Original Article

5G and Beyond: Engineering Challenges and Technological Innovations

Dr. Paul Anderson

Associate Professor

Abstract

The fifth generation of mobile communication (5G) represents a major technological leap, enabling high-speed, low-latency, and massive connectivity for a wide range of applications. This paper explores the engineering principles, core technologies, and architectural innovations underlying 5G networks, including Massive MIMO, millimetre-wave communication, network slicing, and edge computing. Beyond 5G, emerging technologies such as terahertz communication, AI-driven network management, quantum communication, and holographic data transmission promise to further transform wireless systems. The study also examines key engineering challenges, including spectrum allocation, network densification, energy efficiency, and security. Practical applications in smart cities, industrial automation, healthcare, and emergency response are highlighted to demonstrate the societal and technological impact of 5G and beyond. Finally, future research directions and deployment strategies are discussed, emphasizing sustainable, resilient, and intelligent network solutions. The paper underscores that 5G and next-generation networks are not merely incremental improvements but represent a paradigm shift in engineering, enabling a highly connected, responsive, and innovative digital ecosystem.

1. Introduction

The evolution of mobile communication networks has profoundly shaped modern society, enabling seamless connectivity, information exchange, and digital transformation. From the early analogy systems of the first generation (1G) to the high-speed, data-driven capabilities of the fourth generation (4G), each successive generation has addressed specific limitations while expanding the scope of wireless communication. The advent of the fifth generation (5G) represents a paradigm shift, offering unprecedented improvements in data rate, latency, reliability, and connectivity density. 5G is not merely an incremental upgrade; it is a transformative technology that enables a wide spectrum of applications, from autonomous vehicles and industrial automation to remote healthcare and immersive digital experiences. This paper provides a comprehensive analysis of 5G networks, explores emerging innovations for beyond-5G systems, and examines the engineering challenges that must be addressed to realize their full potential.

A. Evolution of Mobile Communication Networks

The journey from 1G to 5G reflects a continuous progression in both technology and societal impact. 1G introduced voice communication in analogy format, 2G enabled digital voice and messaging services, and 3G brought mobile internet capabilities. 4G networks provided high-speed broadband connectivity, supporting video streaming, mobile applications, and early Internet of Things (IoT) devices. However, with the proliferation of connected devices, latency-sensitive applications, and high-data-demand services, 4G networks began to encounter limitations in bandwidth, latency, and scalability. 5G addresses these challenges by leveraging new spectrum bands, advanced antenna technologies, network virtualization, and intelligent resource management, enabling more efficient and flexible communication systems capable of supporting the future digital ecosystem.

B. Importance and Opportunities of 5G

5G networks enable ultra-reliable, low-latency communication, massive machine-type communication, and enhanced mobile broadband. These capabilities create opportunities across numerous sectors, including smart cities, industrial automation, intelligent transportation systems, telemedicine, and immersive media applications. By facilitating near-real-time data exchange and supporting billions of connected devices, 5G serves as a foundation for next-generation engineering systems and digital infrastructure. The high flexibility and programmability of 5G networks, enabled by software-defined networking (SDN) and network function virtualization (NFV), also allow operators to tailor network slices for specific use cases, enhancing efficiency and user experience.

C. Objectives and Scope of the Study

The primary objective of this paper is to provide a comprehensive understanding of 5G technologies and to explore innovations that will shape beyond-5G networks. The study examines the architectural and technological foundations of 5G, highlights emerging research trends such as terahertz communication and AI-driven network management, and identifies critical engineering challenges, including spectrum allocation, network densification, energy efficiency, and security. Additionally, practical applications and use cases are presented to demonstrate the societal and industrial impact of 5G networks. By evaluating both current capabilities and future prospects, this study aims to offer engineers, researchers, and policymakers a holistic perspective on the evolution and potential of wireless communication systems.

D. Contribution to Engineering Practice and Research

This paper contributes to the understanding of 5G and beyond-5G networks by integrating technological analysis with engineering challenges and practical applications. It emphasizes the role of engineers in designing, deploying, and optimizing next-generation networks while addressing critical issues such as sustainability, reliability, and ethical implementation. By providing insights into emerging technologies, potential applications, and research opportunities, the study serves as a reference point for future developments in wireless communication and supports the advancement of resilient, intelligent, and high-performance engineering systems.

