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Wireless Communication Technology: Evolution, Fundamental Limits and Enabling Technologies Toward 6G

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Abstract : *Wireless communication has progressed from analog voice telephony to programmable, software-defined networks that underpin broadband access, industrial automation, and the Internet of Things (IoT). This paper presents a structured review of wireless communication technology spanning the evolution from first-generation (1G) systems to fifth-generation (5G) and 5G-Advanced networks, and the ongoing transition toward sixth-generation (6G) systems under the International Mobile Telecommunications-2030 (IMT-2030) framework. The review first traces, over four decades, the generational growth in peak data rate, latency, connection density, and service capability, and contrasts the key performance indicators of IMT-2020 with those defined for IMT-2030. A unified link-level system model is then formulated using the Friis free-space relation, the Shannon capacity bound, multiple-input multiple-output (MIMO) capacity, energy efficiency, and radar resolution. A numerical link-budget analysis across 3.5 GHz, 28 GHz, 140 GHz, and 300 GHz carriers shows that, under the stated array-gain assumptions, the 300 GHz link exceeds 100 Gbit/s at a range of 10 m. In contrast, its rate falls by a factor of about seven between 10 m and 1 km, compared with a factor below two at 3.5 GHz. The principal 6G enablers, namely the upper mid-band and terahertz spectrum, cell-free massive MIMO, reconfigurable intelligent surfaces, integrated sensing and communication, AI-native air interfaces, and non-terrestrial networks, are critically compared in terms of their benefits, limitations, and technological maturity. Finally, open challenges in security, energy sustainability, interference management, and standardization are identified, providing a concise technical roadmap for researchers, educators, and practitioners working on beyond-5G and 6G wireless communication systems.*

Keywords: On5G-Advanced, 6G, IMT-2030, integrated sensing and communication, cell-free massive MIMO, reconfigurable intelligent surface, terahertz communication, non-terrestrial networks.cology, Robotic Surgery, Surgical Robotics, Artificial Intelligence, Computer-Assisted Surgery, Cancer Treatment, Minimally Invasive Surgery, Precision Medicine.

I. INTRODUCTION

Wireless communication, the transfer of information through electromagnetic waves without a guided physical medium, has become a critical infrastructure on which economic activity, public services and social interaction increasingly depend. Mobile cellular networks, wireless local-area networks (WLANs), short-range device links and satellite systems together connect billions of people and an even larger population of sensors, machines and vehicles. This growth has transformed the design objectives of wireless systems: beyond raw throughput, contemporary networks must deliver wide-area coverage, millisecond-level latency, very high reliability, massive device density and, increasingly, environmental sustainability [1]. Mobile data traffic continues to grow steadily, driven by high-definition

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video, cloud services and machine-type traffic, and wireless access is now expected to be as dependable as utilities such as electricity and water. Meeting these simultaneous, and frequently conflicting, requirements within a finite and congested radio spectrum constitutes the central engineering problem of modern wireless communication. The fifth generation (5G) of mobile communication, standardized by the Third-Generation Partnership Project (3GPP) and qualified under the IMT-2020 framework, was the first generation explicitly designed around heterogeneous service classes, namely enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC). Its evolution has continued through 5G-Advanced: the Release 18 specifications, which introduced artificial intelligence and machine learning (AI/ML) for the air interface, network energy saving, and extended-reality support, were completed in June 2024 [2], and Release 19 has further enhanced multiple-input multiple-output (MIMO) operation, mobility, and non-terrestrial access while serving as a bridge toward the next generation [3].

At the international level, Recommendation ITU-R M.2160 defines the framework and overall objectives of IMT-2030, commonly referred to as 6G. It identifies six usage scenarios: immersive communication, hyper-reliable and low-latency communication, massive communication, ubiquitous connectivity, AI and communication, and integrated sensing and communication [1]. In February 2026, ITU-R Working Party 5D agreed on a draft report of 20 technical performance requirements for IMT-2030, seven of which are new and specific to 6G, with formal approval anticipated later in 2026; these outcomes will guide the 3GPP specification of the first 6G radio interface [4]. Complementary studies have assessed the technical feasibility of IMT operation in bands above 100 GHz [5]. These milestones indicate that 6G is moving from a visionary concept toward measurable and testable technical criteria.

