Digital Transformation From 5G to 6G Survey

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***Abstract*— Advances in wireless communication technologies have driven the world's digital transformation. While the 5th generation (5G) networks have enabled breakthroughs like smart cities and industrial automation, their limitations in spectrum efficiency, energy consumption, and scalability hinder their ability to support emerging applications such as holographic communications, pervasive Artificial Intelligent (AI), and the Internet of Everything (IoE) a gap that necessitates the transition to 6G. This paper presents a survey of the digital transformation journey from 5G to 6G, examining the technological advancements, challenges, and opportunities that define this transition. It explores the limitations of 5G, the envisioned features of 6G (e.g., terahertz communication (THz), AI-native networks), and the transformative applications it enables. However, critical challenges persist, including unresolved technical barriers (e.g., THz signal attenuation), ethical risks in AI governance, and fragmented global standardization efforts. The survey underscores the necessity for board collaboration to address these barriers and realize 6G's transformative potential. By synthesizing existing research, this work concludes that equitable access, sustainable deployment, and proactive policy frameworks are essential to ensure 6G technology develops in harmony with societal values and industrial needs while bridging the digital divide.**

***Keywords*— 5G, 6G, digital transformation, terahertz communication, AI, IoE**

I. INTRODUCTION

The advancements in wireless communication technologies are a substantial factor supporting digital transformation and changing communities, sectors, and economies at an unprecedented scale. The modalities of connectivity provided by 5G technologies (e.g., ultra-reliable low-latency communications (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB)) [1]. These advancements have driven innovation and efficiency across industries, encompassing transformative technologies like autonomous vehicles, interconnected smart cities, and the expansive Internet of Things (IoT) [2]. However, the increasing demands for higher data rates, lower latencies, and more reliable connectivity grows, the limitations of 5G such as spectrum scarcity, energy inefficiency, and uneven rural coverage become apparent [3, 4]. This necessitates a revolutionary shift toward 6G, expected to overcome these limitations and unlock new opportunities for digital transformation [5]. The evolution from 5G to 6G is a step forward and a monumental leap in wireless capabilities. 6G is anticipated to integrate transformative technologies such as terahertz (THz) communication [6], reconfigurable intelligent surfaces (RIS) [7], and AI-native network management [8], enabling groundbreaking applications like holographic communication, extended reality (XR), and advanced industrial automation [5]. Nonetheless, significant challenges persist, including technology barriers (e.g., THz signal attenuation [9]), regulatory fragmentation [10], and threats to security in AI-driven networks [11]. Overcoming these challenges is crucial to realize the full potential of 6G's [6, 12].

To anticipate the possibilities of 6G, it is prudent to reflect on the history of wireless systems from older 1st generation to disruptive 5th generation across distinct phases of development. Section II traces the historical line of development of wireless communication systems.

II. THE EVOLUTION OF WIRELESS COMMUNICATION TECHNOLOGIES

The evolution of wireless communication technologies has been marked by significant advancements. Each generation has introduced new possibilities, addressing rising demands for connectivity, speed, and reliability, which will be discussed as follows:

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A. A Review of Network Generations Progression: From 1G to 4G

The progression of wireless communication technologies highlighted in the following points:

- This 1st generation 1G, began in the 1980s, marked the beginning in mobile telephony, using analog technology, which was limited to voice communication with limited coverage and poor sound quality, the 1G set the foundation for mobile telecommunication.
- The 2nd generation 2G began in the early 1990s, and it adopted digital technology, as well as setting the stage for mobile data, which includes voice communication, text messaging (SMS), and basic data services [1], improving call quality and security.
- The 3rd generation 3G technology was launched in the early 2000s which allowed internet access that provided multimedia services such as video calling, mobile browsing, and email [1]. With this generation, the smartphone era began.
- The 4th generation 4G, wireless communication was introduced in the 2010s by utilizing Long-Term Evolution (LTE) technology, and revolutionized wireless communication. 4G wireless networks offered much higher data rates than previous generations, lower latency, and higher capacity making possible high-definition video streaming, online gaming, and heavy bandwidth usage applications [2]. Global deployment of 4G enabled a digital transformation of industries and promoted IoT usage.

