A Critical Review of 6G Use Cases and Challenges

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***Abstract*— Sixth-generation (6G) communication systems are visioned to deliver extremely high data rates, sub-millisecond latency, AI-native connectivity, holographic telepresence, and ultra-dense device integration. However, the historical evolution from 1G to 5G indicates that each generation has consistently fallen short of its most ambitious expectations—whether it was seamless global coverage in 1G/2G, true broadband in 3G, gigabit mobility in 4G, or ultra-reliable connectivity in 5G. This paper critically analyzes whether 6G can realistically achieve its promised capabilities by examining key technological enablers such as terahertz (THz) communication, Li-Fi–IoT integration, cell-free massive MIMO, reconfigurable intelligent surfaces (RIS), AI-native network intelligence. Drawing insights from five recent IEEE research works and the other sources, we assess hardware constraints, propagation limits, energy consumption, scalability challenges, deployment costs, and device limitations that may hinder practical realization. A comparison between realistic and unrealistic 6G expectations is provided. Finally, the paper proposes strategic directions to mitigate technical barriers, including hybrid RF–THz architectures, intelligent topology design, semantic-aware resource control, and energy-optimized sensing/communication co-design. This study aims to present a balanced, critical perspective on what 6G can genuinely deliver.**

I. Introduction

The evolution of mobile communication systems from first-generation (1G) analog voice to fifth-generation (5G) broadband connectivity has been driven by the continuous demand for higher data rates, improved mobility, enhanced reliability, and global-scale connectivity. Despite major breakthroughs at each generation, the historical trajectory shows a persistent gap between theoretical expectations and practical realizations. Early systems such as 1G and 2G promised voice coverage, yet rural connectivity remained inconsistent for decades. Third-generation networks introduced mobile broadband and multimedia services, but real-world throughput rarely approached the theoretical limits due to spectrum scarcity, cell-edge degradation, and capacity constraints. Fourth-generation long-term evolution (LTE) significantly improved peak data rates and latency, but sustained gigabit-class mobility remained limited, particularly under high user density and mobility scenarios. With 5G, expectations of ultra-reliable low-latency communication, massive machine-type connectivity, and millimetre-wave (mmWave) densification have been only partially achieved, constrained by device power limits, propagation challenges, and the high cost of ultra-dense deployment.

The anticipated sixth-generation (6G) communication system aims to overcome these long-standing gaps by targeting extreme performance metrics across multiple dimensions: terabit-per-second peak data rates, sub-millisecond end-to-end latency, centimetre-level localization, integrated sensing and communication, holographic data transfer, and pervasive intelligence across all network layers. To achieve these goals, 6G research emphasizes new physical-layer paradigms and architectural innovations such as terahertz (THz) communication for wide contiguous bandwidths, reconfigurable intelligent surfaces for channel shaping, Li-Fi and optical wireless integration for high-speed indoor access, cell-free massive multiple-input–multiple-output (MIMO) for uniform service quality, and AI-native networking frameworks that embed learning, reasoning, and semantic communication into the communication stack.

Network	Peak speed	Average speed
5G	264.7 Mbps	72.37 Mbps
4G	45.56 Mbps	17.50 Mbps

Fig.1

(Live 5G vs 4G speed test performed via Rant Cell App)[6]

Network	Peak speed	Average speed
5G	10 Gbps	400 Mbps
4G	1 Gbps	50 Mbps

Fig.1.1

(Theoretical 5G vs 4G speed-Rant-Cell)[6]

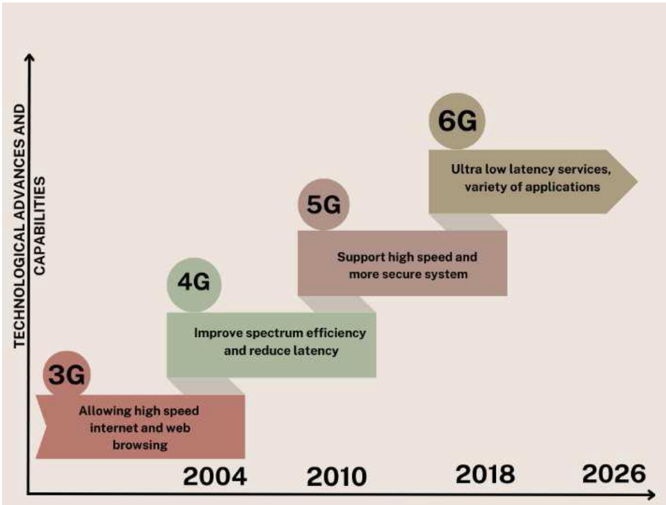

Fig 1.3

Growth of technologies[3]

