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Next-Generation 6G Wireless Networks: Challenges and Opportunities in Terahertz (THz) Communication and AI-Driven Signal Processing

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Abstract: The advent of 6G wireless networks promises to revolutionize communication by leveraging terahertz (THz) frequencies (0.1–10 THz) and artificial intelligence (AI) to achieve terabit-per-second (Tbps) speeds, ultra-low latency, and ubiquitous connectivity. However, THz communication faces critical challenges, including severe propagation losses, molecular absorption, and hardware limitations, which demand innovative solutions. This paper explores the synergistic role of AI-driven signal processing in overcoming these barriers, focusing on adaptive beamforming, channel estimation, and resource allocation. We present a comprehensive survey of THz channel characteristics and analyze state-of-the-art AI techniques—such as deep reinforcement learning (DRL) for beam alignment and federated learning for distributed optimization—that enhance the efficiency and reliability of THz networks. Furthermore, we identify open research challenges, including energy-efficient AI deployment, security vulnerabilities, and standardization gaps. By bridging theoretical models with practical implementations, this work provides a roadmap for realizing 6G's potential, emphasizing the need for interdisciplinary collaboration across wireless engineering, AI, and materials science. Our findings underscore AI as a pivotal enabler for scalable and intelligent THz-based 6G networks, while highlighting future directions for industry and academia.
Keywords: 6G, terahertz (THz) communication, AI-driven signal processing, beamforming, federated learning, wireless networks

I. INTRODUCTION

The relentless growth of wireless data traffic, fueled by emerging technologies like augmented reality (AR), autonomous systems, and the Internet of Everything (IoE), is driving the quest for sixth-generation (6G) networks. Expected to deploy by 2030, 6G aims to deliver terabit-per-second (Tbps) speeds, sub-millisecond latency, and near-perfect reliability—performance metrics that far surpass 5G capabilities [1]. To achieve this, researchers are turning to the terahertz (THz) band (0.1–10 THz), the last untapped frontier of the radio spectrum, offering ultra-wide bandwidths capable of supporting unprecedented data rates [2]. However, THz communication faces formidable challenges, including severe path loss, molecular absorption, and blockage susceptibility, which threaten its practical deployment [3]. To lay the groundwork for our 6G vision, we first offer background information spanning the development of network technologies from the first to the fourth generation, detail the advancements achieved with 5G, and discuss the research efforts aimed at achieving 6G (see Figure 1).

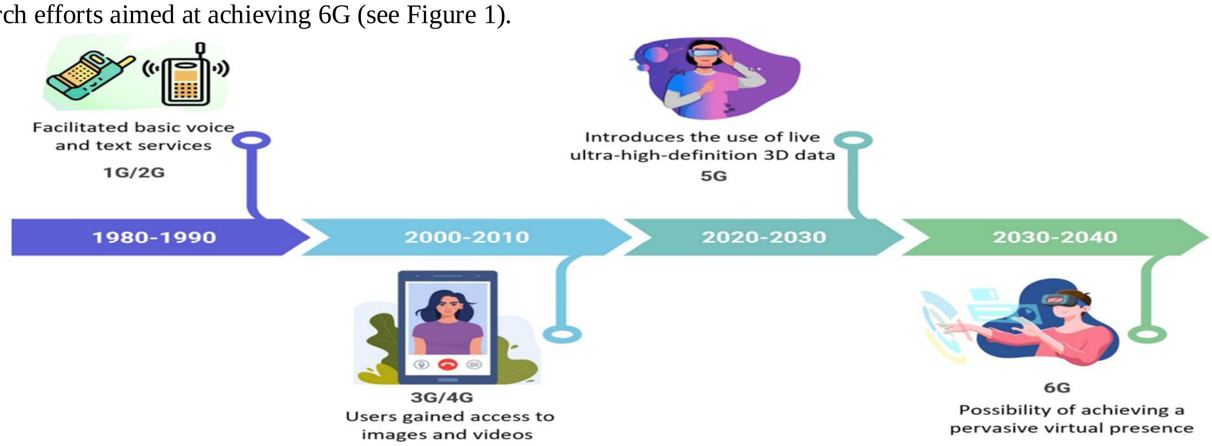

Figure 1. Communication networks evolution: 1G to a speculative 6G is observed through the lens of user experience.