The research literature supporting this transition has expanded rapidly. Recent surveys have examined terahertz (THz) communication and sensing [6], ultra-dense cell-free massive MIMO [7], [8], reconfigurable intelligent surfaces (RIS) [9], [10], integrated sensing and communication (ISAC) [11], [12], AI-driven air interfaces [13], [14], satellite-based non-terrestrial networks (NTN) [15], [16], and energy-aware network design [17]. Although these works are comprehensive within their respective domains, they are necessarily specialized and assume considerable prior knowledge. Moreover, they typically analyze individual technologies in isolation, so the interplay among spectrum, antenna technology, sensing and intelligence, and the common physical constraints that bind them is rarely examined together. Consequently, there remains a need for a concise, unified treatment that connects the historical evolution of wireless generations, the physical limits governing every radio link, and the emerging technologies proposed to overcome those limits, in a form accessible to students, educators, and practitioners entering the field.

Motivated by this gap, the present paper makes four contributions. First, it consolidates the evolution of mobile generations from 1G to 6G and contrasts the key performance indicators of IMT-2020 and IMT-2030 within a single comparative framework. Second, it formulates a compact link-level system model based on free-space propagation, Shannon capacity, MIMO capacity, energy efficiency, and radar resolution, thereby linking communication and sensing performance to the same physical parameters. Third, it provides a reproducible numerical link-budget analysis that quantifies the throughput-range trade-off across sub-6 GHz, millimeter-wave (mmWave), and sub-THz carriers. Fourth, it critically compares the principal 6G enabling technologies and identifies open research challenges in security, energy efficiency, interference management, and standardization.

The remainder of the paper is organized as follows. Section II reviews the evolution of wireless generations and their key performance indicators. Section III presents the system model and fundamental performance limits together with the numerical analysis. Section IV discusses the enabling technologies for 6G. Section V outlines representative applications and open challenges, and Section VI concludes the paper and outlines directions for future work.

II. EVOLUTION OF WIRELESS COMMUNICATION SYSTEMS

Each mobile generation has emerged roughly once per decade, enabled by advances in modulation, multiple access, antennas, and network architecture. Fig. 1 illustrates the growth of the nominal peak data rate from 1G to the IMT-2030

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targets, which spans roughly eight orders of magnitude. At the same time, Table I summarizes the defining technology and principal services of each generation.

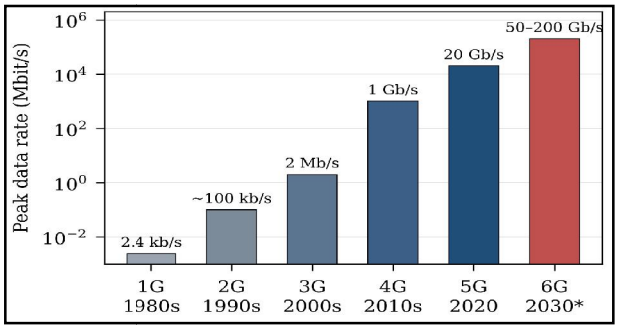


Fig. 1. Evolution of nominal peak data rate across mobile generations (logarithmic scale). Values for 3G–5G correspond to IMT targets; the 6G range follows the IMT-2030 framework [1]. *Expected deployment.

A. From Analog Voice to All-IP Broadband (1G–4G)

First-generation systems of the 1980s used analog frequency-division multiple access (FDMA) to provide circuit-switched voice. Second-generation (2G) systems digitized the radio link through time- and code-division multiple access, enabling encryption and the short message service. Third-generation (3G) systems introduced wideband code-division multiple access and packet-switched mobile data, establishing the mobile Internet. Fourth-generation (4G) Long-Term Evolution (LTE) adopted orthogonal frequency-division multiplexing (OFDM), MIMO and a flat all-IP core, enabling mobile video at scale.

TABLE I: Comparison of Mobile Communication Generations

Gen.	Key technology	Peak rate (target)	Principal services
1G	Analog FM, FDMA	2.4 kbit/s	Analog voice
2G	Digital TDMA/CDMA	~100 kbit/s	Digital voice, SMS
3G	WCDMA, packet data	2 Mbit/s	Mobile Internet, multimedia
4G	OFDM, MIMO, all-IP	1 Gbit/s	Mobile broadband, video
5G	NR, massive MIMO, mmWave, SBA	20 Gbit/s	eMBB, URLLC, mMTC
6G	Sub-THz, ISAC, AI-native, NTN	50–200 Gbit/s	Immersive, sensing, AI services

B. 5G and 5G-Advanced

The 5G New Radio (NR) introduced a flexible numerology, operation in both sub-6 GHz and mmWave bands, massive MIMO beamforming, and a cloud-native, service-based core that supports network slicing. 5G-Advanced extends this foundation with AI/ML-based channel state information feedback and beam management, network energy-saving modes, enhanced positioning, reduced-capability devices, and integrated satellite access [2], [3]. As shown in Table II, the IMT-2030 framework raises most IMT-2020 targets by up to an order of magnitude. It adds entirely new capabilities, including sensing, positioning accuracy, AI-related functions, and sustainability [1], [4].

