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Research on Key Technologies, Application Scenarios, and Development Challenges of 6G Communication

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Abstract. The iterative evolution of mobile communication technology serves as a core driver of the digital economy's growth. With 5G having achieved large-scale global commercialization, research into 6G—aimed at meeting the demands of the "Internet of Intelligent Things" and ubiquitous connectivity—is now fully underway worldwide. This paper employs a literature review approach to synthesize domestic and international research findings on 6G, focusing on its key enabling technologies, typical application scenarios, and development bottlenecks. The study reveals that technologies including terahertz communication, reconfigurable intelligent surfaces (RIS), integrated sensing and communication (ISAC), and space-air-ground-sea integrated networking serve as the core pillars of 6G. 6G is poised for deep integration into scenarios like intelligent immersive communication and the Industrial Internet, while hardware development, algorithm optimization, and the unification of standards remain primary challenges. Future work needs to coordinate progress in core technological breakthroughs, standardization and engineering deployment to achieve high-performance and ubiquitous intelligent connectivity.

Keywords: 6G communication, key technologies, terahertz communication, reconfigurable intelligent surfaces (RIS), integrated sensing and communication (ISAC)

1. Introduction

Leveraging technical characteristics such as high data rates, low latency, and massive connectivity, 5G technology has achieved initial application in sectors like the consumer internet and the industrial internet, thereby driving the in-depth integration of the digital economy and the real economy [1]. However, the rapid development of emerging fields—such as artificial intelligence, the metaverse, and Industry 4.0—has placed higher demands on mobile communication technologies. Requirements such as faster data transmission, lower end-to-end latency, ubiquitous coverage, enhanced reliability, and integrated communication and sensing capabilities have become core needs for the next generation of mobile communications, prompting research and exploration into 6G technology [2]. Currently, 6G technology has no unified international standards and remains in a critical phase of technical exploration, architectural design, and preliminary standardization research. Countries across the globe have prioritized 6G R&D as a core strategy of the communications industry, investing substantial resources to make breakthroughs in key technologies [2-7]. Focusing on the key technologies of 6G communications, this paper employs a literature

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review approach to comprehensively summarize the latest research progress and achievements in the field, both domestically and internationally [1]. It analyzes the core technical framework of 6G, typical application scenarios in future society, and the primary challenges and issues facing technical research and industrialization, while systematically outlining the current status and development trends of 6G technology [1, 2, 4, 5]. This study holds significant theoretical and practical value: theoretically, it clarifies the technical system and research framework of 6G, thereby enriching the theoretical foundation of next-generation mobile communication technologies [2]. Practically, it provides communication engineering researchers with clear guidance on research directions and offers practitioners references for technology development and deployment. It ultimately promotes the research and industrialization of 6G and drives the iterative development of the mobile communications industry [1].

2. Key technologies for 6G communication

The 6G communication architecture is a complex system integrating multiple technologies; it builds on 5G core technologies, introduces a set of brand-new core technologies, and delivers in-depth optimization and innovation of existing techniques [1]. Technologies such as terahertz communication, intelligent reflecting surfaces, integrated sensing and communication (ISAC), space-air-ground-sea integrated networks, and ultra-massive MIMO form the core technical foundation of 6G; these technologies work in synergy to realize the high-performance metrics and application objectives of 6G [1, 4-6].

2.1. Terahertz (THz) communication technology

Terahertz communication is the core wireless transmission technology for 6G and acts as a key enabler for delivering 6G's ultra-high data rates [5]. Spanning the frequency range of 0.1 THz to 10 THz—situated between millimeter waves and infrared—this band offers abundant spectrum resources that far exceed those of the millimeter-wave bands used in 5G; it effectively addresses the scarcity of spectrum resources in current mobile communications and provides the necessary spectral foundation for ultra-high-speed data transmission [5]. Compared with conventional microwave and millimeter-wave communication, terahertz technology features high data rates, broad spectral bandwidth, strong anti-interference performance and superior security. Its single-carrier bandwidth can reach tens of gigahertz, supporting peak rates above 1 Tbps and satisfying 6G's high bandwidth demands [5]. Current research mainly centers on the development of core components including terahertz sources, detectors and antennas, as well as the optimization of terahertz propagation properties. Scholars aim to tackle issues such as large transmission loss and short transmission distance via high-gain antennas, relay communication technologies and optimized transmission algorithms, promoting the practical deployment of terahertz communication from laboratories to real scenarios [5].

