6G Vision, Performance Targets, and Candidate Radio Technologies

Whitepaper

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ROHDE & SCHWARZ

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1 CONTENTS

1 6G IN A NUTSHELL

While the fifth-generation (5G) cellular technologies are being deployed around the globe, work has already begun on the sixth-generation (6G) cellular communications technology. Compared to all predecessor generations of cellular communications, 6G is expected to serve a much more comprehensive set of use cases, including the user cases that reflect significant contributions to society and the environment. 6G is anticipated to be more flexible and more complex than previous generations of cellular technologies. The International Telecommunication Union (ITU) has identified services and performance targets for 6G in the form of target IMT-2030 requirements. Initial 6G deployments are expected to occur around 2030. The Third Generation Partnership Project (3GPP) will create baseline specifications for 6G. Design, deployment, and operations of 6G would use the work performed by the 3GPP and other organizations such as the Internet Engineering Task Force (IETF) and the European Telecommunications Standards Institute (ETSI). Furthermore, implementation of a 6G Radio Access Network (RAN) may utilize the specifications developed by the O-RAN Alliance [Tripathi_O-RAN_2024]. The O-RAN specifications available as of Fall 2024 utilize 3GPP-defined fourth-generation (4G) and fifth-generation (5G) specifications as baseline and add O-RAN-specific functionalities to the RAN to create an open, disaggregated, and intelligent RAN.

1.1 Evolution from 1G to 6G

Figure 1 illustrates how cellular communications has evolved from the first-generation (1G) to 6G.

