

CHAPTER 8

Overview of 6G Networks & Technology

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ABSTRACT

The article investigates 6G technology by presenting its future objectives and its technological advancements and its research obstacles which develop new wireless communication networks. The 6th generation mobile communication system will succeed the 5th generation mobile communication system which will operate in the year 2030. The 6th generation mobile communication system will provide users with exceptionally fast internet speeds and minimal connection delays which enable wireless networks to deliver intelligent services through actual and virtual communication channels. The 6th generation mobile communication system will develop its systems through the ITU IMT-2030 vision and the 3GPP mobile communication system standardization roadmaps. The 6th generation mobile communication system will improve and expand existing 5th generation mobile communication system functions through new services which include immersive extended reality and digital twins and autonomous systems and worldwide service in remote areas. The 6th generation mobile communication system will use multiple technologies which include millimeter wave and terahertz band operation and integrated artificial intelligence and machine learning throughout all protocol layers and reconfigurable intelligent surfaces and cell-free and extremely large MIMO and combined sensing and communication systems. The development of 6th generation mobile communication systems faces multiple research obstacles which include establishing spectrum distribution and improving energy efficiency and maintaining sustainable energy use and managing hardware limitations that apply to terahertz technology and protecting user data through security systems and applicable regulations and international standards.

Keywords: *6G technology, ITU IMT-2030 vision, digital twins etc.*

INTRODUCTION

Wireless mobile communication systems have progressed from their first generation analog voice-based mobile systems to their fifth generation mobile systems which will deliver improved mobile broadband and machine-type communication and ultra-reliable low-latency communication. Each mobile communication system generation has improved data transmission speeds and spectral efficiency while creating new communication methods which began with text messaging in 2G systems and advanced to mobile Internet and apps in 3G and 4G systems and finally reached massive IoT applications in 5G systems.

The ongoing global rollout of 5G and 5G-Advanced has not stopped ITU-R 3GPP Industry Alliances and academic consortia from beginning their research work on 6G pre-standardization activities because they require time to develop and standardize new technological systems. The 2023 ITU IMT-2030 framework establishes a comprehensive view of 6G system capabilities which 3GPP will use to develop Releases 20 and 21 that will form the basis of 6G technology specifications scheduled for this decade.

EVOLUTION FROM 1G TO 5G AND THE NEED FOR 6G

The first generation (1G) and 2G networks were mainly used to support voice and low-rate messaging, with the introduction of 3G providing mobile data, and the 4G/LTE network enabling high-speed broadband, which has powered the app economy. The fifth generation (5G) has further enhanced the capabilities of wireless networks with the introduction of ultra-reliable low-latency applications and massive IoT connectivity, which will support the deployment of industrial automation, connected autonomous vehicles, and smart cities, etc.

However, even 5G-Advanced has limitations in providing immersive extended reality, large-scale digital twinning, and highly controlled autonomous cyber-physical systems, which will need orders-of-magnitude improvements in latency, reliability, positioning accuracy, and network intelligence, etc. Furthermore, there is a growing need to connect the remote and underserved, reduce the environmental footprint, and integrate security and privacy into the network, which are the key drivers for the need to deploy 6G, which will be able to deliver the following:

- The performance of 5G needs to be enhanced across all present performance dimensions which include data rate and latency and reliability and mobility and connection density.
- The system will deliver new functionalities through its capability to provide integrated sensing and AI support throughout all areas and extended coverage through non-terrestrial network systems.

6G VISION AND IMT-2030 FRAMEWORK

The IMT-2030 framework, established by ITU-R Recommendation M.2160, presents a comprehensive framework which defines six-generation mobile systems through its high-level vision and usage scenarios and system capabilities. The key capabilities identified for 6G include 15 in total. Out of these 15 key capabilities, 9 are enhanced capabilities that have already been identified for 5G. The enhanced capabilities for 6G include enhanced versions of peak data rate, user experienced data rate, latency, reliability, mobility, connection density, spectrum efficiency, and energy efficiency. In addition to the enhanced capabilities, there are 6 new capabilities that have been identified for 6G. The new capabilities for 6G include extended coverage, sensing-related capabilities, AI-related capabilities, etc. The sensing-related capabilities include range estimation, velocity estimation, angle estimation, object detection, localization, imaging, and mapping. Similarly, the AI-related capabilities include distributed data processing, distributed learning, AI computing, model inference support, etc.

