6 G Networks: The next frontier in wireless communication

Thejiya.V[1]

[1]*Department of Computer Science, Krupanidhi Group of Institutions, Bangalore, India*

Abstract-*As the deployment of 5G networks accelerates globally, the focus of researchers, technologists, and policymakers is rapidly shifting toward sixth-generation (6G) wireless networks. 6G promises a dramatic transformation of communication paradigms by introducing ultra-high throughput, near-zero latency, and AI-native networking. It is envisioned as a transformative leap in mobile communication, promising ultra-low latency, terabit-per-second data rates, pervasive AI integration, and seamless global connectivity through integrated terrestrial, aerial, and satellite networks. This paper examines the foundational shifts proposed by 6G, identifying the limitations that drive the need for it. It probes into the architectural innovations underpinning 6G, including terahertz communication, AI-native networking, 3D network topologies, and intelligent reflecting surfaces. Key use cases such as real-time holography, tactile internet, and brain-computer interfaces are analysed alongside technical challenges and global pilot projects. Through extensive analysis and simulation, this paper provides a detailed roadmap toward a 6G-enabled future. The paper concludes with research directions, implementation strategies, and policy considerations necessary for realizing the 6G vision by 2030 and beyond.*

Keywords: Wireless networks, Mobile communication, Satellite networks, Global connectivity, 3DNetwork topologies, Simulation, Global connectivity, Architectural innovations

1. INTRODUCTION

The journey of wireless communication has been marked by a generational leap approximately every decade each one reshaping the way humans interact, share, and access information. Starting with 1G analog voice in the 1980s, followed by 2G's digital voice and SMS, 3G's mobile data, 4G's broadband internet, and 5G's low latency and high-speed connectivity, each generation has addressed the demands of its era. However, the increasing convergence of digital, physical, and biological systems coupled with the explosive growth in devices, data, and AI applications has exposed the limitations of even the most advanced 5G systems.

5G, despite its massive improvements in speed, capacity, and latency, is not fully equipped to support emerging demands such as real-time holographic communication, high-precision industrial automation, immersive extended reality (XR), and ubiquitous global connectivity. These use cases require not only faster data transfer but also intelligent, adaptive, and context-aware networking features that lie at the core of 6G.

6G is not merely an extension of 5G; it represents a paradigm shift in how wireless systems are designed, implemented, and experienced. It promises peak data rates exceeding 1 terabit per second, end-to-end latencies below 0.1 milliseconds, and native support for artificial intelligence (AI) throughout the network. Additionally, 6G is expected to integrate communication with sensing, computing, and localization, enabling hyper-connected environments and intelligent services that adapt dynamically to users' needs.

As of early research and standardization efforts, 6G is projected to reach initial deployment stages by 2030. Several countries and institutions such as the United States, China, South Korea, Finland, and the European Union have already launched strategic initiatives and pilot projects to lead this transition. While the vision is ambitious, it also brings significant challenges: from managing spectrum in the terahertz range to ensuring energy efficiency, privacy, and equitable access.

This paper explores the evolution of wireless technology leading to 6G, outlines its foundational innovations, and examines its transformative potential across industries and societies. Through technical analysis, simulation studies, and current global developments, the paper aims to provide a comprehensive view of what 6G means for the future of communication.

2. EVOLUTION FROM 5G TO 6G

While 5G networks brought major breakthroughs in wireless communication such as enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC), and massive machine-type communications (mMTC) they are not sufficient for the anticipated demands of the next digital era. As new applications such as real-time digital twins, holographic conferencing, brain-computer interfaces, and fully autonomous systems emerge, the pressure to develop a more capable and intelligent network architecture is mounting. This pressure has catalysed the evolution toward 6G.

