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6G Technology and Future Wireless Communication Systems

Prof. K. M. Jadhav[1], Ms. Dhanashri Kulkarni[2], Ms. Shreya Jadhav[3], Ms. Sneha Jagtap[4],
Mr. Om Mali[5], Mr. Akshay Kumbhar[6], Mr. Utkarsh Kumbhar[7], Mr. Pratik Karande[8],
Mr. Aryan kamble[9], Mr. Satish Lokhande[10]
[1]Assistant prof General Sciences and Engineering, AITRC, Vita.
[2-10]Students, General Sciences and Engineering, AITRC, Vita.

Abstract- The sixth generation (6G) of wireless communication technology represents a transformative leap beyond the capabilities of current 5G networks, promising data rates of up to 1 Terabit per second (Tbps), sub-millisecond latency, and seamless integration of artificial intelligence (AI), terahertz (THz) communications, intelligent reflecting surfaces (IRS), satellite networks, and Internet of Things (IoT) ecosystems. This paper explores the technological foundations, enabling paradigms, key challenges, and far-reaching applications of 6G communication systems. A qualitative and analytical research approach is adopted, drawing from recent IEEE publications, ITU reports, and global standardization initiatives. The study identifies significant research gaps including immature THz propagation models, insufficient AI-native architectures, security vulnerabilities in post-quantum environments, and deployment feasibility constraints in developing regions. Through systematic synthesis of the literature, this paper provides a comprehensive reference for researchers, engineers, and policymakers navigating the 6G landscape.

Keywords: 6G wireless communication, Terahertz (THz), Artificial Intelligence, Intelligent Reflecting Surfaces, IoT, Holographic Communication, Satellite Integration, Smart Cities.

I.INTRODUCTION

The evolution of wireless communication has followed a consistent generational cycle, with each decade ushering in new technologies that redefine connectivity. From the first-generation (1G) analog voice systems of the 1980s to the fifth-generation (5G) networks currently being deployed worldwide, each transition has delivered exponential improvements in data speed, latency, and network intelligence. With 5G now reaching its architectural limits, the global research community has turned its attention to sixth-generation (6G) wireless systems, envisioned for commercial deployment between 2027 and 2030.

6G is not merely an incremental upgrade of 5G; it represents a fundamental reimagination of what a wireless network can be. While 5G brought millimeter-wave spectrum access, massive MIMO antenna arrays, and network slicing to support enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), these capabilities fall short of the demands posed by emerging applications such as holographic telepresence, wireless brain-computer interfaces (BCI), fully autonomous vehicle systems, and global satellite-terrestrial integration. Specific devices such as extended reality (XR) headsets demand minimum data rates of 10 Gbps, already straining 5G infrastructure in dense deployments.

The vision of 6G encompasses a global communication fabric that transcends geographic limitations—providing coverage from deep underwater environments to low-earth orbit satellites—while embedding intelligence at every layer of the network stack. AI will no longer be a feature added onto the network; it will be the foundational design principle, enabling autonomous spectrum management, predictive beamforming, self-healing network architectures, and real-time resource orchestration. Combined with the exploitation of terahertz (THz) frequency bands, reconfigurable intelligent surfaces (IRS), optical wireless communication (OWC), quantum-secured channels, and ultra-dense small cell deployments, 6G aims to deliver 1 Tbps peak data rates, 0.1 ms latency, and connectivity densities of 10 million devices per square kilometre.

This paper provides a comprehensive analysis of 6G technologies, tracing the evolution from 5G limitations to 6G solutions, and examining enabling technologies, practical applications, implementation challenges, and future research directions. The structure is as follows: Section 2 surveys relevant literature; Section 3 articulates research objectives; Section 4 describes the methodology; Sections 5-7 discuss advantages, challenges, and applications; Section 8 outlines the future scope; and Section 9 concludes the study.