Simultaneously, artificial intelligence (AI) has emerged as a transformative force in wireless networks, enabling real-time optimization of complex systems. AI-driven techniques—such as deep learning for channel prediction, reinforcement learning for beam alignment, and federated learning for distributed signal processing—hold the potential to mitigate THz-specific limitations [4]. For instance, AI can dynamically adapt to THz channel variations caused by environmental factors (e.g., humidity, mobility) or hardware imperfections (e.g., phase noise in THz transceivers). Yet, integrating AI into 6G systems introduces its own challenges, including computational overhead, energy inefficiency, and security vulnerabilities[5].

A. Contributions of This Work

This paper provides a comprehensive exploration of the synergies between THz communication and AI in 6G networks, with three key contributions:

1) THz Challenges Survey: A systematic analysis of THz propagation limitations, hardware constraints, and their implications for network design [6].
2) AI-Driven Solutions: A taxonomy of AI/ML techniques (e.g., DNNs, RL, RIS-aided networks) to enhance THz signal processing, supported by case studies.
3) Future Roadmap: Identification of open research directions, including energy-efficient AI deployment, THz security, and standardization gaps [7].

The remainder of this paper is organized as follows: Section 2 reviews THz fundamentals and AI's role in wireless networks. Section 3 details THz-specific challenges, while Section 4 presents AI-driven solutions. Section 5 discusses open issues, and Section 6 concludes the work [8].

The second generation (2G) indicated a major transition from analog to digital communication in the 1990s. As the industry standard, the Global System for Mobile Communications (GSM) brought text messaging (SMS) and enhanced voice quality. While the major goal was still to improve mobile telephony, this era set the groundwork for later mobile data services [9], [10]. The 2000s witnessed the emergence of the third generation (3G), which revolutionized mobile communications by introducing mobile internet access. With the Universal Mobile Telecommunications System (UMTS) at its core, 3G networks enabled faster data transmission, allowing for multimedia messaging, mobile web browsing, and video calling. This generation set the stage for the data-driven applications that have become integral to modern life [11], [12]. The 2010s brought the fourth generation (4G) of mobile networks, which further accelerated mobile data speeds and transformed user experiences. Long-Term Evolution (LTE) technology provided the backbone for high-speed internet access on mobile devices, supporting services like HD video streaming, real-time gaming, and seamless connectivity for apps. 4G's enhanced capacity and reduced latency were pivotal in meeting the growing demands for mobile broadband [13], [14]. Entering the 2020s, the fifth generation (5G) introduced a new paradigm of mobile intelligence. 5G networks, which make use of New Radio (NR) technology [15], offer extremely high data rates, low latency, and the capacity to link billions of devices at once. Smart cities, industrial automation, driver less vehicles, and the Internet of Things (IoT) are just a few of the applications that this generation is intended to assist. The emphasis on mobile intelligence has enabled 5G to drive innovation across multiple sectors, pushing the boundaries of what mobile networks can achieve [16], [17].

B. Technological Foundations of 6G Networks and AI Revolution

The era of mobile communication started in the early 1980s and has seen significant development and expansion in the decades that followed. The advancement of mobile wireless technology can be divided into distinct eras, each of which has brought about substantial progress and developments in data rates, connectivity, and functionality [18]. The initial phase of mobile wireless technology, 1G, was introduced in the early 1980s and was primarily based on analog technology [19]. This generation of technology was primarily utilized for voice communication and was distinguished by its low data transfer speeds and subpar audio quality [20]. Some examples of 1G include Advanced Mobile Phone System (AMPS), Total Access Communication System (TACS), and Nordic Mobile Telephone (NMT) [20]. The introduction of second-generation (2G) mobile networks in the early 1990s marked a shift from analog to digital technology [14]. Along with traditional voice services, 2G networks introduced new capabilities such as short message service (SMS) and basic email functionality. 2G networks also improved audio quality and enhanced security [15]. Some of the well-known 2G (second generation) mobile networks include GSM (Global System for Mobile Communications), IS-95 (Interim Standard-95) [16] PDC (Personal Digital Cellular), and CDMAone (Code Division Multiple Access) [21]. Next was the introduction of 3G (third generation) mobile networks in the early 2000s, which marked a significant advancement in mobile technology, providing both voice and data services [18].