2.1 Limitations of 5G

Despite its achievements, 5G technology faces several constraints:

- Latency Floor: 5G targets latency as low as 1 millisecond, which is not enough for emerging use cases like real-time remote surgery or haptic internet, which require sub-millisecond responsiveness.
- Bandwidth Saturation: Even with millimetre-wave (mm Wave) bands, 5G cannot deliver the ultra-high capacity needed for terabit-level services such as high-resolution holograms or persistent XR environments.
- Limited Intelligence: 5G networks use AI primarily for optimization. They are not inherently AI-native, meaning decision-making is still partially manual or semi-automated.
- Patchy Coverage: 5G relies heavily on dense infrastructure (e.g., small cells), making deployment expensive and leaving rural and remote areas under-served.
- Energy Consumption: With billions of devices connected, 5G networks consume substantial energy, raising sustainability concerns in both network operation and device-level interaction.

2.2 The Need for 6G

6G is envisioned as a holistic solution to these limitations, offering technological upgrades and architectural shifts:

- Terabit-Scale Throughput: 6G aims for peak data rates of up to 1 Tbps using frequencies in the terahertz (THz) range (100 GHz to 10 THz), enabling extremely high-speed data transfers.
- Sub-Millisecond Latency: 6G targets end-to-end latency below 0.1 ms, which will unlock truly real-time applications such as tactile internet, real-time remote operations, and precision control systems.
- AI-Native Architecture: In 6G, AI and machine learning are built into the fabric of the network itself, enabling autonomous optimization, self-healing capabilities, and real-time decision-making.
- 3D Network Topology: By integrating satellites, high-altitude platforms (HAPs), and unmanned aerial vehicles (UAVs), 6G offers 3D coverage to eliminate blind zones and extend services to underserved areas.
- Energy-Efficient Design: 6G promotes low-power protocols, energy harvesting technologies, and green AI to make networks more sustainable and cost-effective.

2.3 Emerging Use Cases Driving 6G

The following emerging use cases highlight the inadequacy of 5G and justify the transition to 6G:

- Real-Time Holography: Requires extremely high throughput and synchronization beyond 5G's capabilities.
- Brain-Computer Interfaces (BCIs): Demand ultra-low latency and uninterrupted high-bandwidth connectivity.
- Fully Autonomous Vehicles: Require constant and reliable communication, even in rural or obstacle-dense environments.
- Digital Twins and Cyber-Physical Systems: Need synchronized sensing and actuation with near-zero delay.

3. KEY ARCHITECTURAL INNOVATIONS IN 6G

The architecture of 6G is expected to be fundamentally different from its predecessors. While 5G introduced cloud-native infrastructure, network slicing, and edge computing, 6G envisions a converged, intelligent, and three-dimensional (3D) communication system. It will natively embed artificial intelligence (AI), operate in the terahertz (THz) frequency bands, and seamlessly integrate terrestrial, aerial, and satellite networks. The following are the most significant architectural innovations driving 6G.

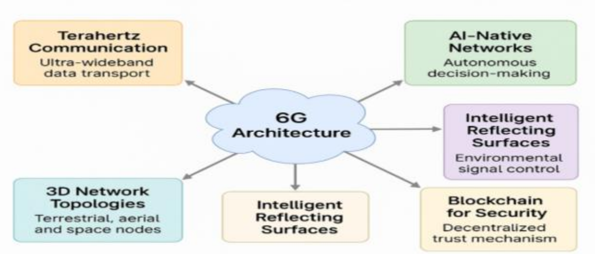

Fig - 1: Key Architectural Innovations in 6G Networks

3.1 Terahertz (THz) Communication

THz communication operates in frequencies between 100 GHz and 10 THz. These frequencies offer ultra-wide bandwidth, enabling data rates up to 1 Tbps, which are essential for applications like real-time holography and massive sensor data exchange. Challenges are High path loss, limited coverage distance, and hardware immaturity (e.g., THz antennas and circuits). Solutions includes development of high-gain antennas, beamforming, ultra-massive MIMO, and intelligent surfaces to focus signal energy.

3.2 AI-Native Networking

In 6G, AI isn't just an enhancement it becomes an intrinsic part of the network.AI-native systems allow self-organizing, self-optimizing, and self-healing networks, enabling real-time adjustments in routing, resource allocation, and anomaly detection. Benefits include predictive QoS based on user behaviour, real-time fault management, cyber-threat mitigation and personalized/context-aware services.