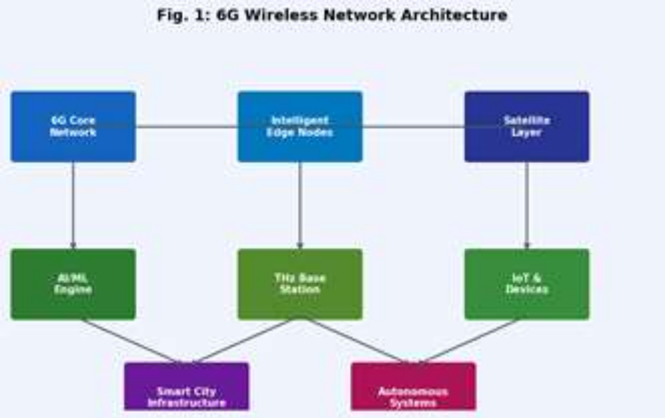

Fig. 1: 6G Wireless Network Architecture showing Core, Edge, Satellite, and Device Layers

II. LITERATURE SURVEY

The academic literature on 6G has grown substantially since 2019, when researchers began systematically defining the requirements, enabling technologies, and societal implications of post-5G communication systems. Chowdhury et al. (2020) provided one of the most comprehensive early frameworks for 6G, cataloguing technologies such as THz communication, AI, blockchain, quantum communications, unmanned aerial vehicles (UAVs), intelligent reflecting surfaces, and 3D networking. Their work projected that global mobile traffic would grow from 7.46 exabytes per month in 2010 to over 5,000 EB/month by 2030—a 670-fold increase—underscoring the urgency of 6G development.

Saad, Bennis, and Chen (2019) articulated a vision of 6G wireless systems as "connected intelligence," arguing that the defining feature of 6G is not raw throughput but the seamless integration of machine learning at every network layer. Letaief et al. (2019) reinforced this position in their widely cited IEEE Communications Magazine paper, mapping a technology roadmap for AI-empowered 6G networks including federated learning, transfer learning, and reinforcement learning as tools for real-time network management. Nawaz et al. (2019) extended this further, proposing quantum machine learning (QML) as a necessary paradigm for managing the extreme complexity of 6G optimization problems.

On the spectrum frontier, Rappaport et al. (2019) documented the challenges and opportunities of wireless communications above 100 GHz, providing measurement data for channels above 100 GHz and demonstrating that THz links are viable for indoor and short-range applications. Akyildiz, Jornet, and Han (2014) established the foundational work on THz band communications, showing that the 0.1-10

THz range offers bandwidths orders of magnitude larger than current radio frequency (RF) allocations. The ITU-R has proposed the 275 GHz-3 THz band as the primary cellular THz allocation, a range that remains globally unassigned as of 2024, representing a massive untapped capacity resource.

Basar et al. (2019) introduced the concept of reconfigurable intelligent surfaces (RIS/IRS) as "wireless communications through reconfigurable intelligent surfaces," demonstrating theoretically that IRS-assisted links can achieve energy efficiency gains impossible through conventional massive MIMO. Strinati et al. (2019) proposed a 6G roadmap encompassing visible light communication (VLC) and sub-THz technologies for holographic messaging, while Dang et al. (2020) in Nature Electronics argued that 6G must treat privacy, security, and ethics as primary design constraints, not afterthoughts. Collectively, the literature confirms that 6G must be simultaneously faster, smarter, more efficient, more secure, and more inclusive than any prior wireless generation.

