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Terahertz Communications: Applications, Challenges and Open Research Issues for Next Generation 6G Wireless Networks

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ABSTRACT

In the approaching 2030s, transformative applications like 3D call, haptic communication, and Tele-operated driving are set to reshape communication networks. These applications require substantial bandwidth, ranging from gigahertz (GHz) to terahertz (THz) levels, differing from the current megahertz standards. Despite this, the existing radio frequency spectrum struggles to meet these escalating needs, particularly below 0.09 THz (90 GHz). Surprisingly, a solution lies in the THz frequency band, offering contiguous radio spectrum blocks. The concept involves achieving a data transmission rate of one terabit per second, which necessitates a substantial amount of available frequency spectrum. The increased and noteworthy interest in 6G communication is centered on terahertz (THz) communication in an implied manner, signifying a departure from its purely technical intrigue in previous times. This study deeply examines THz wave attributes, including significance, recent regulations, applications, and research opportunities, providing a crucial foundation for anticipated 2030s networks. By decoding THz wave intricacies and revealing uncharted research avenues, this article becomes a catalyst propelling exploration into the forthcoming communication landscape.

Keywords: THz Spectrum, Wireless Communication Networks, THz Challenges, 6G

1. INTRODUCTION

In previous times, substantial endeavors have been dedicated to surmounting diverse challenges and uncovering novel insights into various dimensions of THz communications, encompassing components, basic functional elements, packaging, antennas, channel modeling, interference mitigation with passive services, and target application areas. Nonetheless, while recognizing the immense advantages stemming from the expansive bandwidth, many within the THz community find themselves in contemplation. They seek to elucidate how the realization of terabit-per-second (Tbps) data rates can be achieved at these elevated frequencies and how the implementation of energy-efficient and dependable THz beamforming transceivers can be attained. The aspiration for Tbps data rates, anticipated for the future, presents an intricate challenge that cannot be solely addressed through the vast bandwidth inherent to the THz realm. The substantial signal loss linked to extensive phased-array antennas necessitates additional amplification, subsequently leading to heightened power dissipation. In this discourse, we delve into these two foundational inquiries that demand resolution in the upcoming decade. Our exploration draws upon recent preliminary findings and analytical methodologies to provide insights into these complex quandaries.

The standardization of 5G has concluded, with deployment initiated in numerous global cities [1]. However, the exponential surge in data traffic driven by the escalating number of connected devices, potentially surpassing hundreds of devices per cubic meter, poses a challenge. Furthermore, future applications like virtual reality (VR), augmented reality (AR), 4K/8K UHD video, 3D communication, and unforeseen scenarios like autonomous driving emerge [2]. The existing 5G infrastructure might struggle to meet the data rate and ultra-low latency demands of these applications. These challenges underscore the impetus for the evolution toward a new era of wireless networking, known as the sixth generation (6G). Considering the groundwork laid by 5G networks and their potential evolution, the divergence between 6G and both 5G and its long-term progression becomes evident. Academic, industrial, and research communities have already embarked on identifying, defining, and assessing pivotal enabling technologies that will shape 6G [3,4], projected for deployment by 2030 [5].

The overarching vision driving the development of 6G communications is to enhance data rates and diminish latency limitations while enabling seamless ubiquitous connectivity. This paradigm shift will introduce novel strategies that facilitate unique communication experiences, enabling virtual presence and universal accessibility across all locations. This transformation will further facilitate the integration of groundbreaking applications such as holographic calls, flying networks, and Tele-operated driving [6]. Moreover, the forthcoming 6G communications framework aims to surpass conventional wireless networks in terms of reliability and security.

Of all the technological advancements pertaining to 6G, THz and Artificial Intelligence (AI) stand out as the most promising. These transformative technologies hold the potential to revolutionize the wireless networking landscape, prompting the industry to reevaluate its design principles. The inaugural 6G wireless summit, initiated in March 2019 under the banner of "ubiquitous wireless intelligence" [7], is the first step in this transformative journey. Anticipated to differ significantly from its predecessors, 6G wireless networks are poised to redefine the wireless evolution from "connected things" to a realm of "connected intelligence."

The scope of 6G communications extends beyond conventional mobile Internet services, encompassing robust support for ubiquitous AI services. This holistic integration spans from the core network, inclusive of data centers, through transmission backhauls, and culminating at end devices. This transformation heralds an era of interdisciplinary collaboration between information technology and wireless communication, propelling the fusion of these domains. In this landscape, AI's role becomes paramount in designing and optimizing 6G networks, from configurations and protocols to overall operations [5, 8].