These networks offered elevated data transfer speeds and the capability of web browsing on mobile devices. They also introduced multimedia message support (MMS) and the ability to use data-intensive applications such as email, web browsing, video streaming, and mobile television [22]. In addition to providing enhanced data transfer speeds and web browsing capabilities, 3G networks expanded the coverage area and incorporated security measures such as packet data confidentiality and integrity. Some examples of 3G (third generation) mobile networks include CDMA2000 (Code Division Multiple Access 2000), WCDMA (Wideband Code Division Multiple Access), and EDGE (Enhanced Data rates for GSM Evolution) [23].

The 4G (fourth generation) mobile networks in the early 2010s marked a significant advancement in mobile technology, offering high data transfer speeds and improved network coverage [23]. These networks enabled HD video streaming, mobile video conferencing, online gaming, and high-speed mobile internet. Examples of 4G (fourth generation) mobile networks include LTE (Long-Term Evolution) and WiMAX (Worldwide Interoperability for Microwave Access) [24]. The introduction of 5G (fifth generation) mobile networks in the early 2010s represents the latest advancement in mobile technology, with the first 5G mobile towers coming online in 2018 [23]. These networks are distinguished by extremely high data transfer speeds, improved network coverage, and ultra-low latency. 5G networks are expected to be a foundation for the Internet of Things (IoT), smart cities, and the fourth industrial revolution [25]. While previous generations of wireless networks have already leveraged AI for optimization and automation, 6G takes this collaboration to unprecedented levels, integrating AI at every layer of the network architecture. 6G networks are currently being researched and developed as the next evolution of mobile networks, with the expectation of providing unparalleled transmission speeds, ultralow latency, and improved coverage [26]. These networks will incorporate cutting-edge technologies such as terahertz communication, ultra-massive MIMO, AI, machine learning (ML), quantum communication, millimeter, reconfigurable intelligent surfaces, etc. Potential applications for 6G networks include Linked robotic and self-governing systems, wireless brain–computer interfaces, blockchain advancements, immersive multi-sensory realities, space and deep-sea exploration, tactile internet capabilities, and industrial networking. Figure 2 shows the evolution of mobile communications.