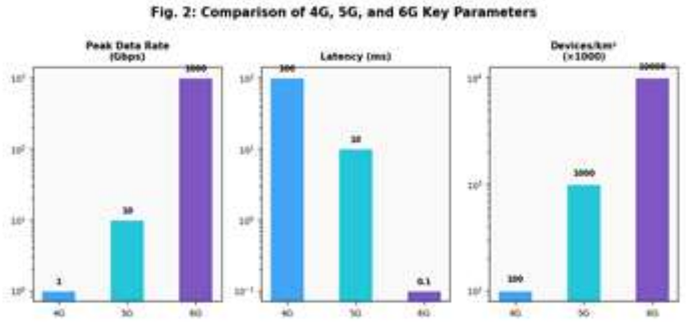

Fig. 2: Comparative Analysis of 4G, 5G, and 6G Key Performance Indicators

Table 1: Comparative Parameters of Wireless Communication Generations

Parameter	4G LTE	5G NR	6G (Target)
Peak Data Rate	1 Gbps	10 Gbps	1 Tbps
End-to-End Latency	100 ms	10 ms	< 0.1 ms
Spectral Efficiency	15 bps/Hz	30 bps/Hz	100 bps/Hz
Connected Devices/km^2	100K	1 Million	10 Million
Max Frequency Band	6 GHz	90 GHz	10 THz
AI Integration	None	Partial	Full (Native)
Satellite Integration	No	No	Fully Integrated
Energy Efficiency	Baseline	10× better	100× better

- **Objectives**

The primary objectives of this study are as follows:

1. To examine the key enabling technologies of 6G wireless communication, including terahertz (THz) spectrum, AI-native architectures, intelligent reflecting surfaces, and optical wireless communication.
2. To identify and evaluate the limitations of existing 5G infrastructure that necessitate a transition to 6G systems.
3. To analyse the practical applications of 6G technology across diverse sectors including healthcare, smart cities, autonomous systems, and holographic communication.

4. To investigate the technical, regulatory, economic, and ethical challenges associated with 6G deployment.
5. To outline the future research directions and standardization efforts required to realize the 6G vision by 2030.
6. To provide a structured reference framework for academic researchers, technology engineers, and policymakers engaged in 6G planning and development.

III. METHODOLOGY

This study adopts a systematic qualitative and analytical research methodology, structured into five primary phases to ensure comprehensive coverage of the 6G technological landscape.

1) Literature Review and Data Collection

A structured search was conducted across IEEE Xplore, Springer Link, arXiv.org, the ITU database, and Google Scholar. Search terms included combinations of "6G wireless communication," "beyond 5G," "terahertz communications," "intelligent reflecting surfaces," "AI-native networks," and "6G applications." Publications from 2014 to 2024 were considered, with priority given to post-2019 papers reflecting the current state of 6G research. Official white papers from NTT DOCOMO, Samsung Research, Ericsson, and the University of Oulu 6G Flagship programme were also incorporated.

2) Technology Analysis and Classification

Identified technologies were classified into four thematic pillars: (i) spectrum and physical layer technologies including THz, mmWave, and OWC; (ii) network intelligence and AI-driven architectures; (iii) connectivity paradigms including satellite integration, UAVs, and IRS; and (iv) application domains. Each technology was evaluated against standardized performance metrics drawn from ITU-R IMT-2030 recommendations.

3) Comparative Performance Evaluation

A structured comparison of 4G, 5G, and 6G parameters was conducted across dimensions of data rate, latency, spectral efficiency, device density, and energy efficiency. Data was sourced from ITU-R M.2370-0 traffic projections, Chowdhury et al. (2020), and NTT DOCOMO white papers. Results are summarised in Table 1.

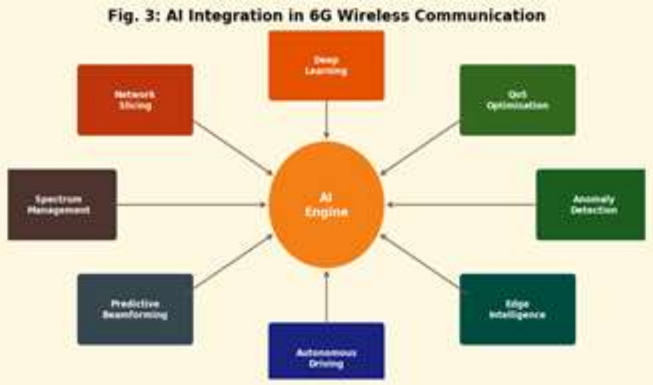

Fig. 3: Artificial Intelligence Integration Framework in 6G Wireless Systems

4) Gap Analysis

Research gaps were identified by cross-referencing technology readiness levels (TRLs) from the European Commission framework against the projected deployment requirements of 6G. Critical gaps in THz channel modelling, AI integration scalability, IRS real-world deployment, and post-quantum security are documented and prioritized for future research attention.

