The Evolution of Next-Generation Wireless Networks

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Abstract

The evolution of wireless generations is illustrated to demonstrate that 6G is the sixth generation of wireless communications and not an extension of Fifth Generation technology. Defining concepts, technologies, use cases, and a roadmap is pursued to enable sound and consistent progress within the 6G community. Society Mobility, latency, reliability, and location-aware requirements demand connective solutions are met rapidly adopted. Global connectivity, ubiquitous sensing, ultra-high data rates, latency and energy-efficiency are paramount. Advanced waveform, multiple-access technology, Terahertz communications, and novel materials enable 6G evolution.

Wireless connectivity is indispensable as humans and machines become increasingly mobile, dependent on connectivity, and converge in the Industrial Internet of Things. Communication, computation, and storage requirements are growing hierarchically, prompting demands for higher, lower latency, more reliable, and location-aware services. The long-term potential of Digital Twins and the nearness of the tactile Internet further shape 6G service definition, ushering in a period of global connectivity and a sensing ecosystem. Such requirements prompt the creation of dedicated solutions and associated application domains, as distinguished from service extensions. The vision of Digital Twins of the Environment, Technological Dressing, and Mind at Scale serves as decoupled benchmark.

Keywords: Sixth Generation Wireless Communications, 6G Vision And Roadmap, Beyond 5G Evolution, Ultra-High Data Rates, Terahertz Communications, Advanced Waveform Design, Novel Multiple Access Technologies, Latency-Critical Connectivity, Ultra-Reliable Communications, Location-Aware Networking, Energy-Efficient Wireless Systems, Global Ubiquitous Connectivity, Industrial Internet Of Things, Integrated Communication Computation And Storage, Digital Twin Systems, Tactile Internet, Ubiquitous Sensing Ecosystems, Novel Materials For Wireless, Human–Machine Convergence, Future Wireless Application Domains.

1. Introduction

In just a few decades, mobile communication systems have progressed from the first generation of voice services in the 1980s to the global deployment of the fifth generation, capable of transporting hundreds of gigabytes and connecting people, vehicles, and devices. From the first Web browser launch to the era of Big Data, Cloud Computing, Artificial Intelligence, and IoT. Every decade has seen transformative and disruptive advances, capable of shaping society, the economy, and even ways of life, requiring scientists, technologists, and engineers to constantly reflect on the requirements for future generations. Sixth-generation wireless communication systems (6G) are envisioned as a key enabler for further reshaping society and the economy through seamless global connectivity for all people, devices, and things, virtually supported and interconnected immersive experiences, XR, tactile Internet, ultra-reliable and low-latency wireless communication for autonomous systems, Industry 4.0, Machine-to-Machine (M2M) and Machine-to-Human communications, wireless augmented sensing, and support for AI-based service delivery. The ultimate goal of 6G is to connect the unconnected, overlay urban environments with a digital twin, and detect and characterize events even in absence of any specific transmitting sensor.

The foundations of 6G feasibility and success, including technological drivers, requirements, key important characteristics, potential use cases and application fields, networking architecture and enabling technologies are briefly analysed. Attention is devoted to the global necessity of ensuring universal and shared access to the technology and to the assets that make its use increasingly possible, as well as to the role of privacy-preserving synthetic data generation and transfer in augmenting the sensing capabilities of wireless networks. The overall syllabus identifies the critical aspects that future research must focus on to make 6G wireless communication systems an effective means for the envisaged transforming and disruptive role.

1.1. Overview of Document Structure and Purpose

Recent global developments and societal challenges signal a step change toward 6G. Specifically, the widespread adoption of advanced mobile services has resulted in unprecedented connectivity demand, for both people and machines. Such demand is accompanied by ever-increasing requirements for mobility, reliability, position awareness, and latency. At the same time, the notion of global connectivity for all remains unfulfilled, while high-risk and high-value applications (including health, transportation, and energy infrastructures) are emerging. In this context, enabling technologies are rapidly maturing, including support for very high data rates, advanced multiple access schemes, and terahertz communications.

Supported by these developments, the research community has begun to reflect on the vision and requirements of 6G. Consequently, the first supporting white papers have recently been published. The anticipated service capabilities will enable the realization of applications that exploit immersive extended reality, the tactile Internet, industrial and autonomous systems, and distributed smart services. Satisfying these applications will therefore guide both the research agenda and the evolution of wireless systems throughout the next decade. The scope of these services, together with the related performance indicators, is discussed subsequently.

2. Historical overview of wireless generations

Throughout its ongoing development life cycle, 6G wireless communications technology stands at the intersection of many trajectories, while incorporating a comprehensive set of target parameters and requirements that drive its evolution. The full scope, overarching features and highly anticipated use cases for the sixth generation of wireless communications are supported by technological advancements in artificial intelligence and machine learning; hardware and software design; security; radio and antenna technologies; waveform design; resource management; wireless-sensing-centered communications; and high-bandwidth services.

Yet many of these enabling technologies continue to advance at varying rates. Consequently, the anticipated release date for the ITU's IMT-2020 report on global connectivity and the Digital Divide continues to shift as the shaping features for IMT-2030—the 6G Global Standards—remain unidentified. Traceability of future use cases back to service-based wireless communications support enables a focus on a diverse range of enveloping wireless systems, whose standardization history captures the shift from Radio-Data Systems to IMT, as well as the major milestones, content areas, main bodies, release chronology and amendment dates of the wireless generations. Since the formal start of 6G research towards technology availability for commercial launch from 2030, a growing number of architecture and technology roadmaps have emerged, as well as a Tech Horizon report identifying requirements, potential applications and KPIs.

