iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: XII Month of publication: December 2025

DOI: https://doi.org/10.22214/ijraset.2025.76261

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

5G and Beyond: The Evolution Toward 6G Networks - Architecture and Emerging Challenges

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Abstract: This transition, from 5G to 6G wireless communication, represents a full-scale technological leap in global connectivity. While 5G wireless communication has been successful in introducing URLLC, mMTC, and eMBB, it still has its limitations in terms of scalability, energy efficiency, and use of the radio frequency spectrum. 6G communications will offer terabit-per-second data rates, submillisecond latency, and an entirely intelligent, AIoperated network architecture. This paper discusses the transition path from 5G to B5G and 6G, presents an analysis of the 6G network architecture evolution, and discusses new challenges facing the areas of spectrum management, security, and sustainability. As global communication systems get closer to 5G systems' limits, the industry and research community are actively investigating Beyond 5G and Sixth-Generation (6G) technologies. In addition to integrating into intelligent communication systems, next-generation networks promise to achieve previously unheard-of performance in data rate, latency, reliability, and intelligence. In addition to important enabling technologies, potential uses, and significant data communication challenges, this overview highlights the architectural details of Beyond 5G and 6G. The path from 5G to 6G is highlighted, along with the evolution of architecture, the incorporation of edge computing, terahertz communication, AI, and non-terrestrial networks. Along with initiatives for interoperability, security, and sustainability in global communication infrastructures, this paper also outlines future research directions.
Keywords: Beyond 5G, 6G, architecture, terahertz, AI-native networks, edge computing, non-terrestrial networks, security, data communication

I. INTRODUCTION

From 1G's analog voice to 5G's high-speed data and IoT integration, wireless technologies have been continuously evolving due to the global desire for faster, smarter, and more dependable communication systems. Since its commercial deployment in 2020, the fifth-generation (5G) network has revolutionized various industries with its high capacity, ultra-low latency, and improved connectivity. But new uses like digital twins, brain-computer connections, and holographic telepresence require even more capabilities than 5G can offer. Consequently, both industry and academia are concentrating on sixth-generation (6G) and Beyond 5G (B5G) networks, anticipated to be operational by 2030. These networks aim to utilize artificial intelligence (AI), terahertz (THz) transmission, quantum technologies, and intelligent reflecting surfaces (IRS) to achieve data rates of up to 1 Tbps, latency below 0.1 ms, and extensive coverage. Through enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC), 5G networks have transformed mobile communication. However, emerging applications such as real-time holography, autonomous vehicles, industrial automation, and the extensive Internet of Everything (IoE) demand greater capabilities than what 5G can offer.

Consequently, studies have explored technologies surpassing 5G and 6G that incorporate artificial intelligence, cloud-edge continuum, terahertz communication, and non-terrestrial connectivity.

II. INCREASING 5G AND 6G

The transition from 5G to B5G and eventually 6G is characterized by a number of developments:

1) The Enhanced Mobile Broadband (eMBB) features of 5G networks allow for high data rates for streaming and cloud applications. Ultra-Reliable Low-Latency Communication (URLLC) enables mission-critical applications such as autonomous vehicles and remote surgery. Billions of Internet of Things devices are effectively connected by massive machine-type communication, or mMTC. Millimeter-wave (mmWave) spectrum, edge computing, massive MIMO, and network slicing are significant technologies.

2) 5G coverage is limited by high propagation loss at mmWave frequencies. Energy consumption and network complexity in dense deployment.
3) Beyond 5G (B5G) Beyond 5G (B5G) refers to the phase of transition between 5G and 6G. By incorporating AI/ML for resource allocation and traffic prediction, it aims to improve the existing 5G infrastructure. To improve spectral efficiency, sub-THz frequencies (100–300 GHz) are employed. Improved energy efficiency through the use of green communication strategies. Real-time data processing through edge-cloud collaboration.

Parameter	5G	Beyond 5G	6G
Data Rate	20Gbps	50-100Gbps	1Tbps(aggregate)
Latency	~1 ms	< 0.5 ms	< 0.1 ms
Spectrum	Sub-6GHz, mmWave	sub-THz, THz	optical spectrum
Intelligence	software-defined	AI-assisted	AI-native, self-learning
Coverage	Terrestrial	Extended Aerial	Ubiquitous + (space–air–ground–sea)
Applications	IoT, AR/VR, autonomous vehicles	Real-time XR, AIoT, automation	Holographic, digital twins, quantum communication

III. 6G ARCHITECTURE AND DESIGN GOALS

B5G and 6G network architecture will be intelligent, adaptable, and fully integrated across multiple domains. Some critical elements in this aspect include:

1) Cognitive and AI-Native Architecture: While 5G systems are AI-assisted, 6G will embed intelligence into every layer of the network stack. The AI and machine learning will power resource allocation, fault detection, beamforming, routing, and traffic prediction to enable the self-optimization and self-healing of the network.
2) The Edge-Cloud Continuum: Computation and storage are spread across an edge-cloud continuum to meet the needs for low latency and high bandwidth. Data processing occurs dynamically at a device, edge, or cloud depending on application needs.
3) Non-Terrestrial Networks (NTN): Drones, HAPS, and satellites are integrated into Beyond 5G and 6G systems for global coverage. This would ensure seamless communication in areas that are isolated, rural, and affected by disasters.
4) Optical Wireless Communication and Terahertz (THz): THz and VLC have data rates of up to terabits per second; however, they also have disadvantages such as alignment sensitivity and high route loss. The use of ultra-massive MIMO and RIS can mitigate these effects.
5) Virtualization and Network Slicing: Advanced network slicing will provide for performance isolation and adaptability by offering tailored virtual networks for various services, such as industrial automation, healthcare, and AR/VR.