5) Synthesis and Framework Development

Findings from all phases were synthesized into a unified analytical framework mapping 6G enabling technologies to their corresponding application domains, performance targets, and outstanding research challenges. This framework forms the basis of the discussion presented in subsequent sections.

IV. ADVANTAGES

The 6G communication ecosystem offers a range of transformative advantages over prior wireless generations:

Ultra-High Data Rates and Capacity

6G systems are designed to deliver peak data rates of up to 1 Tbps per device, compared to 10 Gbps in 5G and 1 Gbps in 4G. This 100-fold improvement over 5G is achieved through the exploitation of the terahertz (THz) frequency band (0.1-10 THz), advanced massive MIMO systems with intelligent reflecting surfaces, and optical wireless communication links. Such capacities make real-time 3D holographic streaming, 8K immersive video, and multi-sensory data transfer practical for the first time.

Sub-Millisecond Latency

6G targets end-to-end latency below 0.1 milliseconds—100 times lower than 5G's target of 10 ms. This is achieved through edge computing architectures deployed in close proximity to end users, AI-driven predictive resource allocation that eliminates queuing delays, and direct device-to-device (D2D) communication links. Such latency enables entirely new application categories including real-time remote surgery, wireless brain-computer interfaces, and true tactile internet experiences.

Native AI Integration

Unlike 5G, where AI is applied as a network management overlay, 6G embeds machine learning directly into every layer of the protocol stack. AI-native base stations can autonomously manage spectrum allocation, beam management, interference cancellation, and network slicing without human intervention. Federated learning allows distributed AI models to be trained across edge devices while preserving user privacy. This native intelligence enables the network to self-optimize, self-heal, and self-configure in response to changing traffic patterns and environmental conditions.

Fig. 4: 6G-Enabled Smart City Ecosystem with Interconnected Services

Massive Device Connectivity

6G supports up to 10 million connected devices per square kilometre—10 times the capacity of 5G—enabling truly pervasive IoT deployments. This includes networks of industrial sensors, agricultural monitors, environmental measurement stations, wearable health devices, and autonomous vehicle fleets, all simultaneously connected and communicating without congestion. Battery-free IoT devices powered by wireless energy harvesting through Wireless Information and Energy Transfer (WIET) technology will extend the operational lifetime of sensor networks to decades.

Global and Three-Dimensional Coverage

Through the integration of terrestrial base stations, low earth orbit (LEO) satellite constellations, unmanned aerial vehicle (UAV) relay nodes, and underwater acoustic networks, 6G provides truly global coverage including maritime, aviation, arctic, and deep-rural environments currently unserved by 5G. This three-dimensional network architecture eliminates coverage gaps that have persisted through all prior generations, realising the ITU vision of connectivity as a universal utility.

Enhanced Security and Privacy

6G introduces physical-layer security mechanisms including quantum key distribution (QKD), AI-driven anomaly detection, and decentralized blockchain-based identity management. Post-quantum cryptographic protocols replace RSA-based systems that are vulnerable to quantum computing attacks. Secure multi-party computation allows data to be processed without exposing raw information, enabling privacy-preserving AI model training across healthcare, finance, and government sectors.

V. CHALLENGES

Despite its transformative potential, 6G deployment faces formidable technical, economic, regulatory, and societal challenges:

THz Propagation and Hardware Limitations

The THz frequency band offers extraordinary bandwidth but suffers from severe atmospheric absorption, molecular noise, and limited propagation range—particularly under rain, fog, and high-humidity conditions. Generating and receiving THz signals requires solid-state devices operating at frequencies not yet achievable with mature, cost-effective semiconductor processes. No generalized THz channel model validated across diverse outdoor environments currently exists, making system-level design highly uncertain. Developing compact, power-efficient THz transceivers suitable for mobile handsets remains an open engineering challenge.