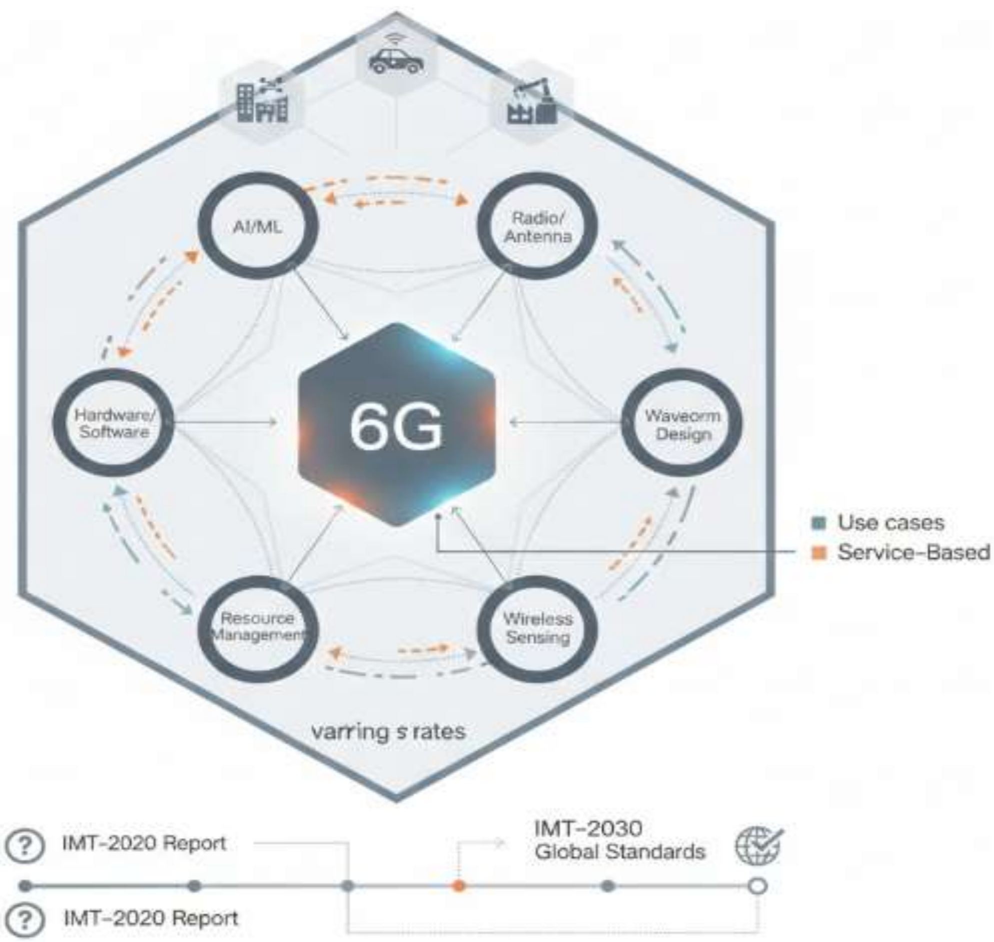


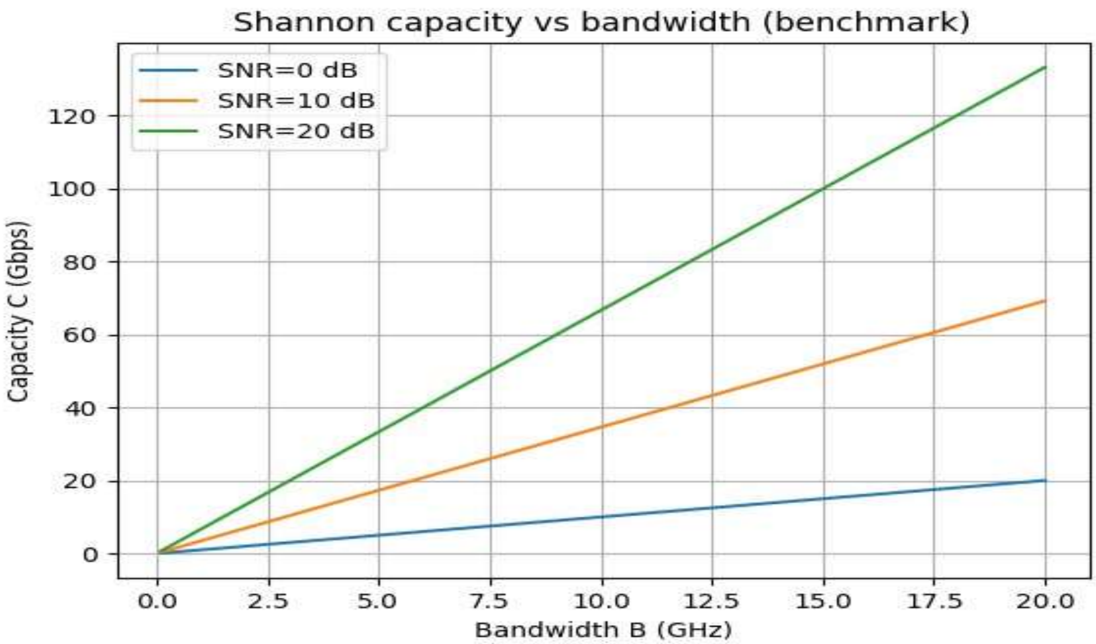
Fig 1: From IMT-2020 to IMT-2030: A Tech-Horizon Framework for 6G Standardization, Requirements, and Architectural Roadmaps

2.1. Evolution of Wireless Standards

The first wireless standards emerged through the development of commercial systems. 1G supporting voice services was released as Advanced Mobile Phone Service (AMPS) by Bell Labs in 1979. The development of wireless cellular telephony standards was gradually adopted by the International Telecommunication Union (ITU) with Movable Satellite Service (MSS) and International Mobile Telecommunications2000 (IMT2000). In 1994, the European

Telecommunications Standards Institute (ETSI) published Global System for Mobile communications (GSM) specifications that supported voice, short message services, and wireless data services. 2G was defined through GSM and IS-95 alliances. In 1997, a combined effort for a third-generation standard for wireless telephony was formed for Universal Mobile Telecommunications Systems (UMTS) that supported wider area wireless data connections. The UTC published IMT-2000 specifications in 1998 with the Japanese aiming for satellite, terrestrial, and Code Division Multiple Access (CDMA)-based wireless. The IMT2000-based versions for DSSS and CDMA were released between the 1990s and the early 2000s.

Evolved Universal Terrestrial Radio Access Network (E-UTRAN)-based wireless technology was published as 3GPP-LTE by 3rd Generation Partnership Project (3GPP) in 2008 and as an evolved standard by International Telecommunication Union (ITU) in 2011 as -=4G. Wireless technology described as LTE-A was branded 4G by ITU for meeting the requirements for IMT-Advanced. Wireless systems that support connected object application services on individual cells covering smaller geographic areas were deployed in the mid-2010s. In the late 2010s, specifications created by 3GPP for a next-generation wireless network technology were published. The assistance of 5G New Radio in supporting unlicensed spectrum, lower latency, enhanced mobile broadband, and ultra-reliable low-latency communications make it a suitable solution for mobile networks, connecting smart cities, enabling local consumers to access ultra-broadband, and facilitating traffic collection and infrastructure operation.