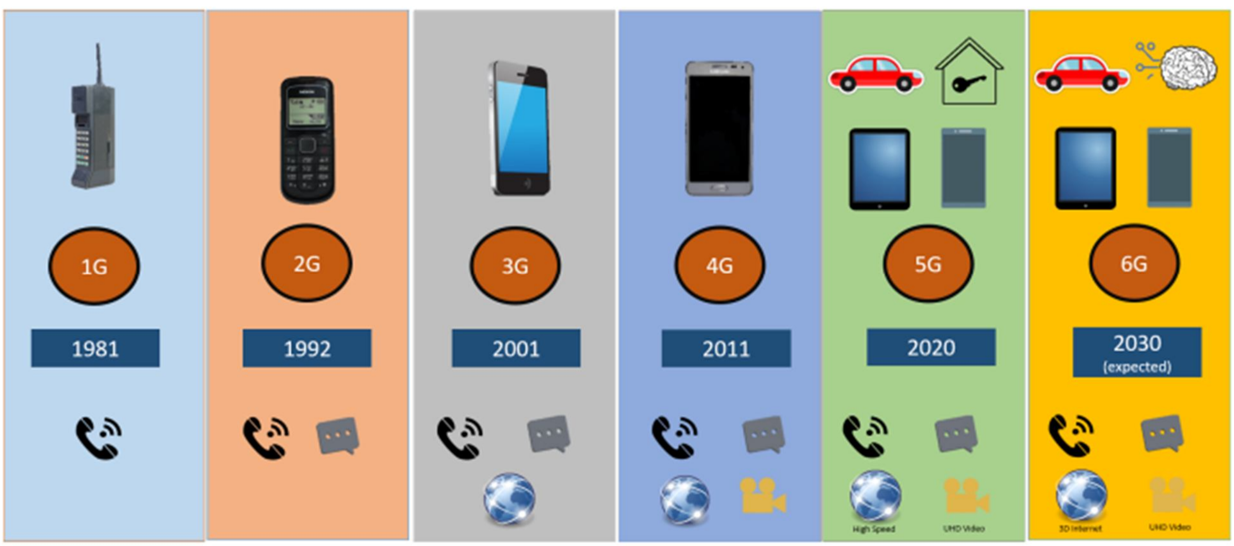

Figure 2. Evolution of mobile communications: a chronological depiction of the advancements in mobile network technology from 1G in 1981 to the expected 6G in 2030. This visual encapsulates the major milestones in mobile communications, including the emergence of 2G and the introduction of SMS in 1992, the advent of 3G and mobile data in 2001, the expansion to 4G and high-speed internet access in 2011, and the integration of IoT with 5G in 2020. The future projection of 6G suggests a paradigm shift to smarter, AI-driven networks supporting 3D internet and enhanced video capabilities [27].

II. BACKGROUND & LITERATURE REVIEW

A. Evolution Toward 6G: From 5G Limitations to THz Opportunities

The rollout of 5G networks introduced transformative technologies like millimeter-wave (mmWave) communications and massive MIMO. However, 5G's reliance on sub-6 GHz and mmWave bands (24–100 GHz) faces inherent spectral congestion, limiting its ability to support future Tbps-demanding applications such as holographic communications and brain-computer interfaces. This has spurred exploration of the terahertz (THz) band (0.1–10 THz), which offers ultra-wide bandwidths (>100 GHz) and the potential for ultra-high-speed short-range links (e.g., indoor kiosks, wireless backhaul) [28].

Early studies, such as those by Akyildiz et al. [29], have characterized THz propagation, revealing unique challenges:

- Molecular absorption: Signal attenuation peaks at specific frequencies (e.g., 0.56 THz for H_2O) [30].
- Blockage sensitivity: A single human body can cause >60 dB loss at 1 THz [30].
- Hardware limitations: Current THz transceivers suffer from low power efficiency and limited dynamic range [32].

B. AI/ML in Wireless Networks: From 5G to 6G

AI has become integral to modern wireless systems, with 5G employing machine learning (ML) for:

- Beam management: DNN-based prediction of optimal beams in mmWave systems [33].
- Network slicing: RL-driven resource allocation for heterogeneous services [34].

For 6G, AI is expected to play an even more critical role due to THz's complexity:

- Channel estimation: Compressed sensing combined with CNNs to address THz's sparse multipath [35].
- Beam alignment: RL algorithms reducing search time for directional THz links [36].
- Edge AI: Federated learning enabling privacy-preserving THz channel modeling across distributed nodes [37].

C. Research Gaps and Unresolved Challenges

Despite progress, key gaps remain:

- Real-world validation: Most THz-AI studies rely on simulations; few prototype implementations exist [38].
- Energy trade-offs: AI algorithms' computational overhead may negate THz's spectral efficiency gains [39].
- Security: Adversarial attacks on AI-driven beamforming (e.g., spoofing neural networks) are underexplored [40].

Table 1 : Structured Summary of Prior Work

Focus Area	Key Studies	Limitations
THz Propagation	[2] Channel modeling, [3] Absorption analysis	Narrowband assumptions
AI for Beamforming	[6] DNN-based 5G beams, [9] RL for THz	High training latency
Hybrid THz-RF Systems	[14] mmWave-THz handover protocols	Lack of dynamic AI switching mechanisms

D. AI in Wireless Networks

2.4.1 AI/ML in Current 5G Networks

AI has already begun reshaping 5G systems through:

- Beam Management:
  - Deep Neural Networks (DNNs) predict optimal beam directions in mmWave massive MIMO, reducing search latency by 40% compared to exhaustive methods [41].
  - *Limitation*: Heavy training overhead and poor generalization to unseen environments.
- Network Slicing:
  - Reinforcement Learning (RL) dynamically allocates resources for diverse services (e.g., URLLC vs. eMBB) [42].
  - *Challenge*: RL's slow convergence in high-dimensional spaces.