Motivated by these considerations, this paper presents a critical analysis of 6G use cases and enabling technologies by synthesizing insights from recent IEEE research, including THz propagation characteristics, Li-Fi–IoT integration, 6G wireless surveys, AI-native semantic communication architectures, and comprehensive 6G system-level perspectives. The objective is not only to summarize proposed capabilities but to evaluate them against real-world limitations involving hardware feasibility, propagation physics, network scalability, deployment cost, and device capabilities. This analysis aims to distinguish between realistic and overly optimistic expectations, providing engineering-grounded reasoning to guide future research and practical deployment strategies

II. RELATED WORK

A considerable body of recent literature has analyzed the prospective capabilities and technical foundations of sixth-generation (6G) communication systems. The most comprehensive system-level perspectives are provided in survey-style works such as The Road Towards 6G: A Comprehensive Survey [1], which outlines the architectural evolution, key enabling technologies, and service requirements expected to define 6G. This work emphasizes that achieving terabit-per-second throughput, integrated sensing and communication, and ultra-low-latency intelligent networking will require breakthroughs in spectrum usage, network topology, hardware design, and computational intelligence. The survey also highlights that earlier generations have consistently faced limitations in coverage, scalability, and performance realization, motivating deeper architectural changes rather than incremental enhancements.

Another relevant stream of studies focuses on specialized technologies proposed for 6G. For example, the integration of Light Fidelity (Li-Fi) with Internet of Things (IoT) ecosystems is examined extensively in Integration of Li-Fi and IoT for Sixth-Generation Communication Systems [2]. This paper presents Li-Fi as a complementary high-speed indoor access technology capable of alleviating radio-frequency (RF) congestion while providing enhanced security and low interference. The authors propose hybrid Li-Fi–RF architectures that enable seamless connectivity under varying illumination conditions. However, they also highlight significant challenges related to ambient light interference, line-of-sight requirements, modulation complexity, and deployment cost, which may limit large-scale adoption without additional innovations.

A broader overview of 6G trends and capabilities is provided in Review on 6G Wireless Communication [3], which discusses anticipated data rate improvements, THz-band opportunities, advanced localization, and the roles of artificial intelligence (AI) and machine learning (ML). The paper identifies THz spectrum access, semantic communication, and ML-driven network optimization as core elements of next-generation systems. It also point the limitations of 5G in sustaining rapid traffic growth, especially with emerging XR (extended reality), high-resolution sensing, and fully autonomous systems. At the same time, the paper stresses that achieving 1 Tbps user data rates or extremely dense connectivity will require a re-examination of hardware, spectrum management, and energy consumption frameworks.

The physical-layer feasibility of THz communication is explored in detail in Terahertz Propagation Characteristics for 6G Mobile Communication Systems [4], which provides unique empirical insights into human blockage loss, building shadowing, and scattering behaviour from 0.8 to 150 GHz. The study demonstrates that signal attenuation increases sharply with frequency, and blockage becomes more severe as the Fresnel zone shrinks. These findings support the argument that THz links will require highly directional antennas, extremely short communication ranges, dense access point deployment, and intelligent topology design to maintain link reliability. The authors also propose non-traditional deployment approaches such as spatially overlapping networks, integrated access and backhaul, and window-glass-embedded antennas to mitigate propagation limitations.