Equation 1: Data rate, bandwidth, and spectral efficiency

Step 1: Define spectral efficiency

Let:

- R = data rate (bps)
- B = bandwidth (Hz)
- η = spectral efficiency (bps/Hz)

By definition:

$$\eta \triangleq \frac{R}{B} \quad \Rightarrow \quad R = \eta B$$

Step 2: Use the Shannon benchmark (upper bound)

For an AWGN link:

$$C = B\log_2(1 + \text{SNR})$$

So the **spectral efficiency limit** is:

$$\eta_{\text{max}} = \frac{C}{B} = \log_2(1 + \text{SNR})$$

Step 3: Rearrange to find bandwidth needed for a target rate

Set $R_{\text{target}} = 1$ Tbps $= 10^{12}$ bps:

$$R_{\text{target}} = B\log_2(1 + \text{SNR})$$

Solve for B:

$$B = \frac{R_{\text{target}}}{\log_2(1 + \text{SNR})}$$

SNR (dB)	$\eta = \log_2(1 + \text{SNR})$ (b/s/Hz)	Bandwidth for 1 Tbps (GHz)
0	1.00	1000.0
10	3.46	289.1
20	6.66	150.2
30	9.97	100.3

3. Technological drivers and requirements for 6G

At the heart of potential 6G demand are a rural connectivity gap and global ubiquitous coverage. Despite earth's growing population and ongoing urbanization, a significant portion—roughly 2.5 billion people—remains offline, unable to enjoy the benefits enabled by connectivity and the use cases already demonstrated by 5G networks. Providing coverage for users without wired infrastructure has been challenging and remains cost prohibitive. As a result, satellite and high-altitude platforms are being increasingly considered for extended coverage. At the same

time, enterprise, academic, and government research activities utilizing high-throughput LEO constellations are proliferating worldwide. and offer an unprecedented opportunity to connect the unconnected—if the right technology enablers and business models emerge. The rising demand for global connectivity across land, air, and sea is now being augmented by the broader vision of full sensing capability across the globe, where everything is continually sensed to improve situational awareness, inform incident response, facilitate safe and secure transport, and support climate monitoring and action.

From health and environmental sensing through visual surveillance of crowd behavior, to terrestrial, aerial, and underwater tracking and scene monitoring, the range of potential sensing use cases is staggering. Making ubiquitous-area sensing a reality involves obviating the innate limitations of cellular and Wi-Fi-like networks in distributing resource-constrained sensor nodes across land, sea, and air, as well as the privacy risks associated with large-scale external data collection. The capacity of the network must support a much higher density of sensing-and-communication-capable devices, as well as providing very low-power service to small form-factor and resource-constrained applications. At the same time, supporting proactive rather than reactive event response places stringent requirements on very low latency end-to-end, device-to-device, and more recently, device-to-edge computing-cycle time system requirements across a broad range of applications.

3.1. Global connectivity and ubiquitous sensing

The aspiration for global connectivity is a recurring and ambitious theme in the evolution of wireless communication systems. The International Telecommunication Union (ITU) highlighted the vision of bridging the digital divide in its World Telecommunication Development Report. Completion of the first-generation system in the early 1980s fulfilled only the communication needs of a limited number of countries. Since then, connecting the entire globe has remained an unchained motivating goal of subsequent generations. Various stakeholders continue to devote their efforts and resources to satisfy this requirement.

6G is expected to enable ubiquitous connectivity by providing a seamless experience for users interacting across multiple modalities or media. Wireless communications served predominantly macro-cellular human communication until the introduction of 5G support for the Internet of Things (IoT) and machine-type communications (MTC) in the form of massive MTC. The 6G specification is expected to expand this notion of connectivity to include human-centric and networked service applications, including sensing, awareness, and computation. As an

analogy, consider a self-driving vehicle with radar and LiDAR sensors to detect other vehicles in its vicinity, cameras to recognize traffic signals and lanes, and accurate GPS to determine its precise location. Such a vehicle must either receive input from an external source (e.g., weather, traffic conditions) or relay the accumulated information to an external entity for higher-level decision-making processes. Such communication requirements are critical for operational safety and reliability.

3.2. Ultra-high data rates and spectral efficiency

Ultra-high data rates are considered a key performance indicator (KPI) for 6G wireless communications, where ambitious goals such as 1 Tbps peak data rate and 1 Gbps user experience have been proposed. Similar to prior generations of wireless communications, the desire for high data rates largely stems from the combination of bandwidth-hungry applications, growing user demands, and a growing number of devices consuming similar applications. However, it should be noted that the mobile traffic forecast indicates that by 2025, only 20% of users in the world will consume AR/VR applications, 47% will play video with 4K resolution, and less than 10% of consumer subscribers will be using 8K resolution streaming. Moreover, the Ultra High Speed Communication use case does not fall into the Top 10 use cases for 6G—and is often superseded by use cases with no explicit data rate requirements but rather requirements on latency, reliability, or energy.

That said, capacity requirements of wireless systems increase over time in order to accommodate the diverse needs to support aquantilope applications. As a result, the mobile operator community has included efficiency and capacity targets relative to data rate growth in their 6G perspective report, where a year-on-year increase of 5-10x in spectral efficiency is expected during the next decades. More specifically, a relative increase in spectral efficiency of 100x in comparison to 5G is expected for 6G by 2030 and 1000x by 2035 at a 3x lower cost per bit. These capacity goals are often expressed as more efficient use of available bandwidth, and spectral efficiency is used as an indicator for determining how efficiently the resource of bandwidth is utilized.