B. The Role of 5G in Digital Transformation.

The 5th generation (5G) technology, which was standardized in the latter part of the 2010s and commercially launched from 2019, has played a key role in driving digital transformation across industries. By supporting three fundamental use cases—enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). 5G enables applications requiring high-speed connectivity, real-time responsiveness, and effortless integration of Internet of Things (IoT) ecosystems [1, 13]. In Smart cities, where 5G enables IoT-based infrastructure, a use case includes Barcelona's smart city initiative, which leverages 5G-connected environmental sensors to monitor air quality and optimize waste management systems, reducing energy consumption and enhancing urban sustainability [2]. In industrial automation, 5G enables real-time data analytics for predictive maintenance, leading to greater operational uptime and boosting productivity. For instance, smart factories leverage 5G's URLLC capabilities to synchronize robotic systems and ensure precision in manufacturing processes [2, 3]. Some of the underlying technologies facilitating 5G's effectiveness include millimeter waves (mmWave) for high bandwidth, massive MIMO (multiple-input-multiple-output) for enhanced capacity, and network slicing for customized service provision [13]. These innovations have revolutionized fields such as healthcare (e.g., remote surgeries through low-latency networks) and logistics (e.g., real-time monitoring of autonomous vehicles) [3].

While 5G has driven significant digital transformation, its limitations have encouraged the next leap forward in wireless communication, the development of 6G. Section III examines these constraints and emerging requirements that 6G must address.

III. LIMITATIONS OF 5G AND THE NEED FOR 6G

5G has brought significant advancements, but it has limitations to meet future demands. These limitations can be categorized into technical challenges and emerging application requirements, as summarized in Table 1 below.

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TABLE I
QUANTIFYING INNOVATION THROUGH THRESHOLD-BASED EVOLUTIONARY ANALYSIS

Category	5G Baseline	6G Projection	Enabling Innovations	Critical Challenges	Future Research Directions
Peak Data Rate	**20 Gbps (mmWave bands)**	**1 Tbps (THz LOS, >300 GHz)**	**Photonic ICs (low-loss THz circuits), graphene meta-surfaces (adaptive antennas)**	**300 GHz atmospheric attenuation (100 dB/km rain fade), device miniaturization**	**Hybrid RF-optical systems, dynamic spectrum sharing for THz bands**
Latency	**1 ms (URLLC for industrial IoT)**	**0.1 ms (theoretical edge-AI)**	**AI-optimized RAN (predictive resource allocation), edge-native serverless compute**	**Jitter control in multi-operator slicing, synchronization for global edge networks**	**Federated learning for latency-critical apps, quantum networking prototypes**
Energy Efficiency	**3 μJ/bit (dense small cells)**	**0.1 μJ/bit (sustainability target)**	**RIS-assisted beamforming (passive signal focus), spiking neural networks (event-driven AI)**	**THz transceiver power consumption, thermal management for photonic systems**	**Energy harvesting RIS, neuromorphic hardware for base stations**
Mobility Support	**500 km/h (high-speed trains)**	**1000 km/h (hyperloop, drones)**	**Doppler-resilient waveforms (OTFS modulation), cell-free massive MIMO**	**Handover at THz frequencies, beam alignment for hypersonic mobility**	**AI-driven beamtracking, integrated satellite-terrestrial protocols**
Localization Accuracy	**1 m (indoor GPS-assisted)**	**1 cm (mm-precision ISAC)**	**ISAC with 10 GHz bandwidth (joint comms-sensing), sub-λ wavelength imaging**	**Multipath interference in dense urban environments, privacy-preserving sensing**	**Meta-surface-enabled "smart walls" for multipath suppression, blockchain for secure sensing**
Security & Privacy	**Post-quantum algorithms (e.g., lattice-based crypto)**	**AI-driven zero-trust architectures (self-healing networks)**	**Homomorphic encryption, decentralized identity ledgers (blockchain)**	**Scalability of quantum-resistant protocols, explainable AI for trust**	**Post-quantum standardization (NIST integration), AI-auditable security layers**
Network Density	**10^6 devices/km²** **(massive IoT)**	**10^7–10^8 devices/km² (ambient IoT)**	**Holographic MIMO, sub-THz ambient backscatter (passive device connectivity)**	**Interference in ultra-dense networks, energy per device (<1 μW)**	**Fluid antenna systems, symbiotic radio networks**

