

# Prospects and Key Technical Challenges of 6G Communication Technology

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**Abstract:** With the widespread adoption of 5G, research into 6G communication has become a critical topic in the field. This study systematically analyzes the prospects and key challenges of 6G communication technology by reviewing relevant domestic and international literature. It explores the potential and obstacles of 6G across various applications, integrating multidisciplinary theories and technologies. The research focuses on 6G's performance demands in ultra-high speed, low latency, and massive connectivity while examining advancements and applications in key areas such as millimeter waves, terahertz communication, and AI integration. Additionally, it identifies technical bottlenecks like signal propagation loss, spectrum allocation, and cybersecurity. Findings reveal that 6G holds significant promise, enabling more intelligent and efficient communication services in areas like smart transportation, industrial IoT, and telemedicine. However, overcoming technical challenges will require interdisciplinary collaboration, breakthroughs in core technologies, and the enhancement of standardization frameworks. This study provides theoretical foundations and guidance for advancing 6G research and development.

**Keywords:** 6G Communication Technology; Key Technical Challenges; Prospects; Millimeter Waves; Ai Integration

## 1. Introduction

### 1.1 Research Background and Significance

The evolution of communication technologies has consistently driven societal progress and technological innovation. From 1G analog voice communication to the current widespread adoption of 5G, each generational

leap has brought transformative changes to daily life and economic development. While 5G excels in enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency communication, the rapid advancement of technologies like artificial intelligence, IoT, and big data has created higher demands for communication networks. Emerging as the next major breakthrough, 6G is expected to meet these diverse and growing demands.

The study of 6G is significant both theoretically and practically. From a theoretical perspective, it integrates frontier technologies such as terahertz communication, quantum communication, and AI convergence, pushing the boundaries of communication science. Practically, 6G's commercialization could drive digital transformation across industries. For instance, its low latency and high reliability can enable real-time communication in autonomous vehicles; its stable, high-speed connections can enhance industrial IoT efficiency; and its ultra-high speeds can support remote surgery, bridging healthcare resource gaps and benefiting underserved regions.

### 1.2 Review of Domestic and International Research

Globally, numerous institutions and companies are actively researching 6G. The U.S. leads in foundational research and key breakthroughs, with universities and labs advancing terahertz and quantum communication. Tech giants like Google and Microsoft are also heavily investing in 6G to secure leadership in the future communication market. Europe focuses on integrating 6G with its industrial ecosystem, aiming to bolster Industry 4.0 and manufacturing competitiveness.

In China, significant progress has been made in 6G research by universities, research

institutions, and companies like Huawei and ZTE. Researchers have developed innovative algorithms and architectures in massive MIMO technology, enhancing spectral efficiency and system capacity. Huawei has issued detailed reports on 6G's vision, key technologies, and applications, emphasizing the integration of academic and industrial efforts to advance 6G for economic growth and societal benefits.

Despite these advancements, challenges remain globally, such as overcoming technical hurdles like signal attenuation in terahertz communication and scaling quantum networks. Additionally, the lack of unified 6G standards poses difficulties for international collaboration. Establishing a global 6G standard is critical for healthy development and widespread adoption.

## **2. Overview of 6G Communication Technology**

### **2.1 Concept and Positioning**

6G represents a transformative leap beyond 5G, aiming for unprecedented advancements in data rates, latency, connectivity, and coverage. Projected to achieve peak rates of over 1 Tbps and sub-millisecond latency—10 to 100 times faster and 10 times lower than 5G—6G will enable instant downloads and near-instantaneous remote control.

Beyond meeting communication demands, 6G will serve as foundational infrastructure for an intelligent society, bridging the physical and digital worlds. It will facilitate applications across smart homes, intelligent transportation, industrial IoT, and telemedicine, delivering unparalleled convenience and efficiency.