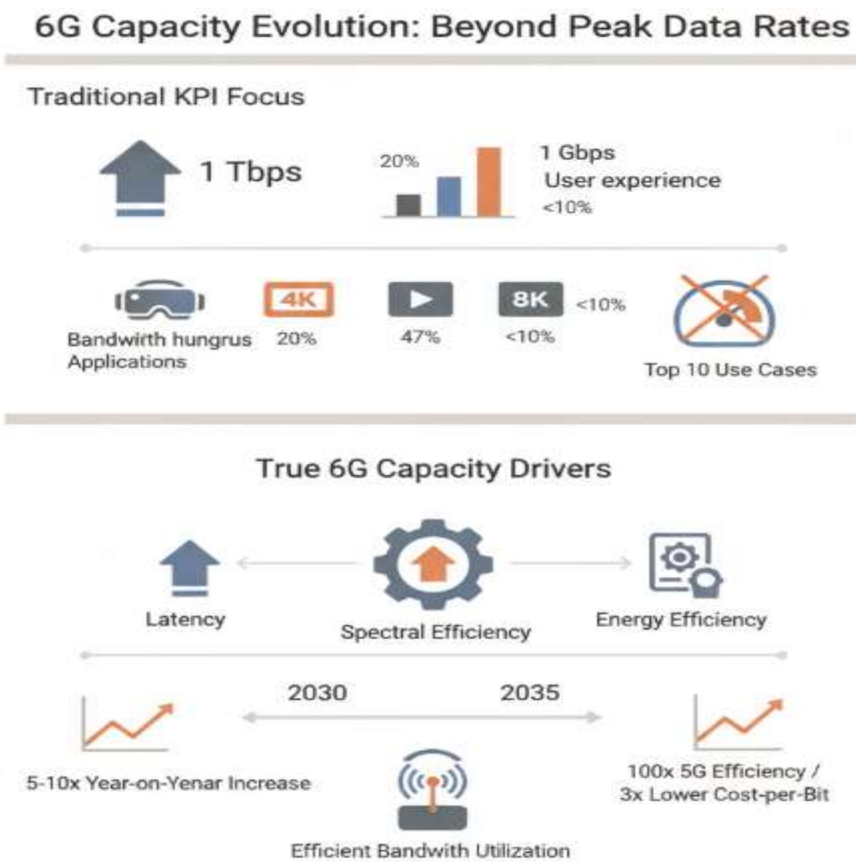


Fig 2: Reassessing 6G Performance Indicators: Balancing Ultra-High Data Rates with Spectral Efficiency and User-Centric Capacity Targets

4. Core enabling technologies

Supporting technologies for 6G comprise high-frequency radio propagation, THz communications, ultra massive MIMO Layers of Array (LMA), spectrum utilization underpinned by the newest waveforms and modulation schemes, artificial-intelligence-enabled networking, integrate-then-apply sensing, and a host of other expected concepts, demands, and features. These technologies can be endorsed now as the enablers of future 6G networks and can be allocated to likely highest-level performance criteria through 6G services, with some expected before 2030.

Advanced timestamp and spectral-efficient waveform technologies for 6G are continuously investigated, particularly those that overcome the limitations of current technologies. Their design criteria must reflect the exhaustive demands of 6G services. The several proposed schemes, e.g., alternative phase and index modulation techniques, promise high spectral efficiency, seamless seamless integration with sensing, and relaxing requirement on the channel estimation performance but, without incorporation of new bases for the final combinations into the multiband or bandless transmitted signals in a THz band naturally available in practically the whole globe will necessitate very costly approximations through choice of critical values of all involved managing functions in their fundamental operation such as the Padè nature of the basis sinc function that generates the temporal waveform.

4.1. Advanced waveform and multiple access schemes

The advancement of orthogonal frequency-division multiplexing (OFDM) enables achieving superior spectral efficiency only within narrow bandwidths. Enhanced unavoidable bandwidth demand, decreasing carrier frequency of upcoming systems, and the exploration of the Explore–Discover–Produce spectrum paradigm spur ongoing investigation of alternative waveforms. Precoding-filtered OFDM (PF-OFDM) and generalized frequency-division multiplexing (GFDMA) reside on the same ultimate spectral efficiency and introduce accessibility issues. 6G aiming at circular data packets explores PF-OFDM and other non-orthogonal multiple access assignment methods—though OFDMA is an influence factor—resilient to interference from symmetrical and other signals.

The 2020s' focus shifts toward establishing 6G beyond the Explore-Discover-Produce spectrum. The substantially increased demand superimposed on the decreased Explore-Discover envelope requires the speed of existing and other suitable technologies. Spectral efficiency per hz and numbers of service instances per km2 approach saturation, propelling further demands on the 6G Terahertz Service Incubation. Service-level and physical-layer demands on latency and reliability approach saturation at 5.5G. User demand for understanding both human and machine drives the study of Establish-Locate-Track-Predict sensing relevant to the Terahertz frequency. Massive spectroscopy is still advancing.

Equation 2: Link budget and SNR

Step 1: Start from Friis (free-space)

Friis transmission:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$

Where:

- P_t, P_r = transmit/receive power (W)
- G_t, G_r = antenna gains (linear)
- $\lambda = \frac{c}{f}$
- d = distance

Step 2: Convert to "path loss" form

Define free-space path loss:

$$L_{\text{FS}} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d f}{c}\right)^2$$

In dB:

$$L_{\text{FS}}(\text{dB}) = 20\log_{10}\left(\frac{4\pi d f}{c}\right)$$

Step 3: Received power in dB form

$$P_r(\text{dBm}) = P_t(\text{dBm}) + G_t(\text{dBi}) + G_r(\text{dBi}) - L_{\text{FS}}(\text{dB}) - L_{\text{other}}(\text{dB})$$

Step 4: Noise power and SNR

Thermal noise:

$$N = kTB$$

In dB (practical form):

$$N(\text{dBm}) \approx -174 + 10\log_{10}(B_{\text{Hz}}) + NF$$

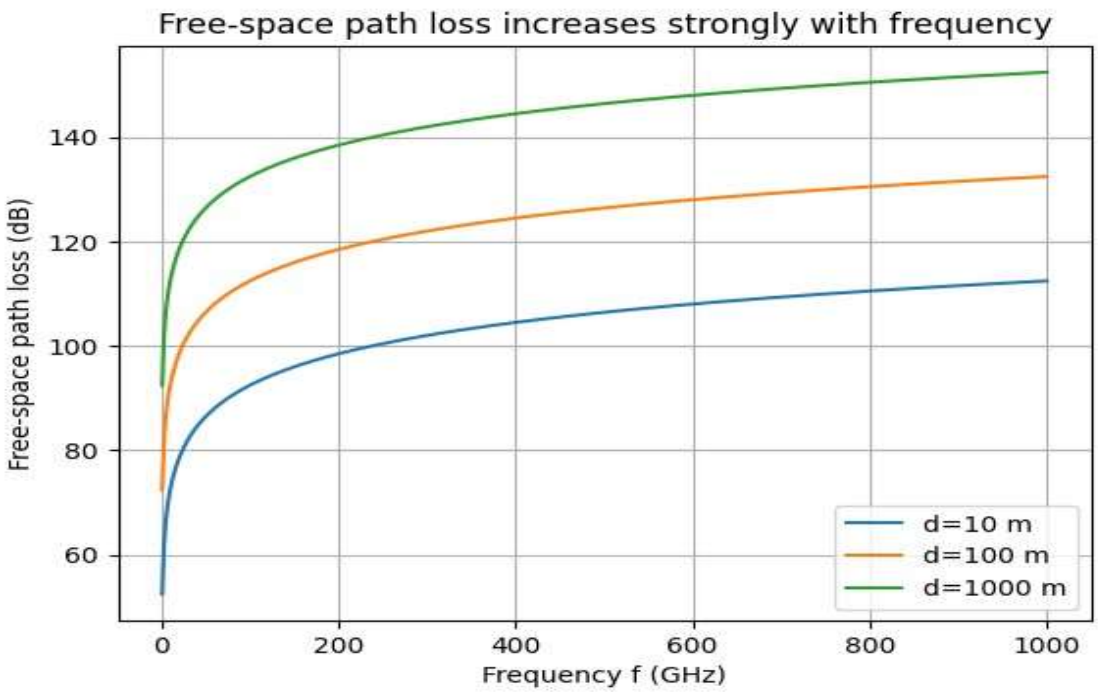
So:

$$\text{SNR}(\text{dB}) = P_r(\text{dBm}) - N(\text{dBm})$$

4.2. Terahertz communications and novel materials

Albeit only recently promoted from the abstract conception phase, terahertz (0.1–10 THz) communications hold promise as a viable 6G technology, due to their ability to facilitate ultrahigh data rates by exploiting the abundant bandwidth available in this frequency range. However, several discrete adjacent long-standing technical challenges related to the propagation and generation of terahertz signals need to be addressed, including the engineering of ultrawideband antennas, development of novel materials with subwavelength dimensions, and radiosystems capable of operating in the terahertz regime. The potential of these solutions is assessed along two principal axes: first, feasibility from the perspective of latest progress; and second, anticipated realistic rollout timelines. The ultimate feasibility of any specific hardware solution will depend on a delicate balance among performance in the practical environment, technical complexity, and cost of realization.

Further progress towards integrated terahertz wireless communications will ultimately rely on the development of mid- and far-infrared (2–40 μm) opto-/microelectronic components and circuits. Groundbreaking work on 2D materials beyond graphene can enable hybrid integration of infrared laser sources, modulators, filters, detectors, and other key devices onto a single chip unit, paving the way for the smallest and lowest-cost complete terahertz wireless radios, routers, and networks yet imagined. These integrated circuits must be coupled to dielectric- or metal-filled antennas with effective areas maintaining the 2D scaling trend, and capable of supporting layered zonal-rectangular or zonal-trapezoidal-wavelength excitation with builtin-enhanced-3D-collection-efficiency-solid-angle in the far terahertz region of the spectrum.



5. Architecture and network paradigms for 6G

Design principles, deployment scenarios, supporting technologies, and system-level orchestration characterize the architecture and network paradigms for sixth-generation wireless communications and networking.

Network architecture and paradigm descriptions articulate the topological, structural, normative, technological, and operational features in support of anticipated use cases and application domains. An edge-centric topology addresses the need for ultra-low latency and high reliability; a cloud-native architecture, the desire for agile service creation and consumption. Tailored distributed intelligence enables increased resilience and scalability, facilitati ng the orchestration of ultra-reliable control operations of mission-critical applications in a zero-trust context. Inter-service orchestrators supply and manage diverse application services spanning heterogeneous 6G environments, underpinned by edge-centric physical-layer and core services.

The core supporting technologies of sixth-generation communications and networking underpin the hardware and software requirements of different deployment scenarios. A high-priority technology path recognizes the need for unified end-to-end ultra-high-capacity communications, smart-aware-enabling services, near-field capabilities for zero-distance and zero-privacy communications, quantum-enhanced security and resilience, and cyber-sensing capabilities. A secondary, forward-looking technology path addresses the drastic increase in scale, complexity, and heterogeneity that supports new generation needs.

5.1. Edge-centric and cloud-native designs

A growing number of verticals are exploring the potential of 6G networks for real-time, high-performance applications that require ultra-reliable, low-latency communication and minimized data processing time. Edge-centric designs that accommodate local service requests and edge-cloud resource distribution near service users reduce delays and improve resource utilization. The low propagation delay through the radio part ensures that the service latency requirement is met. Service requests can thus be shifted to the edge cloud to meet the QoS and latency requirements of time-sensitive services. Edge-centric designs also reduce movement distance for transmission and processing and, therefore, energy consumption. Above all, they can substantially meet non-IID distribution when heterogeneous terminals provide their services in local areas. However, consistency along the edge and between edge and external services is hard

to guarantee.