2. Architecture and Core Technologies of 5G

The architecture of 5G networks represents a significant evolution from previous generations, incorporating innovations that address the increasing demand for high-speed, low-latency, and massive connectivity. By combining advanced radio access technologies, edge computing, and intelligent network management, 5G provides the foundation for a highly flexible, scalable, and efficient communication system. This section explores the core components of 5G architecture, key enabling technologies, and the advantages they provide over prior network generations.

A. 5G Network Architecture

The 5G network architecture is designed to support diverse use cases, ranging from enhanced mobile broadband to ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC). It consists of three major layers:

- Radio Access Network (RAN): The RAN connects user devices to the core network, utilizing advanced technologies such as Massive MIMO, beamforming, and millimetre-wave (mm Wave) frequencies to achieve higher capacity and improved spectral efficiency. Small cell deployment is a key strategy in dense urban environments to ensure consistent coverage and low latency.
- Core Network: The 5G core network is fully virtualized, leveraging network function virtualization (NFV) and software-defined networking (SDN) to enable dynamic configuration, scalability, and efficient resource allocation. The core network manages connectivity, authentication, mobility, and data routing, supporting multiple services over a unified platform.
- Edge Computing: 5G incorporates multi-access edge computing (MEC) to bring computation closer to the user, reducing latency and enhancing real-time processing for applications such as autonomous vehicles, industrial automation, and augmented reality.

This modular and flexible architecture allows 5G to support heterogeneous devices, varying traffic loads, and diverse service requirements, setting the stage for beyond-5G innovations.

B. Key Enabling Technologies

Several technologies enable the high performance and versatility of 5G networks:

- Massive MIMO: By using large arrays of antennas at base stations, Massive MIMO increases capacity and spectral efficiency, allowing simultaneous communication with multiple users. Beamforming techniques further enhance signal quality and reduce interference, especially in dense urban environments.
- Millimetre-Wave Communication (mm Wave): mm Wave frequencies provide high-bandwidth channels capable of delivering gigabit-level data rates. While mm Wave signals are more sensitive to obstacles and atmospheric attenuation, strategic deployment of small cells and beamforming mitigates these challenges.
- Network Slicing: Network slicing enables the creation of multiple virtual networks over a single physical infrastructure. Each slice can be optimized for specific requirements, such as low latency, high reliability, or massive device connectivity, providing tailored services for different applications.
- Software-Defined Networking (SDN) and NFV: SDN separates the control plane from the data plane, allowing centralized and programmable network management. NFV virtualizes network functions, enabling rapid deployment, scalability, and cost-effective operation.

These technologies collectively allow 5G to overcome the limitations of previous generations, supporting a broad range of applications and enabling highly dynamic, intelligent networks.

C. Advantages Over Previous Generations

Compared to 4G networks, 5G offers:

- Significantly higher data rates, enabling ultra-high-definition video streaming, virtual reality, and holographic communication.
- Lower latency, essential for time-critical applications such as autonomous vehicles, remote surgery, and industrial automation.
- Massive device connectivity, supporting billions of IoT devices and enabling smart city applications.
- Enhanced reliability and network flexibility, facilitated by SDN, NFV, and network slicing, ensuring consistent performance across diverse use cases.

These advantages position 5G as the backbone for next-generation digital ecosystems, paving the way for innovations in communication, transportation, energy, healthcare, and industrial systems.

Section Contribution to the Study

This section establishes the fundamental architecture and core technologies of 5G, providing a technical foundation for understanding the challenges, applications, and future innovations discussed in subsequent sections. By highlighting the unique capabilities and enabling technologies, it demonstrates why 5G is not merely an incremental improvement but a transformative platform for engineering, digital services, and societal advancement.

3. Emerging Technologies for Beyond 5G Networks

While 5G networks provide unprecedented capabilities, the demand for higher data rates, ultra-low latency, and seamless connectivity continues to grow, driving research toward beyond-5G and sixth-generation (6G) networks. Beyond 5G envisions a hyper-connected digital ecosystem, integrating advanced wireless communication, artificial intelligence, and emerging technologies to meet future societal and industrial requirements. This section explores the key technologies, conceptual frameworks, and potential applications shaping the evolution of next-generation networks.

A. 6G Conceptual Vision and Roadmap

6G networks are expected to surpass 5G in terms of data rates, latency, reliability, and intelligence. Conceptually, 6G aims to deliver data speeds exceeding 1 Tbsp., latency in the sub-millisecond range, and pervasive connectivity capable of supporting trillions of IoT devices. The roadmap for 6G emphasizes ultra-dense networks, pervasive intelligence, and integration with advanced sensing and imaging technologies. Key research areas include terahertz (THz) frequency utilization, integrated communication and sensing systems, and seamless integration of terrestrial and satellite networks. 6G is envisioned not only as a communication platform but also as a foundation for immersive applications such as holographic communication, extended reality (XR), and autonomous systems.