In light of the spectrum limitations that prompted the introduction of millimeter wave (mm Wave) spectrum in 4G communications, it becomes evident that this bandwidth cannot adequately cater to the demands of holographic videos. The subsequent challenges encompass spatial spectral efficiency and requisite frequency bands for seamless connectivity. Consequently, a wider bandwidth at the THz band becomes essential. Positioned as the spectrum between microwaves and optics (Fig. 1), THz waves emerge as a focal point for exploration in this study, addressing the distinct challenges and opportunities posed by THz waves.

This paper is dedicated to the exploration and discourse surrounding the distinctive attributes of THz waves. The core contributions of this endeavor are outlined as follows:

Primarily, this paper offers an encompassing overview of contentious research subjects related to THz waves. It takes into account the latest advancements within the industry, contextualizing them within the broader scope of primary application domains and challenges. Our approach distills the key research subjects into distinct categories: (i) illuminating the intrinsic features and significance of THz frequency, (ii) assessing the most recent regulatory landscape, (iii) identifying the most promising applications, and (iv) uncovering potential research areas that remain open for exploration.

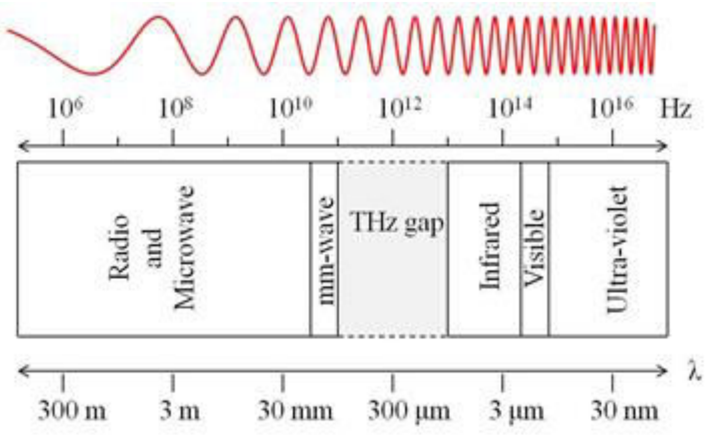

Figure1. Schematic Diagram for mapping the THz Band within the Electromagnetic Spectrum

This work also serves as a repository of fresh references, thereby extending a helping hand to researchers. The insights provided herein hold the potential to forge new trajectories for future research ventures, fostering the evolution of THz wave technology. This comprehensive investigation is intended to make a significant contribution to enhancing the comprehension and progress of THz waves. Its ultimate goal is to stimulate innovation and foster exploration within this captivating field.

2. FUNDAMENTALS OF THz FREQUENCY BANDS

The primary advantage of utilizing THz frequencies for communication, as opposed to other frequency ranges, lies in the generous bandwidth it offers. However, the transition to higher frequencies brings inherent limitations in the form of reduced communication range and intermittent link behavior. These occurrences at THz frequencies stem from three fundamental factors such as a) Elevated path and reflection losses, b) Irregular availability of Line-of-Sight (LoS) connections c) Molecular absorption.

The first factor reveals itself when moving towards higher carrier frequencies. Remarkably, these losses resemble those experienced at mmWave frequencies, albeit more prominently pronounced in the THz range. Despite this, the distinct characteristics of molecular absorption and the constrained, narrow LoS links are exclusive attributes to the THz spectrum. The ensuing discussion will delve into these distinctive THz properties.

Pencil Beam LoS Links and their Repercussions

THz links prioritize LoS conditions; higher frequencies widen LoS-NLoS power gap. Reflected paths' power attenuates more (15 dB+) than LoS at 300 GHz - 1 THz [9]. Pencil beam LoS connections counter attenuation via beamforming, but pose beam tracking, alignment, and mobility challenges. Obstacles disrupt pencil beams, causing blockages (static, dynamic, self). Blockage models must capture environment-specific behaviors. mmWave solutions don't fit due to range, narrower beams, and greater attenuation. Precise models are vital for stable LoS in applications like XR [10]. Densely deploying THz nodes mitigates short-range nature but may amplify interference and handovers due to sensitive beam alignment.

Molecular Absorption Effect

At THz frequencies, path and reflection losses coincide with another detrimental communication factor – molecular absorption. This phenomenon not only degrades received power but also augments noise, introducing molecular absorption noise alongside thermal noise seen in lower bands. Molecular absorption is present across all frequencies, but notably pronounced at THz frequencies, overlooked for lower ones (mmWave, sub-6 GHz) [11]. mmWave bands, richer in multipath and NLoS links, with wider LoS beams, find beam alignment and mobility management less intricate than at THz frequencies. Molecular absorption arises from energy state differences in transmitted medium molecules, mainly water and oxygen vapor in THz band, making THz communication more apt to indoors due to lower water vapor levels.