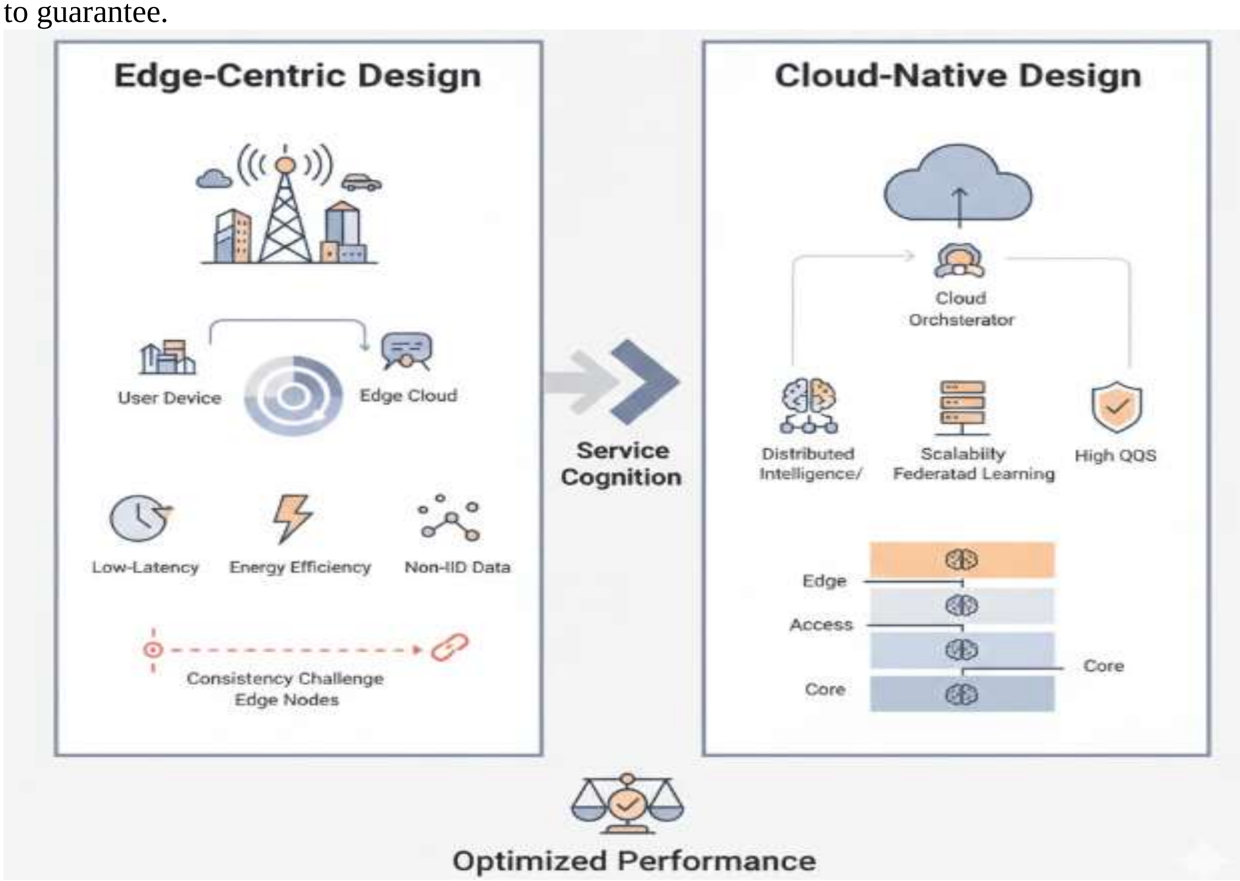


Fig 3: Synergizing Edge-Centric Design and Distributed Intelligence: A Cloud-Native Architectural Framework for 6G Latency-Critical Services

Apart from edge-centric designs, a plethora of service cognition paradigms with distributed intelligence along the network have emerged. Data should be learned, communicated, and processed in a distributed manner. A cloud-native design paradigm is preferable in terms of evolving network architecture, service requirements, deployment flexibility, performance goals, and quality assurance. Neural network-based services with extra low latency can scale to billions of users. A centralized orchestrator making use of more complete data can thus ensure high QoS guarantees. Multilayer architectures with emergent federated learning on different scales can employ distributed intelligence along the edge, access, and core networks.

5.2. Distributed intelligence and cooperative networks

Distributed Intelligence enhances the AI capabilities of networks and offers systemic resilience and scalability through federated learning. Major advances in ML, AI, and DL are shifting traditional network planning and management toward automated learning-based paradigms. These algorithms require a variety of input data that are difficult to obtain from a single source. A promising solution to overcome data ownership challenges is federated learning (FL: also known as cross-silo or crossover learning), a distributed approach that enables different parties to jointly train an AI model without sharing their data. Users in different administrative domains can exchange control parameters such as model weights without revealing locally gathered specific data, thus preserving privacy. As Federated Learning meets the fundamental architectural characteristics of 6G – wide-scale access, networking, and intelligence – it is expected to be widely adopted in end-to-end 6G networks that promise dense connectivity and multi-domain service orchestration across multiple administrations.

The Concurrent Wireless & Sensing Network supports Multiple Autonomous Agent Systems (MAASs) through cooperative communications, situational awareness, and mutual services. MAASs consist of several agents that collaborate to accomplish a complicated task that a single agent cannot carry out alone. Such systems have attracted growing interest due to their remarkable adaptability and flexibility, providing a solution for general-purpose real-time sensing and communication services in complex and dynamic environments. MAAS-related technologies will be further enhanced and integrated with future communication systems, enabling features such as relay assistance in social networks and mutual sensing for advanced driver-assistance systems. By fusing these features with independent recurrent communication learning in edge intelligence, a Concurrent Wireless and Sensing Network (CWSN) capable of supporting multiple heterogeneous MAASs will be formed.

6. Use cases and application domains

The consideration of use cases is essential to an application-driven design of the next wireless generation. Technical capabilities must translate into real-world impact. Typical application domains of 6G wireless systems include extended reality, the tactile Internet, industry automation and control, and autonomous systems. The prerequisites in terms of quality of service, bandwidth demand, reliability, latency, and positioning leading to mobile non-terrestrial networks (NTNs) are anonymized.

The immersive experience offered by extended reality (XR) becomes increasingly convincing and attractive both in gaming/media applications and in the sharing of real-life real-time experiences across geographic distance. Technically, XR spans a wide range of Quality-of-Service (QoS) requirements. Frame size, frame rate, depth of field, Quality-of-Experience (QoE), and latency represent critical performance indicators. Video-bandwidth consumption for ultra-high-definition (UHD) XR applications with 360-degree view is extremely high, in the order of multiple terabits per second, rendering a direct transmission unfeasible. The metasurfaces enabling spatially controllable/steerable wireless propagation patterns and the introduction of display technologies for holography and volumetric displays are rapidly emerging as major fields of engineering efforts that can possibly shape the ensuring holo-telepresence experience in the later years of this decade.

An alternative appealing area of application is the Tactile Internet. Apart from immersive XR experiences, other tactile applications can amplify human experience by enabling interactions with remotely located haptic-capable robots. In such use cases, the human is present in an Augmented Reality (AR) environment composing real-world inputs and digital contents. Robots provide capabilities exceeding human physical properties delivering objects in environments dangerous for people. These applications have extreme QoS requirements with targeted tolerable delays in the 1 ms range and bidirectional haptic video bandwidth demand in the order of terabits per second, with required link reliability exceeding 99.9999999%. Control over the QOSthe haptic-coupling channel, guaranteeing the reception of tactile and force signals with maximum delay in the order of 1 ms and providing satisfactory feedback-stimulation may also lead to fatalities.

In industrial applications, mobile devices connect IT systems on the factory floor with business systems, enabling analytic capabilities, system optimizations, and real-time decision making. Mobile automation expands machine capabilities by providing workers with access to the complete production process with minimal effort. Visual and auditory aids help workers requesting information and/or assistance. Guaranteeing a reliable communication service with minimum latency and the highest availability is crucial. A key requirement for mobile and industrial NTNs encompasses all aspects related to safety. In additional to the above conditions, radio communications must consider that its failure may result in life-threatening situations.

Autonomous systems encompass autonomous driving, vehicle-to-everything (V2X) communications, unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV) applications, etc. Requirements also differ greatly between these applications but can typically be

identified with ultra-high reliability and ultra-low latency enabling the replication of perception and decision-making functions. The growing deployment of these applications forms another line of business for wireless communications. Dispersion of location users with very special latency and/or reliability focused requirements may require the revisitation of traditional phased networks exploiting also non-terrestrial wireless links, such as satellites or UAVs.

