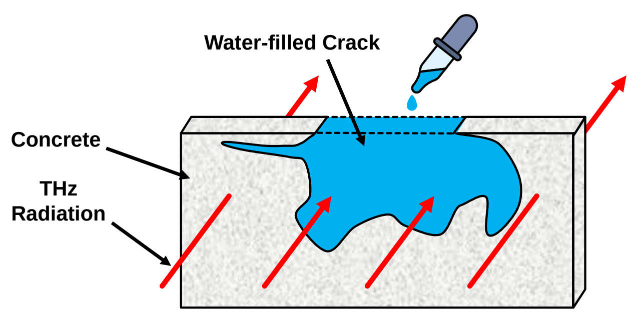


Fig. 9: Schematic of water-enhanced crack detection in concrete. The diffused Water enhances the sensitivity of crack detection for its large absorption coefficient of THz radiation.

Pharmaceutical Quality Control. Shen et al. [51] explored the ability of TPI for characterizing the structures of pharmaceutical tablets. Their system achieved: (1) Coating layer thickness measurement and interface uniformity determination via time-domain THz waveform, as shown in Fig. 10; (2) Internal 3D structural mapping with 30-μm axial and 150-μm lateral spatial resolution. Furthermore, the potential of the TPI technology for chemical substance identification, polymorphic discrimination, and 3-D chemical mapping was demonstrated in their work.

Other Applications. Diverse implementations confirm THz technology's growing prominence in industrial nondestructive evaluation systems: (1) **Ma et al.** [52] and **Lu et al.** [53] re-

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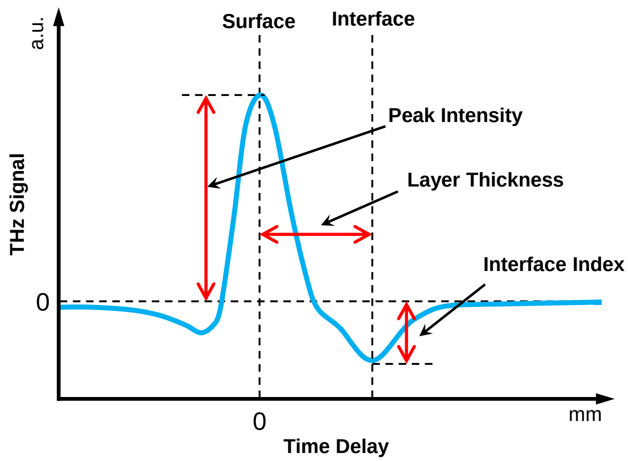

Fig. 10: Schematic of tablet coating analysis based on the THz waveform. The peak and the trough correspond to the reflections from the surface (air/coating interface) and the coating/core interface, respectively. Arrows illustrate how the peak intensity, layer thickness, and interface index are determined.

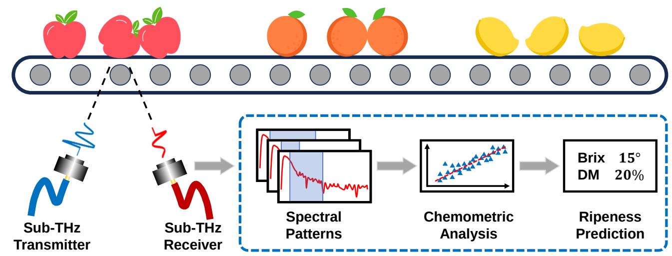

Fig. 11: Schematic of AgriTera.

spectively achieved aerogel defect imaging through refractive index and 4-mm resolution inspection of aerospace composite materials. (2) **Chen et al.** [54] reconstructed THz 2D images of cable terminal insulation materials. (3) **Luo et al.** [55] identified critical defects in insulating paperboard through THz spectral analysis and imaging.

3) Food Quality Evaluation: To guarantee food safety, it is important to develop a contactless and non-destructive method with speed, convenience, and high precision to evaluate the quality of food, which THz sensing is capable of. Recently, two innovative implementations in fruit ripeness monitoring demonstrates its industrial and commercial potential.

Fruit Ripeness Estimation for Producers. AgriTera [56] is an accurate and non-invasive solution for fruit quality and ripeness estimation via sub-THz signals (0.05-0.6 THz). As shown in Fig. 11, the core idea is that the dielectric properties of the fruit change as it ripens, leaving unique spectral footprints in the spectra of the reflected signals. Then the key metrics of ripeness are predicted with a Partial Least Squares Regression (PLSR) model according to the spectral signatures. In comparative trials, the conventional visual method showed slow structural similarity values (SSIM) decrease in surface-level images, while AgriTera accurately tracked Brix and Dry Matter (DM) throughout maturation. With more application of such THz-based sensing systems in the future, the food quality control processes can be fully automated with superior accuracy and effectiveness.

Fruit Inner Quality Detection for Consumers. Similar to AgriTera, **Meta-Sticker** [57] introduces a low-cost and non-invasive method for consumers to estimate the inner quality of the fruit accurately. It is a metamaterial sticker attached to the fruit that resonates in the sub-terahertz regime, particularly in the D-band (0.11-0.17 GHz). Fig. 12 demonstrates the ripeness sensing with Meta-Sticker. During the fruit ripening process, the change of its dielectric properties results in a unique spectral signature in the resonance response of Meta-Sticker, which can be used to infer the ripeness/quality metrics like Brix and DM. Meta-Sticker bridges the gap between laboratory-grade analysis and consumer accessibility. Since the D-band is emerging as a candidate band for 6G wireless technology [58, 59], D-band transceivers may be available on next-generation mobile devices, laying the foundation for non-invasive fruit quality sensing with mobile phones.

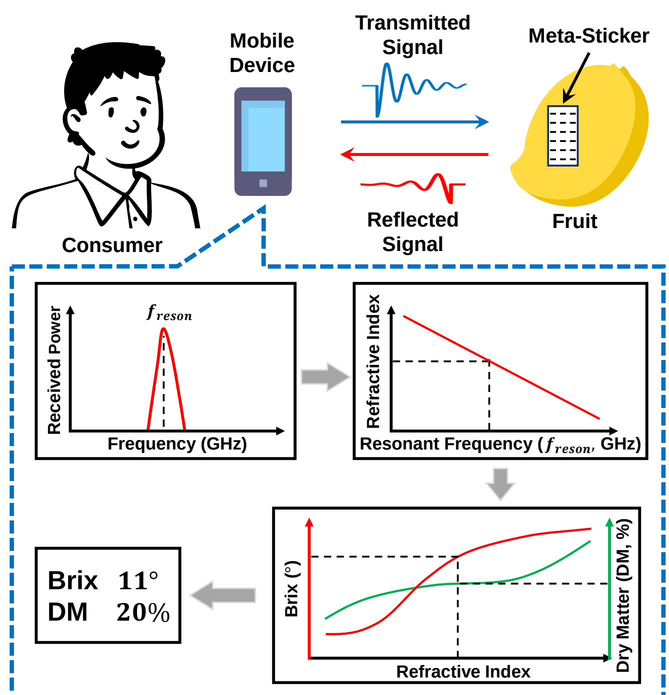

Fig. 12: Schematic of Meta-Sticker.