Finally, the emerging paradigm of semantic and goal-oriented communication is captured in Goal-Oriented and Semantic Communication in 6G AI-Native Networks: The 6G-GOALS Approach [5]. This work argues that traditional content-agnostic communication is insufficient for AI-driven networks, where relevance, intent, and task-specific information need to be conveyed efficiently. The proposed 6G-GOALS architecture integrates semantic extraction, causal reasoning, and goal-oriented data reduction into the Open RAN framework, enabling more sustainable, low-latency, and bandwidth-efficient communication. While promising, the authors acknowledge substantial barriers, including ontology standardization, distributed semantic consistency, model robustness, and on-device intelligence requirements.

Collectively, these works establish a foundation for evaluating realistic 6G performance. They highlight both the technological promise and the physical, architectural, and computational constraints that must be addressed to translate 6G concepts into deployable systems. These insights motivate a deeper analysis of use cases, technical enablers, and practical limitations, as discussed in the subsequent sections.

III. 6G USE CASES

The visioned sixth-generation (6G) mobile communication system aims to support a diverse set of advanced use cases that extend well beyond the capabilities of 5G. These use cases are done by extreme performance requirements involving multi-terabit-per-second peak data rates, sub-millisecond latency, large-scale sensing, and embedded intelligence across devices and networks. This section provides a concise overview of representative 6G use cases that form the basis for analyzing realistic and unrealistic expectations in later sections.

Some of the highlighted 6G services are holographic type communication which requires real-time transmission of multi view, volumetric, or light field data, another major 6G pillar is extremely high precision localization and sensing, enabling centimetre level positioning accuracy and high resolution environmental perception. With THz frequencies, ultra-dense access points, and joint communication–sensing waveforms, 6G aims to support applications such as autonomous mobility, industrial automation, smart manufacturing, and digital twins.

TABLE II. MMWAVE AND THZ APPLICATIONS[3]

Applications	**Example Use Cases**
Wireless Intelligence	Robotic control, autonomous vehicles
Sensing	Air quality detector, gesture detection
Imaging	See in the dark, THz security body scan
Communication	Mobile wireless communication, Intra radio device communication
Positioning	Centimetre-level positioning

These use cases collectively define the performance boundaries that 6G technologies must meet. They also highlight the problem between theoretical expectations and realistic constraints, motivating the need for a detailed feasibility analysis presented in the following sections.

IV. REALISTICVS. UNREALISTIC 6G EXPECTATIONS

6G promises a set of extremely high capabilities across data rate, latency, reliability, sensing, intelligence, and sustainability. However, the feasibility of these targets depends heavily on physical constraints, hardware, deployment and device capabilities. This section examines which expectations appear technically achievable and which are likely to face significant challenges or may remain unrealistic.

A. Data Rates: Terabit-per-Second Links

6G aims to achieve peak data rates approaching 1 Tbps using wide contiguous bandwidths in the sub-terahertz (sub-THz) and THz ranges. The primary motivation comes from applications such as holographic communication and high-fidelity XR. While theoretical models indicate that such data rates are possible with 100–300 GHz[3] spectrum and highly directional antennas, real-world constraints significantly limit their practicality.

Sub-THz propagation suffers from severe free-space path loss, high atmospheric absorption, sensitivity to blockage, and short communication ranges, as demonstrated experimentally in the THz propagation measurements reported in [4]. These studies show that increases in human-blockage loss and building-shadowing loss with frequency, implies that Tbps links will only be feasible for short-range, line-of-sight conditions with dense access-point. As a result, while peak Tbps rates may be realistic in hotspots or indoor environments, but achieving Tbps is probably unrealistic due to propagation and infrastructure limitations.

B. Latency and Reliability: Sub-Millisecond End-to-End Operation

6G visions sub-millisecond latency for critical operations such as distributed robotics, tactile Internet, and real-time digital twins. Achieving such latency requires communication across multiple layers, including radio interface, core network, computation complexity.

Although incremental improvements over 5G are possible, achieving consistent sub-millisecond latency in outdoor networks is limited by processing delays, scheduler overhead, multi-hop routing, and variable wireless channel conditions. Even with AI-native resource control, fixed latency may be achievable only for localized or short-range services[5], not for wide-area deployments. Thus, sub-ms latency can be considered partially realistic, but only with some restricted network topologies and not at national or continental scale.