Equation 3: THz propagation with molecular absorption (why THz is hard)

A common THz channel model adds absorption loss:

Step 1: Add Beer–Lambert absorption

Power decays with absorption coefficient $\kappa(f)$:

$$P_r \propto e^{-\kappa(f)d}$$

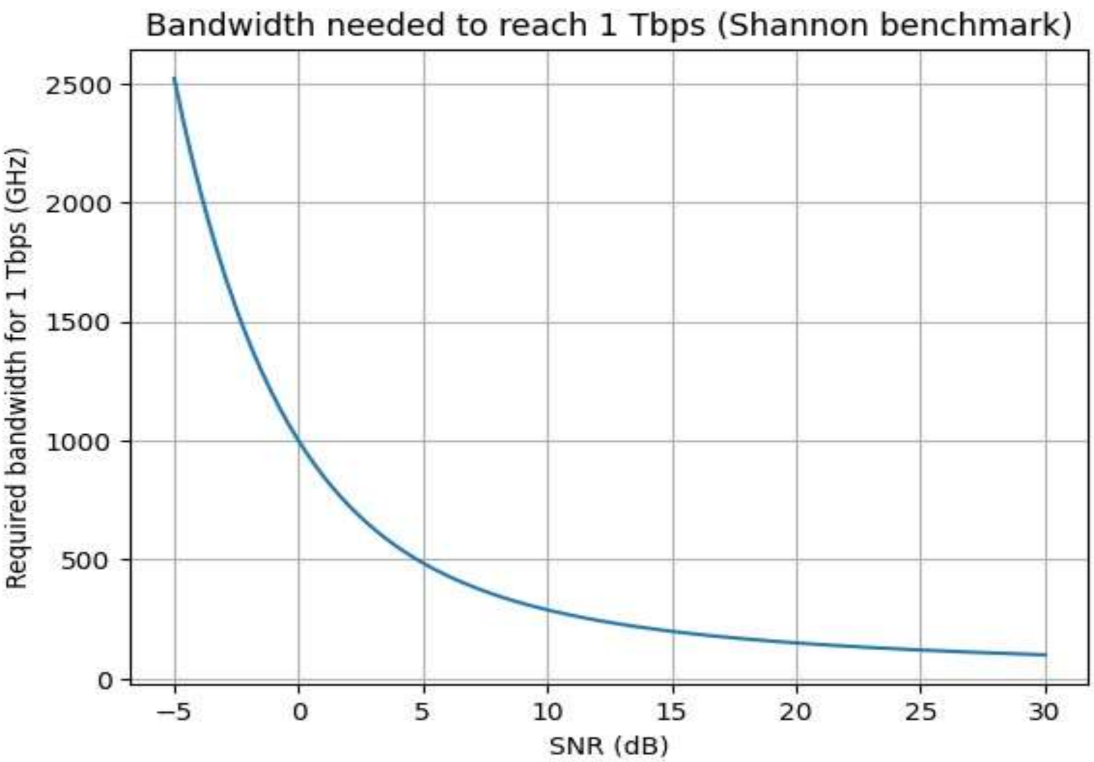
In dB, absorption loss:

$$L_{\text{abs}}(\text{dB}) = 10\log_{10}\left(e^{\kappa(f)d}\right) = \frac{10}{\ln 10}\kappa(f)d \approx 4.343\,\kappa(f)d$$

Step 2: Total path loss (simple model)

$$L_{\text{tot}}(\text{dB}) = L_{\text{FS}}(\text{dB}) + L_{\text{abs}}(\text{dB}) + L_{\text{scat}}(\text{dB}) + \cdots$$

So THz isn't “just more bandwidth”—it changes the whole link budget.



6.1. Immersive extended reality and tactile Internet

Wireless communications have been paving the path toward a Science Fiction world since the first generation of 1G. Immerse extended reality (XR) and tactile Internet are the two classic cases that have been widely discussed and foreseen, both of which put individual users and society in XR and provide multi-sensory immersive experience close to reality. XR includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). It aims to provide an immersive visual experience with high sense of presence and sense of of atmosphere for users through Presented 3D images at a deep level. Space, scale, and use scenario unbound, and long-distance interactivity; meet the demands of overall immersion quality, bandwidth, and delay for multi-user use, and support cloud hosting and cross reality. The tactile Internet realizes the tele-robotic control of machines, devices, and vehicles, including wearable robots, through high-speed, low-latency, and high-reliability networks, thus exhibiting human-computer synthesizability and perceptive capability. The network must support multi-sensory interactive

tele-surging with high speed, ultra-reliability, and high-fidelity multi-modal information for multi-user, long-distance, and cross-hospital scenarios with a higher degree of emotion and consummate content. For XR and tactile Internet support, the QoS, bandwidth, and delay requirements are: 3D/audio/video/force-feedback multi-modal fidelity, photographic-like real-time transmission in mask, ceiling, human eye, and laser dof; 500M/450M/5K/14K/16K deep immersive interactive at 120-frame/m; bit-rate point cloud in dozens Gbps; sight/track/scale-conceal demand in cloud-simulation dressing/contrast; force feedback within 5ms delay and tracking in less than 20μs.

6.2. Industrial and autonomous systems

Industrial systems, based on established standardization for advanced wireless private networks, encompass a diverse array of vertical markets—including manufacturing, energy production and distribution, mining, transportation, commercial aviation, supply chains, and logistics—for which private networks can provide fundamental advantages of control, reliability, security, and low latency. Autonomous systems, comprising transport systems (e.g., road, rail, air, and sea) and robotics and drones, require reliable, low-latency communications networks; risk mitigation through redundancy, diversity, and security; and mechanisms for scaling within and across regions producing different types of non-normal traffic. Requirements for tactile Internet services and systems are more challenging than for factory automation. The safety-critical nature of these systems places even greater emphasis on reliability while lowering acceptable latency margins.

The required QoS parameters for closed-loop remote-controlling operations must be determined. Typically, such parameters are derived from timing and operational distances while taking into account safety margins. Supporting a human sensorium requires a minimum data rate of 1 Gb/s per user with submillisecond latency. Industrial and autonomous systems are significant Internet users that support the national and global economies and reduce the impact of economic decline, environmental degradation, and strong investment cycles. Key components in achieving a green, digital economy are digital twins and predictive maintenance systems implementing machine learning using regular real-time updates. Such Internet services will require ultra-low-latency, high-reliability mobile links—especially in safety-critical systems.

