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LEO-Integrated 6G Networks: Evolution, Architecture, Implementation, and Challenges

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Abstract- Since about 1980, a new generation has appeared approximately every decade. Mobile phones started with first-generation (1G), then the successful second generation (2G), and then mixed successful auctions since the launch of 3G. According to business terms, 1G and 2G were providing voice and gradually include data (3G is unsuccessful, 4G is very successful). Today, we have 5G with an ultra-high 20 Gb/s bit rate, an ultra-low latency of just 1 millisecond, and a very high capacity. Given the enormous potential of 5G communication networks and their expected evolution,6G communication networks should deliver improved range and data speeds, as well as the ability to connect users from anywhere. This paper details possible 6G communication networks. More specifically, the primary influence of this research is to deliver a complete synopsis of the development of wireless communication networks from 1G to 6G. This paper gives a clear overview of how wireless communication has developed from 1G to the upcoming 6G era. Each generation brought major improvements—starting from basic analog voice calls in 1G to high-speed data, IoT support, and low-latency services in 5G. However, several challenges still remain, such as limited coverage at high frequencies, network congestion, security risks, high energy use, and the need for faster and more reliable connections for new applications like autonomous systems and immersive media. To address these issues, 6G aims to introduce new technologies including terahertz communication, intelligent surfaces that improve signal quality, AI-driven network management, better integration of satellites and ground networks, and stronger security methods. These advancements are expected to deliver extremely high data rates, near-instant response times, improved coverage, and more efficient use of energy and spectrum.

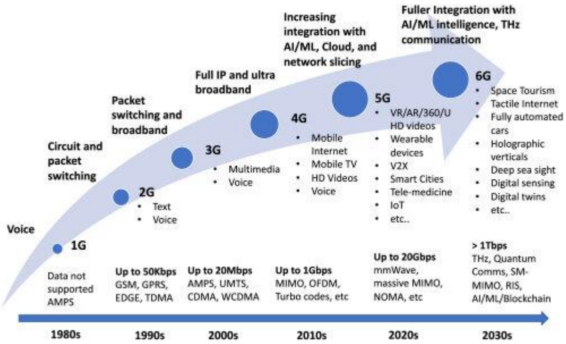
I. INTRODUCTION

The development of wireless communication has progressed through several generations, each designed to improve service quality and respond to increasing user and industry demands. The first generation (1G) systems of the early 1980s introduced mobile voice communication using analog technology, but they suffered from low capacity, poor voice clarity, and minimal security. The second generation (2G) in the 1990s moved to digital transmission, enabling services such as SMS and basic data, although data rates remained limited.

As the need for mobile internet grew, the third generation (3G) in the 2000s supported web browsing, multimedia messaging, and video calling. Despite these improvements, network congestion and moderate speeds restricted performance. The fourth generation (4G), introduced around 2010, provided high-speed broadband suitable for streaming, social media, and application-based services, yet challenges such as high latency for real-time applications and the growing number of connected devices remained.

The fifth generation (5G) in the 2020s addressed many of these issues by offering higher data rates, low latency, and support for massive IoT deployments. However, coverage limitations at high frequencies, high infrastructure costs, and increasing security concerns highlight the need for further advancement.

In response, the upcoming sixth generation (6G) aims to deliver terabit-level speeds, ultra-low latency, AI-driven network optimization, and enhanced reliability. It is expected to overcome the constraints of earlier generations and enable new applications such as immersive communication, autonomous mobility, and large-scale smart environments.



Picture 1. Brief overview of the evolution of wireless access technologies from 1G to 6G.

1. EVOLUTION FROM 1G TO 6G

The evolution of mobile communication from 1G to 6G reflects continuous efforts to improve speed, reliability, coverage, and service quality. Each generation introduced new capabilities and addressed the limitations of the previous one, leading to today's vision of intelligent, high-performance networks for future digital applications.

1.1 Evolution of Wireless Generations

1G – First Generation (1980s)

- Services: Analog voice calling.
- Advantages: Enabled mobile voice communication for the first time.
- Limitations: Poor voice quality, low capacity, weak security, no data.
- How 2G improved it: Shifted to digital signals for better clarity, higher capacity, and secure communication.