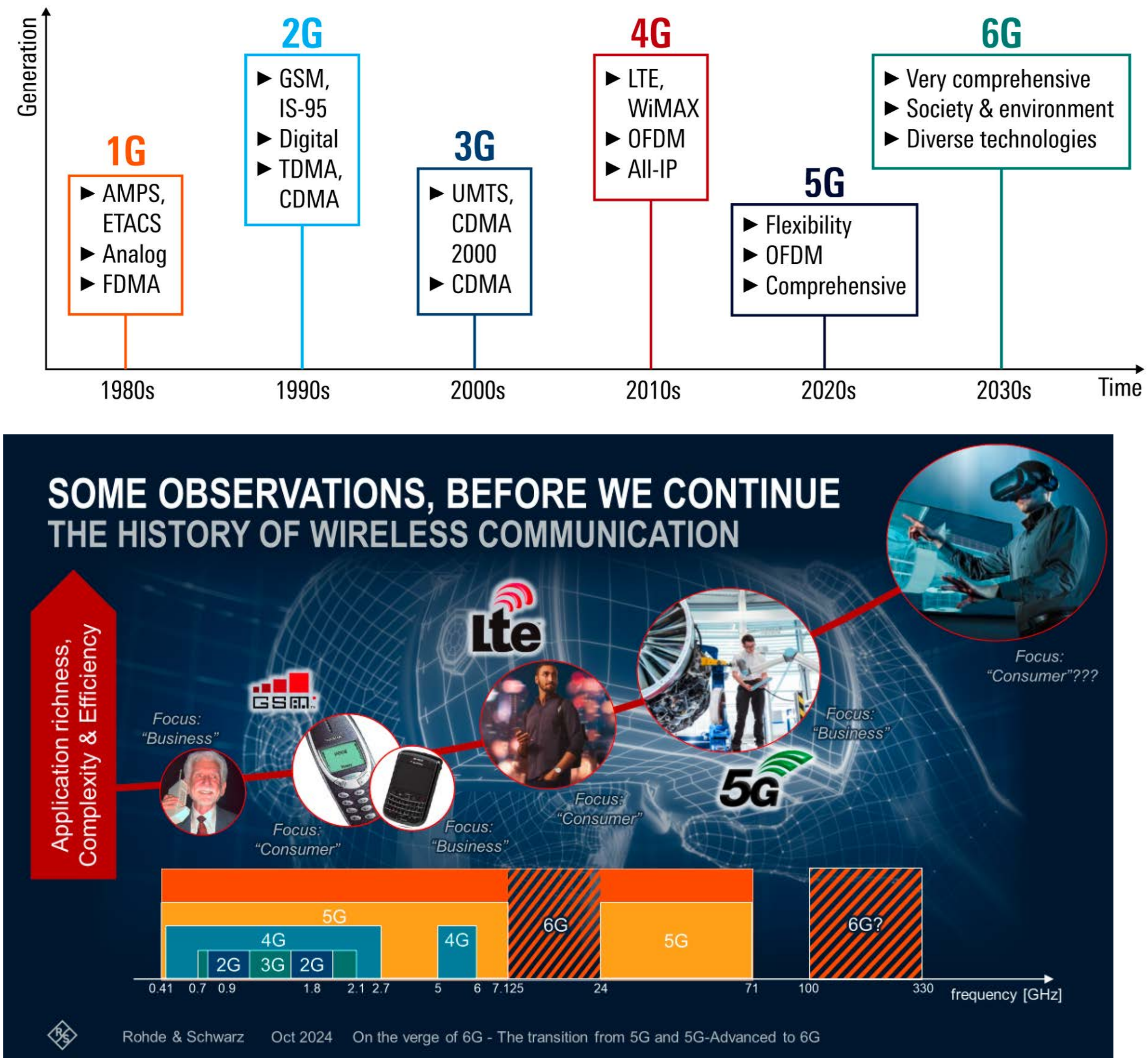


Figure 1.1: 1G to 6G: Evolution of Cellular Communications

1G cellular systems revolutionized communications by supporting communications on the move and eliminating the need for a wire attached to the user device. The concept of cellular communications was born at Bell Labs [Tripathi2014_Cellular]. 1G systems such as Advanced Mobile Phone System (AMPS) in the US and European Total Access Communication System (ETACS) in Europe were analog in nature and used Frequency Division Multiple Access as the multiple access technique on the radio interface to simultaneously serve multiple users in a given physical cell or sector. 1G systems were widely deployed in 1980s and supported voice services. The second-generation (2G) systems such as Global System for Mobile communications (GSM) and Interim Standard- 95 (IS-95) are digital in nature. GSM used Time Division Multiple Access (TDMA) and FDMA, while IS-95 used Code Division Multiple Access (CDMA) [Tripathi2014_Cellular]. 2G systems were widely deployed in 1990s and supported digital voice services and low-rate circuit-switched data services. Examples of the third-generation (3G) systems include CDMA2000 and Universal Mobile Telecommunication System (UMTS), and both systems, deployed in 2000s, use CDMA as the multiple access technique with UMTS systems using wider channel bandwidths than CDMA2000 systems. 3G systems provide circuit-switched digital voice services and medium data rate services. The 3GPP-defined 4G technology, Long Term Evolution (LTE), became a unified cellular technology in the world with widespread deployments occurring in 2010s. While 4G WiMAX deployments did occur, they were later replaced by 4G LTE. 4G LTE is an all-IP system with voice services supported as Voice over IP (VoIP). LTE supports VoIP (known as Voice over LTE (VoLTE)) and broadband data rates. The 3GPP defined LTE in Release 8. LTE utilizes Orthogonal Frequency Division Multiple Access (OFDMA) and its variation called Single Carrier- FDMA (SC-FDMA) on the radio interface. Enhancements to baseline Release 8 LTE specifications led to features such as Carrier Aggregation in Release 10 as part of LTE-Advanced and (IoT) technologies such as Narrowband- Internet of Things (NB-IoT) as part of LTE-Advanced Pro in Release 13.

The 3GPP introduced 5G in Release 15. 5G builds on LTE and is significantly more flexible than LTE. 5G supports network architectures such as Standalone (SA) New Radio (NR) with the 5G Core network and Non-Standalone (NSA) NR with the 4G Evolved Packet Core network. LTE and 5G support Orthogonal Frequency Division Multiple Access (OFDMA) and its variation called Single Carrier- FDMA (SC-FDMA) on the radio interface. 5G supports even higher data rates than 4G. For example, the peak data rate target for 4G as specified by the ITU's IMT-Advanced is 1 Gbps and the peak data rate target for 5G as specified by the ITU's IMT-2020 is 20 Gbps [Tripathi2019_5G]. The 3GPP has specified multiple 5G releases in Release16, 17, and 18. The 5G features beginning with Release 18 are considered part of 5G-Advanced. Example features of 5G and 5G-Advanced include a Non-Terrestrial Network (NTN), Reduced Capability (RedCap) or NR-Light devices, NR-based Integrated Access and Backhaul (IAB), and NR-based Sidelink [R&S_5G_Evolution].

As of Fall 2024, sunset of 1G, 2G IS-95, and many 2G GSM and 3G systems has already occurred around the world [KORE_Sunset]. 4G and 5G systems are quite widely used in the world with widespread 5G deployments occurring in the late 2010s and early 2020s.

1.2 6G: Quite a Unique G!

6G is expected to be unlike any other G before! While previous generations of cellular technologies have focused largely on consumers and to some extent on enterprises, 6G is expected to contribute significantly to society and the environment. According to the ITU's IMT-2030 framework, 6G aims to build an inclusive information society and contribute to support the United Nations Sustainable Development Goals (SDGs) [ITU_IMT-2030_Framework]. Key IMT-2030 goals include inclusivity, ubiquitous connectivity, sustainability, innovation, enhanced security and resilience, standardization and interoperability, and interworking. Furthermore, six audacious goals for 6G identified by the Next G Alliance (NGA) are (i) Trust, Security, and Resilience, (ii) Digital World Experience, (iii) Cost Efficient Solutions, (iv) Distributed Cloud and Communications Systems, (v) Artificial Intelligence (AI)-Native Network, and (vi) Sustainability [NGA_Roadmap].

6G will facilitate connectivity among humans, machines, and other entities. Humans can have immersive and multi-sensory experiences though advanced human-machine interfaces, eXtended Reality (XR) displays, haptic sensors and actuators, and multi-sensory interfaces. In the 6G timeframe, machines are expected to be intelligent, autonomous, responsive, precise, and AI-based. Example 6G applications include real-time interactive and immersive videos, holographic telepresence; remote operations of machines; digital twins or replicas for industries such as health care, agriculture and construction; smart industrial applications involving real-time information collection and sensing; digital health and well-being; networked-enabled robotic and autonomous systems, distributed sensing and communications, and personalized user experiences [ITU_IMT-2030_Framework] [NGA_6G_ApplicationsUseCases]. See Section 2 for a closer look at 6G services and use cases.

6G will use 5G as baseline for technologies and make use of a variety of new technologies. Figure 2 illustrates example building blocks of 6G. Section 4 to Section 12 discuss these 6G building blocks and advanced 6G radio technologies.