Table 1 presents 6G as a step forward from 5G, targeting 1 Tbps peak rates in the Terahertz (THz) spectrum, 0.1 ms latency, and centimeter-level localization. This is achieved through via new capabilities: Integrated Sensing and Communications (ISAC). This vision realization depends on pervasive AI for network optimization and proactive security, alongside innovations like Reconfigurable Intelligent Surfaces (RIS) for enhanced efficiency. Nevertheless, it also introduces significant challenges, the physical limitations of THz propagation, such as atmospheric attenuation and high-power consumption.

A. Technical Limitations

While 5G can transform experiences, it faces significant technical challenges. The most critical is spectrum scarcity. The rise of connected devices and bandwidth-intensive applications is saturating lower-frequency bands (sub-6 GHz), historically used for wide-area coverage and penetration. Higher frequency mmWave bands offer greater bandwidth but suffer from shorter propagation distances and susceptibility to physical obstructions, limiting their use in dense urban or indoor environments [3]. Energy consumption is another hurdle: 5G networks require nearly triple the energy for a single base station compared to 4G as a results of small-cell proliferation, massive MIMO antennas, and persistent connectivity demands, escalating operational costs [4]. Coverage gaps persist in rural and remote areas, where high infrastructure costs and low population density render 5G deployment commercially impractical. For urban centers, the technological capabilities contrast sharply with those in rural regions, such as Barcelona's's smart city ecosystems [2], where living costs create significant disparities. Subsidized deployment models, notably India's BharatNet program for rural broadband [16], offering a scalable solution for ensuring future 6G equity, such as hybrid satellite-terrestrial networks, that bridge the urban-rural divide.

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Even in cities, 5G struggles with indoor coverage due to mmWave limitations, hindering access to telehealth and remote education. Ultra-massive connectivity strain's reliability and latency [17], while network congestion, interference, and technologies like network slicing and edge computing [18] compound operational complexity. These challenges underscore the need for 6G's globally interoperable, energy-efficient architectures.

B. *Emerging Application Requirements*

Next-generation technologies, including holographic communication and XR, require terabit-per-second data rates speed and sub-millisecond latency, super passing the capabilities of current 5G networks [18]. Similarly, AI-driven applications demand seamless integration of wireless communications with AI functionalities a challenge for existing 5G infrastructure [8]. Future applications also require integrated sensing and communication (ISAC), a feature 5G cannot accommodate [12]. Likewise, smart cities and IoT applications rely on ultra-massive connectivity, high reliability, and low latency capabilities beyond 5G's current scope [19]. Furthermore, 5G's reliance on dense infrastructure and high-bandwidth frequencies complicates deployment in underserved regions, limiting its adaptability to emerging use cases [20]. These limitations underscore the need for advancements beyond 5G to meet next-generation requirements.

After discussing the limitations of the 5G architecture from a technical capability and requirement application perspective. Section IV will introduce how 6G groundbreaking technologies such as THz communications and AI-native networks.

