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Terahertz Communication for 5G and beyond: A Comprehensive Review

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ABSTRACT

The rapid growth of mobile data traffic, supported via applications like extended reality (XR), communication-based holographic, and huge machine-type connectivity, led 5G network communications to the performance restrictions. Terahertz communication in 5G mobile communications has appeared as a promising solution for overcoming the limited spectrum lack and performing ultra-high data rates, in addition to capacity. This review paper supplies a thorough overview of modern evolution in Terahertz (THz) wireless communication systems, focusing on their potential to uphold data rates exceeding hundreds of gigabits per second. This review paper argues that the new key trends, like the availability of spectrum, the channels-based ultra-broadband, and consolidated arrays of utilized antennas, which are used to make THz communication necessary progress for the next generation of mobile communication systems. Crucial challenges consisting of coverage restrictions, propagation loss, hardware complexity, and scarcity of standardization are examined. Prospect strategies for mitigating such challenges have also been surveyed via the combination of intelligent considering surfaces, transceivers-based photonic-assisted, and characterized beamforming. Total, this paper concludes that THz mobile communication introduces a transformative move in realizing the ultra-high-capacity, very low latency, and high-efficiency aims of 5G mobile communications and beyond generations. The presented analysis in this review paper illuminates the practical trade-offs that presently restrict empirical deployment of THz and summarizes the extremely promising research study trends to get the better of them. This will provide a base for future expansion aimed at combining THz communication systems with 5G and beyond mobile communication network systems.

1. INTRODUCTION

The exponential growth in mobile data communications is expressed as one of the defining technological directions of the last years [1]. The increasing use of intelligent devices, the huge utilization of Internet of Things (IoT) devices, and streaming schemes have been leading to a crucial request for high throughput, minimum latency, and more connectivity in wireless communication systems [2, 3]. The fifth generation (5G) was intended to handle a lot of such requirements via innovative schemes like massive multiple-input multiple-output (MIMO), beamforming, and millimeter-wave (mmWave) spectrum utilization [4 – 6]. Though as the world makes a move toward further data-hungry and latency-crucial applications, even 5G communication networks working at mmWave frequencies suffer restrictions in the availability of spectrum and capacity as well [7 – 9]. In order to meet the rising data demands, many studies are being conducted to address their concerns in the Terahertz (THz) frequency band, mainly ranging from (0.1 THz) to (10 THz) [10]. The THz spectrum utilizes an overall free of utilized region between the microwave domain and infrared domain, contributing extensive bandwidth possible in ultra-high-speed wireless communication systems [11]. The capability of THz waves for supporting data rates above 100 Gbps produces an

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attractive applicant for the next-generation mobile communication networks, consisting 6G. Nevertheless, combining THz with the current 5G ecosystem presents many challenges, like attenuation in signal, complexity in hardware, and overall cost [12, 13].

The transition toward THz is not only an incremental improvement of 5G communication systems; furthermore, it demonstrates a pattern shift of how the spectrum is used [14]. Conventional frequency bands under (6 GHz) are becoming filled, and the mmWave frequencies between (24 GHz and 100 GHz) have opened further possibilities, but they remain short of the greatest capacity visualized for future communications. Also, THz provides unequaled spectral properties, allowing multi-gigabit-per-second connections and giving support for applications like telepresence-based holographic, tangible internet, and ultra-high video streaming. Thus, the use of those facilitates heavy spatial reuse, major to enhanced communication network capacity [15 – 17]. Many technologies have been designed to make THz more practical. These consist of advanced beamforming schemes, plasmonic antennas, and new modulation approaches [18]. Besides, hybrid RF-optical schemes have been examined to relieve propagation waste and enhance connection reliability. Also, the combination of THz transceivers and silicon photonics has a promising trend, permitting minimum cost, consolidation, and efficient THz power systems [19, 20]. Even THz faces different challenges, but its propagation has been critically influenced by atmospheric absorption, molecular echo, and propagation. While the frequency widens, the signal spread via obstacles like building walls is minimized in a way that is likely to have a strong or far-reaching effect [21, 22]. Thus, preserving communication connections as reliable as possible needs line-of-sight (LoS) footpaths and advanced beam-steering techniques. Besides, performing high antenna gains and power amplifiers at the THz frequencies is still demanding. Both the cost and the complexity of THz communication system design have increased due to the shortage of forward criteria and trade hardware [23 – 25]. For example, THz links supply ultra-connectivity among base stations. Meanwhile, intelligent reflecting surfaces (IRS) and reconfigurable intelligent surfaces (RIS) form the spread environment for overcoming blockage and enhancing coverage. THz applications as shown in Fig. 1