2G – Second Generation (1990s)

- Services: Digital voice, SMS, basic data (GPRS/EDGE).
- Advantages: Clearer voice, encryption, text messaging.
- Limitations: Very low data speed; not suitable for multimedia and internet use.
- How 3G improved it: Introduced higher bandwidth and packet-based data for mobile internet and video calling.

3G – Third Generation (2000s)

- Services: Mobile internet, multimedia messaging, video calling.
- Advantages: Faster browsing, better data support, global roaming.
- Limitations: Insufficient speed for HD content; network congestion; high battery use.
- How 4G improved it: Provided broadband-level speeds suitable for streaming, apps, and cloud services.

4G – Fourth Generation (2010s)

- Services: High-speed internet, HD video streaming, VoIP/VoLTE, online gaming.
- Advantages: High data rates, stable internet, improved mobility support.
- Limitations: Latency still not low enough for real-time control; struggles with massive IoT connections.
- How 5G improved it: Reduced latency to milliseconds, supported massive IoT, and increased network capacity.

5G – Fifth Generation (2020s)

- Services: Enhanced mobile broadband, IoT, AR/VR, autonomous systems.
- Advantages: Very high speed, ultra-low latency, large device connectivity, network slicing.
- Limitations: Limited coverage with high-frequency bands (mmWave), high deployment cost, energy consumption
- How 6G will improve it: Introduces terahertz communication, AI-driven management, wider coverage, and higher efficiency.

6G – Sixth Generation (2030s, upcoming)

- Services (expected): Terabit-level speeds, real-time holography, digital twins, advanced automation
- Advantages: Near-zero latency, AI-native networks, smart surfaces for extended coverage, stronger security
- Remaining challenges: THz hardware complexity, high energy demand, spectrum management—active research is ongoing.

The journey from 1G to 6G shows a clear pattern of solving previous problems:

Generation	Main Limitation	Next Generation's Solution
1G	Analog, poor quality	2G introduced digital communication
2G	Low data speed	3G enabled mobile internet
3G	Limited speed, congestion	4G provided broadband-level connectivity
4G	Higher latency, not fit for massive IoT	5G delivered low latency + massive IoT support
5G	Coverage limits, energy use	6G aims for THz bands, AI optimization, wider coverage.

II. INTRODUCTION TO 6G

The forthcoming sixth-generation (6G) communication system has emerged as the next major step in wireless evolution, promising a level of performance far beyond the capabilities of 5G. While earlier generations primarily focused on increasing data rates and improving mobility, recent studies highlight that 6G aims to integrate communication, sensing, computing, and intelligence into a unified framework. This shift is driven by the rising demands of immersive applications, large-scale automation, precision services, and the need for seamless global connectivity.

2.1 Functional Basis of 6G Networks

6G operational network will depend on several advanced technologies working together.
First, terahertz (THz) bands are expected to provide extremely wide bandwidth, enabling data rates in the tera bit per second range.

a. Terahertz (THz) Frequency Bands

The terahertz band refers to the portion of the electromagnetic spectrum ranging from 0.1 THz to 10 THz. These frequencies offer extremely large bandwidth, allowing data rates in the terabit-per-second range.
However, THz signals suffer from high propagation loss, are easily blocked by walls, and have a short transmission range.

To make THz usable in 6G, researchers are exploring advanced antennas, beamforming, and intelligent surfaces to guide signals efficiently.

Second, AI-native networking will allow networks to self-learn, self-optimize, and predict user and traffic patterns, reducing errors and improving reliability.

b. AI-Native Networks

AI-native networks are communication systems where artificial intelligence is built directly into the network architecture, rather than being added as a separate tool.

These networks can:

- predict traffic patterns.
- allocate resources automatically.
- improve reliability.
- detect failures early.
- reduce energy consumption.

Machine learning models operate in real-time, enabling the network to self-adjust under changing conditions—this is known as self-optimizing and self-healing behaviour.

Third, Integrated Sensing and Communication (ISAC) will enable base stations and devices to function simultaneously as communication units and environmental sensors, supporting high-precision localization and context awareness.

c. Integrated Sensing and Communication (ISAC)

ISAC is a technique where the same hardware and frequencies are used for both communication and sensing.
This allows base stations and devices to:

- detect motion.
- measure distance.
- identify objects.
- support precise localization and tracking.

ISAC is useful for autonomous vehicles, smart factories, health monitoring, and security systems. Instead of installing separate sensors, 6G integrates sensing directly into the communication network.