Other Applications. (1) **Wang et al.** [60] combined THz-TDS and principal component analysis (PCA) to detect shell contaminants in walnut kernel, achieving 95% accuracy (2) **Sun et al.** [61] utilized THz-TDS coupled with baseline correction and variable selection algorithms to discriminate insect foreign bodies in finished tea products. The precision, accuracy and recall achieved 95.7%, 97.7%, and 100.0% respectively. (3) For analysis of potassium sorbate in milk powder, **Lian et al.** [62] constructed a Sub-PLS model based on the THz absorption spectrum and applied partial least squares discrimination analysis (PLS-DA), achieving 92.8% quantitative and 96% qualitative accuracy.

4) Biological and Medical Research: Terahertz technology has demonstrated significant potential in biology and medicine due to its non-ionizing nature, penetration ability, and sensitivity to biomolecular interactions. Its applications have been investigated for biomolecular detection, tissue analysis, and disease monitoring.

Scar Condition Monitoring. Fan et al. [63] studied both hypertrophic and normal scars and achieved wound healing process monitoring via THz reflection imaging. Fig. 13 shows the setup of the experiment. The refractive index of normal scars was lower than that of the surrounding healthy tissue, while hypertrophic scars presented the opposite trend, showing the capability of THz imaging to discriminate different kinds of scars. Besides, the change in both the refractive index and absorption coefficient of the scar was observed during the healing process, which is useful for non-invasive quantitative wound assessment and improvement of post-injury treatment.

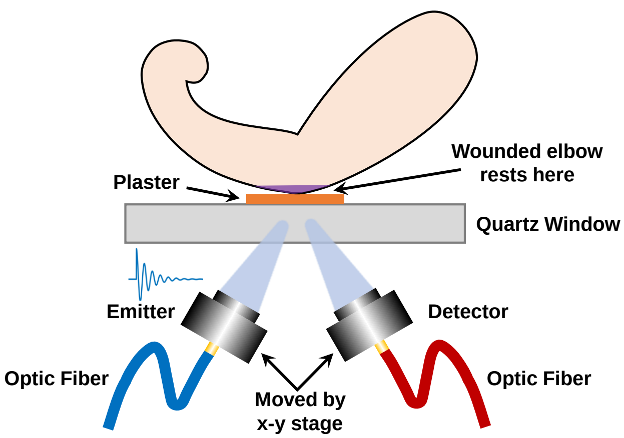

Fig. 13: Schematic of the experimental setup for scar imaging.

Cancer Diagnosis. The differences between cancer cells and normal cells, especially in water content, are reflected in terahertz signal characteristics. (1) **Joseph et al.** [64] developed a CW THz transmission imaging system to obtain 2D images of nonmelanoma skin cancers at 1.39 and 1.63 THz. The cancerous regions appeared as distinguishable areas of low transmission in images, while the average transmittance of normal areas was approximately two times higher. (2) For the analysis of living cells, **Guan et al.** [65] compared three materials and finally selected polypropylene to design Petri dishes with high transmission of THz waves. The spectral characteristics of hepatoma cells and normal cells, such as refractive index and absorption coefficient, showed significant distinction, which is available for cancer detection at the cellular level.

Other Applications. (1) **Markelz et al.** [66] explored the sensitivity of THz-TDS to distinguish different molecular species, different mutations within a single species, and different conformations of a given biomolecule. (2) To classify *Radix Angelicae Dahuricae* (RAD, a kind of herb) by origin, **Tian et al.** [67] analyzed the THz-TDS data of RAD samples by principal component analysis (PCA) and k-subspace clustering. (3) **Shao et al.** [68] achieved quantification analysis of progesterone based on THz spectroscopy. They identified its characteristic peaks, established two linear correlation models, and finally applied multivariate curve resolution-alternating least squares (MCR-ALS) to analyze progesterone capsules, with an error rate of less than 5%.

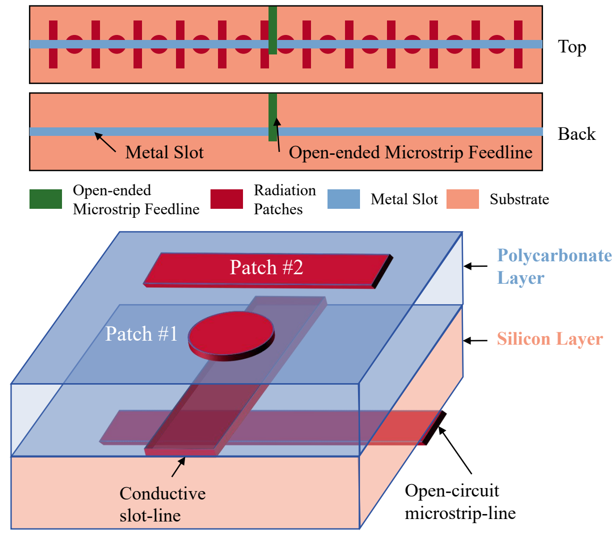

Fig. 14: Silicon-based integrated on-chip antenna.

VI. COMMUNICATION

Reliable communication is fundamental to modern technological advancements across industries [69–80]. This section mainly summarizes the current research in THz systems.

A. Antenna Design

The antenna design [81] is an essential component in communication systems. THz antennas require specialized design due to their compact size and directional characteristics. Research has focused on their applications in beam control, high-capacity transmission, and radiation enhancement across multiple domains, including satellite communications and biomedical systems. This section reviews these advancements.

1) High-gain Antenna: In the system of wireless communication, due to the high free-space path-loss (FSPL) for THz wave compared with that of current commercial wireless communication systems, it is of great significance to employ a high-gain antenna at both transmitter and receiver to compensate for the high path loss for THz link.

Alibakhshikenari et al. [83] demonstrated the practicability of fabricating a high-gain on-chip antenna on silicon technology for sub-terahertz applications covering a wide frequency range. Specifically, the high-gain on-chip antenna structure with silicon layer aperture excitation designed in this article is illustrated in Fig. 14. The antenna is excited through an aperture-fed mechanism, which facilitates the coupling of electromagnetic energy from a metal slot line positioned between the silicon and polycarbonate substrates, to a 15-element array of circular and rectangular radiation patches situated on the top surface of the polycarbonate layer.