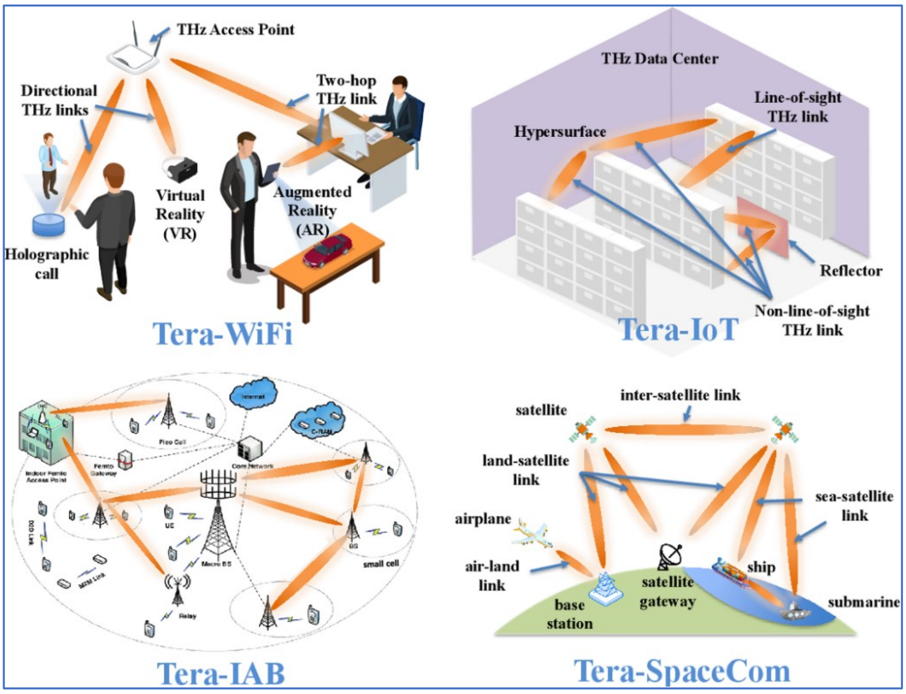

Fig. 1. *Different applications of THz communication [26].*

In conclusion, the move regarding THz bands is unavoidable as the world's request for capacity and data rates becomes high. As many technical and trade challenges continue, current study research and growth efforts specify an encouraging future trend for THz-based 5G and beyond communication networks. This review paper aims to give an overall understanding of such technological development, highlighting modern advances, trends, and challenges, and summarizing probable solutions and future research trends.

2. Literature Review

Jiang et al. (2024) presented a comprehensive treatment and technology survey on THz communications and sensing, covering advantages, applications, propagation characterization, channel modeling, measurement campaigns, antennas, transceiver devices, beamforming, networking, and experimental testbeds and give a holistic view of the current state of the art and highlight the open research challenges towards 6G and beyond [27]. Shi et al. (2023) presented a comprehensive review of various THz technologies employed to investigate the intrinsic characteristics of different materials, discuss THz sources, detectors, and components, and conclude that THz technology has promising potential and offers new opportunities for characterization of composite materials [28]. Ullah et al. (2025) introduced a recent Sensors review on terahertz-bandwidth free-space optical (THz-FSO) communication to synthesize the most relevant discoveries from the literature, aiming to establish how THz-FSO can be a solution to future networks, and highlighting atmospheric attenuation and hardware limitations among its main challenges [29]. Chaccour et al. (2019) identify the need for more expressive learning frameworks for THz networks, discuss multi-agent, multi-task, and meta-learning approaches for time-sensitive and heterogeneous THz data, and argue that current ML frameworks were primarily designed for simple classification tasks and thus require enhancement for real-time reinforcement learning in THz networks [30]. Siddiky et al. (2025) studied several survey papers in THz antennas, sources, detectors, and devices, summarizing those novel materials (e.g., graphene) and device progress are essential to overcome the THz gap, while hardware limitations remain a key barrier for deployment [31]. Shi et al. (2023) overviewed works on AI/ML for THz systems, synthesized opportunities where AI/ML can be employed for signal processing, channel estimation, and optimization of modulation and coding, and they highlight both the potential and the open challenges for ML-assisted THz imaging and sensing [32]. Akyildiz and Jornet (2022) revisited old problems for THz band communication and present open challenges and research directions, emphasizing the grand challenge of limited communication distance caused by high free-space loss, molecular absorption, and device constraints, while surveying solutions such as distance-aware PHY design and UM-MIMO [33]. Chaccour et al. (2022) studied literature studies that focus on propagation characterization, provide measurements and channel models covering path loss, molecular absorption, weather effects, and blockage, noting extreme absorption peaks in the THz band and the need to include atmospheric models (e.g., ITU-R P676 and HITRAN) for accurate link budgets [34]. Singh et al. (2019) focused on beamforming, hybrid/UM-MIMO, and beam-alignment techniques are reported as necessary to compensate for the severe propagation losses and to enable pencil-like directional links for both communications and sensing, while the PDF highlights beam tracking and synchronization as critical open problems [35]. Moltchanov et al. (2022) discussed several contributions regarding THz sensing, imaging, and localization, underlining high spatial resolution, penetration through dielectrics, and spectroscopic fingerprints as unique strengths that enable ISAC (integrated sensing and communications) use cases from security screening to SLAM-based localization [36]. Table 1 summarizes the literature studies with a comprehensive comparison among them in terms of contribution, challenges, insights, and Potential for 5G/6G Integration