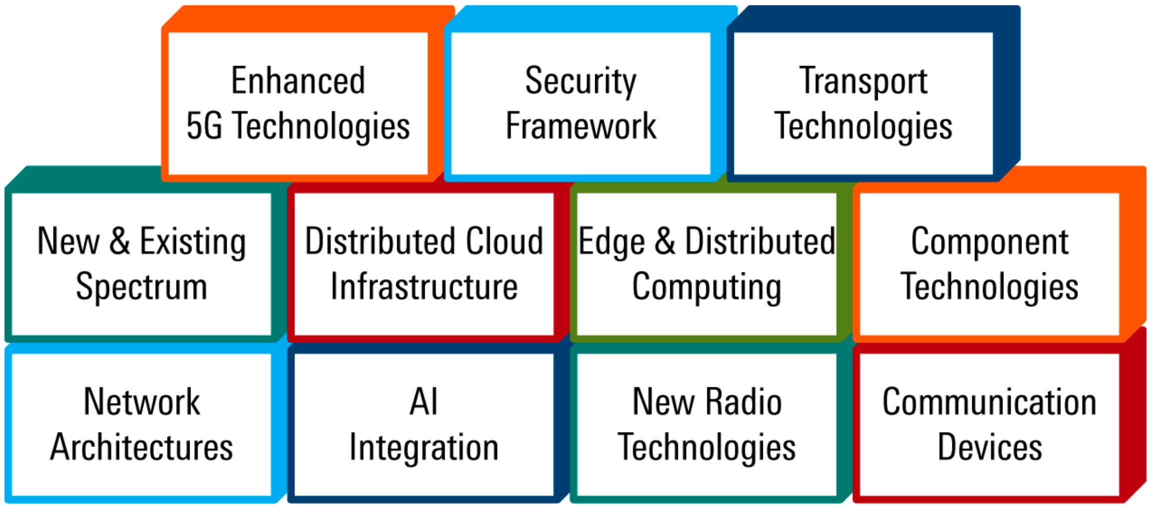


Figure 1.2: Potential Building Blocks of 6G

Examples of 6G building blocks include new spectrum and existing spectrum; network architectures (radio network, core network, services network); distributed cloud infrastructure for radio and core networks; transport technologies; security framework; edge and distributed computing; AI integration; communication devices; component technologies including semiconductor technologies and RF circuits and subsystems; and advanced radio technologies. Examples of candidate advanced radio technologies for 6G include new radio waveforms and associated techniques, new spectrum, spectrum sharing techniques, advanced antenna technologies such as Reconfigurable/Reflective Intelligent Surface (RIS), massively distributed MIMO, cell-free MIMO, holographic beamforming, and Orbital Angular Momentum (OAM), Integrated Sensing And Communication (ISAC), AI-native radio interface, green networks and devices, extreme networking, UE Cooperative Communications, mesh networks, and sematic communications. Features such as Sidelink communications and the NTN, already defined in 5G and 5G-Advanced, will be enhanced in 6G.

2 6G VISION AND REQUIREMENTS

As mentioned in Section 1, 6G is expected to significantly contribute to society and the environment. While 6G deployments are anticipated to occur in the 2030s, work has already begun in different organizations around the globe to define the overall vision and requirements for 6G. New and enhanced services in 6G are being explored. Section 2.1 describes the overall vision and requirements of 6G, while Section 2.2 summarizes potential 6G services and their performance requirements.

2.1 Vision and Goals of 6G

As mentioned in Section 1, the 3GPP will create baseline specifications for 6G. As in the case of 5G specifications, the 3GPP will consider inputs from various organizations and conduct its own studies to define the overall 6G requirements. These 6G requirements will drive the normative specifications work in the 3GPP. Examples of key organizations that are playing important roles in defining 6G requirements include Third-Generation Partnership Project (3GPP), International Telecommunication Union (ITU), Next G Alliance (NGA), and Next generation Mobile Network (NGMN) Alliance. The constituents of the comprehensive wireless ecosystem (e.g., cellular service providers, network infrastructure vendors, device vendors, and test and measurement vendors) contribute to 6G requirements directly through participation in 3GPP and/or indirectly through organizations and initiatives such as the ITU, the NGA, and the NGMN. International bodies such as the ITU and alliances such as NGA, NGMN, and Bharat 6G Alliance have outlined their 6G vision in their publications. Furthermore, several wireless industry leaders such as Samsung, NTT DOCOMO, Qualcomm, Ericsson, and Huawei have also published their vision of 6G in white papers.

Table 1 summarizes key 6G vision themes mentioned by selected organizations or alliances in publications. The 3GPP-identified 6G requirements are not yet known and may be determined as part of 6 G-related studies in Release 20. At the time of this writing, the 3GPP is working on Release 19 specifications. These various organizations/alliances' themes are elaborated on below.

Organization/Alliance	Key 6G Vision Themes
ITU	Inclusivity, Ubiquitous Connectivity, Sustainability, Innovation, Enhanced Security and Resilience, Standardization and Interoperability, and Interworking.
3GPP	To be determined.
NGA	Six audacious goals: (i) Trust, Security, and Resilience; (ii) Digital World Experience; (iii) Cost Efficient Solutions; (iv) Distributed Cloud and Communications Systems; (v) AI-Native Network; and (vi) Sustainability.
NGMN	Build on and extend the existing 5G ecosystem to foster innovations that provide value to customers and simplify network operations.
Bharat 6G Alliance	Ubiquitous, intelligent, and secure connectivity for a high-quality living experience.
NTT DOCOMO	Solving social problems, communication between humans and things, expansion of communication environment, and sophistication of cyber-physical fusion.
Samsung	Four megatrends: (i) connected machines, (ii) AI, (iii) openness, and (iv) social goals.
Qualcomm	Support a smarter society enabled by the connected intelligent-edge.
Ericsson	Trustworthiness, Sustainable world, Simplified life, and Application demands.
Huawei	Three megatrends: (i) new applications and new business, (ii) proliferation of intelligence, and (iii) sustainability and social responsibility.

