



The foundation and future of 6G

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Abstract

The sixth generation of wireless communication (6G) is emerging as a foundational technology for the AI-driven digital era. Building on the advances of 5G in speed, capacity, low latency, Internet of Things (IoT), edge computing, and scalable connectivity, 6G is being designed to support AI-native, real-time, spatially aware applications at scale. The transition toward persistent multimodal AI agents operating across smartphones, vehicles, wearables, augmented reality (AR), and extended reality (XR) devices is creating new demands for sustained uplink capacity, predictable low latency, continuous connectivity, and distributed computing across devices, edge nodes, and the cloud.

The foundation of 6G extends beyond conventional communication by integrating sensing, computing, intelligence, and orchestration. Its anticipated capabilities include higher uplink performance, integrated sensing and communications, multilayer coverage combining terrestrial and nonterrestrial networks, and AI-enabled network management. These technologies can facilitate continuous collection of real-world data and support physical AI applications involving drones, robots, and connected vehicles, while enabling immersive experiences and intelligent systems that operate in physical environments.

The future of 6G therefore lies in transforming connectivity from a communication medium into an intelligent infrastructure for distributed AI. Achieving this vision will require coordinated investment in research and development, open global standards, technical talent, secure intellectual-property frameworks, and timely access to suitable spectrum. Overall, 6G is expected to provide the connectivity foundation for intelligence everywhere, supporting new technological, economic, and societal opportunities throughout the 2030s and beyond.

Keywords: 6G, Sixth-Generation Wireless Communication, 5G Evolution, Artificial Intelligence (AI), AI-Native Networks, wireless connectivity, edge computing, integrated sensing and communication, low latency, high uplink capacity, Internet of Things (IoT), Physical AI, Immersive Connectivity, Augmented Reality (AR), Extended Reality (XR), Non-Terrestrial Networks, distributed computing, network intelligence, spectrum management, future wireless networks.

Introduction

The rapid evolution of wireless communication has transformed the way people, machines, and intelligent systems interact with the digital world. From the voice-centric systems of 1G to the broadband and intelligent connectivity enabled by 4G and 5G, every generation of mobile communication has introduced new capabilities and applications. The emergence of 5G has provided enhanced mobile broadband, ultra-reliable low-latency communication, massive machine-type communication, network slicing, massive MIMO, and support for large-scale Internet of Things (IoT) deployments [1, 3]. However, the rapid growth of connected devices, data traffic, artificial intelligence (AI), immersive applications, and cyber-physical systems is creating requirements that extend beyond the original design objectives of 5G [4, 6].

The sixth generation of wireless communication, commonly referred to as 6G or IMT-2030, is being developed to address these emerging requirements and to provide a foundation for communication systems of the 2030s and beyond [7, 8]. The International Telecommunication Union (ITU) has established the IMT-2030 framework through Recommendation ITU-R M.2160-0, identifying six major usage scenarios: immersive communication (IC), hyper-reliable and low-latency communication (HRLLC), massive communication (MC), ubiquitous connectivity (UC), artificial intelligence and communication (AIAC), and

integrated sensing and communication (ISAC) [9, 10]. These scenarios demonstrate that 6G is intended to go beyond simply increasing data rates and instead support intelligent, immersive, sensing-enabled, and ubiquitous connectivity.

The foundation of 6G is strongly influenced by the limitations and lessons learned from 5G. Although 5G has significantly improved network capacity, latency, reliability, and device connectivity, future applications such as autonomous systems, industrial robots, extended reality (XR), holographic communication, digital twins, and intelligent transportation systems require more predictable performance and greater integration between communication and computing [11, 14]. Research has therefore proposed new architectures involving cell-free massive MIMO, distributed computing, edge intelligence, network slicing, and integrated terrestrial and non-terrestrial networks to overcome the limitations of conventional cellular architectures [15, 17].

One of the most important characteristics of 6G is the integration of artificial intelligence and wireless communication. Unlike conventional networks in which AI is primarily used as an optimization tool, 6G research increasingly considers AI as an integral component of the network architecture. AI can assist with traffic prediction, resource allocation, beam management, network optimization, mobility management, anomaly detection, and autonomous network operation [18, 19]. At the same time, the

network itself can become an infrastructure for AI by providing the connectivity, computing resources, sensing capabilities, and real-world data required by distributed and physical AI systems^[20]. This transition is often described as moving from AI for networks toward networks for AI and eventually AI as a service.