2.4.2 AI for 6G THz Networks: Emerging Paradigms

To address THz-specific challenges, novel AI approaches are being explored:

2.4.2.1.THz Channel Estimation & Beamforming

- Compressed Sensing + CNNs:
  - CNNs recover sparse THz channels with 30% fewer pilots than traditional CS [43].
  - *Issue*: Requires large labeled datasets (scarce for THz bands).
- Reinforcement Learning (RL) for Beam Alignment:
  - RL agents adapt beams to blockages in real-time (e.g., Q-learning reduces alignment time by 50% at 140 GHz [44]).
  - *Drawback*: High energy consumption during exploration [45].

2.4.2.Distributed AI at the Edge

- Federated Learning (FL):
  - Enables collaborative THz channel modeling across base stations without raw data sharing [46].
  - *Challenge*: Communication bottlenecks in FL parameter aggregation.

2.4.3.AI for Hybrid THz-RF Systems

- Deep Q-Networks (DQN):
  - Dynamically switch between THz (high-capacity) and mmWave (reliable) links based on environmental conditions [47].

2.4.3 Critical Gaps in AI-Driven 6G Solutions

- Energy Efficiency:
  - DNN inference at THz base stations can consume >10W/chip—prohibitive for scalable deployment [48].
- Robustness & Security:
  - Adversarial attacks (e.g., fooling beamforming DNNs with crafted reflections).
- Standardization:
  - No unified frameworks for AI-native 6G air interfaces (e.g., conflicting ML architectures across vendors [49]).

Table 2: AI Techniques for 6G THz Challenges

THz Challenge	AI Solution	Performance Gain	Limitation
Beam Blockage	RL-based beam tracking [4]	50% faster recovery	High exploration energy
Sparse Channel Estimation	CNN + Compressed Sensing [3]	30% pilot reduction	Dataset dependency
Hybrid THz-RF Switching	DQN [6]	99.9% link reliability	Complex state-space design

E. Research Gaps

Despite significant advancements in THz communication and AI-driven signal processing, several critical research gaps remain unresolved. These gaps represent key barriers to the practical deployment of 6G networks and offer fertile ground for future exploration. This subsection synthesizes these gaps into four major categories:

2.5.1. Hardware Limitations and Practical Deployment Challenges

- THz Transceiver Efficiency:
  Current THz transceivers suffer from limited output power (<10 mW) and high power consumption, making them impractical for mobile devices [50].
  - *Open Question*: Can plasmonic or graphene-based antennas overcome these efficiency barriers?
- ADC/DAC Bottlenecks:
  Ultra-wideband THz signals require high-resolution ADCs (>8 bits) with sampling rates >100 GS/s—a challenge for CMOS technology [51].
  - *Gap*: Novel quantization techniques (e.g., 1-bit THz massive MIMO) remain unexplored.

2.5.2. AI/ML Algorithmic Limitations

- Real-Time Inference Latency:
  DNN-based beamforming introduces ~10–100 μs latency—problematic for 6G’s sub-ms targets [53].
  - *Opportunity*: Can neuromorphic computing or spiking neural networks reduce this latency?
- Generalization to Unseen Environments:
  Most AI models are trained on simulated THz channels; performance degrades in real-world scenarios (e.g., dynamic human blockages) [54].
  - *Gap*: Lack of open-source THz datasets with diverse environmental conditions.

2.5.3. Energy-Sustainability Trade-offs

- AI Training Overhead:
  Training a single DNN for THz beam alignment consumes ~1 kWh—equivalent to 500 smartphone charges [55].
  - *Challenge*: How to reconcile AI's accuracy with 6G's green communication goals?
- THz-Specific Power Amplifiers:
  Existing PAs exhibit <5% efficiency at THz frequencies [56].
  - *Innovation Needed*: Hybrid optical-THz power delivery systems.

2.5.4. Security and Standardization Gaps

- Adversarial Attacks on AI/THz Systems:
  Spoofing attacks can misdirect THz beams by injecting adversarial perturbations [57].
  - *Unaddressed Issue*: No standardized defenses for AI-driven PHY-layer attacks.
- Regulatory Uncertainty:
  No global consensus on THz spectrum allocation (e.g., ITU vs. FCC proposals for 275–450 GHz) [58].