IV. ESSENTIAL ELEMENTS OF AN AI-NATIVE NETWORK:

It uses AI and ML for predicting faults, automatic configuration at every level, and flexible spectrum management. It promotes autonomy and mental processes.

1) Terahertz layer of communication: Operates at ultra-high-speed data transport frequencies ranging from 100 GHz up to 3 THz. Short-range connectivity but incredibly powerful for interior networks and small data centers.
2) ISAC, Integrated Sensing and Communication: It will detect the position of the user and context of the surroundings by combining data-communication and radar-like sensing.

3) Convergence of Edge and Cloud: It distributes processing power between local edge nodes and centralized clouds. For AI and IoT applications, this reduces latency and enables real-time analytics. Intelligent Reflecting Surfaces: Programmable meta surfaces can control electromagnetic waves to improve coverage and signal quality provides impenetrable data security by introducing quantum key distribution (QKD).
4) Terahertz Communication: This requires technologies, in antennas and modulation yet it offers extremely fast data transfer rates. RIS stands for Reconfigurable Intelligent Surfaces. Signals can be dynamically altered to improve propagation environments. AI and machine learning are behind self-running systems that fix themselves. Integrated Sensing and Communication ISAC enables the merging of radar detection, with data transmission.
5) Quantum Communication & Security: Applies quantum encryption principles to protect data.
6) Non-Terrestrial Networks: Convergence of terrestrial infrastructure with satellite and aerial connectivity. Improve spectrum and energy efficiency through the use of advanced modulation and coding schemes.

V. APPLICATIONS

1) Holographic Telepresence: 3D real-time communication for entertainment, health care, and education.
2) Extended Reality: Very low delay with very high throughput for immersive augmented and virtual reality.
3) Autonomous Transport: mobility enabled by reliable vehicle-to-everything communication.
4) Smart Cities and Industrial IoT: Data-driven manufacturing, logistics, and energy automation.
5) Tactile Internet enables telemedicine applications. This includes haptic feedback for healthcare and remote surgery.
6) Digital twins are the real-time virtual replicas of actual systems applied in simulation and predictive maintenance.

VI. NEW CHALLENGES IN 6G NETWORKS

Digital inclusion and equal access. Although 6G has a lot of potential, there are many technological and social challenges.
1) Frequency Range and Transmission: The THz spectrum is challenging to manage due to significant path loss and molecular absorption. Calls for flexible antennas, highly dense cell placement, and sophisticated beamforming.
2) Sustainability and Energy Efficiency: The incredibly dense infrastructure of 6G could lead to higher power requirements. Investigating energy harvesting, green communication, and AI-driven optimization is essential.
3) Security and Privacy: New techniques for attacking systems with AI and quantum advancements. Need for secure network slicing and encryption that is resistant to quantum computing.
4) Interoperability and compatibility guaranteeing 5G, B5G, and 6G devices run smoothly challenges in overseeing heterogeneous networks.
5) Cost and Deployment of InfrastructureBuilding THz base stations and intelligent surfaces is expensive. Without strategic deployment, the gap between rural and urban areas could get wider.
6) Ethical and Social Difficulties: privacy issues in networks driven by AI: Impacts of a massive 6G infrastructure on the environment.

VII. PROSPECTIVE RESEARCH PATHS

Creation of carbon-neutral networks' green communication frameworks.Investigation of hybrid THz-optical systems for extremely dependable communication.Creation of autonomous network orchestration algorithms with reinforcement and federated learning research on reliable AI models and quantum-resistant security measures.

Examination of architectures for integrated communication, sensing, and computing (ICSC).

Self-learning and self-healing networks are part of AI-Centric Network Management.

Long-term secure communication is ensured by quantum-safe protocols.

1) Satellite-Terrestrial Integration: Low-Earth Orbit (LEO) satellites provide seamless worldwide coverage. Real-time haptic communication for industrial, entertainment, and medical purposes is known as the "tactile internet."
2) Sustainable 6G: Creating low-carbon, environmentally friendly communication networks.

VIII. CONCLUSION

It would be impossible to have a really intelligent networked digital world without going beyond 5G connectivity into 6G. The integrated communication, computing, and sensing in 6G will enable applications that are until now unimaginable, including holographic telepresence, digital twins, and global IoT ecosystems.

Technical issues are to be resolved with energy efficiency, security, and spectrum management so its deployment will be equable and sustainable. In the coming decade, governments, corporations, and academia will work together in developing it to meet the ambition of 6G. Beyond 5G and 6G networks represent the next development in global communication systems, integrating cutting-edge technologies, with advanced technology represented by AI, terahertz communication, edge-cloud computing, and non-terrestrial networks. Beyond 5G and 6G networks include revolutionary use in immersive digital environments, transportation, and healthcare. However, all these ambitions can only be achieved by overcoming considerable technological, energy, and security barriers. The creation of safe, lasting communication systems will need teamwork from governments, businesses, and schools.

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