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A Survey of Digital Transformation from 5G to 6G

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***Abstract*— Advances in wireless communication technologies have driven the world's digital transformation. With the very 5th generation (5G) referred to as ultra-reliable, low-latency, and high-speed connections, the rise of the 6th generation (6G) is disruptive as it will change the human-tech environment completely. 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, and the transformative applications it enables, such as holographic communications, pervasive AI, and the Internet of Everything (IoE). Furthermore, discussing the research directions and standardization efforts required to realize the full potential of 6G.**

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

I. Introduction

The rapid development of wireless communication technologies is a key factor of digital transformation, reshaping societies, industries, and economies worldwide. The deployment of 5G networks has revolutionized connectivity, enabling ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB) [2]. These advancements have affected all industries such as autonomous vehicles, smart cities, and the Internet of things (IoT), leading to unprecedented innovation and efficiency [9]. However, as demand for higher data rates, lower latency, and more reliable connectivity grows, the limitations of 5G are becoming evident. This has led to the need to a new technology that can eliminate the existing limitation of 5G, and this technology is 6G which is promising to address these limitations and expand new opportunities for digital transformation [3].

The transition from 5G to 6G is not merely an incremental improvement but a huge shift, redefining the capabilities of wireless networks. 6G is expected to integrate cutting-edge technologies such as terahertz (THz) communication, reconfigurable intelligent surfaces (RIS), and AI-driven network management, enabling applications like holographic communication, extended reality (XR), and advanced industrial automation [4]. However, this transition presents significant challenges, including technological, regulatory, and security hurdles that must be addressed to realize 6G's full potential [5].

The rest of the paper is organized as follows: Section II discusses the evolution of wireless communication technologies, Section III highlights the limitations of 5G and the need for 6G, Section IV explores the key features and technologies of 6G, Section V examines the applications enabled by 6G, Section VI discusses the challenges in the transition to 6G, Section VII outlines research directions, and Section VIII concludes the paper.

II. The Evolution of Wireless Communication Technologies

The evolution of wireless communication technologies has been marked by significant advancements, transforming how societies and industries work. Each generation has introduced new possibilities, addressing rising demands for connectivity, speed, and reliability, which will be discussed in the following points:

- ***From 1G to 4G: A Historical Perspective***

The evolution of wireless communication technologies has been marked by significant milestones:

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- The 1st generation 1G, introduced in the 1980s, this was the first step in the mobile telephony, which is based on analog technology, 1G provided basic voice communication with limited coverage and poor sound quality [6]. Despite its limitations, 1G laid the groundwork for mobile communication.
- The 2nd generation 2G, introduced in the early 1990s, which adopted digital technology, and bringing in the concept of mobile data, that enables voice communication, text messaging (SMS), and basic data services [7]. This generation improved call quality and security.
- The 3rd generation 3G, launched in the early 2000s, brought internet access, allowing multimedia services such as video calling, mobile browsing, and email [8]. This generation marked the beginning of the smartphone era.
- The 4th generation 4G, introduced in the 2010s, revolutionized wireless communication with Long-Term Evolution (LTE) technology. 4G networks provided significantly higher data rates, lower latency, and greater capacity, providing high-definition video streaming, online gaming, and other bandwidth-intensive applications [9]. The widespread adoption of 4G laid the foundation for the digital transformation of industries and the rise of IoT.

- ***The Role of 5G in Digital Transformation***

The 5th generation 5G, deployed in the late 2020s, represents a pinnacle in connectivity. 5G supports three key use cases: eMBB, URLLC, and mMTC. With this, it is possible to use several applications, one of which is realizing a smart city and automation in industries. An example is the Barcelona Smart City project where 5G IoT sensors are wired to the environment and air quality, monitoring waste systems, and optimizing energy, cutting down on the total urban consumption in the city. Similarly, in the industrial sector, Siemens has implemented 5G technology in its smart factories in Germany. By leveraging real-time data analytics, the company can predict equipment failures, minimize operational downtime, and enhance overall productivity [9]

5G achieves its performance improvement through technologies like millimeter waves, massive MIMO (Multiple-Input Multiple-Output), and network slicing [10]. However, despite its advantages, 5G faces challenges such as limited coverage in rural areas, high energy consumption, and difficulties in supporting ultra-massive connectivity [12]. These limitations have encouraged the development of 6G.

III. Limitations of 5G and the Need for 6G

The 5th 5G has brought significant advancements, it has limitations that hinder its ability to meet future demands. These limitations can be categorized into technical challenges and emerging application requirements as presented in the following points.