C. Reconfigurable Intelligent Surfaces (RIS): Channel Engineering at Scale[1]

RIS technology promises programmable wireless propagation by steering reflected beams to improve coverage and energy efficiency. While RIS has gained significant research attention, its real-world scalability remains questionable.

Large RIS panels require precision, low-power yet fast-switching elements, and real-time control signalling. The overhead of configuring thousands of passive or semi-passive elements becomes significant in dense, fast-varying environments. In addition, integrating RIS into buildings, vehicles, or streetscapes requires new manufacturing processes, backhaul connectivity, and synchronization, which may increase deployment cost significantly. Due to these restrictions RIS outdoor deployment is much uncertain or very costly, so from economic and operational perspective it is unrealistic.

D. AI-Native and Semantic Communication: Realistic but Incremental

Semantic and goal-oriented communication, as described in [5], holds promise for reducing bandwidth by transmitting only task-relevant information. Unlike THz or RIS, semantic communication is primarily a software-level innovation, making it more practical in real deployments. However, achieving a unified semantic framework requires standardized ontologies, robust distributed AI, and interpretability across devices. This makes semantic communication realistic, but its benefits will likely emerge gradually rather than instantly as 6G launches.

E. Energy Efficiency and Sustainability: A Major Bottleneck

Many 6G technologies—THz transceivers, massive MIMO, ultra-dense networks, and edge intelligence—are inherently energy intensive. Without major breakthroughs in low-power hardware and network-level energy optimization, sustaining extreme 6G capabilities will be economically and environmentally challenging. Thus, ultra-sustainable 6G is an important aspiration but remains technically uncertain.

TABLE I. ROLE OF 6G AND PROBLEMS IN 5G[3]

Technical Difficulty	**Role of 6G**
Lower speed	6G offers data rate up to 1Tbps
Difficulty in indoor coverage	6G will femtocells or distributed antenna system (DASs)
Need for high-speed short range wireless communication	THz frequencies, which provide a narrow beam and improved directivity, are used in 6G
Dedicated hardware implementations	6G's emphasis on virtualization will lower the price of networking hardware.
Limited mobile connections with increasing demand	6G aims to support 10X102 per km2
Integration of AI/XR applications	While 5G provides some integration, 6G seeks to completely integrate the application in the post pandemic environment.

V. IMPLEMENTATION CHALLENGES

The realization of 6G capabilities depends on multiple disruptive technologies that confront significant engineering, physical, and architectural obstacles. This section critically evaluates the primary implementation challenges associated with THz communication, reconfigurable intelligent surfaces (RIS), Li-Fi integration, cell-free massive MIMO, and AI-native physical layer design.

A. Challenges in Terahertz (THz) Communication[3]

THz frequencies above 100 GHz are central to achieving multi-Gbps or Tbps-class data rates. However, several physical barriers limit practical deployment.

1) Severe Path Loss and Atmospheric Absorption[3]

Experimental studies reported in [4] show that path loss increases sharply with frequency due to free-space attenuation and molecular absorption. Water vapor causes strong absorption peaks above 100 GHz, reducing effective communication distance to a few meters for non-line-of-sight (NLOS) scenarios. This restricts THz usage to short-range indoor environments, backhaul links, or ultra-dense hotspots.

2) High Sensitivity to Blockage[3]

Measurements from 0.8–150 GHz demonstrate that human bodies cause significant attenuation, which grows rapidly with frequency. THz links can fail with small obstacles such as hands, furniture, or human movement. Maintaining stable THz links requires highly directional antennas, beam tracking, and redundant multi-link topologies.

3) Hardware Limitations[3]

THz transceivers require advanced materials and mixed-signal CMOS or III–V semiconductor technologies. Power amplifiers and mixers at 100–300 GHz suffer from low output power, poor efficiency, and high thermal dissipation. Implementing energy-efficient THz radios on mobile devices remains a major open challenge.

B. Challenges in Reconfigurable Intelligent Surfaces (RIS)[3]

RIS promises channel shaping and energy-efficient control of wireless propagation, but several practical issues remain unresolved.