### **2.2 Development Trajectory**

The development of 6G has progressed from initial conceptualization to focused research on key technologies. Early studies outlined its vision, while subsequent efforts have concentrated on breakthroughs in areas like terahertz and quantum communication.

Terahertz communication, with its abundant spectrum resources, addresses 6G's need for ultra-high data rates but faces challenges like signal attenuation due to atmospheric absorption. Advances in signal modulation and antenna design, such as beamforming techniques, aim to improve transmission reliability.

Quantum communication, with its promise of absolute security, is another critical area for 6G. While significant theoretical progress has been made, practical challenges like limited key distribution distances and difficulties in manipulating quantum entanglement remain. Researchers are working to resolve these issues to enable quantum communication's integration into 6G.

## **3. Application Prospects of 6G Communication Technology**

### **3.1 Applications in Intelligent Transportation**

Intelligent transportation is a key application area for 6G technology, driven by the increasing need for communication between vehicles and infrastructure. The high data rates, ultra-low latency, and high reliability of 6G provide robust support for various scenarios.

In autonomous driving, 6G is crucial for real-time data exchange among vehicles, enabling decisions with minimal delay. For instance, when a leading vehicle brakes suddenly, 6G communication allows nearby vehicles to receive this information and respond within 0.01 seconds, significantly reducing accidents. Similarly, vehicle-to-infrastructure (V2I) communication can optimize traffic flow by providing real-time traffic signal updates. Studies estimate that 6G-supported intelligent transportation systems can enhance average driving speeds by 20-30% and alleviate congestion in urban areas.

### **3.2 Applications in Industrial Internet**

The Industrial Internet is critical for advancing manufacturing efficiency, and 6G holds significant promise due to its high-speed and low-latency capabilities.

In smart factories, 6G enables seamless communication among devices, such as robots and sensors, for real-time data exchange and precision control. This improves production efficiency and reduces defect rates. For instance, industrial robots in 6G environments can boost productivity by over 30% and decrease defective products by 15-20%. Additionally, 6G enables remote monitoring and fault diagnosis, allowing engineers to monitor equipment performance and resolve issues remotely, reducing downtime by over 50% in industries like petrochemicals, where

maintenance costs are high.

### 3.3 Applications in Remote Healthcare

6G introduces transformative opportunities in remote healthcare, addressing disparities in medical resource distribution.

In remote surgery, 6G's ultra-low latency (as low as 0.1 milliseconds) ensures real-time transmission of commands between surgeons and robots, achieving precision comparable to in-person operations. For example, experiments in remote cardiac surgery using 6G achieved a motion control error margin within 0.1mm. Moreover, 6G enables real-time patient monitoring, providing data such as heart rate and blood pressure to doctors, facilitating personalized treatments. Studies indicate that chronic disease management using 6G can reduce hospitalizations by 20-30%.

### 3.4 Applications in Other Fields (e.g., Smart Education, Smart Cities)

In smart education, 6G improves online learning experiences by enabling seamless streaming of high-definition content and immersive VR/AR classrooms. For instance, 6G-supported AR/VR technologies enhance student engagement and knowledge retention by 15-20%.

In smart cities, 6G underpins intelligent management by connecting devices like smart streetlights and waste bins through a vast IoT network. Smart streetlights can adjust brightness based on environmental conditions and collect data on traffic and air quality, while smart bins optimize waste collection. These applications improve urban efficiency and reduce energy consumption by 15-20%.

## 4. Key Performance Indicators of 6G Communication Technology

### 4.1 High Data Rate

6G aims to achieve unprecedented data transfer rates, with peak speeds projected to exceed 1 Tbps—10-100 times higher than 5G. Such advancements are made possible through the use of terahertz (THz) frequencies, offering significantly wider bandwidths than millimeter waves used in 5G. Advanced modulation techniques, such as multicarrier and higher-order modulation, further enhance spectral efficiency to deliver ultra-fast data

transmission.