The requirements of AI-native applications also introduce a significant change in traffic patterns. Conventional mobile networks have largely been optimized for downlink-dominated applications such as video streaming, whereas emerging AI agents, XR devices, autonomous vehicles, robots, and sensor-rich environments can generate sustained and simultaneous uplink traffic^[20]. Many interactive AI and industrial applications also require deterministic and very low latency. Current mobile latency ranges may be insufficient for applications requiring sub-10-millisecond or, in some cases, sub-5-millisecond responsiveness^[20, 21]. Therefore, 6G is expected to provide enhanced uplink capacity, predictable latency, improved reliability, and intelligent resource management.

Another fundamental component of 6G is integrated sensing and communication (ISAC). Traditional wireless systems primarily use radio signals for communication, while sensing is generally performed using separate technologies such as radar, cameras, or specialized sensors. In 6G, communication infrastructure is expected to simultaneously transmit information and sense the surrounding physical environment^[22, 23]. Integrated sensing can provide information about the position, movement, shape, and characteristics of objects, thereby supporting autonomous driving, robotics, smart infrastructure, industrial monitoring, and immersive applications.

The availability of new spectrum is another major foundation of 6G. Increasing data traffic and the need for high-resolution sensing will require additional bandwidth beyond conventional cellular spectrum. Research has consequently investigated millimeter-wave, sub-terahertz, and terahertz (THz) frequencies as potential resources for 6G^[24, 25]. THz communication offers extremely large bandwidth and potentially very high data rates, while its short wavelengths can also support high-resolution sensing. Nevertheless, atmospheric absorption, propagation loss, blockage, hardware limitations, and coverage constraints remain important challenges that must be addressed before widespread THz deployment becomes practical.

Reconfigurable intelligent surfaces (RIS) and holographic MIMO are also being investigated as technologies for controlling the wireless propagation environment. RIS can manipulate electromagnetic waves to improve coverage, spectral efficiency, and energy efficiency, while holographic MIMO can provide highly programmable electromagnetic apertures and advanced spatial processing^[26, 27]. These technologies may become particularly valuable in dense urban environments, indoor deployments, high-frequency systems, and intelligent radio environments.

The 6G vision also extends connectivity beyond conventional terrestrial cellular networks. Non-terrestrial networks (NTNs) involving satellites, high-altitude platforms, and unmanned aerial vehicles can complement terrestrial infrastructure and provide connectivity in rural, remote, maritime, and disaster-affected areas^[28, 29]. The integration of space, air, ground, and potentially maritime communication systems can contribute to ubiquitous connectivity and improved network resilience. This

approach is particularly important for applications that require continuous connectivity independent of geographical location.

The architecture of 6G is consequently expected to become more distributed, programmable, and intelligent. Edge and cloud computing can work together with wireless networks to process data closer to users and machines, thereby reducing latency and communication overhead^[30]. Cell-free massive MIMO is one promising architecture because distributed access points can jointly serve users without the conventional cell boundaries, potentially improving coverage, fairness, reliability, and spectral efficiency^[31]. Recent research also investigates the integration of cell-free MIMO with AI, RIS, mobile edge computing, and other emerging technologies as part of the broader 6G ecosystem. Another emerging concept is semantic communication, in which communication systems focus not only on transmitting bits accurately but also on delivering the meaning or task-relevant information contained in those bits. This approach is particularly relevant to intelligent applications in which transmitting all raw information may be inefficient^[32]. Semantic communication can potentially reduce unnecessary data transmission and improve the efficiency of AI-oriented wireless systems, although significant challenges remain in semantic representation, evaluation, interoperability, and security.

Security, privacy, and trust are equally important in the development of 6G. The combination of AI, pervasive sensing, distributed computing, massive connectivity, and non-terrestrial networks introduces new attack surfaces and privacy risks^[33]. Future networks will therefore require stronger authentication, privacy-preserving mechanisms, trustworthy AI, adaptive security, zero-trust principles, and potentially post-quantum cryptographic techniques. Security must be considered as a fundamental architectural requirement rather than as an additional feature added after deployment.

