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From 5G to 6G: A Systematic and Analytical Survey of Architectures, Enabling Technologies, Applications and Research Challenges

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Abstract

The evolution of wireless communication has formed the bedrock for current digital infrastructures. The fifth-generation communication system brought considerable improvements in data rates, low latency and better reliability, allowing for the interconnection of a vast number of devices. This played an important role as it paved the way for various applications such as smart cities, transport systems and industrial automation. However, the rapid emergence of a number of data-intensive and intelligence-driven services, including immersive XR, real-time digital twin platforms, intelligent robotic systems and pervasive connectivity, has started to expose some core limitations within existing 5G architectures. Consequently, the research community has increasingly directed attention toward sixth-generation wireless networks.

Keywords: *5G, 6G, Terahertz communication, Massive MIMO, Reconfigurable Intelligent Surfaces, AI-native networks, Integrated Sensing and Communication, Network slicing*

1. Introduction

In contrast to the earlier generation, 6G is very much perceived as an intelligent and deeply integrated communication paradigm, integrating communication, sensing, computing and AI into a unified system framework. The foreseen performance targets involve terabit-per-second transmission rates, sub-millisecond latency, ultra-high reliability and seamless connectivity across terrestrial, aerial, maritime and satellite domains. In this context, this paper presents a

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systematic and analytical survey of 5G and emerging 6G communication systems. This survey provides a generation-wise comparative outlook on network architectures, presents a structured taxonomy of key enabling technologies, reviews representative application domains and critically analyses the associated challenges and open research gaps. By shedding light on how the evolutionary journey from 5G infrastructures toward AI-native 6G networks unfolds, this contribution provides well-informed insights and a forward-looking research roadmap on next-generation wireless communication systems.

Exponential growth in data-intensive applications, Intelligent Automation, and large-scale Internet-of-Things deployments have brought very high-capacity, low-latency, and truly reliable wireless communication systems into great demand. Even though 4G LTE networks successfully enabled mobile broadband services, their design was not targeted at accommodating these emerging mission-critical and ultra-reliable applications. It is due to this reason that the enhancement of mobile broadband, ultra-reliable low-latency communication, and massive machine-type communication introduced the new dimension of 5G communication systems.

While there are many, this has not stopped the rapid proliferation of immersive XR applications, real-time digital twins, autonomous robotics, and AI-driven services from revealing fundamental scalability, intelligence, and spectrum efficiency limitations of 5G networks. These challenges have motivated the research community to begin exploring sixth-generation wireless systems-6G-expected to go well beyond connectivity toward an intelligent, adaptive, and context-aware communication fabric.

This paper intends to provide a harmonized and structured survey on 5G and 6G communication systems, focusing on architecture evolution, enabling technologies, applications, and open research challenges.

Contributions of This Survey

The main contributions are summarized as follows:

1. A **systematic architectural analysis** highlighting the evolution from cloud-native 5G systems to AI-native 6G networks.
2. A **taxonomy of enabling technologies** for both 5G and 6G, covering spectrum, physical-layer innovations, and intelligent control mechanisms.
3. A **comparative performance and capability analysis** identifying key limitations of 5G and the corresponding design goals of 6G.

4. A **challenge–research gap mapping** that outlines unresolved technical, security, and sustainability issues.
5. A **future research roadmap** that guides post-5G and early 6G research directions.

2. Survey Methodology and Related Work

2.1 Survey Methodology

This study is grounded on a comprehensive literature review of scholarly literature retrieved using prominent online databases such as IEEE Xplore, Scopus, Elsevier Science Direct, and Springer Link. Articles between 2013 and 2025 were selected using keywords such as "5G architecture," "6G vision," "terahertz communication," "AI-native networks," "reconfigurable intelligent surfaces," and "integrated sensing and communication," among others. These literature works were selected for analysis with respect to their relevance, depth of technical information, and their role to-date in the advancement of wireless communication systems.

2.2 Related Work Analysis

The existing surveys mainly focus on either 5G technologies or conceptual visions for 6G systems. Various works have focused on mmWave communications and massive MIMO as the important enablers of 5G, whereas recent works have stressed THz communication, integration of AI, and RISs for 6G. A holistic comparative study that systematically bridges 5G-6G architectures, technologies, and applications remains rather scarce. This survey will fill such a gap by providing an integrated evolutionary perspective.