Regarding the timeline for the completion of the 6G system specifications, the ITU-R Working Party 5D has proposed that candidate radio interface technologies (RITs) and system proposals for the IMT-2030 should be submitted in the early part of 2029. The system specifications for the 6G system will be completed by 2030. The deployment of the 6G system can be expected in the 2030-2035 timeline. The deployment timeline for the 6G system will follow the deployment timeline for the earlier ITM systems.

USAGE SCENARIOS

The ITU-R Recommendation M.2160 provides a high-level vision for the 6G system. The ITU-R Recommendation M.2160 divides the usage scenarios for the 6G system into several families. The families include ubiquitous connectivity, AI and communications, integrated sensing communication, etc. The scenarios for the 6G system include immersive communication with extended reality (XR), including holographic telepresence and volumetric media streaming.

- The system developed a connection between industrial operations and automated systems through its complete control system which managed robot and drone and industrial operations.
- The system created virtual replicas of factories and cities and transportation networks which received continuous updates through extensive sensor monitoring.
- Extreme coverage use cases that connect remote, rural, maritime, and aerial users via integrated satellite and aerial platforms.

These requirements place stringent joint requirements on data rate, latency, reliability, positioning accuracy, energy efficiency, and AI computation support, which together drive requirements beyond 5G.

KEY PERFORMANCE TARGETS

The performance targets of 6G are still under discussion, and different roadmaps from industry and academia suggest indicative performance targets of 6G systems. The peak data rates of 6G systems are expected to be ten times higher than 5G systems by exploiting wider bandwidths in sub-THz and THz bands. The end-to-end latency of 6G systems is expected to be in the microsecond regime for some ultra-critical links, enabling almost instantaneous responses for tightly controlled cyber-physical systems.

The user experience of 6G systems is expected to be significantly higher than 5G systems in terms of peak data rates. Some white papers suggest terabit per second short-range links for some specialized applications such as chip-to-chip and device-to-device communications. Ultra-high connection density and improved spectral and energy efficiency are also required for massive IoT applications and reducing the carbon footprint of wireless systems.

6G systems also expect to provide higher localization accuracy of centimeters and sensing resolution by exploiting higher frequency bands, wider bandwidths, and larger antenna arrays for integrated communication and sensing service support.

ENABLING TECHNOLOGIES FOR 6G

OPERATION IN MMWAVE AND THZ BANDS

To realize the extreme data rate and high-resolution sensing requirements of 6G systems, researchers have started to consider the mmWave and THz bands for the operation of 6G systems, which extend from sub-THz to THz frequencies, i.e., from 100 GHz to several THz. The mmWave and THz bands have the advantage of having very wide contiguous bandwidths, which are necessary for the operation of 6G systems to achieve terabit per second data rates and fine range resolutions for high-resolution sensing and imaging.

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However, the propagation of THz waves also has the disadvantage of high attenuation and blocking, as well as the limitation of output power and noise figure of RF components. Therefore, researchers have started to consider the use of highly directional beamforming techniques with massive antennas, novel materials, and semiconductor technologies, as well as beam-tracking techniques that can handle mobility and blockages.

RECONFIGURABLE INTELLIGENT SURFACES

RISs are artificial surfaces that consist of a large number of elements that can control the propagation of electromagnetic waves and steer the signal towards the desired direction. For the operation of 6G systems, researchers have started to consider the use of RISs on building facades, walls, and indoor environments to improve coverage and spectral efficiency, as well as to improve the sensing capability of the system.

Recently, researchers have started to consider the integration of AI with RISs operating at THz frequencies to maximize the throughput and energy efficiency of the system based on the intelligent control policy. The integration of RISs with cell-free massive MIMO and distributed antenna systems can be used to realize the ultra-Reliability and ultra-Low Latency Communications requirements of 6G systems.

