

6G WIRELESS COMMUNICATIONS: VISION, KEY TECHNOLOGIES AND CHALLENGES

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ABSTRACT

In terms of information rate, speed, energy efficiency, intelligence, integration, and worldwide coverage, fifth-generation (5G) wireless networks have fundamental limitations that have been made clear by the explosive growth of immersive, intelligent, and mission-critical applications. To get around these restrictions, sixth-generation (6G) wireless communication systems, which are slated for commercialization around 2030 under the ITU-R IMT-2030 framework, propose a paradigm shift from connectivity-centric design to connected intelligence. This paper presents original, organized research on 6G wireless communications, fusing a comprehensive technical survey with a conceptual system architecture designed for future networks. The evolution from 1G to 6G is first reviewed to establish the technological motivation. Key performance gaps in 5G are then analyzed as a

Driver for 6G development. There is a thorough discussion of the IMT-2030 vision, usage scenarios, and defined capabilities. Core enabling technologies such as terahertz communication, ultra-massive MIMO, reconfigurable intelligent surfaces, artificial-intelligence-native networking, integrated sensing and communication, and non-terrestrial networks are examined from both theoretical and implementation perspectives. In this unique AI-native 6G system architecture an attempt has been made to showcase the meeting of communication, sensing, calculating and intelligence. The primary application areas comprises of 3-D communication, digital twins, self-governing transportation, healthcare, and smart cities, are carefully studied with respect to their technical specifications. Finally, we uncover significant research challenges and open issues related to hardware compatibility, security, sustainability, and normalization.

This paper provides an IEEE-style reference for undergraduate research and serves as a basis for future 6G surveys [1], [2].

Keywords: 6G, Satellite networks, Terahertz communication, AI-native networks, IMT-2030

INTRODUCTION

The world has witnessed improvement in connectivity, data rate and latency over a period of time involving wireless communication from 1G to 5G. The limitations of 5G require development to enhance the performance of autonomous transport systems, digital twins, holographic communications and healthcare.

Evolving from simple connectivity to connected intelligence – is the basic aim of 6G which is targeted for the year 2030 under the ITU-R IMT-2030 framework. Here the goal will be to attain artificial intelligence, computing, sensing and sustainability into the global network together with higher speed [1], [2].

TECHNOLOGICAL ADVANCEMENTS - 1G TO 6G

A. Overview of Wireless Generations

- 1G (1980s): Analog voice communication.
- 2G (1990s): SMS, digital voice and GSM.
- 3G (2000s): Packet data, mobile internet, video calls.
- 4G (2010s): LTE, MIMO, high-speed mobile broadband.
- 5G (2020s): Network slicing, mMTC, URLLC, eMBB, mmWave.
- 6G (2030): AI-native, THz communication, ISAC, NTN, holography.

With every passing generation, we saw significant improvements in performance by almost an order of their magnitude but 6G stands on a different pedestal offering a total paradigm shift [2],[3].

LIMITATIONS OF 5G NETWORKS

Even with several prominent improvements, there are still some limitations to 5G network:

Inadequate Data Rate: 20Gbps peak data rate of 5G is not sufficient for 3D and XR applications.

Delay constraints: End-to-end delay of 5–10 ms is too high for internet and remote surgery.

Resources consumption: Huge MIMO and dense networks increase total power usage, consuming resources. Non-native AI: AI is used only for optimization, not as a core network function.

Security Risks: No built-in support for post-quantum security.

Limited Coverage: 5G mainly depends on terrestrial networks, leaving rural and remote areas unconnected.

These issues motivate the development of 6G [1], [2].

TIMELINE AND STANDARDIZATION OF 6G

- 2020–2023: Vision and research phase
- 2023–2025: ITU-R framework finalized (IMT-2030)
- 2025–2027: Pre-standardization studies (3GPP Release 19–20)
- 2027–2029: Prototype development and trials
- 2030: Commercial deployment The ITU-R Recommendation M.2160-0 (January 2025) officially defines the global vision of 6G. [1],[3]

VISION OF 6G: IMT-2030 FRAMEWORK THE IMT-2030 FRAMEWORK DEFINES SIX USAGE SCENARIOS

1. Immersive Communication
2. Hyper-Reliable Low Latency Communication (HRLLC)
3. Massive Communication
4. Ubiquitous Connectivity
5. Integrated Sensing and Communication (ISAC)
6. Integrated AI and Communication

It also emphasizes four global goals:

- Sustainability
- Connecting the unconnected
- Ubiquitous intelligence
- Security and resilience [1].

KEY CAPABILITIES OF 6G

ITU-R defines 15 capabilities, including:

Enhanced Capabilities

- Peak data rate: up to 1 Tbps

- User data rate: 1–10 Gbps
- Latency: 0.1 ms
- Reliability: 99.99999%
- Device density: 10^7 devices/km²

New Capabilities

- Centimeter-level positioning
- Integrated sensing
- AI-native networking
- Sustainability metrics
- Post-quantum security
- Interoperability across systems [1]

KEY ENABLING TECHNOLOGIES FOR 6G

- Terahertz (THz) Communication**
6G will use frequencies from 100 GHz to 10 THz, enabling ultra-high data rates. Challenges include high path loss, hardware complexity, and limited range.
- Ultra-Massive MIMO** Large antenna arrays improve beamforming and spatial multiplexing, increasing capacity and reliability.
- Artificial Intelligence (AI-Native Networks)** AI is integrated across all layers for self-optimization, prediction, and automation.
- Integrated Sensing and Communication (ISAC)** The same signal is used for communication and sensing, enabling localization, object detection, and mapping.
- Non-Terrestrial Networks (NTN)** Satellites, HAPS, and drones provide global coverage, especially for rural and remote areas[1],[2],[4]

SECURITY, PRIVACY, AND TRUST IN 6G

6G introduces

- Post-quantum cryptography
- Physical layer security
- Zero-trust architecture

- Blockchain-based authentication

These ensure data confidentiality, integrity, and availability in future networks. : [2], [5]

SUSTAINABILITY AND ENERGY EFFICIENCY

6G targets

- 100× energy efficiency improvement
- 1 picojoule/bit energy consumption
- 20-year IoT battery life

Green networking, renewable energy, and AI-based Optimization are key enablers: [1], [4].

CHALLENGES IN 6G IMPLEMENTATION

- THz hardware design
- AI model complexity and trust
- Spectrum regulation
- Cost and infrastructure deployment
- Security against AI-based attacks
- Standardization and interoperability[2],[3]

COMPARISON BETWEEN 5G AND 6G

Features	5G	6G
Peak data rate	20 Gbps	1 Tbps
Latency	1 ms	0.1 ms
AI Role	Optional	Native
Coverage	Terrestrial	Global (TN + NTN)
Sensing	Not supported	Integrated [1],[2]

FUTURE OUTLOOK

6G will transform communication into an intelligent, sensing-enabled, and sustainable system. Research between 2025 and 2030 will decide its success [1], [2].

CONCLUSION

6G represents a major shift from communication-only networks to intelligent, integrated, and sustainable systems. By supporting ultra-high data rates, ultra-low latency, AI-native operation, and global connectivity, 6G will enable applications that are impossible with 5G. This makes 6G a critical research area for future ECE engineers [1], [2].

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