Shu et al. [82] proposed a high-gain reflector antenna with beam steering for terahertz wireless communications. **Choi et al.** [84] proposed a Rotman lens-fed Yagi-Uda antenna array capable of achieving ultra-high data rates for 6G wireless

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TABLE V: Comparison of Antenna Design Works

Category	Reference	Structure Type	Gain	Operating Frequency	Size & Characteristic
High-gain Antenna	Shu et al. [82]	Antenna Array	55.19 dBi	220 GHz	-
	Alibakhshikenari et al. [83]	On-Chip Antenna	11.71 dBi	0.290–0.316 THz	20 × 3.5 × 0.126mm
	Choi et al. [84]	Antenna Array	16.2 dBi	150-175 GHz	28 × 28 mm
	Keshwala et al. [85]	Microstrip Patch Antenna	9.03 dBi	0.22-0.32 THz 1.49-2.89 THz	-
	Keshwala et al. [86]	Microstrip Patch Antenna	22.1 dBi	0.46-8.84 THz	600 × 600 μm
Low-cost Anatenna	Wu et al. [87]	Lens Antenna	30.8 dBi	300 GHz	3-D Printing
	Li et al. [88]	On-Chip Antenna	6.7 dBi	340 GHz	-
	Hao et al. [89]	Lens Antenna	27.6 dBi	412.5 GHz	Metal Milling
	Hao et al. [90]	Open Resonator Antenna	16.8 dBi	100 GHz	3-D Printing
Optimized Process Antenna	Rabbani et al. [91]	Antenna Array	-	0.835,0.635,0.1 THz	-

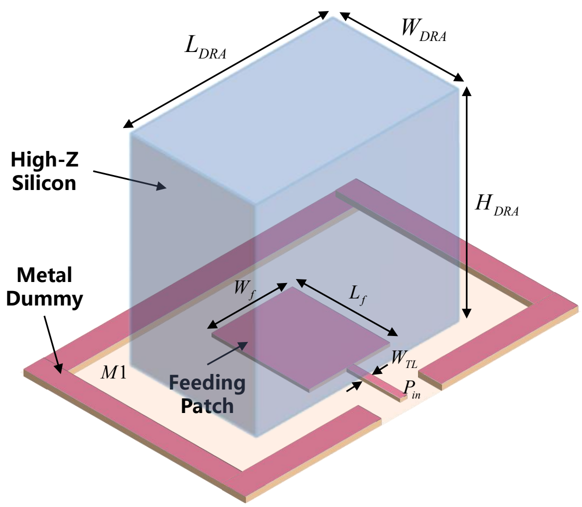
communications. **Keshwala et al.** [85] designed a DNA-shaped antenna for terahertz and sub-terahertz applications. The proposed antenna prototype is fabricated on a polyamide substrate, featuring a fractal antenna in the shape of DNA. This antenna features a simple structure, wide bandwidth, and high gain, making it suitable for WBAN (Wireless Body Area Network) applications.

2) Low-cost Antenna: In the field of THz communication antennas, the need for extremely precise dimensions increases manufacturing and production costs. This high precision also complicates mass production, limiting the antennas' widespread adoption. Therefore, reducing the cost and manufacturing complexity of THz antennas is a crucial task. This section will explore relevant research focused on lowering the costs of THz antenna production.

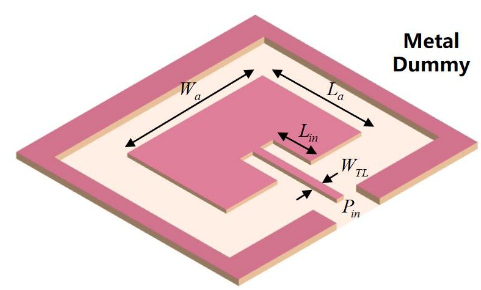
Li et al. [88] proposed a low-cost, high-gain on-chip terahertz dielectric resonator antenna (DRA) designed to operate beyond 300 GHz. This research designs an on-chip patch antenna as a baseline control group to reveal the limitations in antenna performance caused by a thin IMD as shown in Fig. 15 (a). And the basic structure of this antenna is shown in Fig. 14 (b). The antenna consists of a low-loss dielectric resonator (DR) made of high-resistivity (high-Z) silicon material and a feeding patch implemented using 0.18-μm CMOS technology. The DR is fabricated to the required dimensions (400μm × 300μm) using low-cost wafer dicing techniques and is manually attached to the 0.18-μm CMOS chip.

Wu et al. [87] proposed a high-gain circularly polarized (CP) lens antenna fed by a standard linearly polarized (LP) pyramidal horn operating at 300 GHz. **Hao et al.** [89] designed a low-cost terahertz antenna using a metallic lens structure to achieve high gain. The antenna operates at 412.5 GHz and is made using commercial metal milling technology. In addition, **Hao et al.** [90] also designed a low-cost, high-gain terahertz open resonator antenna (ORA) using 3-D printing and a phase-shifting periodic structure.

3) Optimized Process Antenna: As we move from millimeter waves to the THz band, shorter wavelengths create new challenges for antenna design. This has led to a focus on precise fabrication techniques and smaller antenna dimensions.



(a) Proposed low-cost and high-gain on-chip THz DRA.



(b) On-chip patch antenna as a baseline control group.

Fig. 15: The low-cost and high-gain on-chip THz DRA.

Many researchers have explored this area, and this section will discuss some efforts to optimize antenna designs using advanced manufacturing methods.

Rabbani et al. conducted numerous projects on the design of high-performance antennas following process optimization, resulting in the development of numerous microstrip patch antennas (MPAs) with superior performance characteristics. They particularly concentrated on the design and fabrica-

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TABLE VI: Comparison of Reconfigurable Intelligent Surface Works

Reference	System	Technology	Algorithm	Boundedness
Mao et al. [93]	RIS-MU-MIMO	Beamforming, Phasing adjustment, Channel modeling and optimazation	SA Allocation Method, ML Detector, SVD Method, Distributed Mapping Rule	Model simplification, Algorithm complexity, Environmental suitability
Du et al. [94]	RIS-aided THz	Electromagnetic wave regulation, Phase adjustment	Swarm intelligence	Environmental suitability, Security and privacy
Wan et al. [95]	RIS-aided MIMO	Beamforming, Electromagnetic wave regulation, Phase adjustment	Discrete planar array, DL-based CE	Dynamic optimization of RIS, Limit deployment, Limit channel condition
Tekbiyik et al. [96]	RIS-THz-ISL	Multiaerial system, Misaligned fading model, Path loss analysis, Phase adjustment	Resource allocation, Optimization algorithm, Beam optimization	Model simplification, Atmosphere influence, Experimental verification
Huo et al. [97]	RIS-aided indoor communication	Three dimensional ray tracing, Distributed RISs Framework, Energy efficiency optimization	Dynamic IRS Beamforming, System QoS Optimization, SNR Performance Optimization	Model simplification, Limitation of spectrum resources, Security and privacy

tion of microstrip patch antennas at THz frequencies [92]. Part of them fabricated the antenna on RT/Duroid substrate, whose available minimum substrate thickness is 127μm. As a consequence, it may not be suitable for frequencies above 300 GHz due to the encountered side effect of surface wave (SW) at such high frequencies. In addition, they also designed MPA arrays at liquid crystalline polymer (LCP) substrate material [91].