3. Overview of 5G Communication Systems

3.1 5G Architecture

5G is based on a cloud-native, service-based architecture that allows flexible management and scaling of networks. The architecture is composed of the NG-RAN and 5GC, where a clear separation between control plane and user plane can be distinguished. SDN and NFV are important integral components that support dynamic resource allocation and network slicing.

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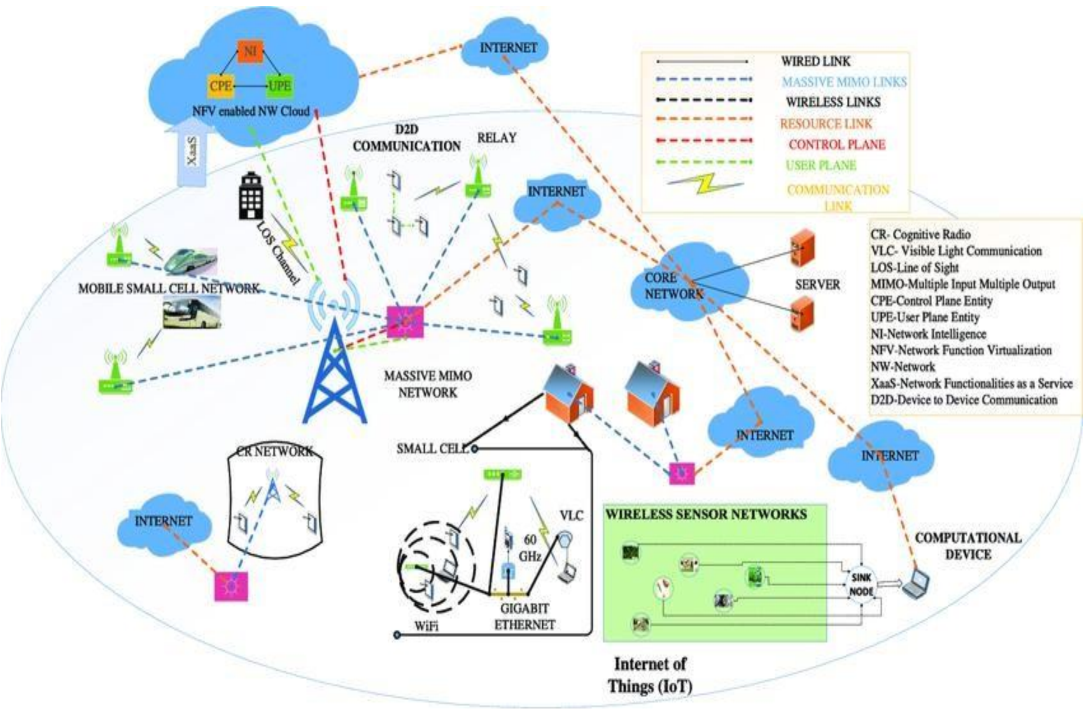

Figure 1. 5G Architecture

3.2 Key Enabling Technologies

3.2.1 Millimeter-Wave Communication

Operating in the 24–100 GHz frequency range, mmWave communication provides wide bandwidth and multi-gigabit-per-second data rates. However, high path loss and limited penetration capabilities necessitate dense base station deployment.

3.2.2 Massive MIMO and Beamforming

Massive MIMO employs large antenna arrays to improve spectral efficiency through spatial multiplexing and directional beamforming, significantly enhancing network capacity and coverage.

3.2.3 Network Slicing

Network slicing enables the creation of multiple logical networks over a shared physical infrastructure, allowing service-specific quality-of-service (QoS) guarantees for diverse applications.

3.2.4 Edge Computing

Multi-access edge computing (MEC) reduces end-to-end latency by processing data closer to the user, making it essential for real-time applications such as autonomous driving and industrial control.

3.3 Performance Capabilities

5G networks target peak data rates of up to 20 Gbps, latency below 1 ms, and support for up to one million devices per square kilometre.

4. Vision and Architecture of 6G Communication Systems

4.1 Design Principles and Vision

6G networks are envisioned as intelligent, adaptive systems that integrate communication, sensing, computing, and AI. Unlike 5G, which primarily enhances connectivity, 6G aims to provide context-aware and goal-oriented services across heterogeneous environments.