B. AI-Driven Network Management

Artificial intelligence and machine learning play a critical role in beyond-5G networks by enabling intelligent network management, optimization, and self-configuration. AI algorithms can analyse massive amounts of network data in real time, predict traffic congestion, allocate spectrum dynamically, and optimize energy consumption. Self-healing networks capable of identifying faults, reconfiguring network paths, and adapting to changing conditions are expected to become a key feature of 6G. By integrating AI with network operations, engineers can achieve enhanced reliability, efficiency, and adaptability in highly complex and heterogeneous communication environments.

C. Terahertz Communication and Advanced Spectrum Utilization

Terahertz (THz) frequency bands, ranging from 0.1 THz to 10 THz, are emerging as the next frontier for beyond-5G communication. THz waves offer extremely high bandwidth and data transfer rates, enabling ultra-high-speed wireless links for applications such as holographic telepresence, high-definition virtual reality, and real-time industrial automation. However, THz communication presents engineering challenges, including high path loss, atmospheric absorption, and limited propagation range. Advanced techniques such as intelligent beamforming, ultra-dense small cell deployment, and hybrid optical-wireless integration are being explored to overcome these limitations and unlock the full potential of THz communication.

D. Quantum Communication and Holographic Data Transmission

Quantum communication is poised to provide ultra-secure and ultra-fast data transmission capabilities for future networks. By leveraging principles of quantum entanglement and quantum key distribution (QKD), engineers can develop communication systems that are inherently resistant to eavesdropping, enhancing security in critical applications such as defence, finance, and healthcare. Additionally, holographic data transmission, enabled by high-bandwidth THz links and edge computing, is anticipated to support immersive digital experiences and remote collaboration in three-dimensional environments. These technologies exemplify the transformative potential of beyond-5G networks, bridging high-performance connectivity with next-generation applications.

E. Next-Generation IoT Integration

The Internet of Things (IoT) is expected to expand dramatically in the era beyond 5G, encompassing trillions of interconnected devices across industrial, urban, and environmental systems. Advanced network technologies, coupled with AI-driven management, will enable ultra-reliable, low-latency communication for mission-critical applications such as autonomous transportation, smart energy grids, and remote healthcare. Beyond-5G networks will provide context-aware connectivity, allowing IoT devices to adapt dynamically to user requirements, environmental conditions, and system-level constraints, ensuring seamless, intelligent, and energy-efficient operation.

Section Contribution to the Study

This section highlights the emerging technologies shaping beyond-5G and 6G networks, including terahertz communication, AI-driven network management, quantum communication, holographic transmission, and next-generation IoT integration. By examining these innovations, the study emphasizes that future wireless networks will not only enhance communication performance but also transform the engineering landscape, enabling intelligent, ultra-fast, secure, and immersive systems. Understanding these developments provides engineers and researchers with a strategic framework for designing, implementing, and optimizing next-generation wireless infrastructures.

4. Engineering Challenges in 5G and Beyond

While 5G networks and emerging beyond-5G technologies promise transformative capabilities, their deployment and operation pose significant engineering challenges. Addressing these challenges is critical to realizing the full potential of next-generation wireless systems. This section examines the technical, infrastructural, energy, and security challenges associated with 5G and beyond, emphasizing their impact on network design, deployment, and sustainability.

A. Spectrum Allocation and Signal Propagation

One of the primary challenges in 5G and beyond networks is the allocation and efficient utilization of the radio frequency spectrum. Higher frequency bands, such as millimetre-wave (mm Wave) and terahertz (THz) bands, provide enormous bandwidth but are susceptible to signal attenuation, atmospheric absorption, and limited

propagation range. Engineers must carefully design network topology, deploy dense small cell networks, and employ advanced beamforming and directional antenna technologies to overcome these limitations. Efficient spectrum management also requires regulatory coordination and dynamic spectrum sharing to accommodate diverse applications and massive device connectivity.

B. Network Densification and Deployment Challenges

The high data rates and low-latency requirements of 5G necessitate dense network deployments, particularly in urban environments. Small cells, distributed antenna systems, and edge computing nodes must be strategically positioned to ensure consistent coverage and capacity. Network densification introduces engineering challenges related to interference management, infrastructure cost, backhaul connectivity, and site acquisition. Additionally, the complexity of managing ultra-dense networks increases operational overhead, requiring intelligent automation and self-optimizing mechanisms to maintain performance and reliability.