TABLE II: Key Capabilities of IMT-2020 Versus IMT-2030 [1]

Capability	IMT-2020 (5G)	IMT-2030 (6G)
Peak data rate	20 Gbit/s	50, 100, 200 Gbit/s
User-experienced rate	100 Mbit/s	300, 500 Mbit/s
Area traffic capacity	10 Mbit/s/m2	30, 50 Mbit/s/m2
Connection density	106 devices/km2	106–108 devices/km2
User-plane latency	1 ms	0.1–1 ms
Reliability	1−10−5	1−10−5 to 1−10−7

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Mobility	500 km/h	500–1000 km/h
Positioning accuracy	Not specified	1–10 cm
New capabilities	—	Sensing, AI, coverage, sustainability

III. SYSTEM MODEL AND FUNDAMENTAL LIMITS

Despite the diversity of wireless technologies, every radio link is governed by a common set of physical relations. Fig. 2 depicts a generalized 6G-oriented link in which a source encoder, a modulation and beamforming stage, a propagation channel, and a receiver are jointly orchestrated by an AI-native control layer, while terrestrial, sub-THz, and non-terrestrial tiers provide the physical connectivity. Its main performance relations are formalized below.

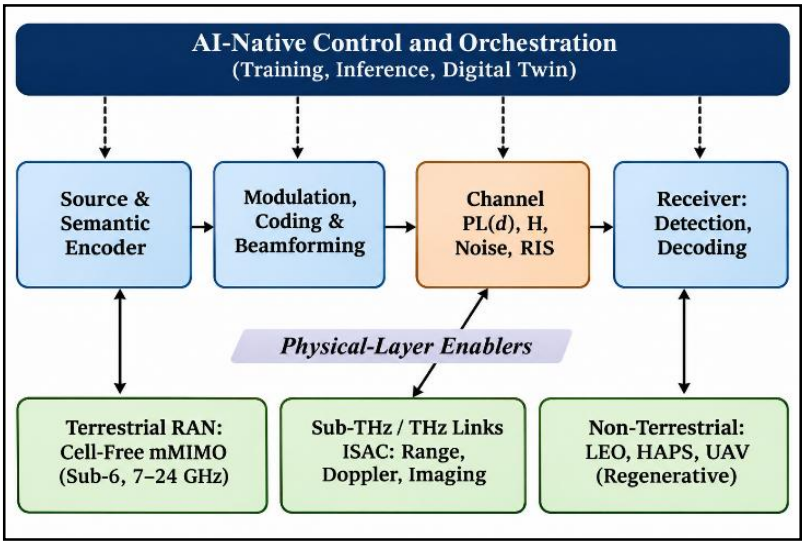


Fig. 2. Generalized architecture of a 6G-oriented wireless link, showing the transmission chain, the AI-native control layer and the physical-layer enablers discussed in Section IV.

A. Propagation and Link Budget

For a line-of-sight link of length d at carrier frequency f, the path loss in decibels is modeled by the Friis free-space term augmented with a molecular absorption coefficient κ(f), which becomes significant above roughly 100 GHz [5], [6]:

$$PL(d) = 20\,log_{10}\left(\frac{4\pi df}{c}\right) + \kappa(f)d \quad (1)$$

where c is the speed of light. With transmit power Pt, transmit and receive antenna gains Gt and Gr, bandwidth B, receiver noise figure F, Boltzmann constant kB, and reference temperature T0, the received signal-to-noise ratio (SNR), with all quantities in linear scale, is

$$\gamma = \frac{P_t G_t G_r}{PL(d) k_B T_0 B F} \quad (2)$$

Equation (1) shows that the loss grows by 20 dB per decade of frequency for fixed antenna gains, which must be offset by larger antenna arrays whose gain increases with frequency for a fixed physical aperture.

B. Capacity, MIMO and Energy Efficiency

The maximum error-free rate of an additive white Gaussian noise channel is given by the Shannon bound.

$$C = B\,log_2(1+\gamma) \quad (3)$$

which grows linearly in B but only logarithmically in γ. For a MIMO channel with Nt transmit and Nr receive antennas, channel matrix H and average SNR ρ, the capacity with equal power allocation is

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$$C_{MIMO} = log_2\, det\left(I_{N_r} + \frac{\rho}{N_t} HH^H\right) \qquad (4)$$

so that, at high SNR, the capacity scales with min(Nt, Nr) spatial streams, which motivates massive and cell-free MIMO [7]. Because 6G also targets sustainability, the energy efficiency in bit/J is defined as

$$\eta_{EE} = \frac{C}{\frac{P_t}{\varepsilon} + P_c} \qquad (5)$$

where ε is the power-amplifier efficiency and Pc is the circuit power. Equation (5) reveals that very wide bandwidths improve energy efficiency only when Pc does not grow proportionally with B [17].