7. Conclusion

Foundations and Implications of 6G Wireless Communications

Traceable milestones highlight the increasing impact of wireless communications on society and the importance of multirole communicators, mass mobility, minimum latency, maximum reliability, smart connectivity, enhanced sensing, societal resilience, industrial sustainability, and economic sustainability, operating requirements at a global scale. Both the vision and needs of the next generation are ambitious and far-reaching. The associated universal framework, which facilitates on-demand connectivity to smart access points, scopes communications-as-a-service, enabling contextualization, orchestration, and fulfillment of service requirements. Success hinges on the emergence of advanced supporting technologies offering an eco-friendly roadmap toward the envisaged information-communications-technology transformation.

Emerging global connectivity goals seeking to bridge the digital divide and lossless attention for deep-space cease-to-exist require newly tapped resources for reliable broadband-in-the-blind connectivity or continuous connectivity with multi --province coverage. Multimodal (passive/active/tactile) outdoor-centric sensing must interrelate access and edge infrastructures—driven by proprietary/societal business objectives—for ubiquitous, privacy-protected context-awareness capability and exploitation. Comprehensive multisensory locating schemes must jointly satisfy soldier, robot, and autonomous driving requirements at wireless levels of accuracy, bandwidth, and latency, while extended-linked analysis systems must wrap on-demand actionable surveillance strategies around these cloud/edge-centric services to deliver squeezable, select-and-protect deep-fear of multitarget-disruption. Ultra-high data rates with THz spectral efficiencies and supporting latency reduced on the milli-microsecond threshold at genuinely low intermodal-interthreat or end--end energy are other demanding indicators associated with super-extended reality experiences and tactile-Internet company.

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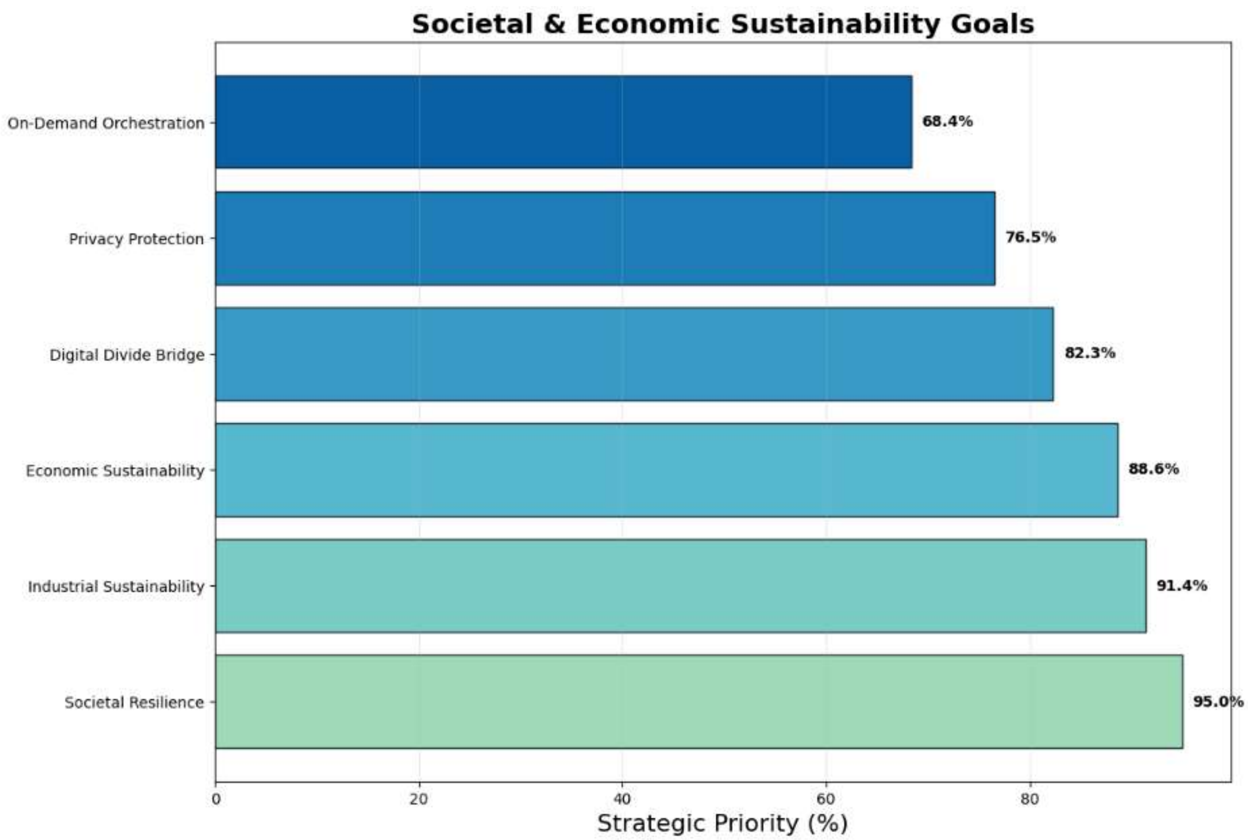

Fig 4: Societal & Economic Sustainability Goals

7.1. Future Directions and Implications of 6G Technology

It is anticipated that the 6G technology and the advanced capabilities of future services will bring valuable and long-awaited benefits to industries and communities worldwide. Fulfilling these anticipated benefits requires careful design and development of the supporting technology, as demonstrated by past experience — some fundamental breakthroughs, design decisions, or development directions taken or missed by previous wireless generations have had major implications on the fulfillment of expected utilization and related benefits. Based on past experience, it is essential to conduct a thorough examination of 6G requirements and technology enablers to draw conclusions about future research directions and priorities, as well as potential

socio-economic implications of a successful 6G completion. By connecting 6G requirements to the underlying technologies, supported by careful argumentation and past experience, appropriate conclusions and future directions can be established.

6G is recognized as a general-purpose service-reaching technology with design objectives beyond pure telecommunications. As a result, it is expected that some form of universal connectivity will serve as the de facto enabler of virtually all 6G services, fulfilling requirements beyond communication, including location sensing, energy harvesting control, and environment interaction for mobile and mass-market applications. Such advanced wireless connections for both people and machines, and the widespread availability of ubiquitous intelligent infrastructure services, are expected to play a key role within smart societies, enabling a diverse range of advanced applications in business, industry, and leisure, including truly immersive extended reality, the tactile Internet, and a scalable and practical end-to-end formulation of the industrial Internet with distributed, fully autonomous systems controlling all aspects of urban and industrial life.

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