Fourth, Reconfigurable Intelligent Surfaces (RIS), consisting of programmable reflective panels, are anticipated to control signal direction, enhance coverage, and mitigate blockages.

d. Reconfigurable Intelligent Surfaces (RIS)

RIS are large, flat panels coated with programmable reflective elements.

These panels can control how radio waves behave by:

- reflecting signals in specific directions.
- strengthening weak signals.
- avoiding obstacles, and
- reducing interference.

RIS is an important 6G technology because THz signals cannot travel far. Installing RIS on walls, buildings, or ceilings improves coverage without the cost of building more base stations.

Finally, the use of edge computing will shorten processing delays, supporting latency-sensitive applications such as autonomous mobility and remote medical procedures.

e. Edge Computing
Edge computing involves processing data near the user, instead of sending everything to a distant cloud server.

This reduces:

- delay (latency).
- network congestion.
- energy consumption.
- dependence on cloud infrastructure.

In 6G, edge computing helps applications that require instant response, such as autonomous driving, robotics, remote surgery, and industrial control systems.

III. IMPLEMENTATION OF 6G NETWORKS

The implementation of 6G requires a systematic and multi-layered approach that integrates advancements in spectrum management, infrastructure design, network intelligence, and non-terrestrial components. Existing literature highlights that 6G deployment cannot rely on traditional cellular expansion strategies; instead, it must adopt a highly coordinated model that supports terahertz communication, dense network architecture, and intelligent control mechanisms.

a. Spectrum Allocation and Regulation
A fundamental step in implementing 6G is the identification and allocation of terahertz (THz) frequency bands, which are essential for achieving ultra-high data rates. Research suggests that regulatory bodies must establish global harmonization of THz spectrum to avoid fragmentation and enable worldwide interoperability. Dynamic and shared spectrum access models, supported by AI algorithms, are considered essential to handle the scarcity and variability of high-frequency bands.

b. Terahertz-Enabled Infrastructure Development
The deployment of 6G will require the introduction of THz-capable base stations, advanced RF front-end components, and highly directional antenna arrays. Due to the limited propagation range of THz signals, the literature recommends a dense small-cell architecture, where multiple low-power nodes are distributed closely within urban and indoor environments. This approach minimizes coverage gaps and compensates for high path loss and signal absorption.

c. Integration of Reconfigurable Intelligent Surfaces (RIS)
RIS technology is identified as a key enabler in 6G implementation. Studies show that RIS panels can be mounted on walls, building facades, and indoor ceilings to manipulate radio signals, redirecting them toward users and mitigating blockages. This reduces the need for excessive base station deployment and enhances energy efficiency. Integrating RIS into the early stages of 6G infrastructure planning allows networks to maintain coverage even in complex propagation environments.

d. AI-Driven Network Management
Literature consistently emphasizes the shift toward AI-native architecture, where artificial intelligence is embedded into all layers of the network. AI will support real-time spectrum allocation, predictive maintenance, traffic forecasting, fault detection, and energy optimization. The implementation of self-organizing and self-healing capabilities will reduce operational complexity and enable autonomous decision-making. This transition requires large-scale datasets, federated learning frameworks, and distributed intelligence at edge nodes.

e. Edge–Cloud Collaboration
6G implementation must adopt a hybrid computing framework combining edge computing with centralized cloud resources. Latency-sensitive applications such as robotics, autonomous driving, and remote healthcare require computation to occur near the user. Therefore, 6G networks will include distributed edge servers integrated with base stations, allowing real-time processing, while cloud systems manage heavier tasks such as analytics and global network coordination.

f. Integration of Non-Terrestrial Networks (NTNs)
To achieve global and uninterrupted coverage, 6G implementation involves the integration of satellites, high-altitude platform systems (HAPS), and unmanned aerial vehicles (UAVs) into the communication ecosystem. Recent studies indicate that a layered NTN structure—combining LEO,

MEO, and GEO satellites—will work alongside terrestrial cells to extend communication to oceans, mountains, remote villages, and disaster zones. Synchronization between satellite and ground networks will be essential for seamless handover and service continuity.

g. Energy-Efficient Network Design

Energy consumption is expected to rise with the introduction of THz bands and AI systems. Therefore, researchers propose adopting energy-aware routing, low-power semiconductor technologies, renewable-powered base stations, and energy-harvesting IoT devices. Efficient thermal management and power-saving algorithms are also required to meet sustainability goals.

