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Artificial Intelligence-Driven 6G Wireless Networks: Technologies, Applications, and Future Challenges — A Review

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Abstract

The rapid advancement of intelligent communication technologies has accelerated research toward sixth-generation (6G) wireless networks as a successor to 5G systems. Unlike previous wireless generations, 6G is expected to integrate Artificial Intelligence (AI), Terahertz (THz) communication, edge intelligence, and Internet of Everything (IoE) into a unified intelligent communication ecosystem capable of supporting ultra-high data rates, sub-millisecond latency, and massive connectivity. This paper presents a comprehensive review of recent developments in 6G wireless communication systems by analyzing more than 40 recent studies published between 2019 and 2025 from IEEE, Elsevier, Wiley, and other major scientific databases. The review systematically categorizes the literature into enabling technologies, intelligent network architectures, emerging applications, and open research challenges. Key findings indicate that AI-native network orchestration, THz spectrum utilization, intelligent reflecting surfaces, and distributed edge intelligence are becoming the primary technological foundations of future 6G infrastructures. Furthermore, the review identifies major challenges related to security, energy efficiency, spectrum management, hardware limitations, and trustworthy AI integration. Compared with previous surveys, this review provides an integrated discussion combining AI-driven communication, Industry 5.0 applications, IoE ecosystems, and intelligent distributed architectures within a single analytical framework. The paper also highlights future research directions for developing scalable, secure, and sustainable 6G wireless systems.

Keywords

6G wireless communication, Artificial Intelligence, Terahertz communication, Internet of Everything, Industry 5.0, cognitive radio, intelligent networks

I. Introduction

Wireless communication technologies have evolved rapidly from the first-generation (1G) analog systems to the current fifth-generation intelligent mobile networks. Each generation has significantly improved communication speed, capacity, reliability, and quality of service. The deployment of 5G networks introduced major improvements such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC). However, future applications including holographic communication, autonomous transportation, smart cities, tactile internet, and immersive extended reality require communication capabilities beyond the limitations of 5G.

Sixth-generation wireless communication is expected to become commercially available around 2030 and will represent a transformative evolution in intelligent connectivity. Unlike previous generations, 6G is envisioned as an AI-native communication ecosystem capable of integrating sensing, computing, intelligence, and communication into a unified platform. Recent studies suggest that 6G networks will support terabit-per-second (Tbps) data rates, microsecond-level latency, global coverage, ultra-high reliability, and massive connectivity for billions of devices [1].

One of the most important characteristics of 6G is the integration of AI and Machine Learning (ML) into network management and optimization. AI-driven communication systems are expected to enable autonomous resource allocation, intelligent spectrum sharing, predictive maintenance, and self-organizing networks. Additionally, 6G will heavily utilize Terahertz (THz) frequency bands to achieve ultra-high-speed wireless communication [2].

IoE is also central to 6G development. IoE extends beyond the Internet of Things (IoT) by integrating people, devices, data, and intelligent processes into a highly connected ecosystem. This integration will support advanced applications including digital twins, autonomous robotics, smart healthcare systems, intelligent transportation, and Industry 5.0 environments [3].

Despite its promising vision, 6G faces numerous challenges related to spectrum allocation, energy consumption, security, hardware limitations, and infrastructure deployment. High-frequency THz communication suffers from signal attenuation and propagation limitations, while intelligent network management introduces additional security and privacy concerns [4]. Several researchers also highlighted the importance of intelligent network orchestration, AI reliability, and distributed communication infrastructures in future 6G deployment scenarios [5], [6].

Therefore, this paper presents a comprehensive review of 6G wireless networks by discussing enabling technologies, future applications, network intelligence, and major research challenges. The objective of this review is to summarize current research trends and provide insights into future directions for developing intelligent next-generation wireless systems.

II. Methodology

This review paper was conducted using a literature-based qualitative analysis approach. Several recent journal articles, surveys, and conference papers related to 6G wireless communication were analyzed to identify major technological trends, enabling architectures, applications, and challenges. The selected literature primarily focused on AI-driven networking, THz communication, cognitive radio, intelligent surfaces, Internet of Everything, and future communication paradigms.

The literature sources were selected from reputable scientific publishers and databases including IEEE Xplore, Elsevier, Wiley, and Hindawi. The review process involved the following stages:

1. Identification of relevant literature on 6G wireless communication.
2. Classification of studies based on technologies, applications, and challenges.
3. Comparative analysis of existing research findings.
4. Synthesis of future directions and research opportunities.