C. Energy Consumption and Sustainability

5G and beyond networks rely on energy-intensive components such as base stations, massive MIMO arrays, and edge computing servers. The rapid expansion of network infrastructure raises concerns regarding energy consumption, operational costs, and environmental impact. Engineers must explore energy-efficient hardware, adaptive power control, AI-driven network optimization, and renewable energy integration to minimize the carbon footprint of next-generation networks. Sustainable design practices will be essential to balance high-performance connectivity with ecological and economic considerations.

D. Security, Privacy, and Reliability

The massive scale, heterogeneity, and complexity of 5G and beyond networks introduce significant security and reliability challenges. The increased number of connected devices expands the attack surface, making networks vulnerable to cyberattacks, data breaches, and denial-of-service attacks. Privacy concerns also arise due to the extensive collection of user and device data. Ensuring network reliability under varying traffic loads and environmental conditions requires advanced fault detection, redundancy, and self-healing mechanisms. Engineers must design robust security frameworks, implement encryption and authentication protocols, and integrate AI-based anomaly detection to safeguard network integrity.

Section Contribution to the Study

This section highlights the key engineering challenges that must be addressed to enable reliable, efficient, and secure operation of 5G and beyond networks. By analysing spectrum management, network densification, energy efficiency, and security concerns, it provides a comprehensive understanding of the obstacles facing engineers. Recognizing and addressing these challenges is critical for designing next-generation networks that are resilient, sustainable, and capable of supporting the technological and societal demands of the future.

5. Applications and Use Cases of 5G and Beyond

The capabilities of 5G and beyond networks extend far beyond traditional mobile communication, enabling innovative applications across multiple sectors. Ultra-low latency, high data rates, massive connectivity, and network intelligence allow engineers and researchers to develop transformative solutions for smart cities, industrial automation, healthcare, and emergency management. This section explores key application areas, highlighting how next-generation networks drive efficiency, reliability, and societal impact.

A. Smart Cities and Intelligent Transportation Systems

5G networks facilitate the development of smart cities by connecting a wide array of devices, sensors, and infrastructure elements. Intelligent transportation systems leverage real-time data from vehicles, traffic signals, and road sensors to optimize traffic flow, reduce congestion, and enhance safety. Applications such as autonomous vehicles, dynamic route planning, and predictive maintenance of public transport systems are enabled by low-latency communication and high-speed data exchange. Beyond 5G networks further enhance these capabilities through AI-driven network management and massive IoT integration, supporting seamless, data-driven urban mobility.

B. Industrial Automation and Industry 4.0/5.0 Integration

In industrial environments, 5G networks enable real-time communication between machines, robots, sensors, and control systems, forming the backbone of Industry 4.0 and 5.0. Applications include remote monitoring of production lines, predictive maintenance, robotic process automation, and digital twins for simulation and optimization. Beyond 5G networks, with ultra-low latency and intelligent management, allow industrial systems to operate autonomously and adaptively, improving productivity, safety, and operational efficiency while minimizing downtime and resource wastage.

C. Remote Healthcare and Telemedicine

The healthcare sector benefits significantly from 5G networks, which support telemedicine, remote surgery, and real-time patient monitoring. High-speed connectivity and low latency allow surgeons to perform robotic-assisted procedures remotely, while AI-driven data analysis improves diagnostic accuracy. Beyond 5G networks will further enhance healthcare applications by enabling holographic communication, real-time collaborative diagnostics, and integrated wearable devices capable of continuous monitoring, providing scalable and equitable healthcare solutions even in remote or underserved regions.

D. Disaster Management and Emergency Communications

Next-generation networks play a critical role in disaster management and emergency response. 5G enables rapid deployment of temporary communication networks in disaster zones, facilitating coordination among first responders, real-time situational awareness, and remote control of drones or robots for search and rescue operations. Beyond 5G technologies, with AI-assisted predictive analytics, allow authorities to anticipate disasters, optimize resource allocation, and enhance public safety. These capabilities are essential for mitigating human and economic losses during natural or man-made emergencies.