Though absorption increases with frequency, it's not uniformly so; dips appear at some carrier frequencies, suggesting targeting these for lower absorption [12][13]. However, air composition tied to meteorology varies, making these windows unreliable. Hence, they suit controlled, indoor setups better. As baseline absorption rises with frequency, more bandwidth can be exploited against absorption's losses and noise. For instance, in indoor AR [14], increased bandwidth refreshed AR content, enhancing communication, but worsened worst-case scenarios due to absorption. Molecular absorption's effect on THz links is non-monotonic; it adds noise, restricts range, and complicates outdoor use. Nonetheless, this effect benefits THz sensing, given its quasi-optical nature and broad bandwidth – attributes discussed further. This quasi-optical nature is one of the seven defining features outlined in Fig. 2.

3. UNIQUE CHARACTERISTICS AND SIGNIFICANCE OF THz WAVES

On the electromagnetic (EM) spectrum chart, the frequency bands above and below the THz frequency band, namely µWave, mmWave, and infrared, are entirely allocated and substantially occupied. Despite the scarcity of spectrum in the µWave, mmWave, and infrared ranges, limited attention has been devoted to comprehending the THz band. This section embarks on an exploration of the THz frequency bands, uncovering their unique characteristics.

Quasi-opticality of the THz band: The distinctive EM properties of the THz band, characterized by quasi-optical behavior, pose specific communication challenges. The molecular absorption effect, a limiting factor for THz wave propagation, is a significant concern. Yet, this quasi-optical nature offers a double-edged advantage in the context of combined communication and sensing. While molecular absorption curtails communication ranges, it introduces unparalleled sensing prospects absent in other frequency bands. This intricate balance highlights the intricate interplay between quasi-opticality, communication, and innovative sensing potentials within the THz spectrum.

THz-tailored Wireless Architectures: Implementing wireless THz systems involves considering several factors, including increased small cell density, reduced communication range, multifunctional capabilities (sensing, communication, imaging), and unique channel conditions. These factors necessitate the adoption of opportunistic THz-tailored network architectures to harness THz system advantages. This underscores the significance of embracing cell-less architectures, alongside their associated challenges and potential benefits. Additionally, the role of reconfigurable intelligent surfaces (RISs) in THz networks is paramount. RISs offer holographic potential due to their compact THz footprint, extensive sensing components, and opportunities and challenges in near-field communication [15]–[17].

Synergy of THz with lower frequency bands: THz communication systems will be implemented within an already densely populated radio spectrum, housing sub-6 GHz and mmWave technologies. Hence, THz systems are anticipated to exhibit a degree of synergy, involving cooperation and seamless coexistence with lower frequency band wireless technologies. For instance, applications like immersive remote presence can strategically utilize available wireless frequencies to ensure a comprehensive end-to-end user experience. This accentuates the importance of strategies fostering the harmonious coexistence of THz frequencies with mmWave and sub-6 GHz bands, their services, and infrastructure. Additionally, this collaborative interplay across varied frequency bands presents exciting prospects for enhanced communication and sensing functionalities.

Joint sensing and communication systems: Given the quasi-optical attributes of THz bands, a harmonious convergence between high-rate communications and high-resolution sensing becomes attainable. This prompts us to underscore the significance of integrated communication and sensing systems within forthcoming THz wireless networks. Specifically, the potential of reciprocal feedback between the sensing and communication functionalities to enhance overall system performance. Embracing such configurations has the potential to revolutionize wireless networks into a new era of multifunctional systems, capable of providing diverse services to users. This paradigm shift further paves the way for innovative services and use cases to be realized within the THz band.

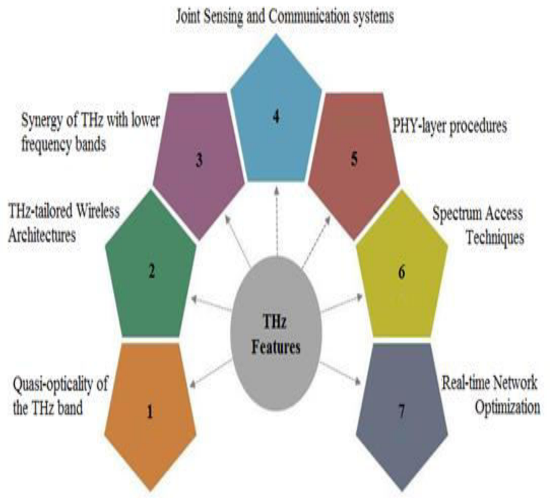

Figure2. Seven Key Characteristics of Wireless THz Systems

PHY-layer procedures: The THz channel's spatial sparsity and low rank characteristics present unique hurdles in PHY-layer operations like wireless channel estimation and initial access. To address these challenges, innovative channel estimation methods that emphasize the involvement of generative learning networks in forecasting comprehensive THz channel state information (CSI) are required. Moreover, it is required to know how sensing plays a pivotal role in optimizing the initial network access process for THz devices, contributing to an enhanced overall network performance.