B. Reconfigurable Intelligent Surface

THz signals are highly sensitive to obstacles due to molecular absorption and atmospheric attenuation, limiting their propagation distance, especially in dense urban areas. Reconfigurable Intelligent Surfaces (RISs) address this issue by using low-cost, tunable passive elements to control signal beams in any direction. Unlike traditional relays, RISs avoid self-interference and thermal noise, can be easily integrated onto various surfaces, and leverage Line-of-Sight (LoS) components to enhance end-to-end communication and reduce high-frequency path loss.

Mao et al. [93] discussed the communication design of a multi-user Multiple Input Multiple Output (MIMO) system assisted by RIS in the THz frequency band, proposing a novel RIS-aided Index Modulation (IM) scheme to enhance the performance of THz communications. As shown in Fig. 16, the proposed RIS array is illuminated by unmodulated THz carriers through a feeding antenna and is equally divided into multiple Sub-Arrays (SAs). Each activated SA serves a unique User Equipment (UE) through directional beams. The design of the RIS primarily relies on the control of the Electromagnetic (EM) responses of the reflecting elements. By adjusting the phase and amplitude responses of each reflecting element through external control signals, beam-forming and modulation of the data symbols are achieved.

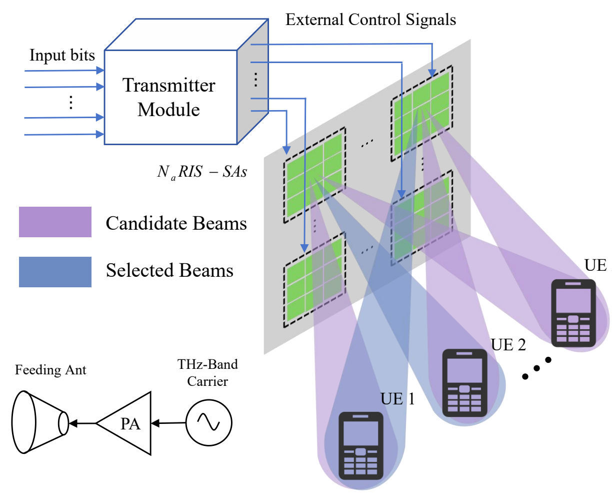

Fig. 16: Diagram of the considered RIS-MU-MIMO system.

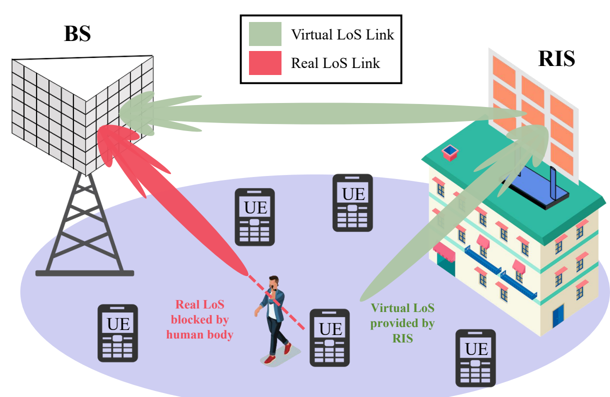

Fig. 17: The model of an RIS-aided THz massive MIMO system.

Wan et al. [95] investigated the application of holographic RIS in Terahertz MIMO systems, proposing a beamforming framework for holographic RIS based on discrete elements and deriving the beam pattern. And the beamforming framework is shown in Fig. 17. They also presented a downlink channel estimation scheme and conducted simulation experiments to evaluate the performance of holographic RIS in THz MIMO systems, demonstrating its superiority over traditional designs. **Du et al.** [94] introduced the RIS design by using a large number of programmable reflecting elements, each capable of independently adjusting its phase. **Tekbiyik et al.** [96] delved into the application of RIS in Inter-Satellite Links (ISLs) within Low Earth Orbit (LEO) satellite constellations. **Huo et al.** [97] explored the analysis of real indoor THz propagation environments based on the 3-D ray-tracing method and how to enhance the overall energy efficiency of THz systems through the design and deployment of RIS systems.

C. Modulation Technique

Modulation technology serves as a core driving force for the performance, efficiency, and adaptability of THz communication systems. Modulation schemes directly determine the methods of information encoding, transmission, and recovery in the time domain, frequency domain, and spatial domain, and their selection exerts a decisive influence on key metrics such as spectral efficiency, power efficiency, anti-interference capability, and compatibility with channel equalization.

1) Single-Carrier (SC): The fewer multipath components and typically frequency-flat channel characteristics in the terahertz band make THz suitable for low-complexity wideband SC systems. **SC-FDE** (Single-Carrier Frequency Domain Equalization) is a communication scheme that integrates single-carrier transmission and frequency domain equalization techniques, aiming to address the performance limitations of conventional single-carrier systems in multipath channels by leveraging low peak-to-average power ratio (PAPR) and low-complexity equalization as its core advantages. Its fundamental principle lies in preserving the low-PAPR characteristic of single-carrier signals at the transmitter while efficiently combating multipath interference through frequency domain processing at the receiver. **SC-FDMA** (Single-Carrier Frequency Division Multiple Access) is a modulation technique that amalgamates the properties of single-carrier modulation with Frequency Division Multiple Access (FDMA), and it is extensively employed in the uplink of mobile communication systems. **CPM-SC-FDMA** is introduced in [98], which combines essential characteristics of single-carrier frequency-division multiple access (SC-FDMA) and continuous phase modulation (CPM) to yield a power-efficient waveform, and this scheme can provide a very low PAPR signal with very low side lobes. **ceCPM-SC** (constant envelope Continuous Phase Modulation Single-Carrier) is a modulation technique based on CPM. Building upon conventional CPM, it extends the strict constant envelope characteristic of traditional CPM by introducing controlled envelope variations. This approach optimizes receiver sensitivity and system performance while preserving the advantage of a low PAPR.