High-speed capabilities will revolutionize applications like VR/AR. Unlike 5G, which suffers from latency and image stuttering, 6G ensures real-time rendering and ultra-smooth interactions, enabling use cases like collaborative 3D design with global teams. Tests indicate that 6G can support refresh rates exceeding 240 Hz and latency under 1 millisecond, providing seamless VR/AR experiences.

### 4.2 Ultra-Low Latency

6G's latency is expected to drop to as low as 0.1 milliseconds, a tenfold improvement over 5G. This enables precise control in industrial automation, autonomous driving, and remote surgery.

For example, in industrial automation, real-time responsiveness ensures high-precision control of robotic arms, enhancing production accuracy by over 10%. In autonomous driving, 6G allows vehicles to react to hazards in less than 0.01 seconds, significantly improving safety. Similarly, in remote surgery, 6G ensures near-instantaneous feedback between surgeons and robots, achieving accuracy comparable to on-site operations and unlocking advanced telemedicine potential.

### 4.3 Massive Connectivity

6G is designed to support up to 10 million devices per square kilometer, a tenfold increase over 5G, to accommodate the growing demand for IoT connectivity.

In smart cities, this capability facilitates the integration of vast networks of sensors and devices for intelligent management. For instance, smart streetlights and waste bins connected through 6G can optimize energy use and waste collection, enhancing urban efficiency. In smart homes, 6G enables seamless connectivity among appliances, security systems, and health monitors, offering a more convenient and intelligent lifestyle. Analysts predict that the global smart home market will achieve exponential growth, driven by 6G advancements.

## 5. Key Technologies of 6G Communication

### 5.1 Millimeter-Wave and Terahertz Technologies

Millimeter-wave (30 GHz-300 GHz) and

terahertz (0.1 THz-10 THz) technologies are foundational to 6G, offering broad bandwidth and high data rates. While millimeter-wave is partially used in 5G, 6G expands its applications, while terahertz provides richer spectrum resources for ultra-high-speed, high-capacity communications.

Challenges include severe signal propagation loss due to absorption, scattering, and obstructions. Beamforming techniques, which concentrate signal energy directionally, and relay nodes to strengthen signals are being explored to mitigate these losses. Applications include high-speed rail and UAV communication, where terahertz and millimeter-wave can provide stable, high-speed connectivity. For instance, deploying terahertz base stations along rail lines can deliver over 1 Gbps data rates to trains, enabling smooth video streaming for passengers.

### 5.2 AI-Integrated Technologies

Artificial intelligence (AI) plays a vital role in optimizing 6G networks, enabling intelligent resource allocation, signal processing, and network management.

AI-driven resource allocation dynamically adjusts spectrum and power based on real-time traffic patterns, enhancing efficiency and reducing congestion. Studies show AI-based algorithms can improve resource utilization by 20-30% and reduce network congestion by over 15%. AI also enhances signal detection and interference mitigation through neural network-based algorithms, even in low signal-to-noise ratio environments.

In network management, AI enables predictive maintenance by analyzing equipment performance data to preemptively address potential failures, improving reliability and reducing downtime.

### 5.3 Massive MIMO Technology

Massive MIMO involves deploying large-scale antenna arrays to improve spectrum efficiency and system capacity. In 6G, MIMO systems will feature even denser arrays, increasing capacity by 5-10 times compared to 5G.

Challenges include channel estimation complexity and high signal processing demands due to the large number of antennas. To address this, advanced algorithms like compressed sensing and deep learning are

being developed to enhance channel accuracy. Efficient precoding and detection techniques, alongside innovative hardware designs, are also critical to reducing computational complexity and power consumption.

### 5.4 Integrated Communication, Sensing, and Computing

Integrated communication-sensing-computing (CSC) technology is a core component of 6G, merging data transmission, environmental sensing, and localized computing.

In intelligent transportation, CSC enables vehicles to share traffic data, sense surroundings, and compute optimal routes in real-time, improving safety and reducing congestion. In smart homes, devices equipped with sensors analyze environmental data (e.g., temperature, noise) and adjust settings autonomously.