Spectrum access techniques: Traditional access methodologies employed in preceding wireless generations encounter challenges when transposed to THz frequency bands, owing to hardware limitations and the distinct propagation characteristics inherent to the THz environment. As a result, exploration of viable spectrum access techniques tailored for THz systems becomes imperative. Particularly, a focus should be directed towards harnessing the benefits arising from orbital angular momentum (OAM) utilization, capitalizing on the quasi-optical attributes intrinsic to THz systems. Notably, the synergy between NOMA and THz bands can be enhanced by the inherent incorporation of reconfigurable intelligent surface (RIS) architectures at these frequencies.

Real-time network optimization: The rise of 6G services like XR, holography, and digital twins requires a comprehensive approach to design, covering communication, control, sensing, and computing. Past attempts have seen limited success, yet the inherent connection between communication and sensing in the THz domain suggests a combined design is necessary and feasible. This demands an exploration of the distinct networking challenges of THz systems and innovative algorithms to optimize them for applications beyond 5G. Moreover, THz band communication holds great potential for a variety of applications, addressing both macro and micro scales [18]. The demand for data-intensive tasks like video streaming has outpaced older wireless technologies. As existing channels near capacity, the need to explore new spectrum is crucial. THz bands offer continuous multi-gigahertz bandwidths, perfectly suited to deliver the required data rates for uncompressed videos.

The integration of THz communication into the realm of 6G is poised to achieve the following, as delineated:

Efficient Energy Use in 6G with THz Waves: Energy efficiency is a pivotal factor in 6G communications, especially with multiple applications concurrently running on devices, generating substantial data. THz waves offer directional beam communication via MIMO antenna arrays, holding the potential to provide ample energy to network devices. The Consumption Factor (CF) theory, quantified as bit per second per watt [bps/W], is crucial. Components close to the transmitter antenna, like the antenna itself and analog-to-digital converter, significantly impact CF [19] [20], as highlighted in [21]. With expanding bandwidth, power efficiency increases, especially for non-signal path components like baseband processors, oscillators, or displays, as opposed to transmission signal path components like power amplifiers, mixers, or antennas [21]. For low-cost IoT applications using radio transmitters, power efficiency remains consistent irrespective of bandwidth [13]. This theory emphasizes the trend towards better energy efficiency as communication antennas move to higher frequencies like mmWave and THz, which offer greater bandwidth and enhanced power efficiency when measured in terms of bps/W.

Reliable THz Connectivity in Mobile Environments: Within the dynamic realm of mobile environments, ensuring a steadfast and highly reliable connectivity infrastructure assumes paramount significance, particularly in light of the diverse array of critical applications that necessitate uninterrupted operation. Nevertheless, the landscape within the THz band frequencies is characterized by substantial atmospheric attenuation, presenting a substantial hurdle to the seamless propagation of signals. As a strategic response to this challenge, the adoption of innovative measures is imperative. This entails harnessing the potential of highly directional beam antennas to counterbalance the adverse impact of heightened path loss [22]. Consequently, the transmission of THz signals poses an intricate puzzle, presenting considerable difficulty for any attempts aimed at interception or unauthorized access [23]. This dual emphasis on reliability and security underscores the complexities inherent in managing THz signals within mobile contexts and highlights the necessity of pioneering solutions to overcome these obstacles.

Secure Communication in mmWave and THz: Both mmWave and THz frequencies will facilitate extensive spatial multiplexing capabilities while also catering to accurate sensing and various other applications [24]. In the THz band, orchestrating passive cyber-attacks or executing man-in-the-middle attacks, particularly within the frequency range of 100 GHz to 3 THz, will become exceedingly challenging. This arises from the distinct characteristics of this frequency range, where extremely short wavelengths enable the development of remarkably high-gain antennas within compact physical dimensions [25]. This phenomenon establishes an environment conducive to secure communication provisions.

Data Rate Enhancement via THz Waves: Achieving ultra-high data rates on a per-device basis, ranging from 1000 to 10000 times the current data rate levels, while ensuring adequate transmission distances in intricate network landscapes characterized by diverse platforms is a formidable challenge. Unquestionably, the realm of wireless communications has undergone a significant transformation in terms of data rates, propelled by the adoption of MIMO and massive MIMO technology accompanied by relevant diversity techniques. However, while these advancements have indeed elevated data rates, the very foundation of this progress, driven by MIMO technology that capitalizes on the fading channel coefficients, is not exempt from limitations due to the heightened computational complexities it introduces. Consequently, the long-term sustainability of this technique comes into question, making the emergence of THz waves a promising solution to address these challenges.