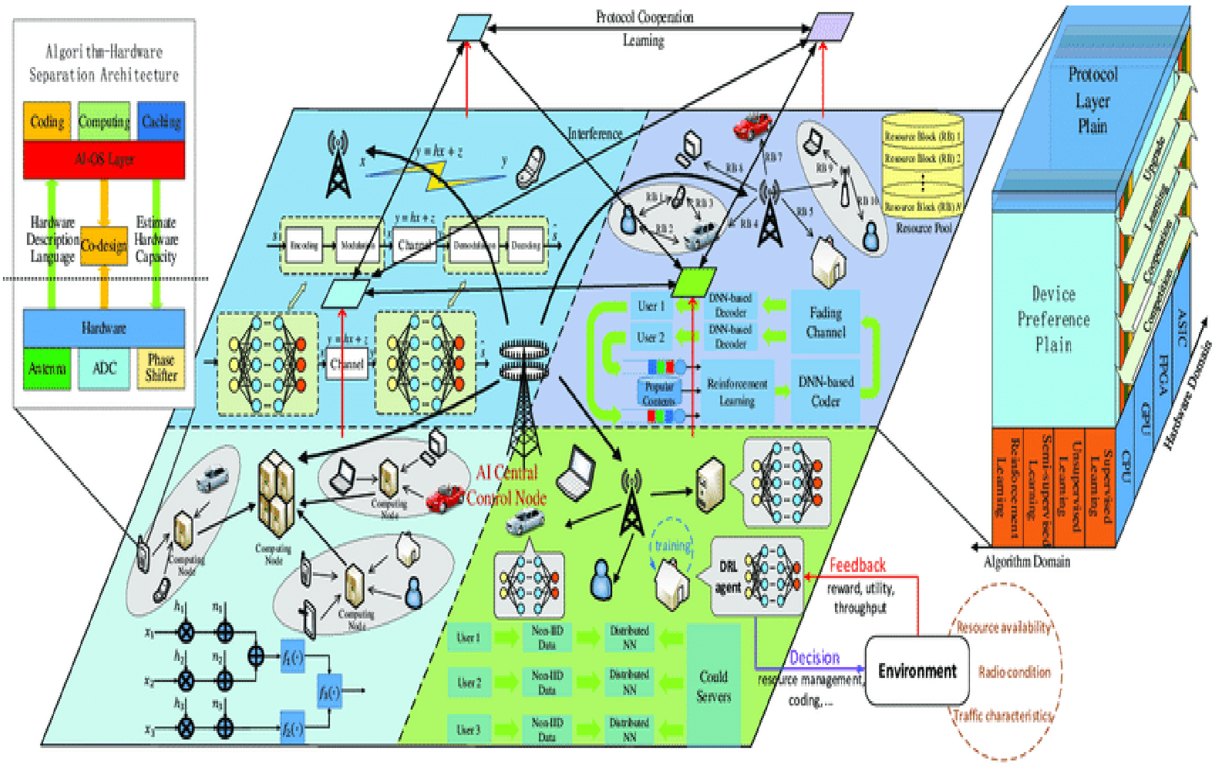

Figure 2. 6G Architecture

4.2 Enabling Technologies for 6G

4.2.1 Terahertz Communication

THz communication (0.1–10 THz) offers extremely large bandwidth, enabling terabit-per-second data rates. However, severe molecular absorption and hardware constraints remain significant challenges.

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4.2.2 AI-Native Networks

AI-native 6G networks incorporate machine learning and deep learning at all layers of the protocol stack, enabling self-optimization, predictive maintenance, and intelligent resource management.

4.2.3 Reconfigurable Intelligent Surfaces

RIS are programmable meta surfaces capable of dynamically controlling electromagnetic wave propagation, enhancing coverage, and improving energy efficiency.

4.2.4 Integrated Sensing and Communication

Integrated Sensing and Communication (ISAC) merges radar and communication functionalities, enabling high-precision localisation and enhanced environmental awareness.

4.2.5 Cell-Less and Space–Air–Ground Architectures

6G networks are expected to adopt cell-less architectures and integrate satellite, aerial, and terrestrial networks to ensure seamless global connectivity.

4.3 Target Performance Metrics

6G aims to achieve data rates up to 1 Tbps, latency below 0.1 ms, ultra-high reliability, and a tenfold improvement in energy efficiency compared to 5G.