Table 2: Key 6G Implementation Challenges and Their Current Development Status

Challenge	Description	Current Status	Priority
THz Channel Modelling	Lack of generalised propagation models	Research Phase	Critical
AI Architecture Design	No standardised AI-native protocol stack	Conceptual	High
IRS Deployment	Real-world scalability unproven	Lab Testing	High
Post-Quantum Security	RSA vulnerable to quantum attacks	Standardisation	Critical
Spectrum Allocation	THz bands globally unassigned	ITU Study	High
Energy Efficiency	Dense networks increase power consumption	Active Research	Medium
Digital Equity	Deployment cost in developing regions	Policy Discussion	Medium

AI Architecture and Standardization Gaps

While AI is universally recognized as the defining feature of 6G, significant disagreement exists on the appropriate depth, modality, and standardization of AI integration. Centralized AI controllers offer global network optimization but introduce single points of failure and latency penalties. Distributed edge AI reduces latency but requires coordinated model updates across millions of heterogeneous devices. No standardized AI-native protocol stack for 6G has been formally defined as of 2024, representing a critical gap that standardization bodies including ITU-R, 3GPP, and IEEE must address.

Infrastructure Cost and Deployment Economics

The transition from 5G to 6G will require massive infrastructure investment, including new THz base stations, IRS panels, edge computing nodes, and satellite ground stations. The deployment of ultra-dense small cell networks—necessary to compensate for THz's limited propagation range—increases both capital expenditure (CAPEX) and operational expenditure (OPEX) significantly. In developing nations, where 4G and 5G penetration remain incomplete, the economic feasibility of 6G deployment without targeted policy intervention is questionable. Patwary et al. (2020) estimated that infrastructure sharing strategies could reduce deployment costs by 40-60%, though regulatory frameworks enabling such sharing remain underdeveloped in most markets.

Regulatory and Spectrum Coordination

The global coordination of THz spectrum allocation across different national regulatory frameworks presents extraordinary complexity. The 275 GHz-3 THz band must be allocated through ITU World Radiocommunication Conferences (WRC), a process that requires consensus among 193 member states with competing commercial interests. Cross-border interference management, spectrum sharing with passive scientific services (radioastronomy, Earth observation), and the development of flexible dynamic spectrum access mechanisms are active areas requiring international cooperation that has historically proceeded slowly relative to technology development timelines.

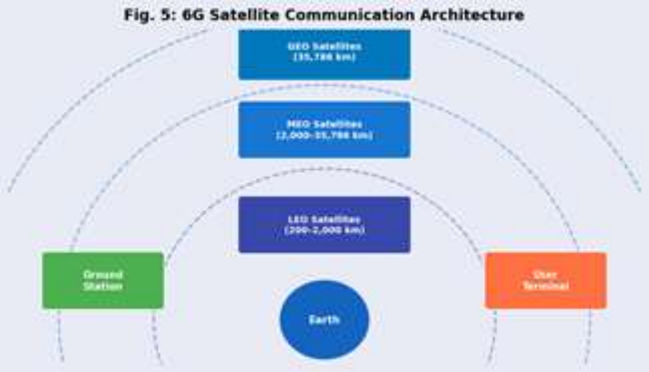

Fig. 5: 6G Satellite Communication Architecture integrating LEO, MEO, and GEO Orbits

Security and Privacy at Scale

6G's hyper-connected environment dramatically expands the attack surface for cyber threats. Traditional encryption systems based on RSA public-key cryptography are vulnerable to quantum computing attacks expected to become practical within the 6G operational era. Physical-layer eavesdropping at THz frequencies, adversarial attacks on AI-driven network management systems, and the exploitation of IRS elements as passive surveillance tools represent novel threat vectors with no established countermeasures. Privacy preservation becomes particularly acute as 6G networks collect and process unprecedented volumes of behavioural, biometric, and locational data from billions of connected sensors.

VI. APPLICATIONS

The superior performance capabilities of 6G unlock a wide range of transformative application domains:

Holographic Communication and Extended Reality

6G's 1 Tbps data rates and sub-millisecond latency make real-time three-dimensional holographic communication feasible for the first time. Users will be able to project and interact with photorealistic holographic avatars of remote participants, fundamentally transforming teleconferencing, remote education, medical consultation, and cultural experiences. Extended reality (XR) applications combining augmented reality (AR), virtual reality (VR), and mixed reality (MR) will become truly immersive and indistinguishable from physical presence, no longer constrained by tethering to fixed computing hardware.