C. Sensing Resolution

When the same waveform is reused for radar sensing, as in ISAC, the achievable range and velocity resolutions are

$$\Delta R = \frac{c}{2B}, \quad \Delta v = \frac{\lambda}{2T_{obs}} \qquad (6), (7)$$

where λ is the wavelength, and Tobs is the observation time [11]. Hence, a 2 GHz sub-THz channel yields a range resolution of 7.5 cm, whereas a 100 MHz sub-6 GHz channel yields only 1.5 m; thus, wider bandwidth benefits capacity and sensing alike.

D. Numerical Link Analysis

To quantify these relations, (1)–(3) were evaluated for four representative configurations: 3.5 GHz with 100 MHz, 28 GHz with 400 MHz, 140 GHz with 2 GHz, and 300 GHz with 10 GHz of bandwidth. A transmit power of 30 dBm was assumed, with combined antenna gains of 30, 45, 58, and 64 dBi and noise figures of 7, 9, 12, and 15 dB, respectively; molecular absorption was approximated as 0, 0.1, 0.4, and 5 dB/km. Fig. 3 plots the resulting path loss, which at 100 m increases from 83 dB at 3.5 GHz to 122 dB at 300 GHz.

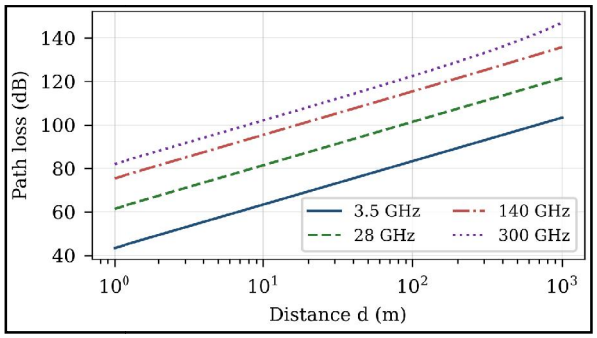


Fig. 3. Path loss versus distance computed from (1) for representative sub-6 GHz, mmWave and sub-THz carriers.

Fig. 4 presents the corresponding achievable rate. At 10 m, the 300 GHz link attains approximately 169 Gbit/s, which is about 60 times the 2.8 Gbit/s of the 3.5 GHz link, confirming that bandwidth is the dominant lever for peak throughput. However, the 300 GHz rate drops to about 23 Gbit/s at 1 km, a reduction by roughly a factor of 7, whereas the 3.5 GHz rate decreases only from 2.8 to 1.5 Gbit/s. Sub-THz links are therefore best suited to short-range, high-capacity scenarios such as fronthaul and data-center links, while lower bands remain essential for wide-area coverage. These conclusions depend on the assumed array gains, and practical links will additionally suffer from blockage and hardware impairments [6], [10].

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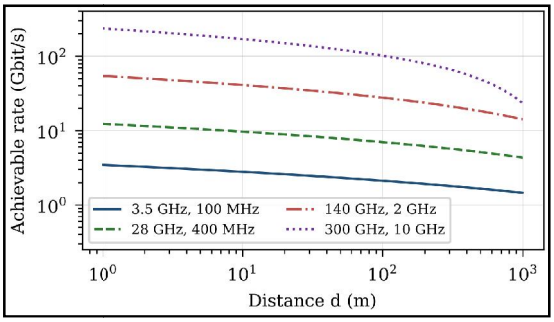


Fig. 4. Achievable rate versus distance computed from (2) and (3) for the four carrier and bandwidth configurations; parameters are given in Section III-D.

IV. ENABLING TECHNOLOGIES FOR 6G

The limits identified in Section III motivate complementary enabling technologies, each addressing a different term in (1)–(7). Table III compares their principal benefits, dominant challenges, and supporting literature; the subsections below discuss each.