2.2. Reconfigurable intelligent surface (RIS) technology

An intelligent metasurface is an artificial electromagnetic surface composed of a large number of passive reflecting elements. By dynamically adjusting the electromagnetic characteristics of each unit, it flexibly controls the reflection angle, phase and amplitude of electromagnetic waves, optimizing wireless propagation environments and boosting the performance of communication systems. It serves as a core technology to improve spectrum efficiency and extend coverage in 6G

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networks [6]. Compared to traditional relay technologies, intelligent meta surfaces offer advantages such as low power consumption, low cost, ease of deployment, and the absence of electromagnetic radiation pollution; they can effectively mitigate issues like shadow fading and multi path effects, thereby improving communication link quality [6]. In 6G systems, intelligent meta surfaces can be deployed in complex environments—such as indoor spaces or among urban buildings—or operate in coordination with communication nodes like base stations and satellites to extend network coverage. Current research mainly targets key challenges, including the miniaturization and integration of reflecting units as well as the optimization of intelligent control strategies [6].

2.3. Integration of AI and communication (integrated sensing and communication)

Integrated Sensing and Communication (ISAC) is a core technical feature of 6G; it realizes the in-depth integration of communication and sensing functions and acts as a key enabler driving 6G evolution from the Internet of Everything to the Intelligent Internet of Everything [4]. Traditional mobile communication systems possess only communication capabilities, while sensing functions rely on dedicated sensor devices; these functions operate independently, leading to issues such as low resource utilization, high equipment costs, and latency in information exchange [4]. ISAC technology enables the integrated transmission and processing of communication and sensing signals by sharing hardware resources—such as spectrum, antennas, and radio frequency (RF) components—thereby endowing communication devices with dual capabilities: they can perform data transmission while simultaneously and precisely sensing information regarding target objects, such as distance, speed, and orientation [4]. Artificial intelligence provides core algorithmic support for ISAC implementation. Current research mainly concentrates on signal fusion algorithms, resource allocation schemes and hardware integration development [4, 8].

2.4. Ultra-massive MIMO technology

Ultra-massive MIMO is a major optimization and upgrade of 5G massive MIMO, and serves as a core enabler to improve spectral efficiency, communication capacity and signal quality in 6G networks [6]. By equipping base stations with hundreds or even thousands of antennas for simultaneous multi-terminal communication, this technology adopts spatial diversity and beamforming technologies to realize precise signal transmission, thus greatly improving the spectral efficiency and channel capacity of communication systems [6]. Compared to 5G massive MIMO, 6G ultra-massive MIMO features a higher number of antennas, greater beamforming precision, and enhanced interference resilience; current research focuses on areas such as antenna miniaturization and integration, as well as low-power design for radio frequency (RF) chains [6].

3. Typical 6G application scenarios

Leveraging core strengths including ultra-high transmission rates, ultra-low latency, seamless ubiquitous coverage and integrated communication and sensing capabilities, 6G will break through the application limitations of 5G. It supports in-depth deployment in diversified scenarios, promotes digital and intelligent transformation across all industries, and offers solid technical support for the construction of future digital society [1, 2].

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3.1. Intelligent immersive communication

Intelligent immersive communication is one of the most representative application scenarios for 6G. Supported by 6G's 1 Tbps peak transmission rate and high-fidelity transmission performance, this scenario empowers the widespread deployment of metaverse services, holographic communication and ultra-high-definition immersive video [1, 2]. In holographic communication scenarios, 6G technology facilitates the real-time transmission and reconstruction of 3D holographic images, allowing parties to engage in face-to-face holographic interactions that transcend spatial limitations —benefiting fields such as remote conferencing and distance education [1]. In the context of the meta verse, 6G technology provides the necessary communication support for simultaneous large-scale user connectivity and high-fidelity virtual environment interactions, bridging the gap between the meta verse concept and practical application [2]. In addition, 6G will boost the advancement of the ultra-high-definition video industry. Combined with VR and AR technologies, it can provide users with seamless immersive sensory experiences [1].