Table 2.1: Key Themes of 6G Vision and Requirements

- **ITU.** Inclusivity ensures affordable and meaningful connectivity for all. Ubiquitous connectivity provides broadband coverage in all areas, including sparsely populated areas. Sustainability involves the use of energy-efficient technologies to help achieve Sustainable Development Goals (SDGs). Innovation facilitates connectivity, productivity, and the efficient management of resources. Enhanced security and resilience enable the 6G system to operate during disruptions and recover quickly after disruptions while providing secure communications. Standardization and interoperability enable products from different vendors to work seamlessly together using standardized interfaces. Interworking enables seamless connectivity between terrestrial and non-terrestrial systems as well as between (i) 6G and (ii) pre-6G IMT and non-IMT systems.
- **NGA.** The NGA has defined six audacious goals for 6G [NGA_Roadmap]. Trust, Security, and Resilience aim to make 6G trustworthy, resilient, secure, privacy-preserving, safe, reliable, and available. Digital World Experience provides multi-sensory experiences to support human-human, human-machine, and machine-machine interactions. Cost-Efficient Solutions should permeate the entire network and support expected data speed and services. Distributed Cloud and Communications exploit virtualization technologies to increase flexibility, performance, and resiliency. An AI-native network incorporates AI right from the design stage and improves robustness, performance, and efficiency. Sustainability should help achieve the goal of making IMT carbon-neutral by 2040.
- **NGMN Alliance.** The NGMA Alliance, an alliance of network operators, envisions 6G as a way to build upon the existing 5G ecosystem and extend capabilities to deliver value to customers while simplifying network operation.
- **Bharat 6G Alliance.** This India-based alliance envisions 6G providing ubiquitous, intelligent, secure, and sustainable connectivity for a high-quality living experience. According to the alliance, 6G will build upon 5G and provide more reliable, ultra-low latency, and affordable solutions to facilitate new applications.
- **NTT DOCOMO.** 6G is envisioned to solve social problems, including addressing SDGs, declining working-age population, deteriorating social infrastructure, and a trend toward an open and sparse environment. 6G will enhance interactions between humans and between machines and other machines. The communication environment in 6G can expand to high-rise buildings, drones, flying cars, airplanes, ships, and space. The

cyber-physical fusion in 6G may support human thinking and activity via wearable devices attached to human bodies and facilitate collaboration among machines.

- **Samsung.** Samsung envisions 6G to have four megatrends [Samsung_6G_WP]. In the megatrend of connected machine, the machine is the main user in 6G, and machines such as vehicles, robots, drones, home appliances, displays, smart sensors, construction machines, and factory equipment will be connected via 6G. Consideration of AI in the architecture of 6G from the conceptual phase will create more opportunities to exploit AI to improve overall network operation. 6G is envisioned to use open interfaces and open-source software. 6G can also help address social issues, including climate change, hunger, and education inequality.
- **Qualcomm.** 6G is envisioned to play an important role in building a smarter society through the connected, intelligent edge [Qualcomm_6G_WP]. Intelligence/AI and processing will be distributed within the network and among devices such as smartphones, computers, vehicles, robots, wearables, and machines.
- **Ericsson.** 6G is envisioned to possess trustworthiness, where industry and society can rely on communication and computing to be trustworthy [Ericsson_6G_WP]. 6G should enable sustained development. AI will be used on a massive scale across the entire end-to-end system for a simplified life. New applications would demand extreme connectivity performance.
- **Huawei.** 6G will support new applications with extreme and diverse requirements. Big data generated for AI will be transported by 6G [Huawei_6G_WP]. 6G will be characterized by the proliferation of intelligence with native AI support, native data protection, native trustworthiness, and a native diversified ecosystem. 6G will be an enabler to achieve SDGs. Deployment, operation, monitoring, and management of 6G is expected to be cost-efficient, energy-efficient, easy, and automated.

2.2 6G Services and Associated Performance Requirements

While the ITU defined a triangle diagram to identify 5G usage scenarios, it has defined a wheel diagram to identify usage scenarios for 6G. Figure 2.1 shows the usage scenarios as well as overarching aspects envisioned by the ITU for 6G [ITU_IMT-2030_Framework]. The overall 6G performance targets determined by the ITU are discussed in Section 3.

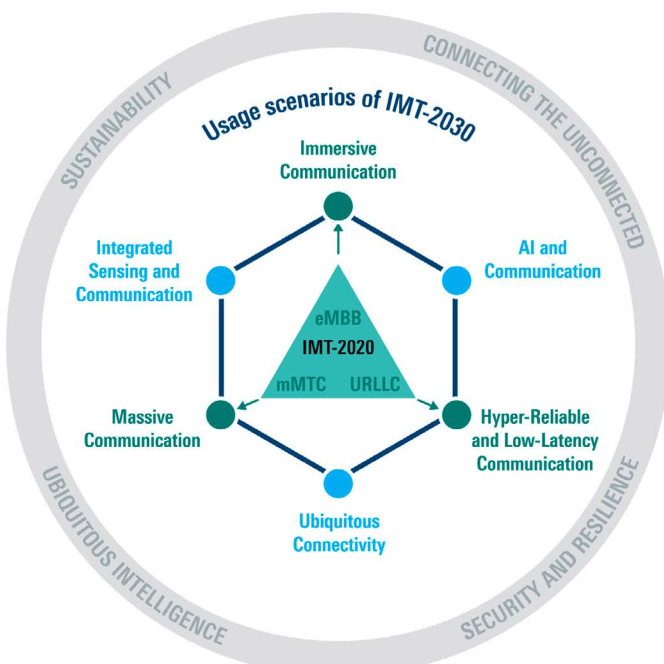


Figure 2.1: ITU-Envisioned Usage Scenarios and Overarching Aspects for 6G

The ITU extended three usage scenarios from 5G to 6G and introduced three new usage scenarios. The enhanced Mobile Broadband (eMBB) usage scenario of 5G is extended to Immersive Communication for 6G, the massive Machine Type Communication (mMTC) usage scenario of 5G is extended to Massive Communication for 6G, and the Ultra-Reliable Low-Latency Communication (URLLC) usage scenario of 5G is extended to Hyper Reliable and Low-Latency Communication (HRLLC) for 6G. Three new 6G usage scenarios are Ubiquitous Connectivity, Integrated AI and Communication, and Integrated Sensing and Communication.