Sustainability is another central objective of the IMT-2030 vision. The increasing number of connected devices, antennas, edge servers, and network components can significantly increase energy consumption. Consequently, 6G research is considering energy-aware network design, intelligent resource management, efficient hardware, renewable-energy integration, and AI-based optimization^[34]. The ITU also identifies sustainability as one of the overarching design principles of IMT-2030, together with security and resilience, ubiquitous intelligence, and connecting the unconnected.

The future development of 6G is already progressing through international standardization and research activities. The ITU has established the IMT-2030 framework and technical requirements, while 3GPP is conducting early 6G studies in Release 20 and plans normative 6G work in Release 21^[35, 36]. Current roadmaps target technology proposals for IMT-2030 around 2029, with complete system specifications expected around 2030.

Industry research similarly envisions initial 6G deployments around 2030, followed by continued evolution throughout the 2030s. Ericsson describes 6G as an AI-native intelligent fabric that unifies connectivity, cloud, computing, sensing, and AI, while Nokia emphasizes AI-native air interfaces, network sensing, extreme connectivity, new spectrum technologies, and secure and trustworthy architectures^[37, 38]. Qualcomm likewise identifies an AI-native RAN, improved

spectrum efficiency, coverage, and energy efficiency as important foundations of the next-generation air interface. Therefore, 6G should not be regarded merely as a faster version of 5G. It represents a broader transformation from communication-oriented networks toward intelligent, adaptive, sensing-enabled, and computing-integrated infrastructures. Its foundation consists of advanced radio technologies, new spectrum, AI-native architectures, edge and distributed computing, integrated sensing, massive and cell-free MIMO, RIS, non-terrestrial networks, semantic communication, and strong security and sustainability mechanisms. Its future will depend on the successful integration of these technologies, together with global standards, spectrum policy, research investment, industrial collaboration, and skilled human resources. The ultimate objective is to create a reliable and intelligent digital infrastructure capable of connecting people, machines, physical environments, and AI systems across the 2030s and beyond.

Background and Related Work

The development of sixth-generation (6G) wireless communication is a natural evolution of previous generations of mobile communication, particularly 5G, which introduced enhanced mobile broadband, ultra-reliable low-latency communication, massive machine-type communication, network slicing, Internet of Things (IoT), and edge computing [1, 3]. These developments established an important technological foundation for 6G, but the rapid growth of artificial intelligence (AI), immersive applications, autonomous systems, and connected devices has created requirements that extend beyond the capabilities of existing networks [4, 6]. Several researchers have investigated the vision and requirements of 6G, emphasizing extremely high data rates, ultra-low and predictable latency, massive connectivity, intelligent network operation, and ubiquitous coverage [7, 8]. The ITU has defined the IMT-2030 framework,

identifying immersive communication, hyper-reliable and low-latency communication, massive communication, ubiquitous connectivity, AI and communication, and integrated sensing and communication as important usage scenarios for 6G [9]. Recent research has increasingly focused on AI-native wireless networks, where artificial intelligence is integrated into network architecture for resource allocation, traffic prediction, beamforming, mobility management, network optimization, and autonomous network operation [18, 19]. In contrast to conventional downlink-dominated mobile traffic, emerging AI agents, augmented reality (AR), extended reality (XR), robots, drones, and autonomous vehicles generate significant uplink traffic and require predictable low latency and continuous connectivity [20, 21]. Integrated Sensing and Communication (ISAC) has therefore emerged as a major research direction, enabling wireless networks to provide both communication and sensing functions for applications such as autonomous driving, robotics, smart infrastructure, and industrial automation [17, 22, 23]. Researchers have also investigated millimeter-wave and terahertz (THz) communication to provide wider bandwidth and extremely high data rates, although propagation loss, blockage, atmospheric absorption, and hardware limitations remain important challenges [24, 25]. Reconfigurable Intelligent Surfaces (RIS), massive MIMO, cell-free massive MIMO, and holographic MIMO are being explored to improve spectral efficiency, coverage, reliability, and control of the wireless propagation environment [26, 27, 31]. Similarly, non-terrestrial networks (NTNs), including satellites and aerial platforms, are being integrated with terrestrial networks to provide ubiquitous and resilient connectivity in rural, remote, maritime, and disaster-affected environments [11, 28]. Edge and distributed computing are also considered essential components of 6G because they allow AI processing and decision-making to be performed closer to users and connected devices, thereby reducing latency and communication overhead [30].