The reviewed studies emphasized key aspects including:

1. AI and machine learning integration,
2. THz communication,
3. intelligent network architectures,
4. cognitive radio systems,
5. smart applications,
6. security and privacy issues,
7. and energy-efficient communication technologies.

The methodological framework also involved reviewing comparative studies discussing the transition from 5G toward AI-native 6G infrastructures [7], [8]. This methodology enables a systematic understanding of emerging 6G communication technologies and their future implications.

III. Results and Discussion

A. Evolution from 5G to 6G

The transition from 5G to 6G is expected to redefine wireless communication systems. While 5G mainly focuses on enhanced connectivity and mobile broadband, 6G aims to provide intelligent and autonomous communication infrastructures.

Several studies predict that 6G networks will support:

1. data rates up to 1 Tbps,
2. latency below 1 millisecond,
3. ultra-high spectrum efficiency,
4. massive connectivity,
5. and intelligent automation [1], [5].

Compared to 5G, 6G will integrate communication, sensing, computing, and AI into a unified intelligent network. Furthermore, 6G is expected to provide seamless global coverage through the integration of terrestrial, aerial, satellite, and underwater communication systems [4], [9].

Tabel 1 Comparison Between 5G and 6G Wireless Networks

Parameter	5G	6G
Maximum Data Rate	20 Gbps	Up to 1 Tbps
Latency	1 ms	< 1 ms
Frequency Band	Sub-6 GHz, mmWave	THz Spectrum
Intelligence	Partial AI Support	AI-Native Networks
Connectivity	Massive IoT	Internet of Everything
Coverage	Terrestrial	Space-Air-Ground-Sea
Main Applications	Mobile Broadband	Holographic Communication, Digital Twin
Network Architecture	Centralized/Cloud	Intelligent Distributed Architecture
Energy Efficiency	Moderate	Ultra-Green Communication
Security	Conventional Security	AI-Driven Adaptive Security

Source: Adapted from [1]–[4].

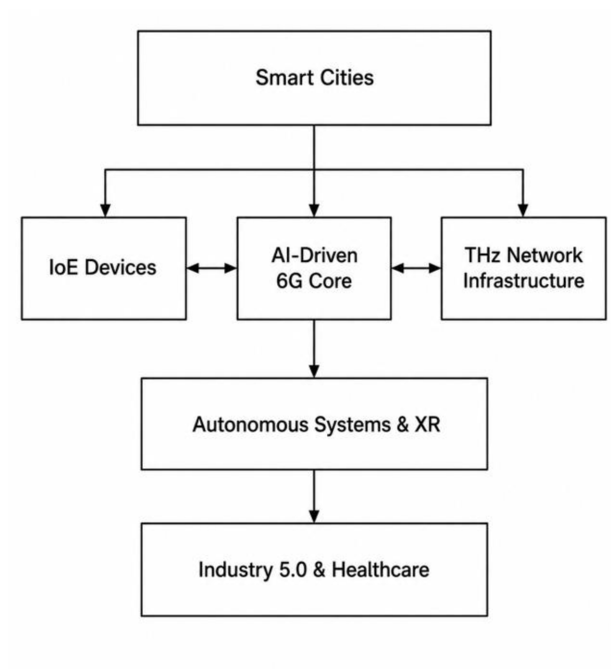

Figure 1 Vision of Intelligent 6G Wireless Ecosystem

Source: Adapted and modified from [1]–[4].

B. Enabling Technologies for 6G

1) Terahertz (THz) Communication

Terahertz communication is considered one of the core enabling technologies for 6G wireless systems. THz frequencies ranging from 100 GHz to several THz can provide extremely large bandwidths and ultra-high data transmission rates.

THz communication is highly suitable for applications requiring massive data exchange such as holographic communication, immersive virtual reality, and ultra-high-definition streaming. However, THz signals experience severe attenuation and short transmission ranges, requiring advanced beamforming and intelligent antenna technologies [5], [7].

2) Artificial Intelligence and Machine Learning

Artificial Intelligence will play a fundamental role in 6G networks. AI-enabled communication systems can optimize:

1. Spectrum allocation,
2. Traffic prediction,
3. Network slicing,
4. Interference mitigation,
5. Mobility management,
6. And energy efficiency.