- **Immersive Communication** [ITU_IMT-2030_Framework]. This usage scenario provides users a rich and interactive video experience and includes human-machine interactions. Examples of use cases are communication for immersive XR, remote multi-sensory telepresence, holographic communications, and standalone voice services. Example requirements for this usage scenario include high spectrum efficiency, consistent service experiences, balance between higher data rates and increased mobility, high reliability and low latency for responsive and accurate interactions of humans with real and virtual objects, and large system capacity for simultaneously connecting numerous devices.
- **Massive Communication** [ITU_IMT-2030_Framework]. This usage scenario addresses connections of a massive number of devices covering numerous use cases and applications. Examples of use cases are applications for smart cities, transportation, logistics, health, energy, environmental monitoring, and agriculture. Example requirements for this usage scenario include support for a high connection density and potential support for different data rates, low power consumption, mobility, extended coverage, high security, and high reliability.
- **HRLLC** [ITU_IMT-2030_Framework]. This usage scenario requires time-synchronized operations and hence demands more stringent requirements on reliability and latency. Examples of use cases are communications in an industrial environment for full automation, control and operation, emergency services, telemedicine, and monitoring for electrical power transmission and distribution. Example requirements of this usage scenario include enhanced reliability, low latency, and potentially precise positioning and connection density.
- **Ubiquitous Connectivity** [ITU_IMT-2030_Framework]. This new usage scenario provides connectivity everywhere and helps address the digital divide. To enhance connectivity, a terrestrial IMT system may use a non-terrestrial IMT system or a non-IMT non-terrestrial system. This usage scenario supports IoT and mobile broadband communications. The main objective is comprehensive coverage, with other requirements specific to the use case.
- **Integrated AI and Communication** [ITU_IMT-2030_Framework]. This new usage scenario is intended for distributed computing and AI applications. Example use cases include 6 G-assisted automated driving, autonomous collaboration among medical devices, offloading of computing across devices and networks, and digital twins. Example requirements of this usage scenario include high area traffic capacity, high user-experienced data rates, low latency, and high reliability. This usage scenario also requires new capabilities such as data acquisition, preparation and processing of data and other information, distributed AI model training, model sharing, distributed inference across multiple systems, and orchestration and chaining of computing resources.
- **Integrated Sensing and Communication** [ITU_IMT-2030_Framework]. This usage scenario supports applications and services that utilize sensing capabilities. Multi-dimensional sensing can provide spatial information about devices and objects in the environment. Example use cases include 6 G-assisted navigation, activity detection and movement tracking, environmental monitoring, and applications of AI, XR, and digital twins. Example requirements of this usage scenario include capabilities related to high-precision positioning and sensing (e.g., localization, estimation of range, velocity, and angle, detection of the presence of an object, detection of objects, imaging, and mapping).

Table 2.2 lists novel 6G services or service categories identified by various organizations or alliances. The 3GPP will target 6 G services in Release 20 and discuss them as part of related studies.

Organization/Alliance	Potential Novel Services in 6G
3GPP	To be determined
NGA	Four service categories: (i) Multi-Sensory Extended Reality, (ii) Personalized User experiences, (iii) Distributed Sensing & Communications, and (iv) Networked-Enabled Robotic and Autonomous Systems.
NGMN	Joint sensing and communications, AI, extended AR/VR, enhanced positioning.
Bharat 6G Alliance	Ubiquitous and affordable connectivity to support a wide variety of services, including digital classes, automated public transport, robotic healthcare, and advanced agriculture.
NTT DOCOMO	Human augmentation, advanced telemedicine use cases, advanced video use cases.
Samsung	Truly immersive XR, high-fidelity mobile hologram, and digital replica (or digital twin)
Qualcomm	Connected intelligent edge with new user experiences and use cases such as collaborative robots, enhanced boundless XR, human augmentation, hologram telepresence, deeper immersion to the digital and virtual worlds, and advanced sensing.
Ericsson	Three use case scenarios: the Internet of Senses, connected intelligent machines, and a connected sustainable world. Example use cases: e-health for all, precision health care, smart agriculture, earth monitor, digital twins, collaborative robots called cobots, and robot navigation.
Huawei	Five usage scenarios: eMBB+, URLLC+, and mMTC+ as extensions of 5G usage scenarios and two new usage scenarios of AI and sensing.

Table 2.2: Novel 6G Services or Service Categories

- **NGA.** The NGA has identified four major service categories for 6G [NGA_6G_ApplicationsUseCases]. The "Multi-Sensory Extended Reality" service category includes services such as ultra-realistic interactive sport (e.g., drone racing), immersive gaming or entertainment, mixed reality co-design, mixed reality telepresence, immersive education, and high-speed wireless connection in aerial vehicles for entertainment services. Examples of services under the "Personalized User Experiences" service category include personalized hotel experience and personalized shopping experience. The "Distributed Sensing & Communications" service category includes remote data collection, untethered wearables, and implants, eliminating the digital divide, public safety applications, synchronous data channels, and in-body networks for healthcare. Finally, the "Networked-Enabled Robotic and Autonomous Systems" service category corresponds to applications such as cooperative operation among (i) service robots in logistics, manufacturing, and medical fields and (ii) field robots in hazardous environments.
- **NGMN Alliance** [NGMN_6G_Position] envisions 6G to natively support network-related APIs to facilitate new services that leverage network capabilities. Examples of 6G services include joint sensing and communications, AI, extended AR/VR, and enhanced positioning.
- **Bharat 6G Alliance** [B6A_6G_Vision]. Ubiquitous and affordable connectivity is expected to significantly reduce differences in (i) regional and social infrastructure and (ii) the availability of economic opportunities to help address challenges associated with rural exodus and mass urbanization. 6G is expected to help (i) fill the gap in the provisioning of e-services for urban and rural populations, (ii) achieve the UN SDGs, and (iii) contribute significantly to improving the quality and opportunities of life. 6G use cases include remote-controlled factories, self-driving cars, and smart wearables taking inputs from human senses. Ubiquitous connectivity is expected to support a variety of applications such as robotic healthcare centers, connected fire stations, online police services, smart electric devices, smart classes for enhanced education, AR/VR, e-Commerce, smart waste management, automated public transport, digital library, advanced agriculture, connected homes, digital post office, and connected retail services.
- **NTT DOCOMO** [NTT_DOCOMO_6G_WP]. NTT DOCOMO envisions 6G to improve the Quality of Life (QOL) of humans and facilitate the transition from a smart society to a well-being society. Human augmentation associated with human senses (e.g., haptic augmentation) allows mutual sharing of senses and feelings; some services can even remove limitations of human physical abilities. Example applications include power assist suits and muscle displacement by sensing physical information such as brain waves or BrainTech. Advanced telemedicine includes remote robotic surgery. Video use cases include (i) expansion of interpersonal services such as 3D, AR, and VR through expansion of representation space and evolution of visual expression evolution, (ii) industrial applications that exploit ultra-low latency 8k videos, and sensing applications that utilize 16k videos.