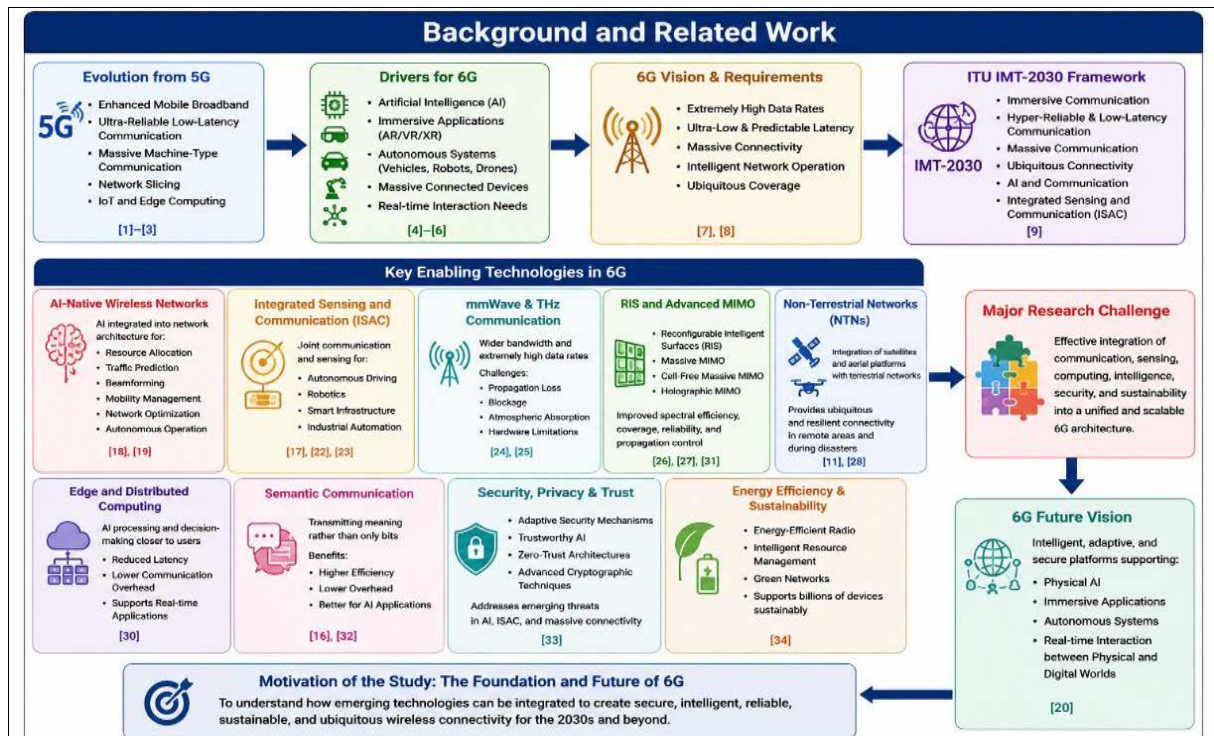


Fig 1: Back Ground and related work

Semantic communication has emerged as another promising approach in which networks focus on transmitting task-relevant meaning rather than only individual bits, potentially improving communication efficiency for AI-driven applications [16, 32]. At the same time, the increasing integration of AI, sensing, distributed computing, and massive connectivity introduces significant security and privacy challenges, requiring adaptive security mechanisms, trustworthy AI, zero-trust architectures, and advanced cryptographic techniques [33]. Energy efficiency and sustainability are also becoming important research objectives because future networks are expected to support billions of devices while managing increasing communication and computational workloads [34]. Overall, existing studies demonstrate substantial progress in individual 6G technologies, but a major research challenge remains the effective integration of communication, sensing, computing, intelligence, security, and sustainability into a unified and scalable architecture. The current 6G vision emphasizes that networks must evolve from conventional communication systems into intelligent and adaptive platforms capable of supporting physical AI, immersive applications, autonomous systems, and real-time interaction between the physical and digital worlds [20]. Therefore, the

study of “The Foundation and Future of 6G” is motivated by the need to understand how these emerging technologies can be integrated to create secure, intelligent, reliable, sustainable, and ubiquitous wireless connectivity for the 2030s and beyond.