Enhanced connectivity via Highly Directional Beams: The aspiration for ultra-high data rates is accompanied by a heightened connection density, aiming for a scale that exceeds the 5G framework by a factor of 1000. The pursuit of augmented capacity finds a solution in the application of highly directional beams, enabling the precise steering of signal beams towards intended mobile devices without triggering interference. Notably, this technique capitalizes on beam steering, a process known for its simplicity of implementation within the higher electromagnetic spectrum, as evident in the existing mmWave technology. This strategic approach holds the potential to significantly enhance both data rates and connectivity, shaping the landscape of future communication networks.

Reliable THz Connectivity for Critical Applications: The establishment of ultra-reliable connectivity is paramount to sustain a multitude of critical applications within dynamic mobility environments. Acknowledging the substantial atmospheric attenuation experienced within the THz band frequencies, a strategic solution involves the incorporation of highly directional beam antennas. These antennas are instrumental in counterbalancing the elevated path loss encountered [22]. Consequently, the implementation of THz signals will introduce a formidable challenge for any attempt to intercept or covertly access them [23]. This approach not only safeguards the integrity of communication but also underscores the potential of THz signals to enhance security measures within various applications.

Anticipated with certainty, the realm of wireless terabit-per-second communication is poised to captivate heightened attention and foster increased research endeavors from both industry and academia in the impending decade. The present state of the physical layer must undergo significant enhancements, culminating in the development of a more advanced physical layer capable of accommodating the demands of these high-frequency bands. Equally crucial is the identification and utilization of novel spectral frequencies, an imperative requirement to facilitate the sustenance of such exceedingly elevated data rates [26]. This trajectory underscores the pivotal role of research and innovation in orchestrating the evolution of wireless communication systems toward the realization of terabit-per-second capabilities.

4. STANDARDIZATION OF THz SPECTRUM FOR COMMUNICATION SYSTEMS

The electromagnetic spectrum is not privately owned; rather, it falls under governmental regulation through specialized agencies. These regulatory bodies have distributed sub-6GHz bands among various entities, leaving frequencies from 100 GHz to 3 THz largely unexplored. These uncharted frequencies offer contiguous bands with substantial potential for high data rates [27] [28]. Crafting a strategic spectrum roadmap for the THz band towards 6G presents a significant and valuable research challenge in the upcoming years. The subsequent section delves into recent regulatory and standardization developments concerning THz frequencies [13].

Collaborative efforts involving global spectrum regulatory and management entities, along with radio standardization bodies like the Federal Communications Commission (FCC) [29], the European Telecommunication Standards Institute [30], and the International Telecommunication Union [31], are underway to allocate electromagnetic frequencies beyond 95 GHz. These frequencies are intended for point-to-point, direct line-of-sight communications, broadcasting services, and other applications [32]. Recently, in March 2019, the FCC unanimously decided to remove restrictions on frequencies beyond 95 GHz, making 21.2 GHz of spectrum available for unlicensed use (Tab. 1) and permitting investigational activities within the electromagnetic spectrum up to 3 THz [33]. Similarly, the National Telecommunications and Information Administration (NTIA) is moving towards a more efficient spectrum policy for America's future and seeks to relax restrictions on frequencies beyond 95 GHz [34]. In 2017, the IEEE established the IEEE 802.15.3d [35] task force to create a global Wi-Fi standard for the 252–325 GHz frequency range. This marked the first worldwide wireless communication standard for this range, featuring a new physical layer (PHY) data rate of 100 Gbps and channel bandwidths from 2 to 70 GHz [13]. Furthermore, the European Commission established the Radio Spectrum Policy Group [33] to address management issues related to THz-band communications.

Table1. Operation Frequency proposed by FCC [29]

Frequency band (GHz)	**Bandwidth (GHz)**
116–123	7
174.8–182	7.2
185–190	5
244–246	2

5. EMERGING APPLICATIONS OF THz COMMUNICATIONS

The THz system is anticipated to have two primary application categories: (i) macroscale THz applications and (ii) micro/nanoscale THz applications [37] [32]. These application categories encompass various fields such as automotive, indoor networking, aerospace, healthcare, location-based services, high-definition holographic communications, and underwater communication.

Astronomy: THz technology has the potential to revolutionize astronomy by enhancing our exploration of the universe. By employing THz-equipped telescopes, whether in space or at high-altitude terrestrial locations, astronomers can capture images and data from outer space within the 100 GHz to 1 THz frequency range. These telescopes offer a unique advantage, as they can bypass much of Earth's atmospheric interference that can distort observations at other wavelengths. This frequency range holds the promise of revealing hidden details about celestial phenomena such as star-forming regions, interstellar matter, and even the cold dust and gas emissions from distant galaxies. THz telescopes could provide insights into the intricate molecular compositions of cosmic environments, aiding in our understanding of star formation, galaxy dynamics, and the evolution of the universe. Their ability to observe these wavelengths could unveil previously inaccessible insights, contributing significantly to the advancement of astronomical knowledge.