- **Samsung** [Samsung_6G_WP]. Examples of key 6G services include truly immersive XR, high-fidelity mobile holograms, and digital replicas (or digital twins). Truly immersive XR can be utilized in diverse fields such as entertainment, medicine, science, education, and manufacturing. High-resolution rendering and high-performance capable devices and networks in 6G can be exploited to support 3D hologram displays. A digital replica or digital twin can replicate physical entities such as objects and people in a virtual world. Consumers or enterprises can explore and monitor reality in a virtual world without temporal or spatial constraints and remotely detect and resolve problems.
- **Qualcomm** [Qualcomm_6G_WP]. 6G is envisioned to provide new user experiences and use cases, including collaborative robots, hologram telepresence, smarter verticals, enhanced boundless XR, wireless sensor fusion, human augmentation (along with digital twins), deeper immersion to the digital and virtual worlds, and advanced sensing.
- **Ericsson** [Ericsson_6G_WP]. Ericsson envisions a cyber-physical world with merged digital and physical worlds. Three use case scenarios are envisioned: the Internet of Senses, connected intelligent machines, and a connected sustainable-world. Connected intelligent machines are AI-powered machines that communicate with one another and solve problems without human intervention. The Internet of Senses makes use of devices, sensors, actuators, and context-aware applications to enrich a user's digital experiences. A connected sustainable-world aims to reduce global carbon emissions. Examples of use cases are e-health for all, precision health care, smart agriculture, earth monitor, digital twins, collaborative robots or cobots, and robot navigation.
- **Huawei** [Huawei_6G_WP]. Huawei envisions five usage scenarios, with three usage scenarios of eMBB+, URLLC+, and mMTC+ being extensions of 5G usage scenarios and two new usage scenarios of AI and sensing. Examples of eMBB+ use cases are immersive cloud VR, haptic and multi-sensory communication, and glass-free 3D and holographic displays. URLLC+ use cases include factories of the future, collaborative robots, cobots and cyborgs, and autonomous vehicles. mMTC+ use cases are smart healthcare, UAV-enabled smart services, and smart buildings. Example applications of the AI usage scenario include network automation, data management, distributed learning, and inferencing. Example applications of the sensing usage scenario are network automation, data management, distributed learning, and inferencing.

3 PERFORMANCE TARGETS FOR 6G

6G is expected to support new services and services supported by 5G. The ITU typically sets the performance targets for a new generation of cellular communication technology. For example, the ITU defined 3G performance targets in the form of IMT-Advanced requirements and 4G performance targets in the form of IMT-2020 requirements. Similarly, the ITU has determined 6G performance targets in the form of IMT-2030 requirements. Section 3.1 explains the IMT-2030 performance targets or capabilities. Section 3.2 summarizes performance goals mentioned by industry organizations in their 6G white papers. Section 3.3 provides examples of early 6G performance demonstrations by Rohde & Schwarz.

3.1 ITU-Defined Performance Targets

Figure 3.1 mentions enhanced capabilities of IMT-2030 compared to IMT-2020 and the new capabilities of IMT-2030 [ITU_IMT-2030_Framework]. 5G related targets specified by IMT-2020 are given in [ITU-R M.2083]. The ITU has not provided numerical values for some capabilities at the time of this writing.

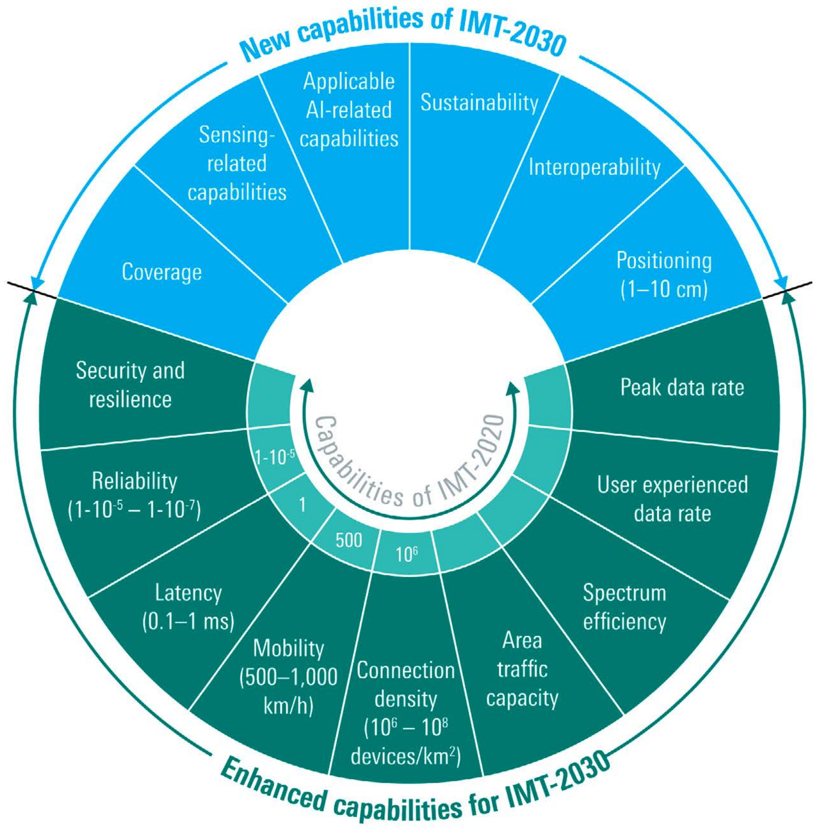


Figure 3.1: ITU-Defined IMT-2030 Capabilities for 6G

In Figure 3.1, the range of values are estimated targets for research and investigation of IMT-2030.