- ***Technical Limitations***

Despite its transformative capabilities, 5G faces several technical limitations. One critical challenge is spectrum scarcity. The expanding number of connected devices and data-intensive applications has congested lower-frequency bands (sub-6 GHz), which are traditionally used for wide-area coverage and penetration. While higher-frequency millimeter-wave (mmWave) bands offer greater bandwidth, their limited propagation range and tendency to be obstructed by physical barriers restrict their practicality in dense urban or indoor environments [12]. This congestion not only degrades network performance but also complicates the allocation of spectrum for emerging technologies such as autonomous vehicles and smart grids, highlighting the need for innovative solutions to optimize spectrum utilization.

The 5G networks require more energy consumption than previous generations due to the widespread use of small cells, the use of large-band MIMO antennas, and the need for continuous connectivity. For instance, a single 5G base station can consume up to three times more energy than a 4G equivalent, adding to operational costs [14].

Limited coverage remains a significant challenge, particularly in rural and remote areas, where deploying 5G infrastructure is often economically impractical due to high costs and low population density. Even in urban environments, ensuring consistent indoor coverage with mmWave frequencies demands expensive infrastructure upgrades, restricting access to essential services such as telehealth and remote education. Additionally, 5G networks face scalability issues in ultra-massive connectivity scenarios, resulting in increased latency and reduced reliability [16]. Achieving ultra-low latency in real-world conditions is further complicated by network congestion and interference [13]. Moreover, integrating advanced technologies like network slicing and edge computing introduces greater complexity, posing further challenges to the effective deployment and operation of 5G networks [17].

- ***Emerging Application Requirements***

Emerging technologies such as holographic communication and extended reality (XR) demand terabit-per-second data rates and sub-millisecond latency, which 5G networks can't support [18]. Similarly, AI-driven applications require seamless integration of wireless communication with AI capabilities, a challenge for the current 5G infrastructure [19]. Future applications also require the integration of sensing and communication, a feature that 5G lacks the infrastructure to accommodate [20]. Furthermore, smart cities and IoT applications rely on ultra-massive connectivity with high

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reliability and low latency, capabilities that 5G cannot fully deliver [21]. Additionally, 5G's reliance on dense infrastructure and high-frequency bands makes it difficult to extend coverage to underserved regions [22]. These limitations highlight the need for advancements beyond 5G to meet the demands of next-generation technologies.

IV. ENVISIONING 6G: KEY FEATURES AND TECHNOLOGIES

Some of the main technologies of 6G are THz Communication, AI and Machine Learning (ML), Reconfigurable Intelligent Surfaces (RIS) and Integrated Sensing and Communication (ISAC). These features will be describes in the following points.

- ***THz Communication***

6G networks are poised to leverage the THz frequency band (0.1–10 THz) to achieve data rates exceeding 1 terabit per second (Tbps), a huge improvement over 5G. For instance, THz frequencies could allow a full-length 8K movie to be downloaded in milliseconds, revolutionizing media consumption and cloud computing [17]. However, THz communication faces significant technical hurdles. Signals in this band suffer from high atmospheric absorption and are easily attenuated by obstacles like rain or walls, limiting their effective range to a few meters. Additionally, current hardware, such as THz transceivers and antennas, remains bulky and energy-intensive, necessitating breakthroughs in nano-material fabrication and photonic-integrated circuits to enable compact, cost-effective solutions. Researchers are exploring graphene-based devices and plasmonic antennas to overcome these challenges, paving the way for THz to address 5G’s spectrum scarcity by unlocking vast unused bandwidth [22]

- ***AI and Machine Learning (ML)***

AI and Machine Learning (ML) will form the backbone of 6G networks, transitioning from assistive tools to core architectural components. AI-native networks will autonomously optimize performance through real-time traffic prediction, self-healing protocols, and dynamic spectrum sharing. For example, an AI-driven 6G base station could predict user mobility patterns and pre-allocate resources to avoid congestion during peak hours, enhancing quality of service (QoS) for applications like autonomous driving [6]. Enabling distributed AI training across edge devices without centralized data aggregation improves privacy. These innovations will address 5G’s limitations in handling heterogeneous data streams and ensure that 6G networks are intelligent and ethically responsible.

- ***Reconfigurable Intelligent Surfaces (RIS)***

Beyond 5G (B5G) and 6G wireless systems, reconfigurable intelligent surfaces (RIS) is a groundbreaking technology that offers elaborate solutions to challenges like limited coverage, energy inefficiency, and interference [13]. RIS can dynamically control electromagnetic waves to enhance signal quality, extend connectivity, and improve energy efficiency, a key element for future applications such as smart cities and integrated sensing. Addressing scalability and interference issues while enabling advanced use cases, like holographic communication and AI-driven network optimization [25].