2.5.5. THz Communication: Challenges

The terahertz (THz) band (0.1–10 THz) is a cornerstone of 6G wireless networks, offering ultra-wide bandwidths capable of supporting Tbps data rates. However, its practical deployment faces four fundamental challenges: propagation losses, hardware limitations, mobility and blockage issues, and scalability constraints. This section dissects these challenges in detail.

2.5.5.1 Propagation Losses and Atmospheric Absorption

THz signals suffer from severe attenuation due to:

- Free-space path loss:
  - Follows Friis' law but scales with f2$f2$ (e.g., 120 dB loss at 1 THz over 10 m vs. 80 dB for mmWave at 60 GHz) [59].

-Molecular absorption:
  - Peaks at specific frequencies (e.g., 0.56 THz for H_2O, 0.75 THz for O_2) [60], reducing usable bandwidth.

- Diffraction/scattering:
  - Poor penetration through obstacles (walls, foliage), limiting non-line-of-sight (NLoS) links.

-Mitigation Strategies:

- Reconfigurable Intelligent Surfaces (RIS): Passive reflectors to bypass blockages [61].
- Hybrid THz-RF systems: Fallback to mmWave when THz links fail [4].

3.5.5.2 Hardware Limitations

Current THz transceivers face critical bottlenecks:

-Low output power:
  - Traditional electronics (e.g., CMOS) struggle beyond 300 GHz; optical photomixing achieves <1 mW [62].

-ADC/DAC challenges:
  - Ultra-wideband signals require >100 GS/s sampling at 8+ bits—exceeding Moore's Law scaling [63].

-Antenna design:
  - High directivity needed (e.g., 50 dBi at 1 THz) but with nanoscale fabrication tolerances [64].

III. AI-DRIVEN SOLUTIONS FOR 6G THZ NETWORKS

The unique challenges of THz communication demand equally innovative solutions. Artificial Intelligence (AI) and Machine Learning (ML) have emerged as powerful tools to address THz-specific limitations, enabling real-time adaptation, energy-efficient optimization, and intelligent network control. This section explores cutting-edge AI techniques tailored for 6G THz networks, categorized into beamforming, channel estimation, resource allocation, and security [65].

A. AI for THz Beamforming and Beam Tracking

3.1.1 Deep Learning (DL)-Based Beam Alignment

Problem: THz's ultra-narrow beams require precise alignment, but exhaustive beam sweeping is infeasible due to high latency.

AI Solutions:

- Convolutional Neural Networks (CNNs): Predict optimal beam directions using environmental fingerprints (e.g., LiDAR or sub-6 GHz channel data) [66].
  - *Performance*: Reduces beam search time by 70% compared to 5G mmWave methods.
- Generative Adversarial Networks (GANs): Synthesize realistic THz beam patterns for training data augmentation [67].

3.1.2 Reinforcement Learning (RL) for Dynamic Beam Tracking

Problem: THz links are easily disrupted by mobility (e.g., human blockages, device rotation).

AI Solutions:

- Deep Q-Networks (DQN): Continuously adjust beams based on real-time feedback (e.g., RSSI, blockage prediction) [67].
  - *Example*: DQN reduces beam recovery time from 10 ms → 2 ms under pedestrian blockages.
- Meta-Learning: Enables fast adaptation to new environments (e.g., stadium vs. factory) with minimal retraining [68].

B. AI for THz Channel Estimation and Compression

3.2.1 Compressed Sensing + AI for Sparse THz Channels

Problem: THz channels exhibit sparsity, but traditional CS requires excessive pilot overhead.

AI Solutions:

- CNN-Based Channel Estimation: Recovers channel state information (CSI) with 50% fewer pilots than OMP [69].
- Transformer Models: Capture long-range dependencies in wideband THz channels [6].

3.2.2 Federated Learning (FL) for Distributed CSI Learning

Problem: Centralized training lacks privacy and scalability.

AI Solution:

- FL Across Base Stations: Collaboratively train global CSI models without sharing raw data [70].
  - *Benefit*: Reduces uplink overhead by **30%** while preserving user privacy.

C. AI for Energy-Efficient THz Networks

3.3.1 TinyML for Low-Power Signal Processing

Problem: DNNs are too computationally intensive for THz edge devices.