Table 1. *Comparison of literature review.*

Study	Contribution	Challenges	Insights	Potential for 5G/6G Integration
Jiang et al. (2024) [27]	Comprehensive survey: propagation, channel modeling, antennas, beamforming, networking, testbeds.	High propagation loss; device limitations; beam alignment.	Holistic view; highlights open research challenges toward 6G.	High — positions THz as enabler for ISAC and Tbps links if challenges solved.
Shi et al. (2023) [28]	Review of THz material research: dielectric properties, components, sources/detectors.	Material response to THz; severe attenuation in air; lack of responsive natural materials.	THz technology promising for material characterization; future trends outlined.	Medium — materials work enables device maturity for 6G hardware.
Ullah et al. (2024) [29]	Literature synthesis for THz-bandwidth free-space optical communications; comparison vs microwave/optical.	Atmospheric attenuation; massive energy consumption; hardware limitations.	THz-FSO has potential for inter-satellite/6G links but faces environmental/hardware limits.	Niche — useful for specific 6G backhaul/inter-satellite links with alignment controls.
Chaccour et al. (2019) [30]	Conceptual/ML frameworks: multi-agent, meta-learning for THz networks.	Existing ML tested only on small datasets; not yet for time-sensitive THz scenarios.	Need for more expressive RL/meta-learning approaches for real-time THz control.	High — ML improvements can enable adaptive 6G THz control loops.
Siddiky et al. (2024) [31]	Survey of THz sources/detectors/antennas and	Low TX power, receiver sensitivity,	Device progress ongoing; materials and novel architectures needed.	Critical — device maturity dictates

	device technologies (QCLs, plasmonics).	integration challenges.		feasibility of 6G THz deployments.
Shi et al. (2023) [32]	Reviews of ML in THz: imaging, sensing, channel estimation, optimization.	Dataset heterogeneity; real-time constraints; explainability.	ML is promising but needs tailored datasets and architectures for THz.	Enabler — AI needed for beam alignment, channel estimation in 6G THz.
Akyildiz & Jornet et al. (2022) [33]	Roadmap/overview revisiting THz challenges: devices, channel, PHY, testbeds.	Communication distance limitation due to path loss and absorption.	Presents directions: distance-aware PHY, UM-MIMO, reflectarrays.	High — defines practical directions to integrate THz into 6G stacks.
Chaccour et al. (2022) [34]	Measurement campaigns; channel modeling; ITU-R P676/HITRAN references.	Molecular absorption, weather, scattering, blockage.	Accurate modeling is mandatory for link design; strong frequency windows matter.	Essential — accurate channel models required for 6G resource planning.
Singh et al. (2019) [35]	Beamforming design, hybrid architectures, beam tracking algorithms.	Beam misalignment, fast micromobility outages.	Beamforming with large arrays is required to compensate FSPL.	Enabler — enables directional Tbps links for 6G hotspots.
Moltchanov et al. (2022) [36]	THz imaging, spectroscopy, SLAM-based localization use cases.	Water/metal blocking; penetration limits; resolution vs range tradeoffs.	THz sensing offers non-ionizing, high resolution imaging useful for ISAC.	High — sensing adds value to 6G services (localization, security).

size.