Breaking through Connectivity Bottlenecks: How 6G Will Deliver Enhanced Capabilities

The rapid growth of artificial intelligence (AI), immersive applications, autonomous systems, and connected devices is exposing several limitations in current wireless networks. Existing networks are largely optimized for downlink-dominated broadband traffic, whereas emerging AI applications require significantly greater and sustained uplink capacity for transmitting sensor, video, and multimodal data. In addition, interactive AI, industrial robotics, autonomous vehicles, unmanned aerial vehicles, and immersive applications require predictable and highly consistent latency rather than only high average data rates. Current mobile latency of approximately 20–40 ms may be insufficient for many AI-native applications, which can require latency below 10 ms and, in some cases, below 5 ms with tight jitter control.

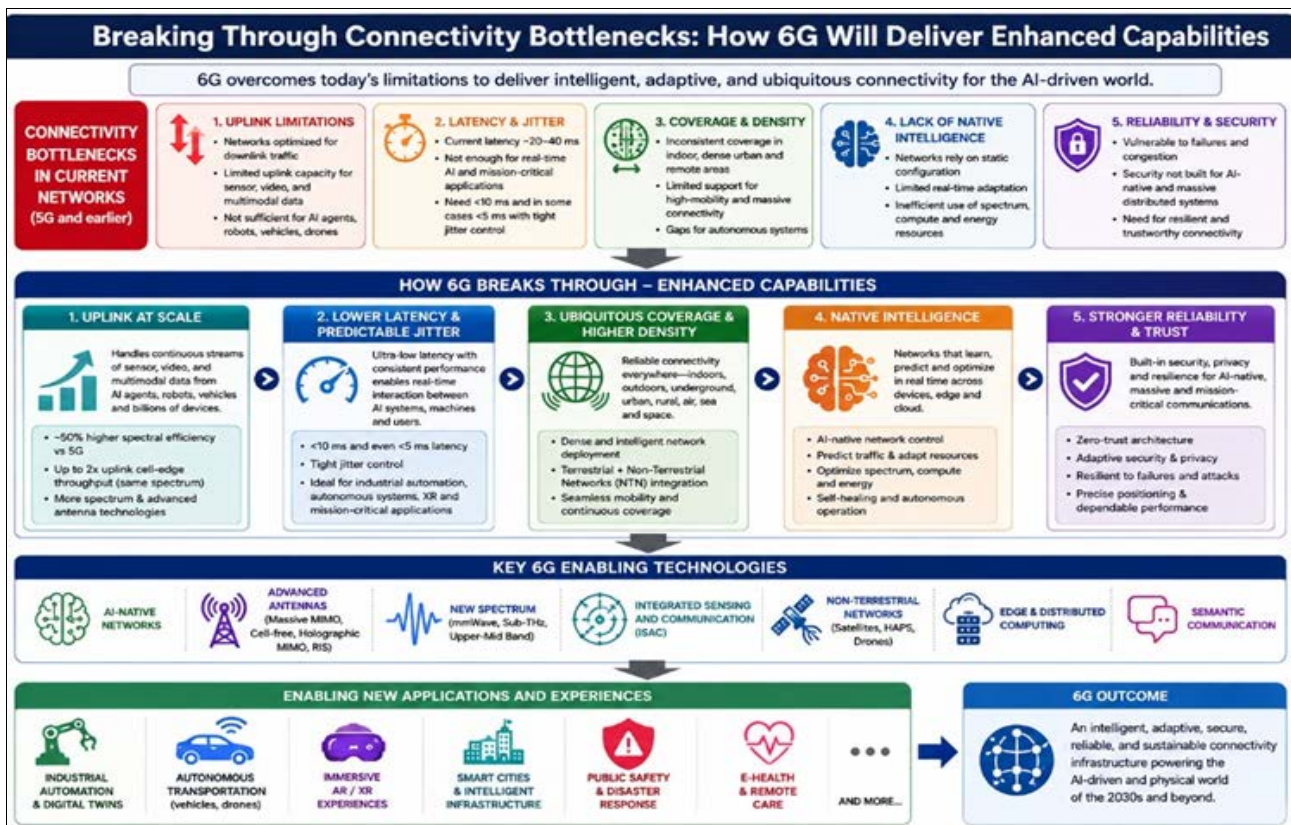


Fig 2: Breaking Through Connectivity

6G is being designed to overcome these connectivity bottlenecks through several major capabilities. First, uplink at scale will enable networks to handle continuous streams of sensor, video, and multimodal data generated by AI agents, robots, vehicles, and other intelligent devices. The report indicates that 6G could increase spectral efficiency by approximately 50% compared with 5G and potentially double uplink cell-edge throughput within the same spectrum band. Additional upper-mid-band spectrum and