3.3 3D Network Topology

Unlike 2D networks limited to ground-based infrastructure, 6G introduces a 3D topology involving: terrestrial base stations, UAVs (drones), high-altitude platforms (HAPs), and LEO satellites. It ensures global coverage, especially in remote and disaster-hit areas where deploying ground infrastructure is impractical. Its use cases are emergency response, rural broadband, defence communications, and maritime/aviation networks.

1) Intelligent Reflecting Surfaces (IRS)

IRS are programmable meta-surfaces that reflect wireless signals in desired directions to enhance coverage and reduce interference. IRS can reshape the wireless environment dynamically, optimizing signal quality and reducing energy consumption. Its applications are enhancing indoor coverage, improving signal reliability in high-mobility scenarios (e.g., moving vehicles), supporting THz and mm Wave signals that are otherwise easily blocked.

2) Blockchain for Decentralized Trust

Blockchain provides distributed, tamper-proof ledgers for authentication, data integrity, and access control. As 6G networks become highly decentralized and data-intensive, trust management without central authorities becomes crucial. The benefits include secure identity management, transparent service-level agreements (SLAs), protection against fraud and tampering in IoT ecosystems.

3) Sensing and Communication Co-Design

6G will integrate sensing as a built-in feature, enabling the network to "see" its environment (e.g., user position, object detection, motion). This will enable applications such as environment-aware services, indoor localization, and cyber-physical coordination. Examples include use of reflected THz signals for 3D imaging and gesture recognition in smart homes or industrial automation.

3.4 Transformative Use Cases in 6G

6G is not merely a faster wireless standard it is a foundation for a new class of applications that require real-time responsiveness, massive bandwidth, intelligent network behaviour, and seamless global coverage. These use cases go far beyond the scope of 5G and promise to reshape industries, societies, and human experiences. 6G is expected to redefine numerous sectors through its advanced capabilities. Some of the most promising applications include:

1) Real-Time Holographic Communication

High-fidelity 3D holograms are transmitted in real time to enable immersive communication experiences. Applications include virtual telepresence for remote collaboration, education and training with real-world simulations, entertainment (e.g., live concerts, virtual actors).

In this application, 6G network delivers extremely high throughput (Tbps-level), requires latency below 1 ms to synchronize motion and speech and will need ultra-low packet loss for image stability.

2) Tactile Internet and Teleoperation

The remote transmission of touch and haptic feedback happens in real time. The applications include remote surgery and medical training, tele-maintenance in hazardous or space environments, remote-controlled robotics in manufacturing or disaster recovery.
In this case, 6G network enables latency as low as 0.1 Ms for real-time tactile feedback, ensures ultra-reliable communication with 99.99% availability and facilitates context-aware, AI-supported control systems.

3) Smart Cities and Infrastructure

Smart city is an integrated system where urban infrastructure traffic lights, public transport, utilities, surveillance, and emergency systems communicates and adapts in real time. Applications are AI-powered traffic flow optimization, automated utility grids (smart electricity, water), and intelligent emergency response coordination.

In a smart city environment, a 6G Network supports billions of IoT devices in dense environments, offers edge computing for ultra-fast local data processing and provides 3D connectivity through UAVs and satellites for resilience.

4) Brain-Computer Interfaces (BCIs)

These are systems that allow users to control devices or communicate using neural signals. The applications are assistive technologies for individuals with disabilities, neural prosthetics and cognitive monitoring, gaming and immersive computing.

6G Networks is essential for proper functioning of BCIs as they require extremely low latency to match neural transmission speed, needs high bandwidth for brain signal decoding and feedback and demands robust privacy and security protocols due to sensitive data.