CELL-FREE AND EXTREMELY LARGE MIMO

A new class of cell-free massive MIMO architectures has been proposed to remove cell boundaries by employing many access points that collectively provide service to users in a geographic region. The architecture design will result in multiple advantages through better user experience delivery and improved spectral efficiency and it will enable easier mobility control without requiring users to perform handovers.

For 6G networks, extremely large MIMO systems, possibly in combination with RIS technology, have been proposed to provide highly directional beams to users, as well as the ability to support multiple users with spatial multiplexing gain. Furthermore, extremely large MIMO systems have been proposed to provide communication-sensing capabilities. Such architectures will require coordination mechanisms to be scalable for very large systems. In addition, AI-based solutions will be required to make extremely large MIMO systems practical.

AI-NATIVE NETWORKS

6G networks have been proposed to be AI-native networks that integrate AI and machine learning at all protocol layers. The integration of new technology, like AI, will maximize the 6G network's performance from the physical layer to the core network. In contrast to 5G networks that employ AI as an external component for analytics and optimization, 6G networks will integrate AI in a closed-loop manner to optimize network performance. One of the major aspects of the core community is to support the AI model development scheme for the whole survival period. In essence, AI will be a first-class network function in 6G networks.

INTEGRATED SENSING AND COMMUNICATION (ISAC)

Integrated sensing and communication (ISAC), also called joint communication and sensing, is one of the main pillars in the research on 6G technology. In ISAC systems, radio waveforms and equipment are used to perform both data communication and sensing operations, including object detection, object localization, object tracking, imaging, and environment mapping.

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The 6G ISAC system achieves centimeter-level position accuracy and high-definition 3D imaging for indoor and outdoor settings through its use of high-frequency bands and wide bandwidths and multiple antenna arrays. The 6G ISAC system enables various applications which include smart home gesture recognition and industrial quality control through contactless methods and the creation of simultaneous localization and mapping systems and non-line-of-sight imaging technologies.

NETWORK ARCHITECTURES AND NON-TERRESTRIAL INTEGRATION

6G is expected to inherit the 5G core network's service-based architecture, along with the incorporation of new features for AI orchestration, data fusion, and support for heterogeneous access networks. The radio access network is also expected to evolve and become more compatible with the tight integration of terrestrial macro and small cells, RIS-based environments, and non-terrestrial networks such as low Earth orbit satellites, high-altitude platforms, and unmanned aerial vehicles.

NTNs are expected to play a major role in the 6G architecture in order to obtain global coverage and reach areas such as oceans, rural areas, and disaster areas. 6G is expected to integrate NTNs in a unified manner, where satellites and aerial vehicles can function as access and backhaul networks, along with terrestrial networks, using common control and management tools.

6G will continue its reliance on end-to-end slicing and network automation and cloud-native networks; however, these fundamental concepts will undergo transformation through their development into advanced systems. The upcoming 6G networks will introduce AI-based slicing technologies which create dynamic service adjustments that respond to changing environmental conditions and service needs.

REPRESENTATIVE 6G USE CASES

IMMERSIVE EXTENDED REALITY AND HOLOGRAPHIC COMMUNICATION

The upcoming 6G technology will enable users to experience complete extended reality environments which combine virtual reality and augmented reality and mixed reality elements with multiple sensory interactions that include haptic communication. The applications require extremely high data rates and extremely low latency which must synchronize audio and video and haptic information to avoid user nausea while creating realistic experiences.

Holographic Telepresence and Volumetric Media Streaming

Holographic telepresence and volumetric media streaming involve transmitting 3D representations of people or objects. These applications would demand rates of hundreds of megabits per second or even gigabits per second for each stream and extremely low latency. 6G would provide the foundations for these applications with its ultra-high-capacity links and edge computing capabilities, as well as its ISAC-based capabilities for localization and tracking.

CONNECTED INDUSTRIES AND AUTOMATION

6G would facilitate greater reliability, latency reduction, and sensing for industrial IoT and automation applications. These applications would include cooperative robots, swarm robotics for warehouse applications, remote operation of machines, and predictive maintenance based on high-resolution sensory information.