IV. ENVISIONING 6G: KEY FEATURES AND TECHNOLOGIES

The 6G emerging technologies such as THz Communication, AI and Machine Learning (ML), RIS and Integrated Sensing and Communication (ISAC) will be described in the following points:

A. *THz Communication*

Through THz frequency band (0.1–10 THz) the 6G networks promise theoretically high speeds of data rates up to 1 Tbps significantly surpassing 5G mmWave systems, which typically peak at 2 Gbps. Leading to revolutionize media consumption, enabling tasks like downloading full-length 8K movies in milliseconds. However, practical deployment faces significant challenges. For instance, atmospheric absorption at higher frequencies causes severe attenuation limiting coverage to short-range line-of-sight (LOS) communication of just a few meters. Additionally, current THz transceivers and antennas remain bulky and energy-intensive hardware. To address this, researchers are exploring nano-material fabrication, such as graphene-based antennas (experimental but promising for reducing losses [21]). These advances in material science are critical to uncover the full potential of the THz band[1].

B. *AI and Machine Learning (ML)*

AI and ML are foundational to 6G networks, transitioning from assistance tools to core architectural components. Optimizing network performance and permitting dynamic spectrum sharing, but they also introduce critical trade-offs. While efficient centralized AI architectures risk creating single points of failure and data privacy breaches, as highlighted in studies on blockchain-AI integration [11]. On the contrary, decentralized federated learning frameworks [14] enhance privacy by decentralizing data but may compromise real-time efficiency due to computational overhead. Ethical challenges also arise, in particular algorithmic bias in resources allocation. For instance, AI models trained on urban-specific data may perform less well in rural areas, exacerbating the digital divide instead of alleviating it [22]. Governance frameworks will need to ensure that efficiency is balanced with ethical issues such as fairness in data representation, and equitable distribution of services [23].

C. *Reconfigurable Intelligent Surfaces (RIS)*

RIS technology enables energy-efficient signal enhancement but faces scalability challenges in dense urban environments. Deploying RIS across thousands of surfaces in large cities introduces synchronization complexities and elevated hardware costs, as noted in studies on RIS deployment logistics [24]. While RIS improves signal quality in multi-user scenarios, it risks amplifying interference signals, necessitating advanced beamforming algorithms to mitigate this drawback [25]. Additionally, the lack of standardized RIS protocols risks vendor lock-in, limiting interoperability between products from different manufacturers [23]. This creates a trade-off between operational flexibility (e.g., safety compliance) and cross-vendor portability.

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[1] These theoretical projections are derived from early-stage simulations and require experimental validation in real-world environments.

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D. Integrated Sensing and Communication (ISAC)

ISAC's dual-purpose functionality optimizes spectrum efficiency but introduces a fundamental trade-off: dedicating spectrum to sensing reduces available bandwidth for communication, degrading Quality of Service (QoS) in high-traffic scenarios [12]. For instance, autonomous vehicles require sub-millisecond latency for real-time sensor data transmission, conflicting with computational delays inherent to ISAC processing [15]. While AI optimization techniques [26] can alleviate some latency issues, hardware limitation such as inefficient THz transceivers [27] hinder ISAC's scalability.

Consequently, ISAC may prioritize niche, critical applications (e.g., emergency response systems) over general-purpose 6G use cases [12].

With foundational technologies for 6G defined, the next Section V illustrates how these technologies become transformative applications in the world, from holographic healthcare to pervasive AI.

V. APPLICATIONS ENABLED BY 6G

With the unbound potential of the next generation network, new application will transform how we work and communicate, some of these applications is summarized in the following points:

A. Holographic Communications

The implementation of 6G is anticipated to be groundbreaking for communication, with the ability to generate real-time 3D holograms, addressing the limitations caused by video conferencing in 2D. 6G networks are counted on to leverage THz frequencies and ultra-low latency (<1ms) to create high-definition holograms for users. For example, engineering teams working collaboratively can now have a holographic workspace to design and iterate prototypes remotely, which would decrease the amount travelled to in person (thereby reducing costs) and improve the velocity of innovation [18]. In the healthcare industry, interactive 3D holograms could allow for better remote surgical assistance and guidance (thus improving access to specialized healthcare). Entertainment and hospitality's usage of 6G may include surplus of options like attending holographic concerts, and immersive games. The only condition to usage is advance THz hardware and protocols to improve energy efficiency to support large-scale users [27, 9].