h. Security and Privacy Considerations

As 6G supports critical services, security must be integrated at the design stage. Implementation guidelines include the use of quantum-resistant encryption, AI-based anomaly detection, strong authentication protocols, and secure hardware modules. Privacy-preserving techniques, such as federated learning, will ensure that user data is processed without compromising confidentiality.

i. Standardization and Interoperability

Successful implementation of 6G requires global collaboration among organizations such as ITU, 3GPP, IEEE, ETSI, and national regulators. Standardization ensures interoperability, cost efficiency, and uniform deployment practices across regions. Early coordination between academia, industry, and government is necessary to establish technical guidelines and testing frameworks.

IV. LOW EARTH ORBIT (LEO) SATELLITES IN 6G: USAGE, IMPLEMENTATION, AND LIMITATIONS

4.1 Usage of LEO Satellites in 6G

Low Earth Orbit (LEO) satellites play a central role in the space–air–ground integrated communication model proposed for 6G. Positioned between 500 km and 2,000 km, LEO satellites provide lower latency and faster response times compared to higher-orbit systems. They support applications such as global broadband, remote sensing, emergency communication, maritime and aviation connectivity, and IoT coverage in remote regions.

In 6G, LEO satellites function as moving base stations, enabling continuous connectivity where terrestrial infrastructure is weak, unavailable, or economically impractical.

4.2 Implementation of LEO Satellites in 6G

4.2.1 LEO Satellite Constellations

6G requires large constellations of LEO satellites arranged across multiple orbital planes to ensure uninterrupted coverage. Each satellite is equipped with:

- Multi-beam or phased-array antennas
- Inter-satellite links (often optical)
- Onboard processing
- AI-supported traffic and network control

These features allow satellites to communicate with each other and coordinate coverage as they orbit the Earth.

4.2.2 Ground Segment Integration

LEO systems rely on a network of ground stations that perform:

- Gateway functions to connect satellites to terrestrial fiber networks
- Tracking and control
- Edge computing to reduce latency

User terminals must be capable of tracking fast-moving satellites and switching links smoothly.

4.2.3 Interoperability with Terrestrial Networks

LEO satellites are integrated with 6G terrestrial networks through standardized communication protocols, shared spectrum models, and advanced mobility management systems. Seamless handover between satellite and ground networks is crucial, especially for mobile applications such as autonomous vehicles and high-speed transport.

4.2.4 AI and Autonomous Operation

AI is used for:

- Predicting user demand
- Beam steering and resource allocation
- Collision avoidance
- Autonomous route and cluster coordination

This reduces operational complexity and improves reliability.

4.3 Limitations of LEO Satellites in 6G

4.3.1 High Deployment and Maintenance Costs

Deploying hundreds or thousands of satellites requires repeated rocket launches, manufacturing cycles, and regular replacements, making the overall cost substantial.

4.3.2 Short Operational Lifespan

LEO satellites typically last 5–7 years due to orbital decay and space radiation, resulting in frequent replenishment of the constellation.

4.3.3 Space Debris and Collision Risks

Large constellations increase the risk of collisions and contribute to space debris, which complicates long-term operations and orbital safety.

4.3.4 Limited Coverage Per Satellite

Because of their low altitude, each LEO satellite covers a smaller footprint. Achieving global coverage demands a large number of satellites in coordinated orbits.

4.3.5 Frequent Handover Requirements

Due to their rapid motion across the sky, user terminals must switch satellites frequently. This increases signaling overhead and may temporarily disrupt service quality.

4.3.6 Weather and Atmospheric Effects

High-frequency communication used in 6G (such as Ka, V, or THz bands) is affected by atmospheric conditions, leading to signal attenuation during rain, clouds, or high humidity.

4.3.7 Spectrum and Interference Challenges

LEO satellites must share spectrum with terrestrial networks and other satellite constellations. Interference management and global spectrum coordination are critical for stable operation.

4.4 Approaches to Overcome Limitations

Several solutions are proposed to mitigate the challenges of LEO deployment in 6G, including:

- Inter-satellite laser links to reduce reliance on ground gateways.
- AI-based collision avoidance and autonomous traffic management.
- RIS-assisted terminals to improve link quality.
- Shared launch infrastructure to reduce costs.
- Adaptive beamforming and multi-connectivity for stable handovers.
- International regulations for space traffic coordination.