- ***Integrated Sensing and Communication (ISAC)***

ISAC represents a critical step forward in 6G, combining sensing and communication functionalities to enhance efficiency and enable advanced applications such as autonomous vehicles, where 6G-enabled cars can simultaneously detect pedestrians and stream sensor data to traffic management systems using the same frequency band, allowing devices to “see” their environment while communicating. ISAC aims to optimize spectrum utilization, reduce hardware costs, and support real-time decision-making in use cases like autonomous vehicles, smart cities, and healthcare. Future research directions include leveraging AI for optimization, exploring terahertz frequencies, and designing scalable architectures to overcome technical barriers [18].

V. APPLICATIONS ENABLED BY 6G

The main application of 6G is summarized in the following points

- ***Holographic Communications***

The birth of 6G will revolutionize communication by enabling real-time 3D holographic interactions, transcending the limitations of 2D video conferencing. Leveraging THz frequencies and ultra-low latency (<1 ms), 6G networks will transmit high-fidelity holograms with outstanding resolution and responsiveness. In remote collaboration, global teams could run virtual meetings where participants appear as lifelike 3D holograms, allowing complex communication and collaborative manipulation of 3D models. For instance, engineers could jointly develop prototypes in shared holographic workspaces, reducing travel costs and accelerating innovation [17]. This capability will transform industries like healthcare, where surgeons might guide complex procedures remotely via holographic interfaces, enhancing access to

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specialized expertise. The entertainment industry will also undergo a paradigm shift with holographic concerts, immersive gaming, and interactive storytelling. Fans could attend virtual concerts by artists rendered as dynamic holograms while gamers explore photorealistic 3D environments with tangible feedback.

- ***Pervasive AI***

6G will embed AI into the fabric of networks, enabling ubiquitous, real-time decision-making and hyper-personalized services. Self-driving cars and drones will leverage 6G's edge-AI capabilities to process sensor data instantaneously. For example, an autonomous vehicle could predict pedestrian movements and adjust its trajectory in milliseconds, significantly improving safety [20]. Similarly, smart grids powered by 6G and AI could dynamically balance energy supply and demand, preventing blackouts during peak usage. In healthcare, wearable devices integrated with 6G will constantly monitor patients and deliver personalized treatment recommendations via AI analysis. A diabetic patient's smartwatch could predict blood sugar fluctuations and alert them in real time, lowering emergency hospital visits [27]. In education, adaptive learning platforms will tailor content to individual student needs, while retailers use AI-driven holographic assistants to offer customized shopping experiences.

- ***Internet of Everything (IoE)***

6G will extend the IoT into the IoE, interconnecting humans, devices, and environments with exceptional scale and intelligence. Smart cities will epitomize IoE, with 6G connecting autonomous vehicles, traffic systems, environmental sensors, and personal devices into a cohesive ecosystem. For example, air quality sensors could trigger traffic reroutes to reduce pollution, while smart buildings modify energy use based on resident preferences [21]. In agriculture, IoE-enabled farms might deploy drones, soil sensors, and autonomous tractors to optimize crop yields sustainably. Standardized protocols in 6G will ensure seamless communication across various devices and platforms. A patient's medical wearables, for instance, could communicate data with hospital systems, pharmacy databases, and emergency services in real-time, breaking down silos between healthcare providers [29]. This interoperability will also drive industrial automation, enabling factories to synchronize robots, supply chains, and global logistics networks effortlessly

VI. Challenges in the Transition to 6G

The transition to 6G, the next generation of wireless communication technology, promises to revolutionize connectivity with unprecedented 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.

- ***Technological Challenges***

The transition to 6G faces complicated technological barriers, particularly in advancing hardware capabilities and ensuring universal connectivity. Hardware development for THz communication requires breakthroughs in antenna design and signal processing. THz frequencies (0.1–10 THz), promising data rates exceeding 1 Tbps, suffer from severe atmospheric absorption and limited penetration through physical obstacles. For instance, signals at 300 GHz and above can experience up to 100 dB/km attenuation [22], necessitating innovations in materials such as graphene-based nano-antennas and photonic integrated circuits to achieve efficient signal transmission. Current semiconductor technologies struggle with the energy demands of THz transceivers, highlighting the need for interdisciplinary collaboration to miniaturize components and reduce power consumption.