Fig. 6: Holographic Communication Pipeline in 6G Networks

Smart Cities and Urban Infrastructure

6G will serve as the nervous system of future smart cities, connecting millions of sensors embedded in roads, buildings, utilities, and public spaces. Real-time traffic management systems will dynamically reroute vehicles based on live congestion data, reducing urban commute times and carbon emissions by an estimated 30-40%. Smart energy grids will balance supply and demand at millisecond timescales using AI-driven demand forecasting. Public safety systems will integrate facial recognition, acoustic anomaly detection, and environmental sensors to enable rapid emergency response. 6G connectivity will also support precision environmental monitoring, providing real-time air quality, noise, and water quality data to urban planning authorities.

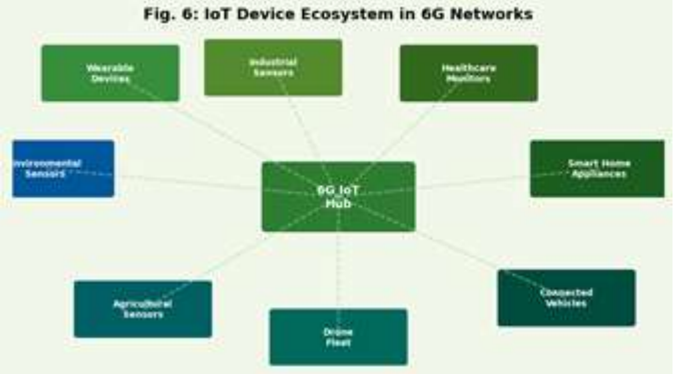

Fig. 7: IoT Device Ecosystem in 6G Networks with Centralised Hub Architecture

Healthcare and Remote Medicine

6G will enable a new era of connected healthcare. Remote robotic surgery—where a specialist surgeon in one location operates on a patient thousands of kilometres away—requires the sub-millisecond latency and ultra-high reliability that only 6G can provide. Continuous health monitoring through battery-free body-area sensor networks will enable early detection of cardiac events, neurological conditions, and metabolic disorders before symptoms manifest. THz imaging, which can penetrate tissue without ionizing radiation, will support new dermatological and oncological diagnostic modalities. AI-driven medical image analysis on 6G edge nodes will democratise access to specialist-level diagnostics in underserved rural communities.

Autonomous Systems and Robotics

6G will be the communication backbone for the next generation of autonomous systems, including self-driving vehicles, delivery drones, industrial robots, and agricultural automation. Vehicle-to-everything (V2X) communications at 6G speeds will enable real-time situational awareness sharing among all vehicles on a road network, dramatically reducing traffic accidents. Drone delivery networks will coordinate thousands of unmanned aerial vehicles simultaneously across urban airspace. In manufacturing, 6G-connected robot swarms will execute complex assembly tasks with sub-millimetre precision, responding to real-time design updates without production downtime.

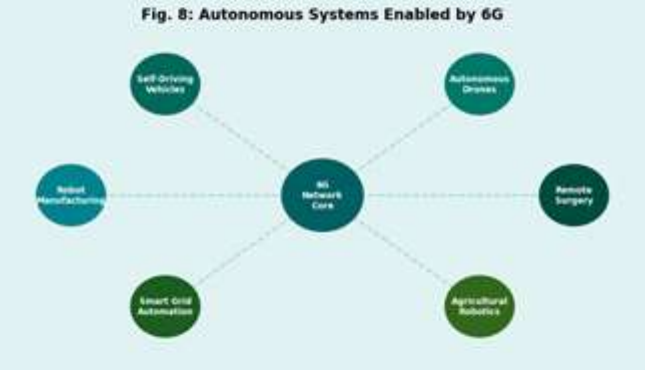

Fig. 8: Autonomous Systems Ecosystem Enabled by 6G Connectivity

Internet of Everything (IoE) and Industry 4.0

6G provides the connectivity fabric for the full realisation of Industry 4.0, connecting every machine, sensor, actuator, and worker in manufacturing environments through a unified digital intelligence layer. Predictive maintenance systems will detect equipment degradation before failure, preventing costly production stoppages. Digital twin technology—creating real-time virtual replicas of physical industrial systems—will enable continuous process optimisation and remote diagnostics. In agriculture, networks of soil sensors, autonomous irrigation systems, and drone-mounted hyperspectral cameras will enable precision agriculture that maximises crop yields while minimising water and fertilizer consumption.