Enhanced Capabilities for IMT-2030

6G is expected to provide better performance or capabilities than 5G from the perspective of several key metrics. While the ITU has specified example numerical targets for several capabilities, other values can also be explored.

- **Peak Data Rate.** This is the maximum achievable data rate for a given device under ideal conditions [ITU_IMT-2030_Framework]. While 5G peak data rate target is 20 Gbps, the ITU has suggested 50 Gbps, 100 Gbps, and 200 Gbps as example targets for IMT-2030.
- **User-Experienced Data Rate.** This is the ubiquitously (i.e., in the target coverage area) achievable data rate for a given mobile device [ITU_IMT-2030_Framework]. Example values include 300 Mbps and 500 Mbps. The target user-experienced date rate in 5G is 100 Mbps.
- **Spectrum Efficiency.** Spectrum efficiency is the average data throughput per unit of spectrum resource and per cell (i.e., bps/Hz/cell) [ITU_IMT-2030_Framework]. IMT-2030 aims for a target spectrum efficiency that is 1.5 and 3 times greater than the spectrum efficiency of 5G.
- **Area Traffic Capacity.** It is the total traffic throughput served per geographic area [ITU_IMT-2030_Framework]. While 5G peak data rate target is 10 Mbps/m2, the ITU has suggested 30 Mbps/m2 and 50 Mbps/m2 as example targets for IMT-2030.
- **Connection Density.** This is the total number of connected and/or accessible devices per unit area [ITU_IMT-2030_Framework]. While 5G aims for a connection density of 10 6 devices/km2, IMT-2030 aims for the connection density of 10 6 devices/km2 to 10 8 devices/km2.
- **Mobility.** This is the maximum speed at which a defined QoS and seamless transfer between radio nodes associated with different layers and/or radio access technologies can be achieved [ITU_IMT-2030_Framework]. 5G supports up to 500 km/h, and IMT-2030 aims to support 500 km/h to 1,000 km/h.
- **Latency.** The latency over the air interface is the contribution by the radio network to the time from when the source sends a packet to when the destination receives it [ITU_IMT-2030_Framework]. The air interface latency in 5G is 1 ms. The target air interface latency in IMT-2030 ranges from 0.1 ms to 1 ms.

- **Reliability.** Reliability over the air interface is the probability of successfully transmitting data within a predetermined time-duration [ITU_IMT-2030_Framework]. The target air interface reliability in IMT-2030 ranges from (1×10^{-5}) to (1×10^{-7}). As a reference, 5G's target air interface reliability is (1×10^{-6}).
- **Security and Resilience.** Security refers to (i) preservation of confidentiality, integrity, and availability of information (e.g., user data and signaling), and (ii) protection of networks, devices, and systems against cyberattacks such as hacking, distributed denial of service, and man in the middle attacks [ITU_IMT-2030_Framework]. Resilience refers to capabilities of the networks and systems to continue operating correctly during and after a natural or man-made disturbance (e.g., the loss of the primary source of power) [ITU_IMT-2030_Framework].

New Capabilities for IMT-2030

In support of new types of services and verticals, new capabilities or performance targets are defined for IMT-2030.

- **Coverage.** It is the ability to provide access to communication services for users in a desired service area. It is defined as the cell edge distance of a single cell through link budget analysis [ITU_IMT-2030_Framework].
- **Sensing Capabilities.** Sensing-related capabilities are the abilities to provide functionalities in the radio interface, such as range, velocity, and angle estimation, object detection, localization, imaging, and mapping [ITU_IMT-2030_Framework]. These capabilities could be measured in terms of accuracy, resolution, detection rate, and false alarm rate.
- **AI Capabilities.** AI-related capabilities are the abilities to provide certain functionalities to support AI-enabled applications such as distributed data processing, distributed learning, AI computing, AI model execution, and AI model inference [ITU_IMT-2030_Framework].
- **Sustainability.** Sustainability refers to the ability of the network and devices to minimize greenhouse gas emissions and other environmental impacts throughout their life cycle. It can be improved by improving energy efficiency, minimizing energy consumption, and reusing resources [ITU_IMT-2030_Framework]. Mechanisms such as optimizing for equipment longevity, repair, reuse, and recycling can be used to improve sustainability. Energy efficiency can be quantified as the number of information bits transmitted or received per unit of energy consumption (i.e., bits/Joule) [ITU_IMT-2030_Framework].
- **Interoperability.** Interoperability refers to the ability of the radio interface to be based on member-inclusivity and transparency to enable functionalities between different entities of the system.
- **Positioning.** It is the ability to calculate the position of connected devices. Positioning accuracy is defined as the difference between the calculated horizontal or vertical position and the actual horizontal or vertical position of a device [ITU_IMT-2030_Framework]. The target air interface reliability in IMT-2030 ranges from 1 cm to 10 cm.

3.2 Industry Performance Targets with ITU Standards

Table 3.1 summarizes key performance targets mentioned by industry organizations in their 6G vision papers to facilitate the comparison between the industry sources and the ITU.