B. AI-Native Network

Real-time decision-making will be a powerful aspect of 6G networks with AI embedded within. Autonomous vehicles could access edge-AI on a 6G network, processing data based off predictive analytics from sensors to anticipate pedestrian actions, making it safer [19]. Smart grids with integrated 6G networks and AI capabilities may enhance the balancing between energy supply and demand in a highly dynamic manner, such as the studies dealing with the combination of IoT and blockchain toward sustainable energy ecosystems. AI embedded control systems would distribute energy across smart cities [29] while resilience algorithms would lower the risk of blackouts via load prediction in real time [28]. The new capabilities ushered in by AI, AIML and 6G networks also raise some ethical distress, such as data privacy and algorithmic bias that leads to systemic discrimination [11].

C. Internet of Everything (IoE)

6G is set to transform the Internet of Things (IoT) into a far more integrated "Internet of Everything" (IoE). This represents a significant transformation, moving beyond just connecting devices to creating a seamless network where autonomous systems, environmental sensors, and human interfaces can interact in real time. For example, traffic solutions could use AI to reroute vehicles according to pollution readings, with energy efficient 6G connectivity offering the fundamental support for this [30, 31]. In agriculture, IoE-based farms may deploy soil sensors and autonomous tractors for sustainable increases in crop yields [20]. Medical wearable data may be disseminated to hospitals in milliseconds [32], while factories could synchronize machines with robots depending on standardized 6G protocols. All these applications rely on technical advances to deal effectively with the issues of scalability and interference, such as graphene antennas [21] and fractional-order algorithms [33].

Despite these groundbreaking applications, the transition to 6G faces formidable challenges. Section VI examines technical, regulatory, and ethical challenges in its deployment.

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VI. CHALLENGES IN THE TRANSITION TO 6G

The transformation towards the 6G of wireless communication technology, promises to change connectivity with unparalleled speeds. However, this leap forward comes with significant challenges, from implementing new infrastructure and spectrum allocation to ensuring energy efficiency, security, and global standardization. The path to 6G is full of technical, regulatory, and economic hurdles.

A. Technological Challenges

The advancement towards realization of 6G entails sophisticated societal and technological challenges, particularly with respect to hardware advances and universal connectivity. The hardware for THz communication requires significant breakthroughs in antenna technological innovations and signal processing capabilities. The expected operating range for THz frequency is (0.1 – 10 THz), which would theoretically achieve up to 1 Tbps. or greater data rates. However, THz communication is very susceptible to noticeable atmospheric absorption and has poor penetration through physical barriers. For example, the attenuation at 300 GHz can be as much as 100 dB/km in free space (atmospheric condition) caused by molecular resonance (e.g., water vapour absorption) [9]. To mitigate through these challenges, significant innovations in advanced materials (e.g., graphene-based plasmonic antennas, [21] and photonic integrated circuits) is critical to meet an efficient transmission of signals. These materials provide higher gain and lower losses at THz frequencies, supported by recent laboratory prototypes achieving 50% lower attenuation [9]. However, the prevailing semiconductor technologies which account for the energy mandate of THz transceivers are challenged by ultra-low power, minimal footprint form-factor components, leading to minimalizing operational requirements, while providing low transmission performance. This gap can only be solved by an interdisciplinary collaboration of material scientists, RF engineers, and AI researchers who not only gauged hardware, but initiate fundamental research of energy efficiency in transmission.