VIII. FUTURE SCOPE

The 6G research landscape continues to evolve rapidly, and several frontier areas will define the next phase of investigation and standardization:

- **AI-Native Protocol Design:** The development of standardized AI-integrated protocol stacks that can be validated across heterogeneous 6G network topologies. This includes frameworks for federated learning across edge nodes, reinforcement learning for real-time resource management, and explainable AI for network fault diagnosis.
- **THz Channel Measurement and Modelling:** Systematic outdoor THz measurement campaigns across diverse geographic environments—tropical, arid, arctic—to build generalized stochastic channel models essential for 6G system design and simulation.

- **Reconfigurable Intelligent Surface Deployment**: Large-scale outdoor IRS testbed demonstrations integrating dynamic phase control, real-time CSI acquisition, and coordination with base station beamforming under practical mobility conditions.
- **Post-Quantum Security Frameworks:** Development and standardization of quantum-resistant cryptographic algorithms and physical-layer security techniques compatible with 6G's hyper-connected and AI-driven architecture, aligned with NIST post-quantum standardization outcomes.
- **Green 6G Architecture:** Energy harvesting and wireless power transfer technologies that enable battery-free IoT device operation at 6G scale, combined with AI-driven sleep scheduling and adaptive power control to meet net-zero sustainability targets.
- **6G for Digital Inclusion:** Policy frameworks, low-cost hardware designs, and community network models enabling 6G deployment in developing nations and rural regions, ensuring that the digital divide does not widen with the arrival of 6G.
- **Quantum Communication Integration**: The gradual integration of quantum key distribution (QKD) links into 6G backbone infrastructure, providing information-theoretically secure communication channels for critical national infrastructure protection.
- **Semantic and Goal-Oriented Communication**: Beyond transmitting raw data bits, 6G networks of the future will communicate meaning—transmitting only the semantic content relevant to the receiver's task—dramatically reducing bandwidth consumption for AI-driven applications.

IX. CONCLUSION

The sixth generation (6G) of wireless communication systems represents a paradigmatic transformation of global connectivity, moving far beyond the capacity-driven objectives of prior generations toward a vision of connected intelligence embedded in every dimension of human activity. This paper has demonstrated that 6G is not a single technology but an ecosystem of converging innovations—terahertz spectrum, AI-native architectures, intelligent reflecting surfaces, satellite integration, optical wireless communication, and quantum-secured channels—that together will deliver 1 Tbps data rates, sub-millisecond latency, and connectivity densities that the 5G generation cannot approach.

The analysis reveals that while the technical vision for 6G is compelling and internally consistent, significant research gaps remain unresolved. THz channel propagation models lack the empirical grounding necessary for reliable system design. AI-native protocol stacks remain unstandardized. IRS technology has not been validated at practical deployment scale. Post-quantum security architectures are still in early standardization phases. Addressing these gaps will require sustained interdisciplinary collaboration across physics, computer science, electrical engineering, economics, and public policy.

From an application perspective, 6G holds extraordinary promise across healthcare, autonomous systems, smart cities, holographic communication, precision agriculture, and industrial automation. Each of these domains will benefit not merely from faster connectivity but from the intelligence, adaptability, and global reach that 6G uniquely provides. For researchers, engineers, standardization bodies, and policymakers, the coming decade represents a critical window to shape the 6G standard in ways that maximise its societal benefit, ensure equitable global access, and embed safety, privacy, and sustainability as foundational design principles. As standardization processes through ITU-R IMT-2030 and 3GPP Release 21 and beyond accelerate, this paper provides a structured reference framework for navigating the challenges and opportunities of the 6G era.

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