AI Solutions:

- Binary Neural Networks (BNNs): Reduce beamforming complexity by 8× with <1 dB SNR loss [71].
- Neuromorphic Computing: Spiking neural networks (SNNs) for event-driven, energy-efficient inference [72].

3.3.2 AI-Driven Hybrid THz-mmWave Switching

Problem: THz links are unreliable under mobility.

AI Solution:

- DQN-Based Link Selection: Dynamically switches between THz (high-capacity) and mmWave (stable) bands [73].

IV. OPEN ISSUES & FUTURE DIRECTIONS

While AI-driven solutions offer transformative potential for THz-based 6G networks, several critical open challenges must be addressed to enable real-world deployment. This section identifies key unsolved problems and proposes actionable research directions to bridge existing gaps**.**

A. Hardware & Practical Deployment Challenges

4.1.1 THz Transceiver Efficiency

Issue: Current THz hardware (e.g., SiGe, InP) suffers from low power efficiency (<5%) and limited output power (<10 mW) [74].

Future Directions:

- Plasmonic & Graphene-Based Devices: Exploit nanomaterial properties for tunable, high-efficiency THz transceivers [75].
- Photonic-Integrated Circuits: Hybrid optical-THz systems to bypass electronic bottlenecks [3].

4.1.2 Scalable Antenna Arrays

Issue: Fabricating ultra-dense antenna arrays (e.g., 1024 elements at 1 THz) with nanoscale precision remains costly [76].

Future Directions:

- 3D-Printed Metamaterials: Low-cost, reconfigurable THz antennas [77].
- RIS-Assisted Beamforming: Offload complexity from active arrays to passive metasurfaces [78].

B. AI/ML Algorithmic Challenges

4.2.1 Real-Time AI Inference

Issue: DNNs introduce latency (10–100 µs) incompatible with 6G's sub-ms targets [79].

Future Directions:

- Spiking Neural Networks (SNNs): Event-driven processing for µs-latency beam tracking [80].
- Analog AI Chips: In-memory computing to eliminate digital overhead [81].

4.2.2 Generalization Across Environments

Issue: AI models trained in simulated THz channels fail in real-world deployments (e.g., rain, dust) [82].

Future Directions:

- Digital Twins: High-fidelity virtual THz environments for AI training [83].
- Meta-Learning: Few-shot adaptation to unseen scenarios [84].

C. Energy-Sustainability Trade-offs

4.3.1 Green AI for THz Networks

Issue: Training a single DNN consumes ~1 MWh—equivalent to 50 households' daily use [85].

Future Directions:

- TinyML on Edge Devices: Binary neural networks (BNNs) for sub-1W inference [14].
- Neuromorphic Hardware: Brain-inspired chips (e.g., Loihi) for energy-efficient learning [86].

4.3.2 THz-Specific Power Amplifiers

Issue: THz PAs exhibit <5% efficiency vs. 20–30% for mmWave [86].

Future Directions:

- Nonlinear Waveform Engineering: Envelope tracking for wideband efficiency [87].

V. CONCLUSION

The integration of terahertz (THz) communication and AI-driven signal processing is poised to revolutionize 6G wireless networks, enabling unprecedented data rates (Tbps), ultra-low latency, and ubiquitous connectivity. However, this paper has identified critical challenges—propagation losses, hardware inefficiencies, mobility limitations, and security vulnerabilities—that must be addressed to realize this vision.

A. Key Contributions of This Work

1) THz Channel Characterization: Demonstrated how molecular absorption and blockages degrade performance, necessitating AI-aided solutions.
2) AI-Driven Optimization: Showed that techniques like reinforcement learning (RL) for beam tracking and federated learning (FL) for distributed CSI estimation can mitigate THz limitations.
3) Energy-Security Trade-offs: Highlighted the need for green AI (e.g., TinyML, neuromorphic computing) and quantum-resistant encryption in THz networks.

B. Future Outlook

1) Hardware Innovation: Graphene-based transceivers and 3D-printed antennas could overcome current efficiency bottlenecks.
2) Standardization: Global cooperation (e.g., ITU, 3GPP) is essential for THz spectrum allocation and AI-native protocol design.
3) Security Frameworks: Adversarial-resistant AI and physical-layer encryption must be prioritized.