Distinct hardware constraints drive the performance of application-layer services. For instance, smart warehouses using 6G's Integrated Sensing and Communication (ISAC) for real-time asset tracking [12] experience degradation in localization accuracy because of multipath interference in high-frequency spectrums. THz propagation studies [34] indicated that reflections off metal surfaces and machinery that are common in industrial environments produce signal nulls and phase distortions, which decreases precision localization measurements by approximately 30% in such setting. Environment-aware beamforming solutions are pivotal for closing the gap between theoretical and practical 6G applications. Recent research [34] illustrates that sub-centimetre's localization accuracy (<1 cm) under line-of-sight (LOS) conditions in high frequency band (THz). However, in multipath-rich industrial environments, signal reflections degrade precision, necessitating dynamic beamforming algorithms tailored to real-time spatial variations [35], the development of dynamic beamforming algorithms that are responsive to real-time alterations in the spatial environment is highly desirable and is already being explored. Advances in AI [35], have also generated the potential for adaptive beamforming, but there are still scalability challenges.

B. Spectrum Harmonization and Standardization Challenges in 6G

The introduction of the THz spectrum (0.1–10 THz) presents major obstacles due to the disconnected international allocation plans. For instance, while the ITU-R identifies the THz band (275 GHz–3 THz) as critical for 6G, regional disparities persist. In Japan, the 40.5–42.3 GHz and 48.4–50.2 GHz bands are prioritized for industrial automation and 6G, whereas the U.S. Federal Communications Commission (FCC) has allocated 3.85 GHz of licensed spectrum in the 27.5–28.35 GHz and 37–40 GHz bands for ultra-high-speed wireless communication. The difference risks interoperability when dealing with cross-border technologies like autonomous shipping or global IoT ecosystems. The International Telecommunication Union (ITU) must prioritize a global allocation process to resolve these issues [10]. Standardization is important for 6G's success. Organizations like 3GPP and IEEE are pushing forward protocols for emerging technologies: 3GPP Release 17 extends 5G NR to unlicensed mmWave bands (52.6–71 GHz), while IEEE 802.15.3d-2017 standardizes 100+ Gbps THz point-to-point links [10]. But they must collaborate with telecom stakeholders to develop AI-native networks and quantum communications [36]. Without unified standards for innovations like reconfigurable intelligent surfaces (RIS) and integrated sensing and communication (ISAC), vendor lock-in, inflated costs, and stifled innovation could prevail [25, 12]. Proactive standardization grounded in evidence-based research, not market speculation, is essential to ensure equitable growth in the telecom sector [36].

C. Ethical and Security Concerns

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The synthesis of AI into 6G networks presents a significant privacy risks, particularly in smart cities where real-time data can reveal personal information's [8]. While privacy-by-design frameworks like federated learning offer technical solutions, they are not comprehensive [14]. Federated learning, for instance, can amplify biases within regional datasets, creating inequitable outcomes [23]. This concern for equity extends from data bias to network access itself, making the prevention of a digital divide both an ethical and technical imperative. To address this, hybrid infrastructure like satellite-augmented networks can bridge the urban-rural gap, with programs such as India's BharatNet serving as models for inclusive deployment [16]. Furthermore, equitable access requires affordable hardware, meaning research must prioritize low-cost designs for components like THz transceivers to ensure global adoption [9, 10, 28]. These efforts must be guided by robust ethical governance to prevent AI-driven 6G from intensifying inequalities, especially in developing nations [16, 23]. Policymakers should therefore align 6G development with global goals to balance innovation with fairness [16, 37].