Internet of Things (IoT): The Internet of Things (IoT) landscape is on a rapid expansion trajectory. Notably, wireless and mobile devices will play a pivotal role, contributing to a significant 78 percent of the overall IP traffic by 2030. This growth in IP traffic is intrinsically linked to the escalating demand for faster data rates. This demand, in turn, is fueling the requirement for a higher frequency spectrum that can accommodate the transmission of substantial volumes of data. This evolution is driven by consumers' insatiable appetite for continuously increasing data usage, underlining the necessity to meet these demands effectively. As we move forward, the correlation between the expansion of IoT and the need for robust, high-frequency data transmission becomes increasingly apparent.

Chemical fingerprinting: Utilizing a frequency spectrum scan, this method discerns internal contents of objects, materials, or packages without causing damage or disassembly. Its distinctive trait lies in revealing hidden substances while preserving item integrity. THz technology's potential impact is significant: identifying concealed contraband, like drugs, even within packages or on individuals, and detecting explosives or weapons for security purposes. This applies to scenarios from individual and vehicle screening to package and roadside bin examination. Key to this concept is emitting and receiving THz signals across frequencies. Reflected signals offer insights into object composition, distinguishing explosive materials like SEMTEX, TNT, or RDX. By analyzing their unique signatures, it's possible to identify their presence in packages or on individuals.

Medical Imaging: Medical imaging employing THz technology brings forth distinct advantages compared to conventional x-rays. The non-ionizing nature of THz radiation ensures its safety for imaging tasks involving human tissue, flesh, and dental applications. Notably, THz radiation poses significantly reduced hazards compared to ionizing radiation like x-rays. Moreover, THz imaging offers superior resolution capabilities when contrasted with traditional x-ray techniques. This heightened resolution empowers the differentiation of soft tissues, rendering it a valuable tool for the early detection of cancer cells. Additionally, THz technology proves highly effective in identifying dental concerns, including the detection of cavities and issues pertaining to enamel layers in human teeth.

XR and Holographic Teleportation: Extended Reality (XR) includes Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR), forming immersive tech spectrum. VR offers full immersion, while AR overlays virtual elements on real world, demanding HRLLC for visual and haptic experiences, ensuring high user satisfaction (QoE). MR blends AR and VR for apps like holographic teleportation, with strict HRLLC needs, needing up to 5 Tbps data rates and sensory sync. THz communications offer high data rates for XR and holography, but QoE needs more than data rates. XR needs low latency, minimal jitter, fresh info (for AR), and cross-sensory sync. Strategic deployment is vital, integrating THz nodes for Line of Sight (LoS) links, like Reconfigurable Intelligent Surfaces (RISs), boosting indoor coverage and network efficiency. Advanced sensing, combining THz sensing, RIS-enabled paths, and mmWave sensing, plays a vital role. Real-time Machine Learning (ML) algorithms combine sensing and comms data, overcoming THz uncertainties, ensuring user QoE. Outdoor XR poses challenges due to absorption, range, and operation-QoE trade-offs. Foveated rendering and compression mitigate content size. Mobility cases like AR for assisted driving need solutions for outdated data, beam tracking, and safety-seamlessness balance. Hybridizing networks via lower bands manages this trade-off efficiently.

Industrial 4.0 and Digital Twins: Industry 4.0's rise drives autonomous operations, demanding precise control in machine and robot processes. Instantaneous control systems are vital, given rapid automation's need for high data rates, low latency, and high density. THz networks offer solutions, but challenges persist for low latency, dense coverage, and precision control. Current industrial systems require flexible data collection; digital twins emerge to enable E2E digitization and autonomy. Trustworthy real-time synchronization between cyber and physical realms is crucial. Achieving real-time control and prediction relies on ML-driven communication links, extending THz optimization algorithms to minimize latency and enhance digital twin efficiency.

Tactile Communication: Having utilized holographic communication to transmit near-realistic visual experiences of people, events, and settings, there arises a need for real-time remote physical interaction via the tactile Internet [38] [39]. The ensuing analysis demonstrates that THz frequencies are poised to deliver the rapid calculations essential for wireless applications involving human cognition [40]. The human brain, comprising approximately 10^{11} neurons capable of firing 200 times per second (5 ms), each interconnected with around 1,000 others, results in a computation speed of 20 × 10^{15} floating-point operations per second (flops) [13]. Accordingly, the human brain's computation speed can be calculated as follows:

Computation Speed of Human Brain = 10^{11} neurons × 200 flops per second × 10^{3} per neuron = 20 × 10^{15} flops/second = 20 peta flops/second = 1 bit per flop (1)= 20,000 Tbps

With each neuron's write access to 1,000 bytes, the memory size can be computed as follows [40]:

Storage = 10^{11} neurons × 10^{3} bytes per neuron = 10^{14} bytes = 100 TB (2)