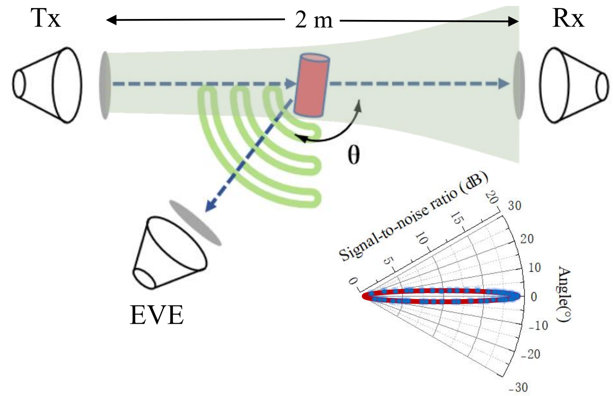

Fig. 18: Schematic of a line-of-sight transmission channel with an eavesdropper.

2) Multi-Carrier (MC): **OFDM** (Traditional Orthogonal Frequency Division Multiplexing) technology divides a high-speed data stream into multiple parallel low-speed sub-data streams, each of which is transmitted over an independent orthogonal subcarrier. This approach offers efficient spectrum utilization and strong anti-interference capabilities. Based on OFDM technology, **CP-OFDM**, **W-OFDM**, **P-OFDM** and **UF-OFDM** are proposed to tackle diverse scenarios. Considering the stringent synchronization requirements and PAPR constraints in the terahertz band, as well as the impact of hardware bottlenecks and the Doppler effect, conventional OFDM technology will encounter numerous novel challenges when applied in the terahertz frequency band. Other MC modulation schemes such as **FBMC-QAM** (Filter Bank Multicarrier with Quadrature Amplitude Modulation) employs a filter bank instead of FFT (Fast Fourier Transform), ensuring subcarrier orthogonality through filter design and supporting QAM modulation. **FBMC-OQAM** (Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation) maintains subcarrier orthogonality via OQAM, eliminating the need for cyclic prefix overhead and achieving the highest spectral efficiency, albeit with complexities in pilot design and MIMO compatibility. **OTFS** (Orthogonal Time Frequency Space) is also a novel wireless communication modulation technology, specifically designed for high-mobility and severely time-varying channel scenarios. Unlike conventional OFDM, which operates in the time-frequency domain, OTFS maps signals to the delay-Doppler domain, achieving more uniform interference resistance capabilities through mathematical transformations. It is regarded as a potential core technology for future 6G and high-speed communications.

D. Security and Privacy

With growing communication technologies, radio systems are now widespread, but this also increases security challenges. Even in the THz band, eavesdropping remains a risk despite its more directional beams. We will now explore recent research on enhancing security in THz communications.

Ma et al. [99] addressed the security issues in terahertz band wireless communications. Even in the directional beams of such high-frequency terahertz bands, eavesdroppers may still

TABLE VII: Comparison of Security and Privacy Works

Conference	Background	Primary Work	Boundedness	Signal Source
Ma et al. [99]	Communication physical layer security	Backscatter detects eavesdroppers	Dependent channel characterization, Limited detection	High frequency directional emission, scattering objects
Cohen et al. [100]	Secure communication architecture	Multi-band antenna blind zone model	Specific antenna configuration, Lower efficiency	Multi-band high-gain antenna
Yeh et al. [101]	LWA security in terahertz WLAN	LWA frequency-angle coupling analysis	Wiretapping risks increase over broadband	LWA antenna frequency-angle coupling

TABLE VIII: COMPARISON OF ISAC WORKS IN NETWORKING

Conference	System	Primary Work	Performance	Background
Wu et al. [102]	SI-DFT-S-OFDM	Waveform Design, Receiver design	PAPR: -2.6dB (OFDM), 5dB better than OFDM	Spectrum resource strain, Doppler effect, RF front-end damage sensitive
Chen et al. [103]	SSB-based JCAS Sys	Beam alignment	Beam misalignment probability: -70%	Narrow beam, Beam misalignment
Han et al. [104]	THz-ISAC Sys	Beamforming, Narrow beam management, ISAC Channel	PAPR: -3dB (OFDM)	Channel challenge, Transceiver challenge

exploit vulnerabilities in wireless signal transmission to carry out eavesdropping attacks as shown in Fig. 18. The illustration depicts the angular distribution of radiation, comparing the measured values (depicted in blue) with the computed ones (depicted in red), emitted by our transmitter when utilizing the horn antenna in conjunction with the dielectric lens, at a measurement frequency of 200 GHz, which indicate a significant directivity level of 34 dBi (relative to an isotropic radiator), with an absence of detectable side lobes.

Cohen et al. [100] explored methods to achieve absolute security in wireless communications and propose a secure coding scheme based on antenna configuration and signal processing. The antenna configurations prevent Eve's detection by forming blind regions, while the secure coding schemes ensure that Bob can correctly decode the messages, with Eve unable to obtain any useful information. **Yeh et al.** [101] studied the security of THz wireless links using Leaky Wave Antennas (LWAs). They analyzed how the frequency-space coupling of LWAs affects security, showing that this coupling leads to non-uniform security across different frequencies and beamwidths. The paper proposed a security assessment method based on normalized secrecy capacity and validated it through experiments. The results demonstrated that narrower beams improve security but reduce data rates, while wider beams increase data rates at the cost of security.

VII. NETWORKING

Terahertz networking refers to the network technology that utilizes the terahertz frequency band for wireless data transmission. Its key technologies encompass multiple aspects. In this section, we will introduce some research related to terahertz networking.

A. Resource Allocation

The characteristics of THz communication pose unique challenges for resource allocation. Proper resource allocation [105] not only enhances the spectral efficiency of the system, augments network capacity and transmission rates, but also improves resource utilization efficiency and economic viability, thereby fostering the development of terahertz communication technology. On the one hand, existing works optimize spectral efficiency through adaptive subterahertz band segmentation. On the other hand, some works enhance network capacity via intelligent beamforming and hybrid orthogonal/non-orthogonal multiple access (HOMA) techniques.

Addressing the resource allocation problem in THz band communication networks, **Han et al.** [106] proposed a distance-aware bandwidth adaptive resource allocation scheme, aiming to extend communication range and support multiple ultra-high-speed links. **Zhang et al.** [107] optimized the resource allocation problem of subband and power allocation by maximizing energy efficiency, aiming to achieve energy efficiency optimization in cache-enabled terahertz dense vehicular networks. **Zhang et al.** [108] studied the resource allocation optimization problem in THz-NOMA downlink systems, considering the communication characteristics of the THz band and the technical advantages of non-orthogonal multiple access. **Shafie et al.** [109] proposed a spectrum allocation scheme with Adaptive Subband Bandwidth (ASB) and investigated its impact on Multi-Connectivity (MC) THz communication systems.