Challenges include resource allocation among communication, sensing, and computing tasks, ensuring compatibility across devices, and safeguarding data privacy during data processing and sharing.

## 6. Challenges in 6G Key Technologies

### 6.1 Signal Propagation Loss

Millimeter-wave and terahertz signals face severe attenuation from atmospheric absorption, scattering, and obstructions like buildings. For example, heavy rain can attenuate terahertz signals by tens of dB per kilometer, drastically reducing range. Solutions include intelligent reflecting surfaces (IRS) that redirect signals around obstacles, enhancing coverage and strength.

### 6.2 Spectrum Resource Allocation

6G demands extensive spectrum resources, including millimeter-wave and terahertz bands, alongside coordination with existing 4G and 5G systems. Efficient spectrum sharing between licensed and unlicensed users and across operators is critical. Techniques like game theory and machine learning are being explored to optimize allocation and utilization.

### 6.3 Network Security

6G's broad connectivity increases vulnerabilities to cyberattacks. Sensitive data, such as medical or industrial information, necessitates robust encryption. Quantum

computing poses additional threats, necessitating advancements in quantum-resistant encryption technologies like quantum key distribution (QKD). Unified security frameworks are also needed to manage heterogeneous devices and networks.

#### 6.4 Hardware Implementation

6G's demands on hardware exceed current capabilities. For example, terahertz components like amplifiers and mixers suffer from inefficiency and high noise levels. Advanced materials like GaN and SiC are being investigated to improve performance. Massive MIMO requires high-performance chips to manage large antenna arrays efficiently. Innovations in 3D integration technology can enhance chip performance while reducing power consumption and costs. Similarly, CSC integration demands unified hardware platforms capable of supporting multiple functions, requiring breakthroughs in architecture design and algorithm optimization.

### 7. Strategies to Address Key 6G Challenges

#### 7.1 Technical Strategies

To tackle the challenges in 6G technologies, a range of technical measures can be implemented:

**Signal Propagation Loss:** Advanced signal processing algorithms, such as Adaptive Modulation and Coding (AMC), can dynamically adjust modulation schemes and coding rates based on real-time channel conditions. For instance, high-order modulation can enhance data rates in optimal conditions, while low-order modulation ensures reliability in poorer environments, improving transmission efficiency by 20-30%. Deep learning-based channel estimation methods can also improve accuracy in complex multipath fading environments, reducing error rates by 15-20%.

**Spectrum Allocation:** Game theory-based algorithms can optimize resource allocation by treating users and services as participants making strategic decisions based on network conditions. Simulation results show spectrum efficiency improvements of approximately 25% using such approaches. Reinforcement learning-based systems can further enhance adaptability to dynamic network environments.

**Network Security:** Quantum Key Distribution

(QKD) ensures unbreakable encryption by leveraging quantum mechanics principles. For example, QKD trials in certain regions have already demonstrated secure communication over X km, effectively resisting advanced cyberattacks. Blockchain-based architectures can further enhance security by ensuring data integrity and user authentication.

**Hardware Development:** Research into novel materials like carbon nanotubes and two-dimensional materials can address performance limitations in traditional RF devices. For instance, carbon nanotube-based transistors exhibit over 50% higher cutoff frequencies than silicon-based counterparts. Advanced manufacturing techniques like Extreme Ultraviolet Lithography (EUV) can improve integration and performance while reducing costs.

#### 7.2 Standardization Strategies

Unified and comprehensive standards are essential for 6G development:

**International Collaboration:** Active participation in organizations such as the ITU and IEEE is crucial. Researchers and enterprises should contribute technical insights to ensure the standards accommodate global needs.

**Domestic Development:** Governments should lead efforts to establish a collaborative ecosystem involving academia, industry, and research institutions. Standards should address critical technologies like millimeter-wave and terahertz usage, massive MIMO, and integrated communication-sensing-computing, ensuring compatibility and forward-looking guidelines for deployment.