Machine Learning algorithms are expected to support self-organizing and self-healing networks capable of autonomous decision-making. Deep learning can also improve channel estimation, resource allocation, and intelligent routing mechanisms [2], [6].

3) Massive MIMO and Intelligent Surfaces

Massive Multiple-Input Multiple-Output (MIMO) systems will continue to evolve in 6G by supporting higher spectral efficiency and better signal quality. Intelligent Reflecting Surfaces (IRS) or Reconfigurable Intelligent Surfaces (RIS) are also promising technologies that can dynamically manipulate electromagnetic waves to improve communication performance.

RIS technologies can enhance signal coverage, reduce energy consumption, and mitigate interference in dense urban environments [7], [8].

4) Cognitive Radio and Dynamic Spectrum Sharing

Cognitive Radio Networks (CRNs) are expected to become essential components of 6G communication systems. CRNs allow intelligent spectrum sensing and dynamic spectrum access, improving spectrum utilization efficiency.

Through AI-driven cognitive radio mechanisms, 6G networks can automatically detect unused spectrum bands and allocate them dynamically according to communication demands [2].

5) Edge Computing and Distributed Intelligence

Edge computing will reduce communication latency by moving computation and data processing closer to end devices. In 6G, edge intelligence combined with AI can support real-time decision-making for autonomous vehicles, industrial automation, and smart healthcare systems.

Distributed intelligence architectures are also expected to reduce cloud dependency and improve scalability in future ultra-dense communication environments [4], [10].

Tabel 2 Key Enabling Technologies for 6G Networks

Technology	Function	Major Challenges
Terahertz Communication	Ultra-high-speed transmission	Signal attenuation
AI and Machine Learning	Autonomous network optimization	Computational complexity
Massive MIMO	Spectral efficiency improvement	Hardware cost
Reconfigurable Intelligent Surface (RIS)	Smart signal reflection	Deployment complexity
Cognitive Radio	Dynamic spectrum sharing	Spectrum sensing accuracy
Edge Computing	Low-latency processing	Resource allocation
Blockchain	Security and trust management	Energy consumption
Digital Twin	Real-time virtual system representation	Data synchronization

Source: Compiled from [1], [2], [6], [7].

C. Applications of 6G Networks

1) Smart Healthcare and Remote Surgery

One of the most transformative applications of 6G wireless communication is smart healthcare. Future healthcare systems are expected to rely heavily on real-time monitoring, intelligent diagnostics, robotic surgery, wearable sensors, and AI-assisted medical decision systems. Unlike conventional telemedicine supported by 5G, 6G networks are expected to provide microsecond-level latency and ultra-reliable communication, which are essential for mission-critical healthcare applications.

Remote robotic surgery requires continuous high-resolution video transmission, precise tactile feedback, and uninterrupted communication reliability. Any communication delay may lead to serious operational risks. Therefore, 6G communication systems integrated with edge intelligence and AI-driven predictive networking can significantly improve surgical precision and healthcare accessibility in remote areas [1], [6].

Furthermore, wearable body sensors and Internet of Medical Things (IoMT) devices will generate enormous real-time biomedical data. AI-enabled 6G networks can process these datasets efficiently using distributed edge computing and intelligent data analytics.

2) Autonomous Transportation and Intelligent Mobility

Autonomous transportation is another major application domain of 6G wireless systems. Future intelligent transportation systems will require extremely reliable communication among vehicles, roadside infrastructure, satellites, and cloud systems. Vehicle-to-Everything (V2X) communication supported by 6G can improve traffic efficiency, accident prevention, and autonomous navigation.

Unlike 5G, 6G communication is expected to integrate sensing and communication functionalities simultaneously. This integrated sensing capability enables vehicles to detect surrounding objects, predict traffic conditions, and coordinate movements in real time [4], [8].

Additionally, AI-based traffic optimization supported by 6G infrastructure can dynamically manage urban transportation systems by analyzing traffic density, environmental conditions, and mobility patterns. This capability will be essential for future smart city ecosystems.

3) Extended Reality and Holographic Communication

Extended Reality (XR), including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), represents one of the most bandwidth-intensive applications in future communication systems. Current 5G infrastructures still face challenges in delivering fully immersive XR experiences because of bandwidth limitations and network instability.

6G wireless networks are expected to support holographic communication and ultra-realistic telepresence through THz communication and ultra-high-capacity transmission technologies. Holographic communication requires transmission speeds approaching Tbps levels due to massive real-time 3D rendering and synchronization requirements [3], [7].