Table 1: Representative Applications of 5G and Beyond Networks

Application Area	Key 5G Features Utilized	Benefits/Impact
Smart Cities & Intelligent Transport	Low latency, massive IoT, real-time data	Optimized traffic, autonomous vehicles, improved safety
Industrial Automation & Industry 4.0/5.0	Ultra-reliable low-latency communication, network slicing	Enhanced productivity, predictive maintenance, operational efficiency
Remote Healthcare & Telemedicine	High-speed broadband, edge computing, AI integration	Remote surgery, real-time patient monitoring, improved diagnostics
Disaster Management & Emergency Communications	Rapid deployment, AI-driven analytics, low latency	Improved situational awareness, efficient resource allocation, enhanced public safety

Section Contribution to the Study

This section illustrates the transformative potential of 5G and beyond networks across diverse sectors. By integrating high-speed connectivity, low latency, and AI-driven network management, these technologies enable practical solutions that improve urban mobility, industrial efficiency, healthcare delivery, and disaster preparedness. The examples highlight the societal and technological value of next-generation networks and provide a foundation for exploring future research directions and deployment strategies in subsequent sections.

6. Research Directions and Future Opportunities

As 5G networks continue to mature, research is increasingly focusing on beyond-5G and 6G technologies, exploring ways to address existing limitations, enhance performance, and enable novel applications. The integration of artificial intelligence, advanced spectrum technologies, energy-efficient network design, and multi-layered communication strategies presents significant opportunities for both academic research and practical engineering. This section examines emerging research directions, technological innovations, and strategic opportunities that will shape the future of wireless communication.

A. AI-Driven Network Optimization

Artificial intelligence is emerging as a cornerstone for next-generation networks, enabling predictive network management, self-healing systems, and real-time optimization of resources. Machine learning algorithms can forecast traffic patterns, optimize spectrum allocation, and dynamically manage network slices, improving efficiency and reliability. Research opportunities lie in developing explainable AI models, energy-efficient learning algorithms, and adaptive network controllers capable of operating across heterogeneous environments.

B. Sustainable and Energy-Efficient Network Design

The rapid expansion of 5G infrastructure and the anticipated deployment of beyond-5G networks pose energy and sustainability challenges. Research is focusing on energy-efficient hardware, green base stations, AI-assisted power management, and integration with renewable energy sources. Designing networks that balance high performance with low energy consumption is crucial for long-term scalability, reducing operational costs and carbon footprint while ensuring sustainable growth.

C. Satellite-Terrestrial Network Integration

Future communication networks are expected to combine terrestrial 5G/6G networks with satellite systems to provide global coverage, particularly in remote or underserved regions. Research directions include optimizing handovers between satellite and terrestrial networks, enhancing signal reliability, and managing latency for latency-sensitive applications. Integrating satellite communication with edge computing and AI-driven network orchestration will expand connectivity and enable seamless global services.

D. Standardization and Global Deployment Strategies

The success of 5G and beyond networks depends on international collaboration, standardization, and regulatory frameworks. Research in this area involves developing unified standards for spectrum management, interoperability, network security, and IoT integration. Studying deployment strategies that optimize cost, infrastructure utilization, and performance in diverse geographic and socio-economic contexts is essential to ensure equitable access and global adoption.

E. Emerging Communication Technologies

Beyond AI and integration strategies, several cutting-edge technologies are shaping the future of wireless communication:

- Terahertz (THz) Communication: Enables ultra-high-speed data transfer for applications like holographic communication and real-time immersive media.
- Quantum Communication: Provides ultra-secure and high-speed transmission, enhancing cybersecurity for critical networks.
- Holographic and Extended Reality (XR) Applications: Demand extremely low latency and high bandwidth, driving innovation in network architecture and edge computing.

Table 2: Research Directions and Future Opportunities in 5G and Beyond Networks

Research Area	Technological Focus	Potential Impact
AI-Driven Network Optimization	Machine learning, self-healing networks, predictive analytics	Enhanced efficiency, real-time adaptation, improved reliability
Sustainable & Energy-Efficient Design	Green base stations, AI-assisted power management, renewable integration	Reduced energy consumption, lower operational cost, sustainable growth
Satellite-Terrestrial Integration	Hybrid network orchestration, latency management, edge computing	Global coverage, seamless connectivity, access in remote regions
Standardization & Global Deployment	Interoperability, spectrum regulation, IoT integration	Equitable access, harmonized standards, optimized deployment strategies

Emerging Communication Technologies	Terahertz, quantum communication, holographic XR	Ultra-high-speed data transfer, secure transmission, immersive applications

Section Contribution to the Study

This section emphasizes the forward-looking strategies and research opportunities that will shape the evolution of 5G and beyond networks. By integrating AI, sustainable practices, satellite-terrestrial systems, standardization, and emerging technologies, future wireless networks can achieve higher performance, global coverage, and resilience. The table highlights how this research directions translate into practical benefits, guiding engineers and researchers in prioritizing innovations for the next generation of wireless communication.