3.2. Intelligent IoT

With an ultra-high connection density of 10^7 connections per square kilometer, 6G will advance the intelligent Internet of Things (IoT) into a new stage featuring massive connectivity and intelligent sensing, realizing full-range and fine-grained perception and interconnection of the physical world [1]. In smart city scenarios, 6G technology will facilitate the massive connectivity and intelligent sensing of diverse IoT devices, thereby supporting the refined management of smart cities [1]; in smart home scenarios, it will enable full connectivity and intelligent coordination among home devices, creating a smart and convenient living environment [1]. Moreover, 6G's integrated communication and sensing functions empower IoT terminals with built-in sensing capacity, promoting the IoT transformation from connectivity-centric mode to sensing-centric and intelligence-centric modes [4].

3.3. Satellite communication and global coverage

6G's capabilities—including ultra-low latency, ultra-high reliability, and integrated communication and sensing—will propel the Industrial Internet into a new phase of full automation and intelligence, serving as a core pillar of Industry 4.0 [1, 4]. In industrial production settings, 6G technology enables real-time communication and precise control of industrial robots and equipment; an end-to-end latency of 0.1 milliseconds meets the requirements for high-speed collaborative operations among industrial robots, facilitating fully automated production line processes [1]. In remote industrial control scenarios, it allows for the precise remote control of equipment in isolated areas, thereby reducing labor costs and safety risks [1]. In addition, 6G integrated communication and sensing functions realize all-round status awareness and real-time monitoring of industrial production procedures, which greatly improves the efficiency of equipment predictive maintenance [4, 8].

4. Challenges and issues facing 6G research

Although research into 6G communication technology has yielded numerous interim achievements, the transition from technical R&D to commercialization still faces a series of core challenges and issues—spanning hardware and component implementation, algorithm and model optimization,

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standardization and security, as well as cost and engineering deployment. These obstacles act as major bottlenecks restricting the industrial progress of 6G, necessitating joint efforts from global academic institutions and industrial practitioners [1, 2].

4.1. Hardware and device implementation challenges

Hardware equipment lays the foundation for the practical deployment of 6G systems. Nevertheless, the research and development of core 6G hardware components still encounter various technical bottlenecks, which have become the leading obstacle restricting 6G industrialization [1]. In the field of terahertz communication, the development of core components—such as terahertz sources and detectors—has yet to achieve breakthroughs; existing devices suffer from issues like low output power and high noise, while miniaturization and integration remain difficult to realize [5]. In the realm of intelligent meta surfaces, miniaturizing and integrating reflecting elements presents significant challenges, and hardware fabrication processes for large-scale intelligent metasurfaces are not yet mature [6]. In addition, technical difficulties still exist in ultra-massive MIMO antenna integration and low-power chip design, as well as the hardware co-design of integrated communication and sensing modules [4, 6].

4.2. Algorithm and model optimization issues

The sophisticated architecture of 6G communication systems puts forward stricter requirements for algorithms and models, and considerable optimization space still exists for algorithm and model design matching diverse core 6G technologies [2]. In the field of terahertz communication, existing transmission algorithms struggle to effectively address the issue of high propagation loss [5]; regarding intelligent reflecting surfaces (IRS), algorithms for the intelligent control of reflecting elements lack sufficient real-time performance and precision, and algorithms for the collaborative operation of multiple IRS units remain immature [6]. For integrated sensing and communication (ISAC), joint signal processing algorithms are still limited by low signal separation accuracy [4, 9]. Meanwhile, for space-air-ground-sea integrated networks, cross-heterogeneous network handover and resource scheduling algorithms have not been fully optimized [3, 10].