TABLE 2
AN ANALYSIS OF THE CORE TRADE-OFFS IN 6G

Aspect	Conflict	Example	Resolution	Key Stakeholders
Speed vs. Equity	**Ultra-fast THz speeds require dense infrastructure, prioritizing urban areas over rural regions.**	**THz's 100 dB/km rain attenuation limits rural coverage due to short-range LOS requirements, escalating deployment costs.**	**Phased THz rollout with hybrid sub-6 GHz + THz networks, funded by public-private partnerships.**	**Telecom operators, policymakers, rural advocacy groups**
Innovation vs. Ethics	**AI-native networks optimize performance but risk surveillance, bias, and algorithmic discrimination.**	**Urban-centric AI training datasets misallocate bandwidth in rural areas, worsening the digital divide.**	**Federated learning (privacy-preserving AI) and third-party algorithmic audits for fairness/transparency.**	**AI researchers, ethicists, civil society groups, regulators.**
Global vs. Local	**Standardization ensures interoperability but risks stifling region-specific innovations.**	**Conflicting THz spectrum allocations: Japan (92–300 GHz) vs. U.S. (95 GHz–3 THz) hinder global harmonization.**	**ITU-coordinated bands (e.g., 275–450 GHz) with carve-outs for regional pilots (e.g., EU Hexa-X initiatives).**	**ITU, 3GPP, national regulators, industry alliances (e.g., Next G Alliance)**
energy Efficiency vs. Performance	**THz transceivers consume high power for ultra-fast speeds.**	**6G's 0.1 µJ/bit target vs. THz hardware energy demands.**	**Green AI models + recyclable RIS materials.**	**Engineers, environmental agencies, chip manufacturers**
Privacy vs. Network Intelligence	**Integrated sensing (ISAC) enables tracking risks.**	**mm-precision ISAC could invade privacy.**	**Blockchain-based anonymization + strict data laws.**	**Privacy regulators, cybersecurity experts**
Standardization Flexibility	**ITU global rules vs. regional innovation needs.**	**EU's Hexa-X vs. U.S. Next G Alliance priorities.**	**"Core-global, edge-local" spectrum policies.**	**ITU, regional alliances (e.g., Hexa-X)**

Table 2 highlights the conflicts facing 6G in terms of critical socio-technical factors, from technical possibility to deployment reality. It underscores the ethical risks of bias and surveillance. The geopolitical tension between global standards and regional innovation is noted, the trade-off between network performance and energy consumption, and the privacy challenges raised by integrated sensing (ISAC). Resolutions require a multi-dimensional approach, combining hybrid technical-policy solutions with privacy-by-design technologies, such as federated learning and blockchain.

VII. RESEARCH DIRECTIONS AND FUTURE WORK

Several critical research areas will reshape wireless networking:

1. THz Communication: The development of terahertz (THz) communication is pivotal for ultra-fast data transmission. Key challenges include designing energy-efficient transceivers and antennas to support high-capacity wireless links in the THz spectrum (0.1–10 THz) [9, 34].

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2. AI-Native Networks: Integrating AI into network design will enable machine learning-driven optimization of resource allocation, user experience, and process automation. This shift toward adaptive, intelligent networks is critical for 6G's scalability and efficiency [8].
3. Energy Efficiency: Sustainable 6G infrastructure demands innovations in energy-efficient architecture and technologies. Prioritizing low-power hardware and green network designs will reduce environmental impact while maintaining global connectivity [4, 28].

In conclusion, Section VIII summarize the paper's insights, emphasizing interdisciplinary collaboration for equitable 6G deployment.

VIII. Conclusions

The transition to 6G signals a significant leap forward, promising transformative applications such as holographic communication and the Internet of Everything (IoE). Realizing this vision, however, requires a concerted effort to balance technological innovation with foundational goals for a sustainable future. The technical trade-offs are profound; while Terahertz (THz) communication offers unprecedented speed, its susceptibility to signal loss necessitates the development of new, energy-efficient hardware. In parallel, while AI-native networks can optimize resources, they pose significant ethical risks of surveillance and bias, demanding robust governance and fair frameworks to uphold principles of justice and privacy. Furthermore, emerging technologies like Reconfigurable Intelligent Surfaces (RIS) and Integrated Sensing and Communication (ISAC) require unified standards forged through international partnerships, such as the ITU and 3GPP. By embracing interdisciplinary collaboration to navigate these challenges, we can shape 6G into an inclusive digital ecosystem that bridges the urban-rural divide and thoughtfully balances technological progress with social equity.

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