Anticipating THz wireless generations employing RF channels up to 10 GHz per user, by considering 10 bits/symbol modulation methods, a 1,000-fold increase in channel capacity, and the use of massive MIMO, data rates up to 100 Tbps are expected:

Data rate = 10 GHz × 10 bits per (Hz·sec) × 10^3 = 100 Tbps

Equations (1) and (2) reveal that a data rate of up to 100 Tbps is achievable using RF channels up to 10 GHz per user, providing 0.5% of real-time human computational power. In a more ambitious scenario, employing RF channels up to 100 GHz could yield 1 petabit per second or 5% of real-time human computational power [40]. Nonetheless, the design of an efficient physical (PHY) and cross-layer communication system must address the stringent requirements of these applications [41].

Human bond Communications: Primarily, 6G technology will steer the concept of communication centered around humans, enabling access to physical data and the sharing of physical attributes. As it matures, this communication paradigm will establish a platform through which the human senses can be transmitted via the Internet [42]. Recently, this idea has gained momentum due to the 'communication through breath' approach, enabling the capture of a human's bio-profile from exhaled breath and even facilitating communication with the human body through the inhalation of volatile organic compounds [43]. Consequently, the potential arises to analyze illnesses, detect emotions, gather biological information, and establish remote connections with the human body. Overall, the development of communication systems capable of emulating human senses and biological characteristics is a burgeoning research domain that necessitates further exploration in the future.

Wireless Cognition: The notion involves a communication link that enables machines or devices operating in real-time scenarios to perform extensive computations from a distance. Consider a scenario where a drone fleet lacks the power resources for significant computations. However, utilizing ample bandwidth and real-time processing, complex tasks and rapid data transfer for perception could occur at a designated fixed base station, offering real-time cognition and wireless connectivity to the drone fleet. Thus, even in the absence of a local cognitive platform, a similar approach can be adopted for designing robots and autonomous vehicles to execute cognitive processing remotely [13].

6. PROMINENT RESEARCH CHALLENGES AND OPEN ISSUES

Design of THz Electronics: The "THz gap," a formidable challenge in THz communications, hinders rapid progress due to signal generation complexities. THz frequencies are problematic for conventional oscillators (too high) and optical photon emitters (too low), necessitating current THz wave generation methods, often combined with frequency multipliers/dividers, resulting in limited output power (typically -10 dBm). Although novel approaches like graphene plasmonic antennas show promise [44], advancement remains gradual, impeding THz communications expansion.

Slower progress contributes to high testing bed costs, restricting research entities capable of access. Nevertheless, the potential benefits and substantial investments from industrial and governmental players continue to drive progress. Developing new transceiver architectures for the THz band is essential. Challenges include imperfect hardware like nonlinear amplifiers, phase noise, and limited modulation index [42], affecting signal quality. Antenna and waveform design, as well as energy-efficient signal processing, could raise concerns. Innovative transceiver technologies are pivotal for advanced THz sources, particularly within medium- to high-frequency THz bands (>300 GHz) [38][29]. Both conventional CMOS technology and emerging nanomaterials like Graphene offer avenues for novel transceiver designs in THz-enabled devices [46]. Practical testing is crucial to fully assess any proposed design's performance.

THz Channel Modeling: Creating a channel model for THz wireless communications entails considering several critical factors. Firstly, the pronounced frequency-selective molecular absorption leads to distinct "transparency windows". Consequently, constructing a propagation model, even for free space conditions, is challenging, necessitating the addition of an extra exponential component to the conventional power law in the path loss equation [47] [48]. Secondly, given the prevalence of indoor scenarios and short communication ranges in most use cases, reflections and penetrations from walls, ceilings, floors, and various objects must be factored in. Due to the high costs associated with THz equipment, only a limited number of studies on this topic have been conducted thus far (e.g., [49] and [50]). Furthermore, considering that THz wavelengths are in the order of hundreds of micrometers, THz waves scatter from nearly any object in real-world settings, whether indoors or outdoors [51]. Lastly, the presence of directional antennas adds complexity to the analysis, as some received components (e.g., those from the main beam) must take precedence over others [52].

Two primary approaches are employed to analyze THz wave propagation within a given environment. The first is the "deterministic" approach, often based on ray-tracing or ray-launching techniques. When the environment's dimensions, shapes, and materials of existing objects are fully described, this approach provides a reasonably accurate depiction [53]. However, this method's main drawback, aside from computational complexity, lies in its limited applicability to altered scenarios, even when minor changes are introduced.

In contrast, the second approach aims to construct a stochastic channel model, averaging the environmental impact instead of focusing on specific configurations. Following this path, two similar stochastic channel models for THz communications have been recently proposed in [3] and [54].