- ***Regulatory and Standardization Challenges***

In the Harmonizing spectrum allocation the THz spectrum, remaining unused in previous generations, is the main difficulty currently, as it lacks a unified regulatory framework. Different countries have proposed dissimilar frequency bands for the 6G network, thus posing a challenge to its deployment. For example, Japan has set the goal of focusing on the 92–300 GHz spectrum for future applications ranging from industrial automation to 6G research, but on the contrary, the United States of America is examining a frequency between 130–175 GHz for applications like ultra-high-speed wireless communication. This spectrum distribution difference could cause an obstacle to cross-border technologies, like autonomous shipping and global IoT ecosystems, which rely on seamless connectivity. Responsible organizations like the International Telecommunication Union (ITU) must urgently coordinate and establish a cohesive global allocation strategy [28].

In terms of standardization smooth integration of 6G technologies will require hard work from both parties. In this case, struggling with conflicting interests among different parties, namely the telecom companies, the governments,

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and the open-source communities, organizations such as 3GPP and IEEE will first have to advance the protocols for the introduction of new features, for instance, AI-native networks and quantum communication. Their input will have a real impact on the development of the protocols for the upcoming 6G features, such as AI-native networks and quantum communication. In addition to this, difficulties like the lack of generalized standards for technologies such as RIS and ISAC can, in turn, make things complicated, for example, vendor lock-in, added costs, and obstructed innovation. To overcome these challenges, establishing a clear standardization process will be crucial. These efforts will not only accelerate growth in the telecom sector but also create a competitive marketplace with diverse vendors [25].

- ***Ethical and Privacy Concerns***

The rise of data privacy concerns amplifies data privacy risks regarding the integration of AI into 6G networks. AI-driven optimization relies on vast datasets, including sensitive user location and behavioral metrics, which could be used in cyberattacks. For instance, in smart cities with real-time networks, individuals' daily routines might inadvertently be exposed, violating privacy ethics [6]. To mitigate and reduce these risks, 6G architectures must embed privacy-by-design principles, such as federated learning and homomorphic encryption, which ensure that the data remains anonymized and decentralized.

Equitable access to the 6G technology is an ethical imperative. Without proactive policies, 6G deployment may prioritize urban regions, which leaves a digital gap. Rural areas in developing nations, already lagging in 5G infrastructure, could face further marginalization due to the high costs of THz-compatible hardware. Initiatives like public and private sectors partnerships and subsidized rural deployments are critical to develop and improve these areas. For example, India's BharatNet project, which aims to connect rural villages with highspeed Fiber, could serve as a model for inclusive 6G rollout [30]. Ensuring universal access is not just a technical challenge but also a moral obligation to prevent social and technological gaps from widening.

VII. RESEARCH DIRECTIONS AND FUTURE WORK

Toward the future of communication technologies, several key research directions are emerging that hold the potential to redefine the landscape of wireless networks. One promising area is the advancement of THz communication, which aims to unlock the vast potential of the THz frequency band for ultra-high-speed data transmission. Developing efficient transceivers and antennas capable of operating in this spectrum will be critical to realizing its full capabilities, enabling applications such as ultra-fast wireless links and high-capacity solutions [22].

Another important direction is the integration of AI into network design and management, giving rise to AI-native networks. By leveraging machine learning algorithms, these networks can optimize resource allocation, enhance user experience, and automate complex operations, paving the way for more intelligent and adaptive systems [6].

Additionally, quantum communication represents a frontier of innovation, with research focused on advancing quantum key distribution (QKD) and building scalable quantum networks. These efforts aim to provide unprecedented levels of security, safeguarding communications against future cyber threats [27].

Lastly, energy efficiency remains a critical focus for future research, particularly in the context of designing sustainable 6G infrastructure. As the demand for connectivity grows, creating energy-efficient technologies and architectures will be essential to reducing the environmental impact of next-generation networks while ensuring their long-term viability [14]. Together, these research areas represent the foundation upon which the future of communication technologies will be built, driving us closer to a more connected, intelligent, and sustainable world.

VIII. CONCLUSIONS

The transition from 5G to 6G represents a revolutionary shift in wireless communication, promising transformative applications and social benefits. The path to 6G is fraught with challenges. From a technical perspective, scientists must go beyond the constraints that relate to the availability of the spectrum, as well as energy efficiency and network security. Developing new materials, such as advanced semiconductors and metamaterials, will be essential to underwrite higher corresponding frequencies and data rates envisioned for 6G. Additionally, integrating AI and ML into network management will be foundational to coping with the multitude and size of 6G systems. Nevertheless, the solution will be to innovate and tackle various technological, regulatory, and ethical hurdles to realize the full potential of 6. Collaborative research and standardization efforts will be essential to ensure a seamless transition and fair access to 6G technologies.

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