C. Final Thought

The journey toward 6G is not merely an evolution but a paradigm shift, demanding cross-disciplinary collaboration among material scientists, AI researchers, and communication engineers. By tackling the open challenges outlined in this paper, we can unlock THz's full potential—ushering in an era of hyper-connected, intelligent networks that transform industries from healthcare to autonomous transport.

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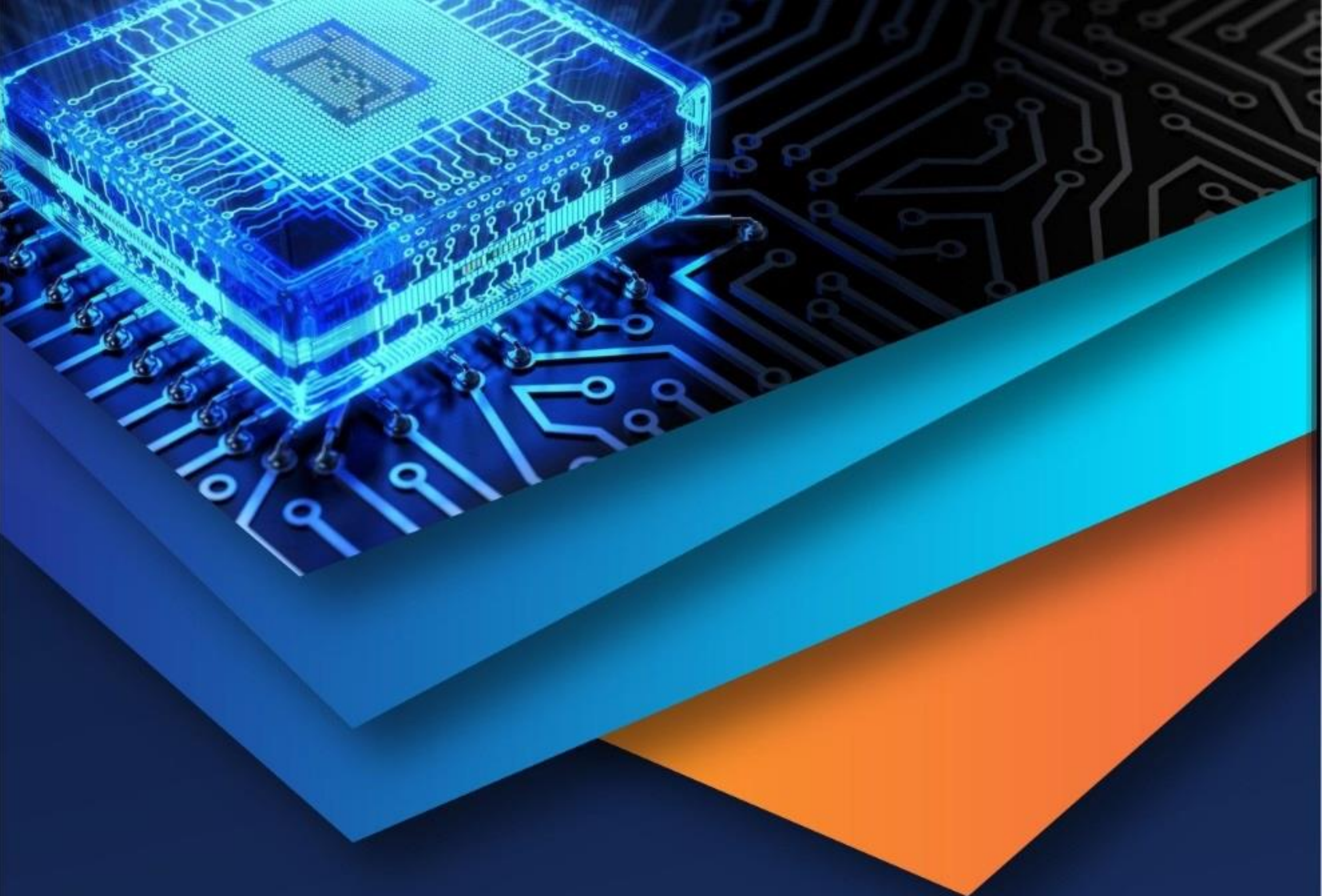

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