For example, future remote education systems may utilize holographic classrooms where instructors and students interact virtually in real time with immersive sensory experiences. Similarly, industrial collaboration can leverage XR technologies for remote maintenance, intelligent manufacturing, and digital twin interaction.

4) Industry 5.0 and Smart Manufacturing

Industry 5.0 emphasizes intelligent collaboration between humans, machines, and AI systems. Unlike Industry 4.0, which focuses mainly on automation, Industry 5.0 integrates human-centered intelligence into industrial operations.

6G communication systems will enable fully connected smart factories through ultra-reliable low-latency communication (URLLC), AI-native automation, and intelligent robotics. Future industrial environments are expected to deploy massive numbers of sensors, autonomous robots, and digital twins connected through IoE infrastructures.

Digital twin technology supported by 6G enables real-time replication of industrial systems in virtual environments. This allows predictive maintenance, operational optimization, and intelligent monitoring of industrial processes [2], [9].

Moreover, AI-enabled edge computing can support distributed industrial intelligence by reducing computational latency and improving real-time responsiveness in manufacturing systems.

5) Smart Cities and Internet of Everything

The evolution from IoT toward Internet of Everything represents a major paradigm shift in future communication systems. IoE integrates people, processes, devices, and data into a unified intelligent ecosystem.

Smart cities powered by 6G communication will support:

1. Intelligent transportation,
2. Smart energy grids,
3. Environmental monitoring,
4. Public safety systems,
5. Autonomous public services,
6. And intelligent infrastructure management.

6G networks can also support massive connectivity for billions of intelligent devices simultaneously while maintaining high reliability and low latency [5], [10].

In addition, AI-driven analytics combined with distributed cloud-edge architectures can provide predictive urban management capabilities. For instance, smart city infrastructures can automatically optimize traffic lights, energy distribution, and emergency response systems based on real-time environmental data.

D. Challenges and Future Research Directions

1) Security and Privacy

The integration of AI, IoE, and distributed architectures introduces new cybersecurity risks. Future 6G systems must address:

1. Data privacy,
2. Authentication,
3. Secure communication,
4. And ai-based cyberattacks.

Blockchain and quantum cryptography are potential solutions for enhancing 6G security [1], [9].

2) Energy Efficiency

The massive deployment of intelligent devices and ultra-dense networks may significantly increase energy consumption. Green communication technologies and energy-efficient architectures are critical for sustainable 6G implementation [6].

3) Hardware and Infrastructure Complexity

THz communication requires advanced transceivers, antennas, and semiconductor technologies capable of operating at extremely high frequencies. Infrastructure deployment costs and hardware limitations remain major obstacles [5].

4) Spectrum Management

Efficient spectrum allocation and interference mitigation remain challenging due to increasing communication density and heterogeneous network environments [2], [7].

5) AI Reliability and Ethical Issues

AI-driven autonomous communication introduces concerns regarding transparency, trustworthiness, and ethical decision-making. Future research should focus on explainable AI and trustworthy network intelligence [4], [8].

IV. Conclusion

Sixth-generation (6G) wireless communication is expected to transform future digital ecosystems through the integration of Artificial Intelligence (AI), Terahertz (THz) communication, edge intelligence, and Internet of Everything (IoE). Unlike previous wireless generations, 6G aims to provide intelligent, autonomous, and human-centric communication systems capable of supporting ultra-high-speed, low-latency, and massive connectivity applications.

This review analyzed recent studies published between 2019 and 2025 and identified key enabling technologies including AI-native networking, intelligent reflecting surfaces, massive MIMO, cognitive radio, THz communication, and distributed edge computing. In addition, the review discussed major applications such as smart healthcare, autonomous transportation, extended reality, Industry 5.0, and smart city infrastructures.

Compared with previous surveys, this paper provides an integrated discussion combining enabling technologies, intelligent architectures, and emerging 6G applications within a single analytical framework. The review also highlights critical research challenges related to energy efficiency, security, hardware complexity, spectrum management, and trustworthy AI integration.

Future research should focus on AI-driven autonomous networking, sustainable THz communication, intelligent spectrum sharing, secure distributed architectures, and green communication systems to support scalable and reliable 6G deployment. Overall, 6G represents a major paradigm shift toward fully intelligent and interconnected communication environments for future digital societies.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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