5) Ubiquitous Extended Reality (XR)

This is a fusion of AR (Augmented Reality), VR (Virtual Reality), and MR (Mixed Reality) experiences that blend the physical and digital world seamlessly. Applications are immersive education and virtual classrooms, remote site inspections and virtual tourism, military simulation and training.
A 6G network is essential for XR as it provides high-resolution, real-time rendering of environments, uses AI at the edge for personalized, adaptive content and offers stable connectivity across geographic regions and devices.

6) Digital Twins and Industry 5.0

It is a real-time virtual replica of physical entities (e.g., machines, humans, cities) used for monitoring, analysis, and optimization. Applications are predictive maintenance in manufacturing, human-machine collaboration in Industry 5.0, urban planning and sustainability modelling.

A 6G network allows instant synchronization of physical and digital systems supports multi-modal sensor data integration and enables closed-loop feedback systems with ultra-low delay.

Each of these use cases relies on 6G's core attributes: ultra-low latency, high reliability, massive device density, and embedded intelligence. As these applications mature, 6G will not only support new services it will enable entirely new industries.

4. TECHNICAL AND IMPLEMENTATION CHALLENGES

The deployment of 6G technologies will confront numerous technical and socio-economic challenges that must be addressed systematically to ensure a viable and inclusive rollout.

First and foremost is the challenge of operating in the Terahertz (THz) band. These frequencies offer vast bandwidth, but their high susceptibility to atmospheric attenuation, rain fade, and molecular absorption severely limits propagation distance. Overcoming these challenges will require innovations in antenna design, beamforming, and materials science. Reconfigurable intelligent surfaces (RIS) and ultra-dense small cells may be employed to overcome propagation losses, but these solutions must be optimized for cost and energy efficiency.

Another critical challenge is power consumption. The ultra-dense, high-throughput nature of 6G networks risks creating unsustainable energy demands. Therefore, energy efficiency must be embedded into all layers of the protocol stack, and hardware must be capable of intelligent sleep modes, energy harvesting, and self-sustaining operation through ambient power sources.

Cybersecurity and privacy represent significant hurdles. With networks becoming more intelligent, decentralized, and heavily reliant on AI, they become susceptible to new attack vectors such as adversarial machine learning, data poisoning, and smart jamming. Future security systems must incorporate real-time threat detection, quantum-resilient encryption, and decentralized identity management using blockchain or distributed ledger technologies.

Standardization and spectrum allocation present logistical and geopolitical hurdles. Countries and regulatory bodies must work together to harmonize spectrum use, particularly in the THz bands. Failure to do so could result in fragmentation, inefficiencies, and incompatibilities between regional networks.

Finally, there's the pressing issue of the digital divide. 6G networks will likely begin deployment in wealthier urban centres, potentially exacerbating inequalities. Governments and organizations must prioritize universal access and ensure that rural and underserved communities' benefit from next-generation networks. Public-private partnerships and international development programs will be essential to achieving this goal.

5. GLOBAL 6G PILOT PROJECTS

The global race to shape the future of 6G has seen the launch of several strategic pilot initiatives by both public and private stakeholders.

- 6G Flagship (Finland): Finland's 6G Flagship, hosted by the University of Oulu, is one of the most prominent academic-led research efforts in the world. The initiative has explored the feasibility of using the THz band for short-range high-capacity communications. It has also made significant advances in intelligent surfaces and AI-native networking. The Flagship has released multiple white papers shaping the global understanding of what 6G should look like, and has served as a collaborative hub for academia and industry partners including Nokia and Ericsson.

- Samsung's 6G Vision: Samsung Research has presented a clear vision for 6G, outlining its aim to provide the 'next hyper-connected experience for all.' Key features include ultra-wideband communications, sub-millisecond latency, and ubiquitous AI. Samsung has conducted successful lab tests simulating real-time holographic video calls. Their approach also emphasizes AI-based network control systems, enabling dynamic resource allocation and fault prediction.