5. Applications of 5G and 6G Networks

5.1 Applications Enabled by 5G

5G supports a wide range of applications, including smart cities, remote healthcare, intelligent transportation systems, smart manufacturing, smart farming, education, media and entertainment and immersive AR/VR experiences.

5.2 Emerging Applications Enabled by 6G

6G is expected to enable holographic telepresence, brain–computer interfaces, cognitive robotics, real-time digital twins, and space–air–ground integrated services.

6. Comparative Analysis of 5G and 6G

Table 1. Comparison of 5G and 6G

Feature	5G	6G
Frequency Bands	Sub-6 GHz, mmWave	THz, optical
Peak Data Rate	20 Gbps	1 Tbps
Latency	~1 ms	<0.1 ms
AI Integration	Limited	Fully AI-native
Architecture	Cell-based	Cell-less
Sensing Capability	Limited	Fully integrated

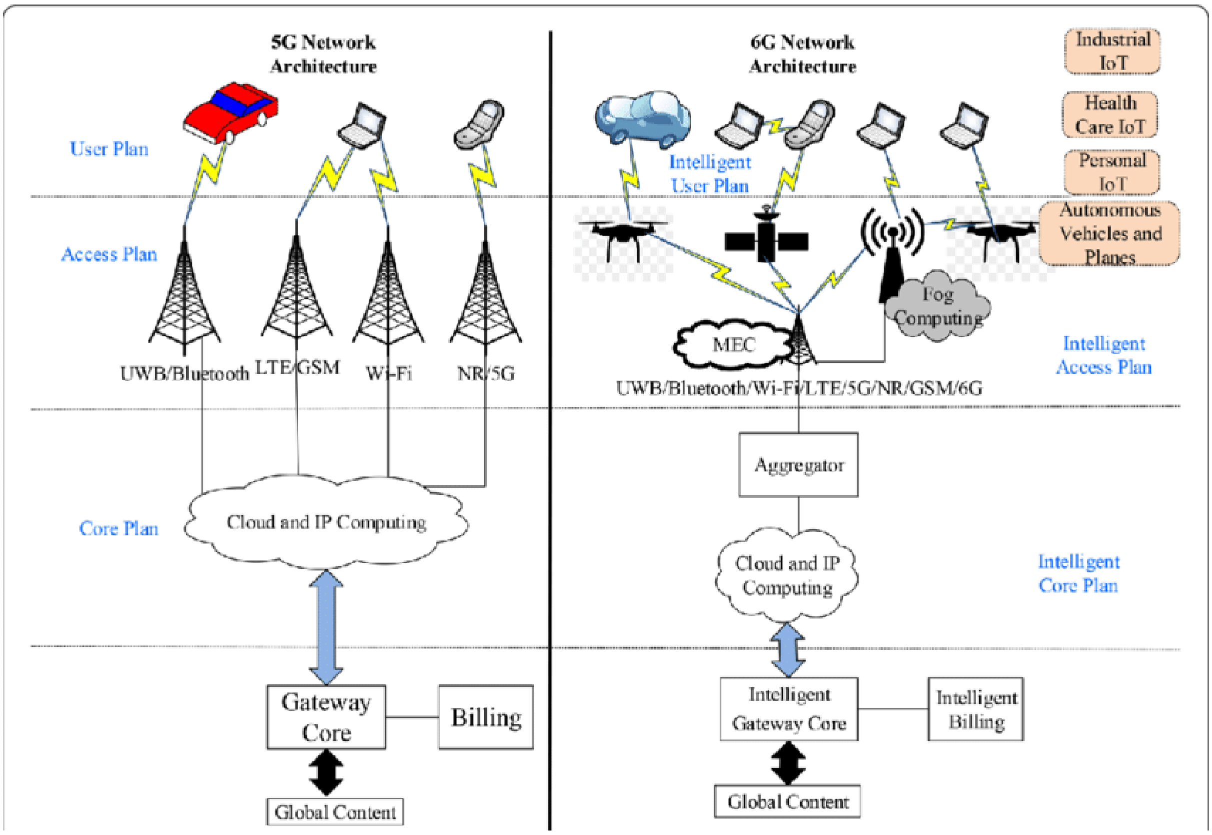

Figure 3. Comparison of 5G and 6G

7. Challenges and Open Research Gaps

7.1 Challenges in 5G

Key challenges in 5G includes the following:

1. **Infrastructure costs**: The installation of 5G networks necessitates large expenditures for new infrastructure, including fiber optic networks and base stations. For operators, this can be a significant obstacle, particularly in places with few populations.