Coverage Planning: Planning coverage for THz networks presents challenges akin to those confronted by mmWave systems operating at a 60 GHz carrier frequency, with focal concerns related to establishing an unobstructed, preferably Line of Sight (LOS), path between the transmitter and receiver. Consequently, THz access networks will probably necessitate coverage from multiple vantage points to ensure a reliable connection [55].

Certainly, appropriate tools must be devised to streamline the planning process, requiring intricate 3D models of the surroundings to guarantee precise outcomes. As a result, automating this planning procedure will likely become imperative due to the substantial number of antennas requiring deployment. The manual planning of an ultra-dense network is both a highly arduous and costly endeavor.

Efficient Media Access Control: The challenges encountered in the design of such a MAC would resemble those found in conventional mmWave systems, but they would be considerably magnified. For instance, if a mmWave system covering a specific range needed to explore 16 antenna configurations during link establishment, a THz system operating at a carrier frequency 5 times higher might need to contend with up to 400 configurations (assuming utilization of 2D planar phased arrays). Naturally, a simplistic MAC design would be inadequate for achieving reasonable link setup times under these circumstances, thus necessitating the application of advanced signal processing techniques like compressed sensing and multi-antenna precoding, among others.

Furthermore, the requisite antenna gains for THz links of practical range mandate the obligatory employment of RF beamforming, even for elementary signaling messages. While mmWave systems like IEEE 802.11ad and Wireless HD might utilize quasi-omnidirectional antenna patterns for certain discovery and signaling messages, THz band protocols will not enjoy such conveniences, thereby demanding a completely new MAC design approach.

Support for Nodes Mobility: Virtually all wireless access links aim to facilitate the movement of communicating entities, and THz access is likely to adhere to the same principle. Nevertheless, given the concerns related to antenna gain addressed earlier, ensuring the tracking of an established beam configuration for mobile devices presents a considerable challenge. For instance, straightforwardly extending the typical beamforming training methodology to THz frequencies leads to impractically extended training sequences for CSMA/CA protocols.

Reliable 3D Networking Deployment: 6G's evolution demands support for communication within 3D space, necessitating comprehensive research across multiple aspects: (i) Measurement and data-driven modeling of 3D propagation environments, (ii) Innovative approaches for 3D frequency and network planning, and (iii) Novel network optimizations for mobility management, routing, and resource allocation in a 3D context. It's also crucial to analyze fundamental 3D performance metrics such as rate-reliability-latency trade-offs and spectral efficiency, while considering the communication requirements for driving applications. Initial steps toward this are evident in recent studies [56] [57].

However, the Poisson point process (PPP) often used to model randomness in network deployment and coverage scenarios relies on the assumption of random object distribution, which isn't entirely accurate due to the static deployment of transmitters in contrast to the randomness of mobile devices. This assumption misaligns with emerging patterns where certain base stations attract more traffic while others do not. In small cell networks, user-centric hotspots coexist with areas of lower traffic in macrocell deployments. The PPP's limitations render it inadequate for modeling the 6G networking environment, especially in 3D scenarios. While PPP has shown versatility in the 2D and 2.5D domains, its extension to a 3D channel model requires addressing these limitations.

Safety and Health Concerns: THz radiation holds photon energy ranging from 0.1 to 12.4 meV, which is less than three times the ionizing photon energy levels. Consequently, THz radiation is classified as non-ionizing photon energy [58] [59]. As such, the primary concern associated with THz frequencies pertains to heating, which is recognized as the primary contributor to potential cancer risks [60]. However, the principles of thermal hazards and non-ionizing radiation standards are established by the FCC and the International Commission, outlined in [61]. Furthermore, introducing the concept of electromotive-force transmission could emerge as a novel approach within 6G to address health-related concerns.

7. CONCLUSIONS AND EMERGING PATHWAYS

The THz band offers a promising and accessible resource for distinctive applications in medical, environmental, and military domains. However, the study of THz communications, with its manifold challenges, has led to a fragmented landscape across various fields, from physics and nanotechnology to medicine and computer science. This paper aims to consolidate this landscape by succinctly summarizing potential applications, open research hurdles, and recent standardization efforts in the field.

Upon analysis, three primary research directions in THz communications become apparent. The first focuses on leveraging lower THz frequencies (275–325 GHz) to enhance existing applications, currently in an applied research and engineering phase. This direction is also the sole consideration of standardization bodies, with emphasis on cost-effective electronics and associated networking protocols. The second direction targets comprehensive THz transceiver development, capable of terabit-per-second data transmission. This direction bridges fundamental and applied research, particularly emphasizing graphene-enabled ultra-massive MIMO systems. The third and most long-term direction centers on enabling communication among micro- and nanoscale devices. Although in its early stages, this direction presents numerous challenges in antenna design, signal processing units, data storage buffers, and energy supplies.

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