- China's 6G Satellite Launch (2020): In November 2020, China launched what is widely recognized as the world's first 6G experimental satellite. The satellite tests frequency bands not yet used in 5G, including those above 100 GHz, and explores the use of non-terrestrial networks (NTN) in 6G. The mission aligns with China's strategic plan to dominate the 6G space by integrating terrestrial, aerial, and space-based platforms for global seamless communication. While still in early stages, it represents a leap toward realizing a 3D

- Communication infrastructure.

6. SIMULATION STUDY: LATENCY ANALYSIS IN A 3D 6G TOPOLOGY

One of the defining goals of 6G is to achieve ultra-low latency ideally below 0.1 milliseconds. Latency refers to the time it takes for data to travel from one point to another. For real-time applications like remote surgery, autonomous driving, and immersive XR, even a small delay can lead to failure or safety risks. To validate the effectiveness of integrating UAVs into 6G network architecture, we conducted a simulation study focusing on latency improvements in an urban environment.

This simulation study explores how 3D networking, which combines ground-based towers, drones (UAVs), and satellites, can help reduce latency especially in complex environments like crowded cities.

A) Simulation Setup

The simulation modelled a 5x5 city block with varying obstacle densities to simulate line-of-sight obstructions. Three network topologies were tested: terrestrial-only, terrestrial with one UAV relay, and terrestrial with two UAV relays. The drone-based relays used line-of-sight beamforming and edge-computing capabilities to optimize path selection and reduce data transmission delays.

- Scenario: A typical urban grid with tall buildings, where wireless signals often get blocked or delayed.
- Objective: Compare latency across three configurations:
    1. Terrestrial-only (traditional base stations)
    2. Terrestrial + 1 UAV relay
    3. Terrestrial + 2 UAV relays
- Parameters:
    - Data rate: 10 Gbps
    - Message size: 1 MB
    - Environment: High-rise interference simulated with random obstructions

B) Results

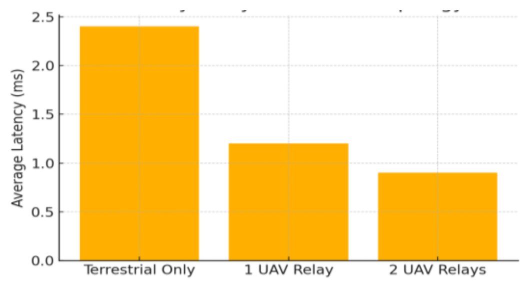

Fig - 2 : Average Latency Comparison in 3D 6G Topology

Table - 1: Latency analysis in 3d 6g topology

Configuration	Average Latency
Terrestrial-only	2.4 Ms
1 UAV Relay	1.2 Ms
2 UAV Relays	0.9 Ms

C) Detailed Explanation

Imagine you're sending a message across a busy city. If it travels only via land-based towers (like walking through traffic), it may get delayed by buildings or congestion. Now, imagine adding flying drones above the city acting like express messengers who skip the traffic by flying over it. This is what UAV relays do.

In this simulation:

- With no drones, the delay was 2.4 Ms.
- Adding just one drone cut the delay in half.
- Using two drones brought the delay under 1 millisecond fast enough for critical applications like remote medical control or emergency drone navigation.

This simulation proves that incorporating 3D network elements like drones, significantly reduces latency in urban environments. However, real-world deployment will require:

- Stable aerial control systems
- Efficient energy usage for flying nodes
- Regulatory frameworks for airspace communication

Still, the gains are clear: 3D networking is a vital tool in achieving the low-latency goals of 6G.

7. RESEARCH DIRECTIONS AND OPEN QUESTIONS

As the vision for 6G becomes more technically defined, it opens up a wide array of research questions that span across communication theory, hardware design, artificial intelligence, network security, and public policy. Addressing these questions is essential for moving from the conceptual phase of 6G to real-world deployment and standardization.

A) Spectrum and Terahertz Communication

- Challenge: How can the THz band (100 GHz to 10 THz) be effectively used despite its extreme path loss and limited range?

- Research Needs:
  - Efficient channel modelling at THz frequencies.
  - Adaptive modulation and coding schemes suited for ultra-high bandwidth.
  - Low-power THz transceiver and antenna designs.