1) Large-Scale Control Signalling[3]

A RIS may contain thousands of passive or semi-passive reflecting elements. Each element must be precisely configured in real time, especially in mobile scenarios. The control overhead, latency, and synchronization required to update RIS states at high speed pose severe scalability issues.

2) Deployment and Integration[3]

RIS must be physically integrated into building façades, indoor walls, lamp posts, or street infrastructure. This requires new installation standards, backhaul options, environmental protection, and reliable power supply. The economic viability of deploying RIS on a large scale remains uncertain.

3) Channel Estimation Complexity[3]

RIS-assisted links require estimating cascaded channels, which increases signal-processing complexity and overhead. Accurate channel estimation for large RIS panels in high-mobility scenarios is still an active research problem.

C. Challenges in Cell-Free Massive MIMO[1]

Cell-free massive MIMO eliminates cell boundaries and offers uniform spectral efficiency, but its implementation introduces several critical bottlenecks.

1) Fronthaul Capacity and Latency[1]

Coordinated access points (APs) must share user data and channel-state information (CSI) through high-capacity fronthaul links. As the number of APs increases, fronthaul requirements scale rapidly. Optical fiber deployment to every AP is expensive and unrealistic in dense networks.

2) Synchronization and Scalability[1]

Maintaining tight time–frequency synchronization across distributed APs is essential for coherent joint transmission. This becomes increasingly difficult as the network size grows. Processing loads at central units become a bottleneck due to global CSI aggregation.

3) Power Consumption

Operating many distributed APs continuously can dramatically increase network-wide energy usage. Without intelligent sleep scheduling or energy-aware coordination, cell-free operation contradicts 6G's sustainability objectives.[1]

D. Challenges in Li-Fi–IoT Integration[2]

Li-Fi offers high-speed access for indoor IoT networks, but multiple issues limit large-scale adoption.

1) Line-of-Sight and Coverage Constraints

Li-Fi communication requires direct visibility between transmitter and receiver. Shadows, user mobility, or occlusion can disrupt connectivity. Coverage is limited to illuminated regions, requiring multiple luminaires for consistent connectivity.

2) Interference from Ambient Light

Ambient illumination—including sunlight and fluorescent lighting—introduces noise and intensity fluctuations. As highlighted in [2], advanced modulation and filtering techniques are needed, adding cost and complexity.

3) Hardware and Retrofit Cost

Existing IoT devices primarily use RF interfaces. Retrofitting them with photodiodes or adapting infrastructure for hybrid Li-Fi–RF support will require significant investment.

E. Challenges in AI-Native and Semantic Communication.

AI-native communication architectures such as 6G-GOALS [5] require integrating intelligence across devices, edge servers, and the core network.

1) Semantic Representation and Standardization

Semantic communication requires shared ontologies and representational models. Differences in device-side semantic extraction can lead to semantic mismatch, reducing communication effectiveness.

2) Computational Load on Edge Devices

Real-time semantic extraction, compression, causal reasoning, and task coordination demand powerful compute resources. Many IoT and mobile devices lack such capabilities.

3) Distributed Intelligence and Reliability

AI-native networks require distributed learning and model updates. Ensuring security, consistency, and robustness against model drift remains a challenge.

VI. CONCLUSION

This paper presented a critical evaluation of sixth-generation (6G) wireless communication systems by examining both the ambitious expectations and the practical constraints highlighted in recent IEEE research. Although 6G aims to deliver extreme data rates, sub-millisecond latency, large-scale sensing, semantic communication, and pervasive intelligence, the technological enablers required to achieve these capabilities—such as THz communication, RIS-assisted propagation, cell-free massive MIMO, Li-Fi–IoT integration, and AI-native architectures—face significant propagation, hardware, energy, scalability, and deployment challenges. Empirical studies on THz propagation show that severe path loss and blockage sensitivity limit long-range performance, while the large control and synchronization overhead associated with RIS and cell-free systems raises questions about their economic feasibility. Similarly, Li-Fi remains a complementary access method rather than a universal solution, and semantic communication, although promising, requires robust modelling and standardization.

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