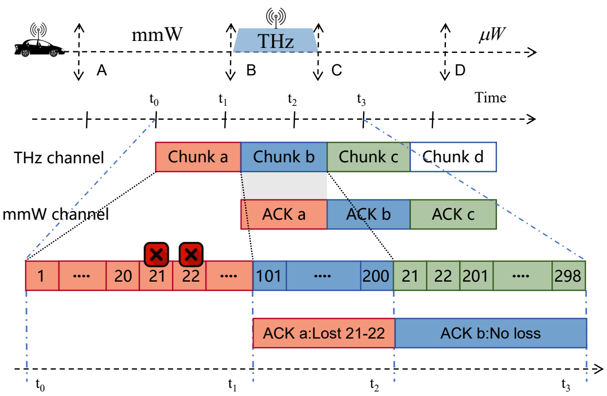

Fig. 19: The structure of proposed protocol.

B. Protocols

In terahertz technology, designing novel network protocols can bridge the gap between terahertz physical layer characteristics and application requirements. By optimizing mechanisms such as resource allocation, beam management, collision avoidance, and energy efficiency, the potential of the terahertz frequency band can be unleashed, laying the foundation for future ultra-high-speed, low-latency, and highly reliable communication networks.

Cacciapuoti et al. [110] proposed a network architecture and a Medium Access Control (MAC) protocol tailored for the next-generation mobile heterogeneous networks (MHNs), which achieves efficient data transmission by switching among millimeter wave, terahertz, and conventional microwave frequency bands. Its general structure is illustrated in the Fig. 19. **Wang et al.** [111] proposed an energy- and spectrum-aware MAC protocol tailored for Wireless Nano-Sensor Networks (WNSNs) operating in the terahertz frequency band. This protocol achieves fair, throughput-optimized, and lifetime-maximized channel access by jointly optimizing the energy harvesting and consumption processes of the nanosensors.

Yao et al. [112] proposed a Terahertz-Assisted Beamforming MAC protocol (TAB-MAC) tailored for terahertz communication networks. By integrating 2.4 GHz WiFi and terahertz band communication technologies, TAB-MAC effectively addresses the challenges faced by terahertz communications and significantly enhances network throughput. **Xia et al.** [113] proposed a link-layer synchronization and Medium Access Control (MAC) protocol for high-speed wireless networks in the Terahertz band. By employing a receiver-initiated handshake and an aggregated packet or sliding window flow control mechanism, the protocol effectively addresses synchronization issues in THz communications and enhances network performance. **Zhang et al.** [114] proposed the DRA-MAC protocol, which effectively addresses the deafness issue in terahertz distributed networks through a dual-radio transceiver architecture and a network table mechanism. This protocol reduces network association delay and enables multi-link ultra-high-speed communication.

C. Multiple Input Multiple Output (MIMO)

The technique of MIMO (Multiple Input Multiple Output) represents a pivotal technology in communication systems, employing multiple antennas at both ends of the communication link (transmitter and receiver). Through space-time signal processing techniques, MIMO achieves higher data rates, enhanced interference rejection capabilities, and broader coverage areas.

Gao et al. [115] proposed two broadband beamforming techniques to effectively mitigate the impact of beam squint in terahertz hybrid massive Multiple-Input Multiple-Output (MIMO) communications. The virtual subarray-based approach achieves analog beam width expansion, partially alleviating the effects of beam squint. Meanwhile, the True-Time Delay (TTD)-assisted method, by redesigning the analog beamformer, attains performance close to that of a fully digital transceiver. In addition, it can be observed from the Fig. 20 that the utilization of a large number of antennas in traditional spatial-domain MIMO for terahertz communications results in a high count of radio frequency (RF) chains, as well as elevated costs and energy consumption. While beamspace MIMO can mitigate this issue by reducing the number of RF chains, the pilot overhead associated with traditional real-time channel estimation schemes remains excessively high. To address this challenge, **Gao et al.** [116] proposed a Prior-Assisted (PA) channel tracking scheme, addressing the challenge of channel tracking in Terahertz beamspace massive MIMO systems by tapping into the temporal variability patterns of physical directions and leveraging the sparse structure of THz beamspace channels. This approach effectively reduces pilot overhead and the requirement for signal-to-noise ratio (SNR).

TeraMIMO [117] is the first comprehensive statistical 3D end-to-end channel simulator designed for Ultra-Massive Multiple-Input Multiple-Output broadband terahertz channels. It accurately captures various characteristics of terahertz channels, with results aligning well with existing measurements and theoretical boundaries. **Xu et al.** [118] proposed a reconfigurable THz communication MIMO system based on graphene antennas to enhance the spectral efficiency of the system.

D. Integrated Sensing and Communication

ISAC (Integrated Sensing and Communication) is a technology that merges sensing and communication into one system to efficiently use wireless resources and enhance performance [119]. It reduces redundancy, improves efficiency, and lowers costs, enabling networks to provide core sensing services and collect data for intelligent applications. In this section, we will summarize the relevant research papers on ISAC.

Wu et al. [102] considered the peculiarities of THz channels and transceivers, a sensing integrated discrete Fourier transform spread orthogonal frequency-division multiplexing (SI-DFT-s-OFDM) waveform is designed. This waveform integrates sensing functionality into its frame structure, comprising data and reference blocks. Compared to cyclic prefix orthogonal frequency-division multiplexing (CP OFDM), the proposed SI-DFT-s-OFDM waveform enhances data rates and reduces