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In intelligent factories, 6G-based sensing would enable millimeter-level resolution for contactless inspection and tracking. This would enable faster and more accurate quality management and asset management. These applications would enable greater accuracy and efficiency for quality management and asset management.

AUTONOMOUS TRANSPORTATION AND SWARM SYSTEMS

Autonomous vehicles and drones and all mobile robots need to establish dependable communication links which allow them to connect with all other vehicles while they maintain complete situational awareness and track their exact location. 6G would provide ultra-reliable links which operate at extremely low latency and use ISAC-based environment sensing to monitor both dense vehicle platoons and swarms of unmanned aerial and ground vehicles.

The non-terrestrial components satellite constellations enable vehicles to achieve wide area coverage in remote areas while terrestrial 6G infrastructure provides urban areas with high capacity links. Joint communication and sensing achieve better safety performance through their capability to detect obstacles and pedestrians and vehicles during times of poor visibility.

SUSTAINABLE PRACTICES AND ENERGY CONSERVATION

The energy efficiency and sustainability aspects are specifically highlighted as objectives in the context of IMT-2030, with increased recognition of the carbon footprint of ICT networks and systems. Although increased data rates and deployment densities can contribute to increased energy consumption, energy efficiency per bit and the inclusion of renewable energy and energy harvesting in 6G research are important objectives.

The proposed research directions include AI-based sleep modes in BS and devices, ultra-low-power communications, and the use of RIS and CF to minimize transmit power while maintaining performance and coverage. Ideas on “zero-energy devices” that can harvest energy from the environment or ambient radio signals are under investigation in the context of massive IoT deployment in 6G.

Sustainability aspects in 6G research also include considerations on spectrum and equipment efficiency, equipment life cycle and manufacturing/disposal impacts, and the use of 6G-enabled applications in other areas of the economy to achieve sustainability and minimize emissions.

RESEARCH CHALLENGES AND OPEN PROBLEMS

Although there has been rapid progress in laying out the vision and early prototypes of 6G, there are many open research challenges that remain to be solved in the context of THz communications, which include severe channel impairments, hardware constraints, and blockage sensitivity. In addition, there are research challenges in the context of efficient multiple access schemes, interference management, and coexistence with lower frequency band systems in multi-band 6G systems.

For AI-native networks, the major open issues include the acquisition of high-quality training data, robustness and explainability of AI models, privacy, and the management of the lifecycle and orchestration of distributed AI components. Standardization of interfaces for AI functions and mechanisms for verification and validation of AI behavior in safety-critical contexts are still at their infancy.

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ISAC poses its own set of challenges for waveform design, resource allocation for sensing and communication, and overall performance optimization under hardware and regulatory limitations. Interference between sensing and communication, synchronization, and scalability of fusion of sensing information across multiple network devices are some of the research challenges.

Lastly, global harmonization of spectrum allocation, pervasive sensing regulations, international security policies, and synchronization of industrial and academic research efforts are essential for a unified 6G framework.

CONCLUSION

6G technology is considered the next major leap in the progression of mobile communication technologies. The deployment of 6G technology will begin in 2030 according to the IMT-2030 vision framework, which serves as the foundation for this new system. 6G introduces new capabilities that deliver exceptional data throughput together with extremely fast response times and advanced sensing and AI functions. The system enables developers to create new applications which will support immersive XR experiences and digital twinning and autonomous systems development and worldwide connectivity.

The development of these capabilities depends on five essential technologies which include mmWave and THz frequency range operation and RIS and cell-free massive MIMO technology and AI-native network design and integrated sensing and communication and TTN and NTN system integration. However, 6G is also challenged with addressing issues related to spectrum and hardware limitations, energy efficiency, security and privacy, and standardization and regulation.

For researchers, 6G is an exciting opportunity for research and offers a large number of research challenges and opportunities related to physical layer design, network architecture, AI and data science, security, and socio-technical aspects. Early research efforts on these topics are essential for ensuring 6G networks are not only faster and more capable but also more inclusive, secure, and sustainable than any of its predecessors.

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