3. Barriers to Realizing Practical Terahertz Communications

With the huge growth of applications related to data-driven technologies like XR/AR, produced using holograms, and commercial automation, present mid-bands within 5G communication spectrum bands have been approaching saturation. The transformation regarding higher frequencies, especially the spectrum of THz, provides a wide modern wireless network. Different from sub-6 GHz and bands-based mmWave, THz supplies multi-gigahertz in terms of bandwidths, can support ultra-high data rates, and very large connectivity. That direction is guided by academic and commercial research studies that converge on taking advantage of the THz-spectrum in backhaul, fronthaul, and entrance connections. The transition to THz communications appears promising so far, technically complex development of 5G and beyond mobile communications. But THz spectrum provides unequaled bandwidth and the possibility for ultra-high data rates; THz as well offering enormous stumbling blocks which have to be handled before global deployment could be a reality. Such challenges include physical spread issues, design of hardware restrictions, and system combination level difficulties [37].

3.1 Coverage and Penetration

The signals of THz are frequently affected by high free-space path loss due to the transmission equation scaling and the frequency square. When a change happened from mmWave (e.g., 60 GHz) to THz (300–1000 GHz), the states of the path loss increased by about (20–30 dB) even on short distances. The second cause-based physical phenomenon is absorption of molecular, in those atmospheric gases (mostly vapor of water or oxygen) show peaks of resonance in the region of THz. Such peaks are used to convert a portion of the EM-energy into molecular-based vibrational provocation, generating strong mitigation in particular spectral windows. The most interesting challenges in communication-based THz are the main trade-off between the coverage area and entries. While the frequency increases, the identical wavelength decreases or lessens, resulting in critical propagation losses. In the same context, the free-space path loss is increasing in proportion with frequency, which creates difficulty in maintaining the communication connection links. Furthermore, the signal of THz is highly open to absorption via atmospheric molecules, which may cause signal mitigation peaks on a particular band of frequency. Such absorption limits the utilizable THz spectrum portions, frequently reserving communications in short-range or LoS schemes. One more vital restriction is the bad penetration capability of the THz-waves. Different from lower-frequency signals, which are able to penetrate walls and other obstacles. Such limits the utilizable in indoor conditions or urban areas [38]. Furthermore, the very small wavelength results (300–30 μm) are poor in deviation, which means THz waves are unable to bend surrounding the obstacles and, for that reason, need a firm line-of-sight (LoS). That explains why the indoor THz connections fail even when blocked by small objects like human bodies. In order that building materials display high dielectric constants on frequencies of THz, the permeation loss through walls and windows may be over 40–80 dB, creating non-LoS communication exceedingly unsuitable. For handling such challenges, many methods are utilized, consisting of ultra-dense deployment in small cells, utilizing intelligent reflecting surfaces (IRS), and combining reconfigurable intelligent surfaces (RIS), which is leading and reshaping beams of THz. Nevertheless, such strategies importantly increase both the cost and complexity [39].