advanced antenna technologies could provide further improvements. Second, lower latency and predictable jitter will support real-time interaction between AI systems, machines, and users. This capability is particularly important for industrial automation, autonomous systems, immersive communication, and mission-critical applications.

Third, ubiquitous coverage and increased network density will allow AI and immersive applications to operate reliably

across homes, workplaces, public spaces, factories, transportation corridors, and other environments. Integration of terrestrial and non-terrestrial networks can provide more continuous coverage and improve connectivity for mobile devices and autonomous systems. Fourth, native intelligence will enable the network itself to continuously learn, predict traffic demand, and optimize communication, computing, and energy resources in real time. Rather than relying solely on static network configurations, 6G is expected to embed intelligence across hardware, software, and protocols to coordinate device, edge, and cloud resources dynamically. Finally, these improvements will enable new applications such as industrial automation, public safety, immersive AR/XR experiences, smart cities, autonomous transportation, and e-health. Industrial robots and digital twins require ultra-low latency, integrated sensing, high device density, and robust uplink connectivity, while public-safety applications require secure communication, precise positioning, resilient coverage, and predictable performance. Similarly, immersive applications require high-capacity bidirectional communication and consistent latency to provide realistic experiences. Thus, 6G is expected to move wireless connectivity beyond conventional broadband toward an intelligent, adaptive, sensing-enabled infrastructure capable of supporting real-time AI and physical-world applications.

From Enhanced Connectivity to New and Improved Capabilities

The evolution of 6G is expected to transform wireless connectivity from a conventional communication service into an intelligent and adaptive digital infrastructure. 6G will address the growing requirements of artificial intelligence (AI), immersive communication, autonomous systems, and intelligent connected devices. One of its major capabilities will be integrated sensing, where the communication network can simultaneously sense motion, position, and environmental conditions. Higher-frequency spectrum, large antenna arrays, and reconfigurable intelligent surfaces can improve sensing accuracy and provide richer contextual information for AI applications.

This capability can enhance autonomous vehicle safety, robotics, augmented reality (AR), and infrastructure monitoring.

Another important development is distributed intelligence within the radio access network (RAN). AI-native controllers will dynamically manage spectrum, beamforming, handovers, traffic, and quality-of-experience requirements. Such intelligent control will allow networks to respond to changing workloads generated by AI agents, industrial systems, and immersive applications. 6G will also support context-aware and multidevice collaboration, allowing smartphones, smart glasses, wearables, vehicles, and other devices to work together seamlessly. This collaboration can enable systems of interconnected AI devices rather than isolated intelligent applications. Furthermore, 6G will provide differentiated services at scale, dynamically matching network performance with the

specific requirements of individual applications. Applications requiring low latency, high reliability, strong uplink capacity, or precise positioning can therefore receive appropriate connectivity resources. The integration of terrestrial and non-terrestrial networks will create layered and resilient network architectures capable of maintaining connectivity across different geographical and environmental conditions.

These capabilities will support industrial automation, real-time digital twins, public safety, autonomous transportation, and smart-city infrastructure. Immersive applications such as high-resolution AR, holographic interaction, and multisensory communication will benefit from high-capacity bidirectional connectivity and predictable latency. Healthcare applications can use continuous biometric monitoring, remote diagnostics, and robotic assistance enabled by reliable and low-latency networks. Similarly, drones, robots, autonomous vehicles, and AI assistants will operate with improved mobility, responsiveness, and reliability. Thus, 6G will extend connectivity beyond traditional broadband communication toward sensing, intelligence, coordination, and distributed computing. The integration of these capabilities is expected to create new technological and economic opportunities across industries and society. Overall, the transition from enhanced connectivity to new and improved capabilities represents a fundamental step toward an intelligent, ubiquitous, and AI-driven wireless ecosystem for the 2030s and beyond.