B) AI Integration and Network Autonomy

- Challenge: How can AI be deeply integrated into network control and decision-making while ensuring accountability and robustness?
- Research Needs:
  - Federated learning and edge AI for distributed environments.
  - Explainable AI (XAI) for network auditing and transparency.
  - Resilience against adversarial attacks and data poisoning.

C) Sensing-Communication Convergence

- Challenge: Can networks that “sense” their environment operate reliably and securely?
- Research Needs:
  - Joint waveform design for simultaneous communication and sensing.
  - Resource allocation trade-offs between sensing accuracy and communication throughput.
  - Context-aware services that utilize environmental feedback.

D) Security, Privacy, and Trust

- Challenge: How can we ensure data integrity and user privacy in decentralized and intelligent networks?
- Research Needs:
  - Quantum-safe cryptographic protocols for long-term security.
  - Lightweight security algorithms for energy-constrained devices.
  - Blockchain and distributed ledgers for trust and authentication.

E) 3D Network Deployment

- Challenge: How can we manage and optimize dynamic multi-layer networks (ground, air, space)?
- Research Needs:
  - Optimal placement and coordination of UAVs and satellites.
  - Interoperability standards across terrestrial and non-terrestrial systems.
  - Energy-aware aerial routing and flight management systems.

F) Energy Efficiency and Green Networking

- Challenge: Can 6G be sustainable while supporting trillions of connected devices?
- Research Needs:
  - AI for adaptive energy management in real time.
  - Integration of ambient energy harvesting technologies.

- Carbon-aware network scheduling and optimization.

G) Ethics and Societal Impact

- Challenge: How can we ensure that 6G promotes equity, accessibility, and ethical use?
- Research Needs:
  - Governance models that balance innovation and public good.
  - Inclusion strategies to bridge the digital divide.
  - Ethical frameworks for technologies like BCIs and ubiquitous surveillance.

The development of 6G is not just a technological endeavour-it is a multidisciplinary challenge that intersects engineering, AI, law, policy, ethics, and sustainability. These open research questions will shape the design, deployment, and societal role of 6G in the coming decade. A collaborative global research ecosystem is essential to tackle them holistically.

8. CONCLUSIONS

The evolution of wireless communication has reached a critical inflection point. While 5G continues to roll out globally, the demands of future applications ranging from real-time holography and autonomous systems to brain-computer interfaces and truly immersive extended reality necessitate a paradigm shift in network capabilities. 6G aims to meet these demands with a bold redesign of communication systems that goes beyond incremental improvements.

With target specifications including terabit-per-second data rates, sub-millisecond latency, ultra-high reliability, and native AI integration, 6G represents a foundational transformation in how we perceive and interact with wireless technologies. Its architecture will be fundamentally decentralized, intelligent, and multi-dimensional, incorporating terrestrial, aerial, and satellite nodes to provide seamless, global coverage.

This paper has examined the technological motivations for 6G, the key architectural innovations that distinguish it from 5G, and the transformative use cases it will enable. Simulation studies and global pilot projects show promising early results, especially in areas like latency reduction through 3D topologies. However, several challenges remain particularly in areas of spectrum availability, energy efficiency, security, and equitable access.

The successful realization of 6G will depend not only on engineering breakthroughs but also on global collaboration, inclusive policy-making, and sustainable practices. It will require a multi-disciplinary effort that combines research in physics, computer science, artificial intelligence, and ethics to build a network that is not just faster, but smarter, more inclusive, and more resilient.

In essence, 6G is not simply about better connectivity it is about redefining the relationship between people, machines, and the digital environment. Its development will shape the future of communication, productivity, and societal progress for decades to come.

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BIOGRAPHY

Thejiya V is an Assistant Professor in the Department of Computer Science, Krupanidhi Group of Institutions, Bangalore. She completed her Bachelors in Computer Science & Engineering and her Masters in Computer Science & Engineering from Amrita School of Engineering, India under Amrita University. Her current research interest lies in the area of Computer Networks.