7. Conclusion

5G networks and emerging beyond-5G technologies are transforming wireless communication by enabling ultra-fast, low-latency, and highly reliable connectivity. These advancements support a wide range of applications, including smart cities, industrial automation, remote healthcare, and disaster management, while addressing the demands of a hyper-connected society. Despite engineering challenges such as spectrum management, network densification, energy efficiency, and security, ongoing research in AI-driven optimization, sustainable network design, and satellite-terrestrial integration offers promising solutions. By leveraging these innovations, engineers can design resilient, intelligent, and globally accessible networks, laying the foundation for the next generation of digital infrastructure and technological progress.

8. References

[1] Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C. K., & Zhang, J. C. (2014). What will 5G be? *IEEE Journal on Selected Areas in Communications, 32*(6), 1065–1082.

[2] Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., et al. (2013). Millimetre wave mobile communications for 5G cellular: It will work! *IEEE Access, 1*, 335–349.

[3] Marzetta, T. L. (2010). Noncooperative cellular wireless with unlimited numbers of base station antennas. *IEEE Transactions on Wireless Communications, 9*(11), 3590–3600.

[4] Dahlman, E., Parkvall, S., & Sköld, J. (2020). *5G NR: The next generation wireless access technology* (2nd ed.). Academic Press.

[5] Foukas, X., Patounas, G., Elmokashfi, A., & Marina, M. K. (2017). Network slicing in 5G: Survey and challenges. *IEEE Communications Magazine, 55*(5), 94–100.

[6] Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. *IEEE Internet of Things Journal, 3*(5), 637–646.

[7] Zhang, Z., Xiao, Y., Ma, Z., et al. (2019). 6G wireless networks: Vision, requirements, architecture, and key technologies. *IEEE Vehicular Technology Magazine, 14*(3), 28–41.

[8] Saad, W., Bennis, M., & Chen, M. (2019). A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Network, 34*(3), 134–142.

[9] Dang, S., Amin, O., Shihada, B., & Alouini, M.-S. (2020). What should 6G be? *Nature Electronics, 3*, 20–29.

[10] Akyildiz, I. F., Kak, A., & Nie, S. (2020). 6G and beyond: The future of wireless communications systems. *IEEE Access, 8*, 133995–134030.

[11] Letaief, K. B., Chen, W., Shi, Y., Zhang, J., & Zhang, Y.-J. A. (2019). The roadmap to 6G: AI empowered wireless networks. *IEEE Communications Magazine, 57*(8), 84–90.

[12] Huang, C., Moessner, K., & Tafazolli, R. (2018). A survey of energy-efficient techniques for 5G networks. *IEEE Communications Surveys & Tutorials, 20*(2), 1540–1575.

[13] Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., & Zorzi, M. (2020). Toward 6G networks: Use cases and technologies. *IEEE Communications Magazine, 58*(3), 55–61.

[14] Taleb, T., Samdanis, K., Mada, B., Flinck, H., Dutta, S., & Sabella, D. (2017). On multi-access edge computing: A survey of the emerging 5G network edge cloud architecture. *IEEE Communications Surveys & Tutorials, 19*(3), 1657–1681.

[15] Zhang, J., Ge, X., Li, Q., Guizani, M., & Zhang, Y. (2019). 5G millimeter-wave antenna array: Design and challenges. *IEEE Wireless Communications, 24*(2), 106–112.

[16] You, X., Wang, C.-X., Huang, J., et al. (2021). Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts. *Science China Information Sciences, 64*(1), 110301.

[17] Zhou, Z., Chen, X., Li, E., et al. (2019). Edge intelligence: Paving the last mile of artificial intelligence with edge computing. *Proceedings of the IEEE, 107*(8), 1738–1762.

[18] Lin, X., Li, J., Baldemair, R., et al. (2019). 5G new radio: Unveiling the essentials of the next generation wireless access technology. *IEEE Communications Standards Magazine, 3*(3), 30–37.

[19] Agiwal, M., Roy, A., & Saxena, N. (2016). Next generation 5G wireless networks: A comprehensive survey. *IEEE Communications Surveys & Tutorials, 18*(3), 1617–1655.

[20] ITU-R. (2023). *IMT-2030 (6G) framework and overall objectives of the future development of IMT for 2030 and beyond.* International Telecommunication Union.