Three Key Enablers of 6G

The development of 6G will require coordinated progress in three key enabling areas: spectrum, software, and hardware. Spectrum is essential because 6G will require a substantial increase in network capacity to support AI, immersive applications, sensing, and high-volume data traffic. New wide-channel mid-band allocations, potentially up to 400 MHz, can increase capacity and enable high-resolution sensing, while AI-optimized scheduling can improve spectrum utilization and reduce the cost per transmitted bit. Software will provide the intelligence and flexibility required for AI-native 6G networks. Intelligent routing, granular network slicing, distributed processing across devices, edge and cloud platforms, and self-healing mechanisms will allow the network to dynamically adapt to changing traffic and application requirements while improving reliability and energy efficiency. Hardware will provide the physical foundation for these capabilities through advances in antennas, radio-frequency components, advanced modem semiconductors, and massive MIMO technologies. These developments will support multilayer and multiband operation, improved coverage, higher reliability, and intelligence at the network edge. Importantly, these three enablers must develop together because spectrum availability, software intelligence, and hardware capabilities are strongly interdependent. Their coordinated evolution will determine the ability of 6G networks to deliver the high-capacity, intelligent, reliable, and ubiquitous connectivity required for AI-native and immersive applications.

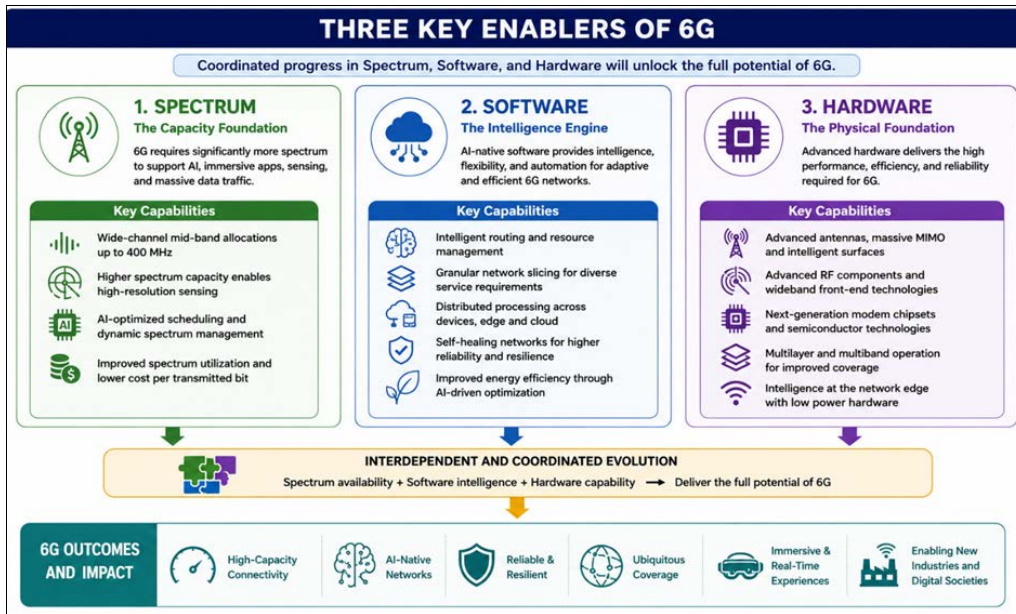


Fig 3: Key Enablers of 6G

Policy Implications for Next-Generation Connectivity: Four Policy Levers for the 6G Era

The transition toward 6G will depend not only on technological innovation but also on effective and coordinated public policy. Policymakers have a decisive role in creating an environment that supports investment, innovation, global interoperability, and technological resilience. The four key policy levers for the 6G era are spectrum, standards, research and development (R&D), and talent. First, spectrum policy is essential because 6G will require additional spectrum and wider channels to support increasing data traffic, AI applications, immersive communication, sensing, and other advanced services. Governments should establish national 6G spectrum roadmaps, ensure timely and transparent allocation, and provide sufficient certainty for long-term infrastructure investment. Second, standards are important for ensuring global interoperability and shaping the technical foundations of the future wireless ecosystem. Policymakers should

encourage open, merit-based, industry-led international standards and support participation by domestic research institutions, network operators, device manufacturers, and semiconductor companies. Third, R&D and intellectual-property policy must encourage long-term investment in advanced radio technologies, AI-native architectures, distributed computing, semiconductors, and wide-channel spectrum technologies. Government incentives, research programs, investment tax measures, strong intellectual-property protection, and university–industry collaboration can help accelerate fundamental 6G innovation. Fourth, talent development is necessary to create the skilled workforce required for AI-native connectivity. Governments and educational institutions should strengthen advanced technical education, research fellowships, university research centers, STEM programs, and specialized training in wireless engineering, artificial intelligence, machine learning, cybersecurity, radio-frequency systems, and semiconductor technologies.