2. **Spectrum availability**: To deliver high data speeds and minimal latency, 5G networks need a lot of spectrums. However, there is a finite amount of spectrum available, and different industries and services may compete with one another for it.

3. **Security**: A variety of cyberthreats, including hacking and data leaks, can affect 5G networks. Operators and other stakeholders may find it extremely difficult to guarantee that the networks are safe from intrusions.

4. **Interoperability**: Cooperation and interoperability amongst various stakeholders, including operators, vendors, and regulators, are necessary for the rollout of 5G networks. Interoperability may be hampered by variations in business models, legal frameworks, and technical standards.

5. **Energy consumption**: The infrastructure of 5G networks needs a lot of energy to run, which could harm the environment and raise operational expenses.

7.2 Challenges and Research Gaps in 6G

7.2.1. Spectrum Scarcity

Spectrum shortage is one of the main issues with 6G communications. The available frequency spectrum becomes a finite resource as the need for greater connection and faster data rates keeps rising. Novel strategies like spectrum sharing, dynamic spectrum allocation, and the use of underutilized frequency bands are being investigated as solutions to this problem. To effectively distribute and make use of the existing spectrum resources, improvements in spectrum management policies and regulations are also necessary.

7.2.3. Ultra-Dense Networks

A high density of linked devices, such as Internet of Things (IoT) devices, sensors, and smart objects, is envisioned by 6G networks. Network planning, resource allocation, interference control, and scalability are all made more difficult by this ultra-dense network paradigm. To guarantee dependable and effective communication in ultra-dense 6G networks, efficient methods for network optimization, intelligent resource allocation, and interference reduction must be developed.

7.2.4. Energy effectiveness

Energy efficiency becomes a crucial issue due to the growing number of connected devices and the enormous data traffic produced by 6G networks. To guarantee sustainable operation and lessen the impact on the environment, network infrastructure and devices' power consumption needs to be minimized. To solve the energy issues in 6G communications, energy-efficient network architecture, power management plans, energy harvesting methods, and improvements in hardware and component efficiency are crucial.

7.2.5. Security and Privacy

Strong security and privacy become crucial as 6G networks enable the transfer of enormous volumes of sensitive data and support vital applications. 6G networks are vulnerable to a variety of security vulnerabilities because to their highly linked and heterogeneous structure, which expands the attack surface. To safeguard the integrity, confidentiality, and privacy of data transferred via 6G networks, strong authentication, encryption, intrusion detection, privacy-preserving protocols, and secure network architectures are essential.

7.2.6. Network Slicing and Orchestration

Network slicing guarantees optimal resource allocation and QoS (Quality of Services) provisioning by enabling the construction of virtual network slices tailored to particular application requirements. However, the diversified and dynamic nature of applications and services makes it difficult to achieve effective network slicing and orchestration in 6G networks. To enable flexible and scalable network slicing in 6G communications, intelligent network slicing algorithms, effective resource management frameworks, and dynamic orchestration methods must be developed.

7.2.7. Ethical and Societal Implications

The development and widespread use of 6G networks have social and ethical ramifications that should be carefully considered. Concerns about privacy, data ownership, the digital gap, and social equity are brought up by the integration of cutting-edge technologies like augmented reality, virtual reality, and artificial intelligence. In order to ensure equitable and responsible use of 6G technologies, promote inclusivity, and reduce potential threats to society, it is imperative to address these ethical issues and create legislation and regulations. Researchers, business experts, and legislators can clear the path for the effective deployment of 6G communications by comprehending and resolving these issues. Overcoming these challenges will allow 6G networks to reach their full potential, transforming wireless communication and promoting revolutionary developments in a number of societal sectors.

8. Conclusion

A thorough and critical review of 5G and upcoming 6G communication systems was provided in this paper. The report emphasized the shortcomings of 5G and the revolutionary possibilities of 6G by looking at architectural progression, supporting technologies, applications, and open research issues. Even though there are still a lot of technological obstacles to overcome, continued research is anticipated to open the door to intelligent, sustainable, and globally connected 6G networks.

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