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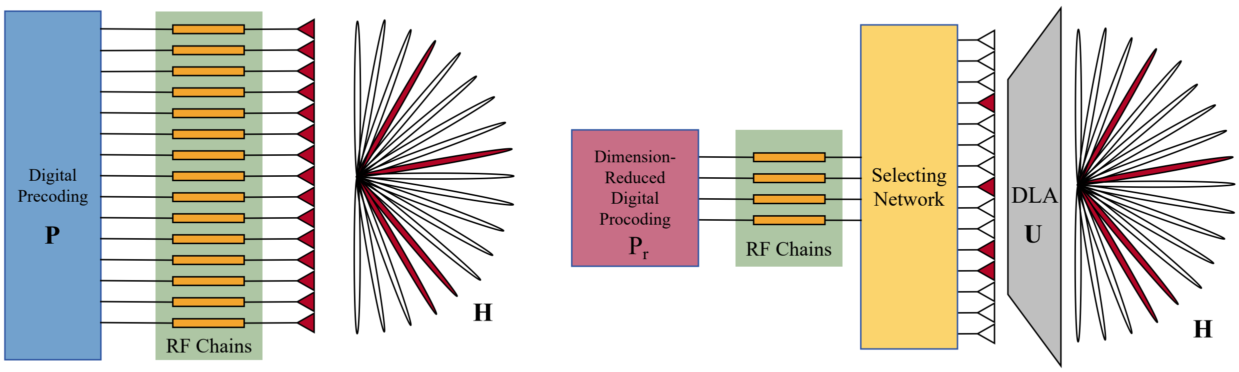
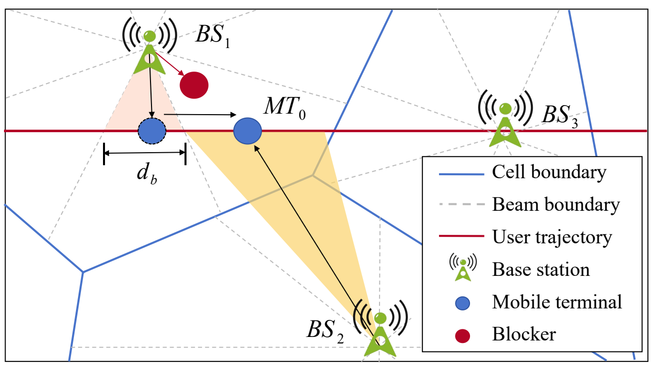
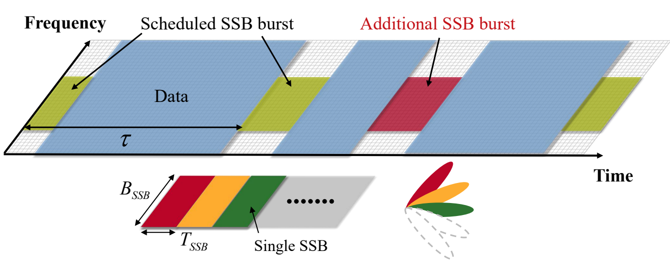


(a) Traditional MIMO in the spatial domain (b) Beamspace MIMO system architectures

Fig. 20: Comparison of MIMO system architectures.



(a) Network deployment



(b) SSB-based ISAC frame structure

Fig. 21: The structure of mentioned system.

peak-to-average power ratio (PAPR). Furthermore, leveraging deep learning techniques in ISAC receivers enhances the system's robustness against Doppler effects, RF front-end impairments, and other challenges, ultimately pushing the boundaries of THz communication and sensing capabilities.

Chen et al. [103] employed Synchronization Signal Blocks (SSBs) as dual-functional Joint Communication and Sensing (JCAS) signals to facilitate beam alignment. The network deployment and system structure is shown in Fig. 21. By optimally allocating the limited sensing resources, they achieved significant performance gains. Furthermore, increasing the sensing signal bandwidth can compensate for the losses incurred due to a fixed SSB duration, thereby providing performance comparable to that of an optimal SSB pattern. They presented relevant use cases tailored for highly mobile and dense THz/mmWave networks, including but not limited to Vehicle-to-Everything (V2X) applications. They analyzed two types of beam misalignment: blockage-induced and mobility-induced. The advantage of their SSB-based ISAC approach lies in the fact that SSBs are essential to control signals during beam and cell switching, and SSB-based sensing aids base stations in perceiving the surrounding environment and tracking users.

Han et al. [104] explored the use of OFDM, DFT-s-OFDM, and OTFS waveforms in THz ISAC, focusing on waveform design challenges such as PAPR and Doppler effect handling. They mentioned methods [120] to reduce nonlinear distortion in OFDM and DFT-s-OFDM systems while noting that OTFS, despite its Doppler handling capability, has high receiver complexity. The study also highlighted that centimeter- or millimeter-level positioning can be achieved using the ultra-wide bandwidth of THz signals. Numerical results showed that DFT-s-OTFS and DFT-s-OFDM have PAPRs about 3 dB lower than OTFS and OFDM.

Performance Metrics. Key communication performance metrics for network systems include data rate, bit error rate (BER), spectral efficiency, channel capacity, latency, and coverage range, while sensing performance is typically assessed through imaging resolution, detection probability, mean square error (MSE), and SNR. Although these metrics can be adapted to evaluate ISAC systems, their inherent dual functionality distinct from standalone communication or sensing systems requires simultaneous optimization of both modalities. For instance, [120] and [102] both considered PAPR, BER and sensing accuracy as performance metrics. In terms of PAPR reduction, DFT-s-OTFS in [120] achieves a 3 dB improvement over OTFS, while SI-DFT-s-OFDM in [102] shows comparable 3 dB reduction compared to OFDM. Regarding BER performance, [120] demonstrates superior communication capability with BER reaching 10^{-4} at 15 dB SNR, outperforming [102]'s BER of 10^{-3} under equivalent conditions. Both systems achieve millimeter-level sensing resolution, but [102] learning approach exhibits enhanced robustness in multi-target scenarios and complex environments.

Co-design Complexity. THz RF front-ends suffer from low efficiency and high noise figures. ISAC hardware demands wideband signal generation and processing, but existing components struggle to balance communication modulation requirements with sensing signal fidelity. The ultra-short THz wavelengths necessitate large-scale antenna arrays for beamforming, which sharply increases hardware complexity and power consumption. What's more, divergent beamwidth and scanning speed requirements between communication and sensing further demand dynamically reconfigurable antenna designs. Additionally, environmental dynamics (temperature, humidity) induce THz channel variations, requiring real-time calibration for both communication and sensing channels.

Interference Management. ISAC devices require simultaneous transmission and reception, but transmitter leakage into the receive path induces severe self-interference. What's more, ISAC systems face resource competition interference, primarily due to conflicting operational cycles between continuous communication transmissions and periodic sensing pulses. Improper time-division scheduling risks causing communication outages or sensing blind spots, while high-power communication signals may mask low-power sensing echoes in long-range detection scenarios. Dense ISAC deployments suffer from multidimensional resource contention (time-frequency-space) among co-channel transceivers, inducing severe multi-user interference through overlapping signal dimensions.

VIII. CHALLENGEs & FUTURE DIRECTIONS

The development of terahertz technology encounters numerous challenges in hardware equipment, channel modeling, and sensing techniques, among other areas. These challenges also outline the future directions for the advancement of terahertz technology. In this section, we will provide a detailed analysis of these challenges.