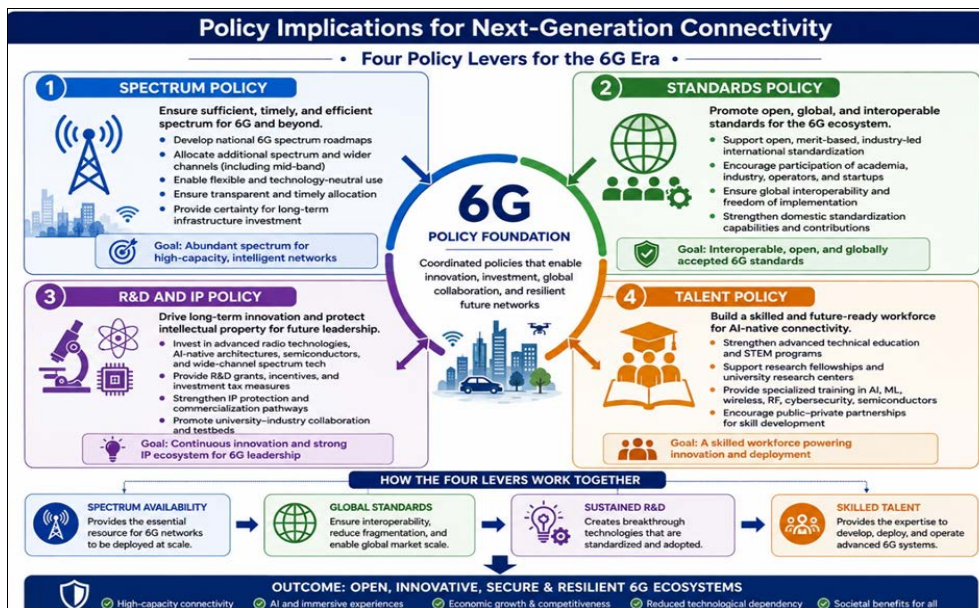


Fig 4: Policy Implications

These four policy levers are strongly interconnected. Timely spectrum availability enables deployment, global standards support interoperability and market scale, sustained R&D creates the technologies incorporated into those standards, and skilled professionals provide the expertise needed to develop and deploy them. Therefore, coordinated action across spectrum, standards, R&D, and talent can help countries establish open, innovative, secure, and resilient 6G ecosystems while reducing technological dependency and strengthening long-term economic competitiveness.

Conclusion

In conclusion, 6G represents a fundamental transformation of wireless communication from conventional connectivity toward an intelligent, adaptive, sensing-enabled, and computing-integrated infrastructure. The study shows that 6G is being developed to address the limitations of 5G and the growing requirements of artificial intelligence, immersive communication, autonomous systems, IoT, and physical AI. Its major capabilities—including enhanced uplink capacity, predictable low latency, integrated sensing and communication, ubiquitous terrestrial and non-terrestrial connectivity, distributed intelligence, edge computing, and advanced wireless technologies—can enable new applications across transportation, healthcare, industry, public safety, smart cities, AR/XR, and robotics. The successful realization of this vision will depend on the coordinated development of spectrum, software, and hardware, which form the three key technological enablers of 6G. At the same time, effective policy support through spectrum availability, global standards, R&D investment, intellectual-property protection, and skilled talent development will be essential for building a competitive and sustainable 6G ecosystem. Security, privacy, energy efficiency, and sustainability must also be incorporated into the architecture from the beginning rather than treated as secondary considerations. Overall, 6G has the potential to connect people, machines, physical environments, and AI systems through a unified intelligent network. Its future success will depend on the effective integration of communication, sensing, computing, intelligence, and policy, creating a reliable, secure, sustainable, and ubiquitous wireless ecosystem for the 2030s and beyond.

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