V. 6G CHALLENGES

The transition to 6G introduces several technical, operational, and regulatory challenges that must be addressed to achieve global, reliable, and high-performance communication systems.

5.1 Terahertz Propagation Limitations

6G relies heavily on sub-THz and THz frequencies, which experience high path loss, limited penetration, and strong atmospheric absorption. These factors restrict coverage range and require dense deployments of small cells and signal-enhancing surfaces.

5.2 High Energy Consumption

The use of advanced antennas, AI processing, dense networks, and high-frequency communication increases overall power demand. Managing energy efficiency while maintaining performance is a major challenge for operators.

5.3 Network Complexity and Management

6G integrates terrestrial, aerial, and satellite components, creating a highly complex environment. Managing mobility, resource allocation, interference, and seamless handover across multiple layers demands advanced automation and intelligent control systems.

5.4 Security and Privacy Risks

As 6G supports real-time applications such as autonomous vehicles, remote surgery, and industrial automation, security threats become more critical. Vulnerabilities related to AI manipulation, quantum computing attacks, and large-scale data collection pose significant risks to user privacy and system stability.

5.5 Infrastructure Cost and Deployment Feasibility

Deploying THz cells, reconfigurable surfaces, edge nodes, and satellite networks requires substantial investment. Rural and remote regions may struggle with economic feasibility, widening the digital divide unless cost-effective deployment models are developed.

5.6 Standardization and Regulatory Barriers

Global 6G deployment depends on coordinated spectrum allocation, approval of satellite–terrestrial integration, and interoperability standards. Achieving international alignment across regulatory bodies remains a major challenge.

5.7 Hardware and Technological Limitations

Developing affordable and reliable THz antennas, nanoscale semiconductor devices, photonic components, and satellite payloads is still under research. Manufacturing complexity and material limitations slow down practical implementation.

5.8 Environmental and Space Sustainability Concerns

Dense satellite constellations and increased energy consumption raise concerns about space debris, carbon footprint, and environmental sustainability. Addressing these issues is essential for long-term network viability.

VI. SOLUTIONS TO 6G CHALLENGES

Although 6G faces multiple technical and operational challenges, ongoing research proposes several strategies to make implementation feasible, efficient, and sustainable.

6.1 Mitigating Terahertz Propagation Issues

To address the limited range and high attenuation of THz signals, several solutions are proposed:

- Reconfigurable Intelligent Surfaces (RIS): Redirect and enhance weak signals to improve coverage in obstructed environments.
- Dense small-cell deployment: Reduces distance between transmitters and receivers.
- Advanced beamforming techniques: Focus energy precisely toward the user to overcome path loss.

These techniques collectively improve THz signal reliability in indoor and outdoor conditions.

6.2 Reducing Energy Consumption

Energy efficiency can be improved through:

- Low-power semiconductor technologies optimized for THz operation.
- Energy-aware routing and sleep-mode algorithms for base stations.
- Green AI models that reduce computational overhead.
- Renewable energy integration, such as solar-powered small cells and satellite units.

This multi-layered approach helps maintain performance while controlling operational costs.

6.3 Managing Network Complexity

The complexity of 6G networks can be handled using:

- AI-driven network orchestration to automate resource allocation and traffic control.
- Self-organizing networks (SON) that adapt to changing conditions without manual intervention.
- Distributed edge computing, which decentralizes processing and reduces network congestion.

These systems support real-time automation and efficient coordination across terrestrial and non-terrestrial layers.

6.4 Enhancing Security and Privacy

To protect sensitive applications, 6G security solutions include:

- Quantum-resistant cryptography to defend against future quantum attacks.
- AI-based intrusion detection systems capable of recognizing unusual patterns.
- Privacy-preserving techniques, such as federated learning, where data is processed locally rather than transmitted.
- Secure hardware modules embedded in user devices and network elements.

These methods strengthen the security architecture from the physical layer to the application layer.

6.5 Lowering Infrastructure Costs

Several strategies help reduce deployment expenses:

- Shared infrastructure models where operators jointly use towers, satellites, and RIS panels.
- Open RAN (O-RAN) to reduce equipment costs and increase vendor flexibility.
- Modular deployment, starting with high-demand areas and gradually expanding coverage.
- Mass production of THz hardware, which will eventually lower unit cost through economies of scale.