4.3. Standardization and safety issues

Standardization and network security act as indispensable prerequisites for the global commercial deployment of 6G. Nevertheless, 6G still encounters prominent challenges in both two dimensions [1, 2]. Regarding standardization, there is no global consensus on the technical architecture or core performance indicators of 6G; different countries have proposed varying technical solutions, slowing the standardization process [7], and technical standards for emerging fields—such as terahertz communication—have yet to be established [3, 5]. From the perspective of network security, inherent features of 6G networks including ubiquitous coverage and massive terminal access bring complicated and diversified security threats. The main risks cover insufficient security defense ability of IoT terminals, as well as obvious security isolation defects among multi-layer network protection systems [11].

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5. Discussion

5.1. Key directions for future research

In light of the current state of research and the challenges facing 6G technology, future research efforts will focus on the following areas: first, the development of core hardware components—specifically, key devices such as terahertz sources and intelligent reflecting surface (IRS) elements—to overcome bottlenecks in materials and manufacturing processes [5, 6]; second, the optimization of core algorithms and models. Priority should be given to terahertz transmission algorithms and ISAC joint signal processing algorithms to improve algorithm accuracy and operational efficiency [3-6, 12]; third, the establishment of a 6G standardization framework, involving global collaboration on standard research and formulation to create unified international standards [1, 2, 7]; and fourth, research into network security technologies, aiming to build a comprehensive, multi-layered security defense system that ensures the secure operation of 6G networks [13].

5.2. Recommendations for engineering applications

To advance the engineering application and industrialization of 6G technology, the following recommendations are proposed: first, promote industry-academia-research collaborative innovation. A complete innovation ecosystem covering universities, research institutes, enterprises and governments should be built to realize tight integration between core technology R&D and practical engineering deployment [1, 2]; second, implement 6G network deployment in stages—leveraging existing 5G infrastructure and adopting a "pilot-first, rollout-later" strategy—by prioritizing terrestrial 6G network deployment before gradually building an integrated space-air-ground-sea network [1, 3]; third, drive the deep integration of 6G with vertical industries by developing industry-specific application solutions, using applications to spur technological iteration and upgrades [1, 4]; and fourth, strengthen international cooperation and exchange to share research findings, collaboratively address technical challenges, and promote the global commercialization of 6G technology [7, 9].

6. Conclusion

This study indicates that 6G communication technology represents an evolution built upon 5G, achieving a qualitative leap in core performance metrics. Characterized by a peak transmission rate of 1 Tbps, end-to-end latency of 0.1 milliseconds, ubiquitous seamless coverage, and the integration of communication and sensing, 6G will enable the transition from the "Internet of Everything" to the "Intelligent Internet of Everything" [1, 2]. Terahertz communication, reconfigurable intelligent surfaces (RIS), integrated communication and sensing, space-air-ground-sea integrated networks and ultra-massive MIMO constitute the core technical support of 6G. These technologies operate synergistically to fulfill the high-performance requirements of 6G [1, 4-6]. 6G technology will find deep application in scenarios such as intelligent immersive communication, the intelligent Internet of Things (IoT), the Industrial Internet and automatic control, and satellite communication with global coverage, thereby driving the digital and intelligent transformation across various industries [1, 3, 4]. Currently, 6G R&D faces multiple challenges covering hardware chip development, algorithm and model optimization, unified standard formulation, network security, cost control and field engineering deployment. These difficulties have become key bottlenecks restricting 6G industrialization and large-scale commercial application [1, 2, 5, 6, 14]. The development of key 6G

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technologies will trend toward convergence, intelligence, miniaturization, and cost-efficiency. Future efforts must prioritize the R&D of core hardware components, optimization of core algorithms, establishment of standardization frameworks, and enhancement of network security. Advancing the engineering application and industrialization of 6G technology requires collaborative innovation among industry, academia, and research sectors; a phased approach to network deployment; integration with vertical industries; and strengthened international cooperation [1-4, 7-9].

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