TABLE III: Comparison of Key 6G Enabling Technologies

Technology	Principal benefit	Dominant challenge	Refs.
Upper mid-band / THz	Wide bandwidth, fine sensing resolution	Path loss, absorption, blockage	[5], [6]
Cell-free mMIMO	Uniform QoS, macro-diversity	Fronthaul, synchronization	[7], [8]
RIS	Low-power coverage control	Channel estimation, optimization	[9], [10], [18]
ISAC	Spectrum and hardware reuse	Interference, privacy	[11], [12], [19]
AI-native air interface	Adaptive, data-driven PHY	Generalization, cost	[13], [14]
NTN (LEO, HAPS, UAV)	Global, resilient coverage	Doppler, handover, spectrum sharing	[15], [16], [20]

A. Spectrum Expansion: Upper Mid-Band and Terahertz

Because capacity scales linearly with bandwidth in (3), 6G research targets both the upper mid-band (7–24 GHz), which offers a balance between coverage and capacity and for which 3GPP initiated channel modeling in Release 19 [3], and the sub-THz and THz bands above 100 GHz, which provide tens of gigahertz of contiguous spectrum [5], [6]. THz systems nevertheless require highly directional beams, efficient transceivers, and robust beam tracking.

B. Cell-Free Massive MIMO and Reconfigurable Intelligent Surfaces

Cell-free massive MIMO deploys many access points that coherently serve users across cell boundaries, providing macro-diversity and a more uniform quality of service than cellular deployments [7], [8]. RIS, consisting of programmable metasurfaces, reshapes the propagation channel at low power and can restore blocked mmWave and THz links, although they require scalable channel estimation and phase-optimization algorithms [9], [10], [18].

C. Integrated Sensing and Communication

ISAC reuses spectrum, waveforms, and hardware for both data transmission and radar-like sensing, enabling localization, imaging, and environmental awareness for autonomous driving and industrial IoT [11]. Key issues include self-interference and clutter management [12], as well as the joint allocation of sensing, communication, and computation resources [19].

D. AI-Native Air Interface

Whereas 5G applies AI as an external enhancement, 6G envisions AI embedded throughout the physical and medium-access layers, including learned channel estimation, CSI compression, and end-to-end transceiver optimization [13].

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Semantic, task-oriented transmission further reduces traffic by conveying task-relevant meaning instead of exact symbols [14].

E. Non-Terrestrial Networks and WLAN Evolution

Low-Earth-orbit (LEO) constellations, high-altitude platforms, and uncrewed aerial vehicles extend coverage to remote, maritime, and disaster-affected regions [15], [16], and RIS-assisted NTN can mitigate their link-budget limitations [20]. In parallel, Wi-Fi 7 (IEEE 802.11be) introduces 320 MHz channels, 4096-QAM, and multi-link operation, targeting throughputs of up to 30 Gbit/s with reduced latency [21], which complements cellular access indoors.

V. APPLICATIONS AND OPEN CHALLENGES

The technologies discussed above are justified by the applications they enable; this section summarizes these applications and the challenges that must be resolved before large-scale 6G deployment.

A. Representative Applications

Immersive extended reality and holographic communication require the peak rates and low latency listed in Table II. Industrial automation and digital twins depend on hyper-reliable links and centimeter-level positioning, while connected and autonomous vehicles benefit from ISAC-based environment perception [11]. Remote healthcare, smart agriculture, and environmental monitoring rely on massive, energy-constrained IoT connectivity, and NTN enables universal service in rural and underserved regions, which is particularly relevant to developing economies [15].

B. Open Research Challenges

Several challenges remain unresolved. First, network energy consumption must decrease even as traffic grows, which calls for energy-aware design, sleep modes, and AI-based optimization [17], [22]. Second, the open radio medium, sensing capability, and AI models expand the attack surface, raising concerns about privacy leakage, adversarial manipulation, and the need for physical-layer and quantum-resistant security. Third, interference among dense terrestrial, satellite, and sensing systems requires coordinated spectrum sharing [12], [15]. Fourth, harmonized global spectrum allocation and timely completion of IMT-2030 evaluation are essential for interoperable 6G systems [4].

VI. CONCLUSION

This paper has reviewed wireless communication technology from 1G to the emerging IMT-2030 generation. The generational analysis showed an increase in peak data rate by about 8 orders of magnitude and a shift toward multi-service, software-defined platforms. The unified system model and numerical analysis demonstrated that, under the stated assumptions, sub-THz links can exceed 100 Gbit/s at short range but degrade much faster with distance than sub-6 GHz links, confirming that 6G will be a multi-band and multi-tier system. Cell-free massive MIMO, RIS, ISAC, AI-native air interfaces, and NTN each address specific physical limits, but their maturity, energy efficiency, and security require further research. Future work will extend the link analysis to include blockage, hardware impairments, and multi-user interference.

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