These approaches improve affordability and make deployment feasible in developing regions.

6.6 Improving Standardization and Regulatory Coordination

Progress in 6G requires:

- International spectrum harmonization, especially for THz and satellite bands.
- Unified standards across 3GPP, ITU, and regional bodies.
- Global policies for non-terrestrial networks, including space traffic rules and orbital coordination.

Coordinated regulation ensures interoperability, safety, and consistent performance worldwide.

6.7 Advancing Hardware and Device Technology

To overcome limitations in THz and satellite hardware, researchers are focusing on:

- New semiconductor materials, such as graphene and III–V compounds.
- Photonic components for high-speed optical links.
- Miniaturized antenna arrays with higher efficiency.

These innovations will enable reliable, mass-market 6G devices and infrastructure.

6.8 Ensuring Environmental and Space Sustainability

Environmental and space sustainability can be improved through:

- Debris mitigation protocols for LEO constellations.
- Low-emission launch technologies for satellite deployment.
- Energy-harvesting IoT devices to reduce long-term power consumption.
- Lifecycle recycling programs for electronic waste.

These measures support sustainable long-term operation.

VII. PERFORMANCE REQUIREMENTS OF 6G

The expected capabilities of 6G demand strict and measurable performance objectives. These requirements ensure that emerging applications—such as holographic communication, autonomous mobility, and global IoT systems—operate reliably and efficiently.

7.1 Data Rate

6G aims to deliver peak data rates up to 1 Tbps and user-experienced rates in the range of several gigabits per second. Such high throughput is necessary for real-time digital twins, ultra-HD immersive media, and large-scale industrial automation.

7.2 Latency

To support mission-critical applications, 6G must achieve end-to-end latency below 1 millisecond. Ultra-low latency is vital for autonomous vehicles, tactile internet applications, remote surgery, and high-precision robotics.

7.3 Reliability

6G networks target reliability levels approaching 99.99999% (seven nines). This ensures consistent performance even in high-density or high-mobility environments where service continuity is essential.

7.4 Spectrum and Bandwidth

6G requires significantly wider bandwidth through access to sub-THz and THz frequency bands (100 GHz to 10 THz). These frequencies provide the spectrum needed for terabit-level communication but require advanced propagation and coverage solutions.

7.5 Massive Connectivity

Future environments will demand connectivity for up to 10 million devices per square kilometer. This is essential for smart cities, industrial IoT, environmental monitoring, and autonomous systems operating at scale.

7.6 Mobility Support

6G must accommodate mobility speeds exceeding 1,000 km/h, enabling stable connectivity for aircraft, high-speed trains, and space–air–ground networks.

7.7 Energy Efficiency

To support sustainable operation, 6G aims to improve energy efficiency by up to 10× compared to 5G. This includes energy-efficient hardware, green AI models, and intelligent sleep-mode algorithms.

7.8 Security and Privacy

Performance targets include:

- Strong protection against quantum computing threats
- Real-time threat detection through AI
- End-to-end encryption.

These measures ensure safe operation in sensitive environments such as finance, healthcare, and defence.

VIII. CONCLUSION

The evolution of wireless communication from 1G to 6G reflects a continuous effort to meet growing demands for speed, capacity, reliability, and global connectivity. Each generation has addressed the limitations of its predecessor, moving from basic analog voice services to advanced broadband, IoT support, and intelligent networks. As the world progresses toward 6G, the integration of terahertz communication, AI-native networking, reconfigurable intelligent surfaces, and non-terrestrial platforms such as LEO satellites marks a significant technological leap.

Despite its potential, 6G faces challenges in propagation, energy consumption, network complexity, hardware readiness, standardization, and environmental sustainability. However, ongoing research offers promising solutions, including AI-powered automation, RIS-assisted coverage enhancement, energy-efficient designs, and global regulatory coordination. With clear performance requirements—such as terabit-level data rates, ultra-low latency, and massive device connectivity—6G aims to transform communication into an intelligent, seamless, and universally accessible system.

Ultimately, 6G represents not just an improvement in wireless technology but a foundational infrastructure for future digital societies. By combining terrestrial and non-terrestrial networks with advanced intelligence and sustainable practices, 6G will enable new levels of innovation across communication, industry, healthcare, education, and mobility.

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