A. Hardware Equipment

The terahertz frequency band imposes stringent performance requirements on components such as power amplifiers, mixers, and frequency multipliers. Currently, the output power and efficiency of silicon-based devices fall short of these demands. Although III-V compound devices, such as gallium arsenide, exhibit superior performance, they come with high costs. Terahertz chips require high-density integration to support large-scale antenna arrays, but high-frequency signal processing causes severe thermal dissipation issues. Traditional CMOS processes exhibit inadequate thermal management capabilities in the high-frequency range. Furthermore, the sampling bandwidth and speed of digital-to-analog/analog-to-digital conversion chips struggle to match the ultra-wide bandwidth (>2 GHz) of terahertz, and the power consumption of baseband processing also increases significantly. The characteristic frequency of existing semiconductor materials limits the performance enhancement of terahertz devices, necessitating the development of novel materials (such as graphene and gallium nitride) or the optimization of heterojunction designs.

B. Sensing Technology

The performance of THz sensing technology is quite limited by high sensitivity to water and the diffraction limit. The former hinders its application in the detection of living organisms and in-vivo measurements by decreasing the signal-to-noise ratio (SNR). The latter determines both sensitivity and spatial resolution, and the solutions include nanostructures, geometrical beam shaping, and optical near-field techniques. In addition, data processing and analysis still remain a challenge. Although machine learning techniques can help address this issue, the lack of training datasets, such as spectroscopic and imaging databases, usually leads to model overfitting, which limits the model's accuracy and robustness. Moreover, a key obstacle to the adoption of THz sensing technology from laboratory research to industrial and daily applications is the large size and high cost of the equipment. With the emergence of miniaturized and cheaper components, especially sources and detectors, THz systems can become compact and highly cost-efficient enough for actual operation in the future.

C. Channel Modeling

Terahertz waves exhibit significant path loss when propagating in free space, and the complexity of their channel modeling is high due to characteristics such as atmospheric attenuation and the inability to penetrate polar molecular materials. Existing statistical models, such as the 3GPP standard model, struggle to accurately depict the sparsity and high-frequency selectivity of terahertz channels. Deterministic modeling approaches, such as ray tracing, suffer from high computational complexity, making them challenging for real-time applications. Moreover, terahertz beams are extremely narrow, necessitating frequent beam and cell handovers when terminals are in motion, while existing protocols, such as those at the MAC layer, are unable to support low-latency beam tracking and switching.

D. AI-driven Technology

The synergy of artificial intelligence and terahertz research is unlocking transformative solutions across beamforming, resource allocation, channel estimation, dynamic spectrum access, and security enhancement. While conventional physics-based approaches struggle to model THz channel characteristics accurately, Convolutional Neural Networks (CNN) and Transformer architectures now enable efficient recovery of high-dimensional sparse parameters from low-dimensional observations. And Generative Adversarial Networks can further mitigate data scarcity by simulating complex propagation environments. Regarding communication security issues in the terahertz band, convolutional autoencoders can be employed to detect and filter out adversarial interference targeting beamforming models. Additionally, quantum neural networks can be integrated to generate dynamic cryptographic keys, thereby safeguarding terahertz physical layer transmission. In the future, it is feasible to integrate artificial intelligence with dynamic spectrum access technology to achieve distributed collaboration via multi-agent reinforcement learning, rapid generalization through cross-scenario transfer learning, privacy-preserving optimization in federated learning, and real-time decision-making in lightweight edge AI, thereby enabling efficient utilization of spectrum resources and adaptation to dynamic environments in heterogeneous networks.

E. Energy Consumption

THz systems encounter severe power consumption issues in practical deployment. In terms of hardware, high-frequency devices exhibit low efficiency, decaying exponentially with increasing frequency, while large-scale antenna arrays incur substantial overheads. Additionally, the high power density of terahertz chips can induce thermal failures, and improper thermal management design may lead to performance degradation or even hardware damage. Regarding signal processing and computational complexity, there are significant pressures associated with broadband signal processing and high computational costs for AI model inference, with signal processing complexity growing linearly with bandwidth. In the future, researchers in the field of terahertz technology may consider addressing the energy consumption challenges through energy-efficient protocols designs, hardware designs, collaborative hardware-algorithm designs, and the exploration of new materials and architectures. For instance, it is feasible to explore approaches such as dynamic dormancy and activation mechanisms, multimodal sensing triggering, and collaborative optimization through federated reinforcement learning, among others. Additionally, the design of high-performance hardware components, including Compute-in-memory chips, intelligent reflecting surfaces, and ultra-low-power radio frequency front-ends, can also be taken into consideration. The energy-efficient protocols that adopt cross-layer design (integrating the physical layer, MAC layer, and network layer) and incorporate AI along with novel hardware technologies should be proposed to reduce the overall system power consumption.

F. Communication Range

The short-range limitation in THz communication is a combined consequence of physical characteristics and current technological limitations. The high path attenuation, molecular absorption, and weak diffraction capability of THz waves impose constraints on communication distance. This will lead to an escalation in network deployment complexity and a surge in costs, heighten the demand for densely deployed base stations and reliance on relay technologies, and pose difficulties in environmental adaptability. Additionally, it will result in severely constrained application scenarios. In the future, potential breakthrough directions include: developing high-gain metamaterial antennas, utilizing reconfigurable intelligent surfaces to enhance non-line-of-sight (NLOS) coverage, optimizing frequency band selection (such as targeting lower-attenuation window bands within the "THz gap"), and exploring relay networking technologies to extend coverage range. However, these solutions still necessitate trade-offs among cost, power consumption, and practicality.

G. Standardization

As early as the beginning of 2008, IEEE established the Terahertz Communications Interest Group (IGthz) under the IEEE 802.15 framework, initiating standardized research on terahertz wireless communications. Nowadays, numerous studies on terahertz standardization have emerged. For instance, the Applications Requirements Document (ARD) encompasses descriptions of applications and use cases, along with their performance and functional requirements; the Channel Modeling Document (CMD) summarizes the primary propagation characteristics of lower THz waves in typical environments; and the Technical Requirements Document (TRD) serves as a guideline for formulating technical proposals. However, certain issues persist. For example, although IEEE 802.15.3d, approved in 2017, represents the first wireless communication standard targeting the sub-terahertz band, it only specifies wireless THz links for fixed point-to-point links. This standard requires that the directions of antennas at both ends of the link are known, and interference can be mitigated through appropriate link planning, with no competition for access rights. These conditions, however, do not hold in potential THz WLAN systems, necessitating the specification of appropriate solutions to address these deficiencies.

IX. CONCLUSION

With rising demands for higher communication rates and capacities, terahertz technology has gained significant attention as a promising solution. This survey offers a comprehensive overview of recent advancements in terahertz sensing, communication, and networking, highlighting key hardware and technologies. It summarizes notable contributions and examines challenges such as hardware limitations, channel modeling, and sensing performance. Future progress will rely on innovative solutions, enabling terahertz's adoption in next-generation wireless systems and beyond.

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