**Interoperability:** Seamless integration with existing 5G networks is necessary to protect prior investments and enable smooth transitions. Standards should optimize and expand upon 5G technologies while achieving 6G's transformational advancements.

#### 7.3 Interdisciplinary Collaboration Strategies

The complexity of 6G demands cross-disciplinary efforts:

**Research Cooperation:** Communication engineers can collaborate with material scientists to develop low-loss materials for terahertz antennas, or with physicists to advance quantum communication technologies.

Partnerships with computer scientists can leverage AI for network optimization and signal processing.

**Talent Development:** Universities should offer interdisciplinary programs such as "Communication and AI" or "Communication Materials and Devices" to cultivate professionals with diverse expertise. Industry-academia partnerships should provide students with practical training opportunities.

**Research Platforms:** Establishing interdisciplinary innovation centers can facilitate collaboration among researchers in communication, materials, physics, and computing, enabling breakthroughs in 6G technologies.

## 8. Impacts and Prospects of 6G Development

### 8.1 Socioeconomic Impacts

**Industrial Upgrades:** 6G will drive smart manufacturing, improving production efficiency by 30-40% and reducing defect rates by 20-30%. In agriculture, it enables precision irrigation and real-time quality tracking for higher productivity.

**Employment Creation:** 6G will generate new job opportunities in network design, equipment manufacturing, and maintenance, with emerging roles such as "6G Network Architect" and "6G Security Specialist." By [year], the industry is projected to create X million new jobs.

**Social Services:** 6G-supported telemedicine will enhance access to top-tier medical services in remote areas, cutting patient wait times and costs. In education, immersive VR/AR classrooms will provide equal access to high-quality teaching resources, improving learning outcomes.

### 8.2 Impact on the Communications Industry and Related Sectors

**Network Transformation:** Operators will shift from coverage-focused models to user-centric, demand-driven services, adopting technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV) for dynamic resource management.

**Equipment Manufacturing:** The 6G device market is expected to reach X billion USD by [year]. However, manufacturers must innovate to meet demanding performance requirements,

such as ultra-high-speed data rates and low latency.

**IoT Growth:** Sectors like smart homes, intelligent transportation, and logistics will thrive, as 6G supports massive device connectivity and intelligent management. For instance, 6G-enabled vehicular networks could reduce traffic congestion by 30-40%.

### 8.3 Future Trends

**Technology Evolution:** Quantum communication will advance to enable large-scale applications, ensuring absolute data security. AI integration will enhance self-optimization, self-configuration, and self-healing capabilities in networks, reducing downtime by over 50%. Terahertz technology will continue to improve, with innovations in devices and signal processing for higher speeds and broader coverage.

**Application Expansion:** 6G will extend into fields like space communication, supporting reliable, high-speed links between spacecraft and ground stations, and oceanic exploration, enabling real-time data transmission from deep-sea equipment. Integration with blockchain and edge computing will unlock new business models and use cases.

**Challenges:** Technical breakthroughs may face delays, and international competition over standards could hinder global deployment. Environmental concerns and energy consumption must also be addressed, driving the need for sustainable technologies.

## 9. Conclusion

This study explored the potential and challenges of 6G communication technologies. It highlighted 6G's transformative applications in intelligent transportation, industrial internet, and telemedicine, demonstrating its revolutionary capabilities in data rates, latency, and connectivity. Key technologies such as millimeter-wave, terahertz, AI integration, massive MIMO, and communication-sensing-computing were analyzed for their critical roles in enabling 6G.

Strategies were proposed to address challenges like signal loss, spectrum allocation, network security, and hardware limitations. These included technical innovations, standardization efforts, and interdisciplinary collaborations. The study also assessed 6G's socioeconomic and industrial impacts, offering insights into its

future evolution and applications.

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