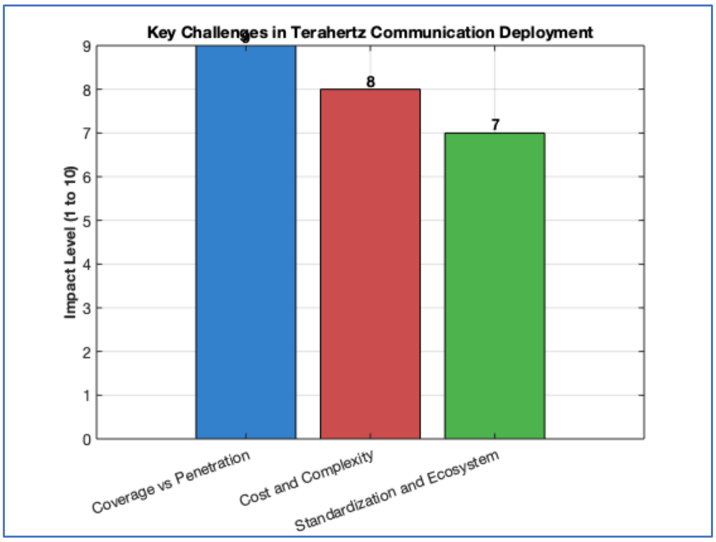

Fig. 2. *Key challenges in THz communication deployment.*

Quantitatively, Figure 2 offers a comparative conception of three main challenges regarding THz communication, including coverage against penetration, cost versus complexity, and ecosystem preparation and standardization. Each one is shown in a different color to underline its severity, and the influence level is rated on a range scale between 1 to 10. This figure illustrates that the coverage and penetration restrictions pose almost all-important barriers (the impact-level is about 9), next the high cost against the complexity of the THz system execution (the impact-level is about 8), and the absence of standardization versus the ecosystem majority (the impact-level is about 7). In this figure, used to convey the magnitude of such challenges, a perceptible hierarchy has been supplied, which indicates their impact on both the feasibility and scalability of THz system communications. Furthermore, it is used to compare the three presiding challenges of THz. This figure confirms that the propagation restrictions (rated 9/10) show the rest issues, consisting of physical-layer barriers, are the main bottleneck. Both complexities, based on cost and hardware, follow the effect level 8/10, indicating the immaturity of semiconductor fabrication for THz systems. Challenges-based standardization (7/10) forms the third layer, reflecting that the system quite needs a coordinated spectrum rule before trading deployment.

3.2 Cost and Complexity

The hardware of THz is very expensive due to standard transistor-based CMOS has no ability to deliver enough gain and/or oscillation frequency above about 300 GHz. To address that, the study utilizes 3 to 5 device-based semiconductor (GaN, InP, GaAs) and transistors made out of graphene plasmonic, that is supports electrons moving 3–10× higher than silicon. Although such materials need complex epitaxial growing and chip bonding remarkably increases in cost [40, 41]. The high-speed based DACs/ADCs needed for THz systems have to support more than (50–100 GSa/s) sampling ratio. Industrialization of such converters needs SiGe BiCMOS or may require preceding nodes of CMOS less than 5 nm, which maximizes the consumption of power and load of thermal. Furthermore, the antennas of THz require micron-level accuracy; even the (5–10 µm) bias error guides to beam-squint and offset-phase. That explains that the front-end THz stay an experimental prototype rather than a traditional product [42, 43].

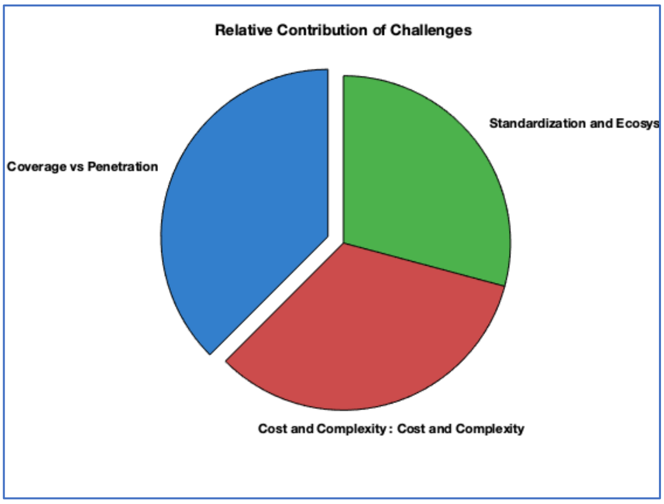

Fig. 3. *Relative contribution of challenges.*

Figure 3 presents the corresponding subscription of every barrier of general THz deployment trouble. Coverage and perforation inhabited the largest sector, which used to align with experimental measurements displaying that the connections of THz fail next a few meters in the absence of LoS. Both the cost and complexity sector summarize the out-of-proportion load placed on hardware industrialists; however, the calibration sector reflects that the system issues remain notably delaying real-world assumptions. The relative contribution of all THz communications, crucial challenges for a comprehensive set of barriers to deployment, leading to dominant obstacle in terms of coverage against penetration, which is presented as the largest sector of such a diagram and a little exploded outward to draw assurance. The rest two slices, “the cost against complexity” and “the standardization against ecosystem”, which are shown as smaller, however, remain a substantial portion of the overall distribution of challenge. Such visual representation supports the idea that physical spread restrictions are still the extremely crucial bottleneck, whilst trade and regulatory features form the following layers of hardness, which present an overview of how such interrelated elements collectively affect the practicability of THz in 5G mobile communication and beyond networks.

3.3 Standardization and Ecosystem Development

The lack of a merged regular approach results from THz propagation features changing in strong way by locations because of humidity and absorption-based molecular effects. Consequently, an international regular spectrum allocation has been tough. Current standards (e.g., IEEE 802.15.3d at 252–325 GHz) handle just fixed point-to-point connections; therefore, no grown-up channel models are available in non-stationary scenarios of high-mobility in THz [44 – 46]. Also, device interoperability has been restricted due to the construction utilization of various materials, including antenna geometries and baseband frameworks. Finally, the absence of a mass market required making components of THz expensive in the fact that production scales have not been performed [47, 48].

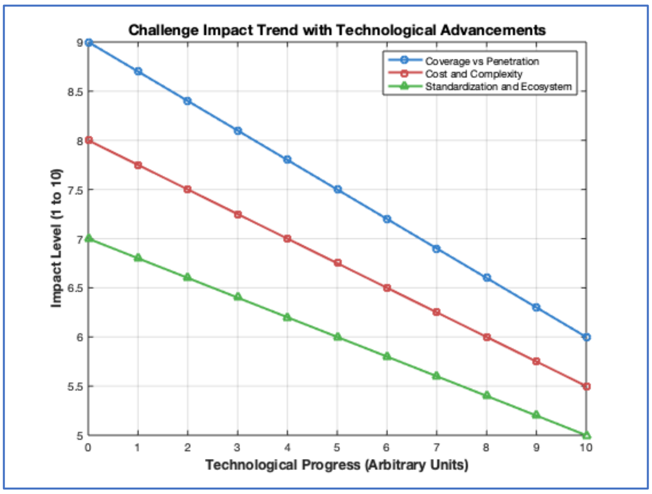

Fig. 4. *Trend of challenge reduction as technology matures, inspired by generalized roadmaps for THz evolution in 6G networks [27, 28].*

Figure 4 shows that the propagation limitations as expected to be handled most quickly because of the progress, like ultra-massive MIMO, the reconfigurable smart surfaces, and photonic-aid THz front-ends. Both the cost and complexity are minimized further slowly due to semiconductor improvements and packaging enhancements need time and trading scale. Standardization influence decreases gradually while remaining steady as IEEE, ITU-R, and 3GPP start embodying THz proposals in initial 6G projects.

4. Broader Perspectives and Future Outlook

In 6G and beyond mobile communication systems, it is expected that THz to play a main functionality role through expanding available spectrum and authorizing applications-based ultra-high-data-rate services like holographic systems, immersive XR, and Tbps frameworks. In time, many innovations have shaped the evolution and development of 5G and beyond networks, for instance, network-slicing, private networks, satellite combination, and potential networking. Standardization is going to be necessary for widespread adoption. Whilst IEEE 802.15.3d provides primary guidance, upcoming 6G functionalities based on ITU-R and 3GPP will be expected to identify mobile operation based on THz, communication models, and spectrum directive. The transformation to the THz spectrum emerges as an extremely impactful design. THz spectrum not only expands spectral limits but also authorizes completely modern class-based applications which have earlier been impossible. By handling the challenges (technical and economic), THz communication network will reshape the international wireless landscape, laying the basis for an accurately connected and smart world. Overall, the THz communication outlook is still promising. Persistent progress into hardware, smart surfaces, photonics, and worldwide standards will qualify bands of THz to advantage a key module for future trends in wireless communication networks, providing application support that requires the greatest data rates, accuracy, and low latency.

5. CONCLUSION

The investigation of Terahertz frequencies appears for a transformative move toward performing ultra-high data rates and huge capacity in 5G and beyond communication networks. This review paper highlights the importance of THz communication networks, their emerging directions, main key challenges, and possible solutions. Though many obstacles still exist, consisting of propagation-loss, high cost in deployment, and absence of standardization, in-progress technological moves forward keep on the bridge of the gap between theoretical possibilities and practical investigation. Through leveraging revolution in designing antennas, signal-processing, and smart network systems, THz bands is able to free the following era of wireless development, immersive support, high-throughput, and latency-crucial applications in next generations of mobile communication systems.
Terahertz communication is expressed as a basic expand of the wireless spectrum in addition to incremental enhancements across mmWave systems. This review paper synthesizes recent findings on propagation physics, technological devices, designing channels, configuring antennas, and modelling the network, exhibitionist that THz is promising and challenging technically at the same time. But loss-based propagation and immaturity-based hardware are still barriers; progress in 3 to 5 graphene devices, transceivers-based photonic-assisted, and smart reflective surfaces has steadily narrowed the gap in THz. The main key perception from the literature studies, there is no development that can widespread THz deployment; as an alternative, progress has to be co-built over materials, electrical circuits, signal processing approaches, and calibration. As the system develops, THz bands have been expected to support Tbps-class connection links, combined sensing and communication, and applications-based immersive proposals for 6G. Consequently, THz communication attitude as a major support for future wireless networks, given that researchers continue to make advancements at the physics-level and advancements of system-level advancements, and international regulatory agreements.

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