Organization/Alliance	Key 6G Vision Themes
3GPP	To be determined
NGA	Not specified
NGMN	Not specified
Bharat 6G Alliance	Data rate up to 1 Tbps, ultra-low latency, quantitative policy goals
NTT DOCOMO	Peak data rate >100Gbps, >100x capacity for next decade, Gbps coverage everywhere, new coverage areas (e.g., sky (10000m), sea (200NM), and space), E2E very low latency <1ms, Guaranteed QoS for wide range of use cases (up to 99.99999% reliability), massive number of connected devices (10M/km2), high-precision positioning (< 1cm)
Samsung	Peak data rate of 1,000 Gbps, user-experienced data rate of 1 Gbps, 2x spectral efficiency of 5G, air interface latency of less than 100 μs and end-to-end (E2E) latency less than 1 ms, jitter in the order of microseconds, error rate of 10-7, support of 500+ km/h speeds, 107 connected machines per square kilometer, energy efficiency improvement by a factor of at least 2 compared to 5G.
Qualcomm	Not specified
Ericsson	Several hundred gigabits per second and end-to-end sub-millisecond latency
Huawei	

Table 2.2: Novel 6G Services or Service Categories

- **NGA.** The NGA has defined six audacious goals for 6G [NGA_Roadmap]. Furthermore, the NGA has identified different applications, use cases, and high-level requirements [NGA_6G_ApplicationsUseCases]. However, the NGA has not specified quantitative metrics like the ITU's IMT-2030 requirements.
- **NGMN Alliance.** The NGMA Alliance has identified examples of 6G services and operational priorities. The NGMN Alliance has also specified overall requirements and value indicators for 6G [NGMN_6G_Requirements]. While the NGMN Alliance has not specified any quantitative requirements for 6G at the time of this writing, it is planning to define 6G KPIs in the future [NGMN_6G_Requirements].
- **Bharat 6G Alliance.** This 6G alliance from India has mentioned 1 Tbps data rate and ultra-low latency for 6G. It has also specified quantitative policy targets such as 100 Mbps to every citizen and 90% households with broadband speeds.
- **NTT DOCOMO.** NTT DOCOMO has specified numerical performance targets for various metrics in its 6G vision paper. The target peak data rate is >100Gbps, and the capacity increase is by a factor of more than 100. Gbps coverage is expected everywhere. The End-to-End (E2E) latency target is less than 1 ms. The reliability target is 99.99999%. The number of connected devices is targeted to be 10 million /km2. High-precision positioning with an accuracy below 1 cm is expected.
- **Samsung.** Samsung has specified several numerical performance targets for 6G in its 6G vision paper [Samsung_6G_WP]. The peak data rate target is 1 Tbps, and the user-experienced data rate target is 1 Gbps. 6G spectral efficiency target is 2x the spectral efficiency of 5G. 6G air interface latency target is less than 100 μs, and the E2E latency target is < 1 ms with jitter in microseconds. The reliability target is an error rate of 10-7. The mobility target is the support of 500+ km/h speeds. The target number of connected machines is 107 per square kilometer. 6G energy efficiency is targeted to be higher by a factor of at least 2 compared to 5G.
- **Qualcomm.** While Qualcomm has outlined its 6G vision to build a smarter society through the connected intelligent edge, quantitative performance targets have not been specified for 6G [Qualcomm_6G_WP].
- Ericsson. Ericsson has mentioned potential data rate and latency targets for 6G [Ericsson_6G_Journey] [Ericsson_6G_WP]. The target peak data rate may be several hundred Gbps, and the target latency may be below 1 ms.
- **Huawei.** Huawei has mentioned quantitative performance targets for specific cases [Huawei_6G_WP]. For example, in case of collaborative robots, a localization accuracy of 1 cm, an E2E latency of approximately 1 ms, and reliability greater than 99.9999% may be desirable in 6G. In case of motion control, reliability greater than 99.9999% and sub-ms or even μs latency may be needed. A latency target of 0.1 ms may be necessary for haptic communication.

Initial 6G deployments are not expected to meet all the 6G performance targets. As 6G products evolve from one version to another in the 6G evolution path, the actual 6G performance for different performance metrics is expected to be closer to the performance targets.

3.3 Examples of Early 6G Performance Demonstrations (R&S Tested)

Rohde & Schwarz has executed a series of early 6G-oriented testbed demonstrations to validate feasibility and measurement methodology ahead of formal 3GPP studies. These activities focused on sub-THz RF generation and analysis, ultra-wideband baseband, AI-assisted physical layer blocks, and integrated communication and sensing (ICAS) signal designs.

- **Sub-THz link bring-up and EVM budget:** Wideband vector signal generation with sub-THz frequency extenders and matched signal analysis verified end-to-end Error Vector Magnitude (EVM) vs. SNR for candidate higher-order constellations beyond 1024-QAM. Results established repeatable calibration procedures for converter linearity, IQ impairment control, and phase-noise dominated regimes at D-band.
- **Waveform prototyping at >1 GHz occupied bandwidth:** Prototype OFDM/OTFS frames with scalable numerology were generated and analyzed to study PAPR, ACLR, spectral confinement, and synchronization robustness under high phase-noise, validating capture/replay workflows for link-level evaluation.
- **AI-assisted channel estimation and detection:** A data/model-hybrid pipeline replaced classical pilot patterns and parts of the MIMO detector with learned components. Offline training and online inference reduced pilot overhead at the same BLER, providing a reference recipe for "learned PHY" A/B comparison against classical baselines.
- **ICAS signal co-design:** Joint communication and sensing bursts were exercised to measure range/velocity estimation accuracy vs. communication throughput, confirming measurement hooks required to characterize trade-offs between sidelobe suppression, range resolution, and user-plane KPIs.

Together, these demonstrations harden the measurement stack that future devices, component, and algorithm suppliers will rely on when targeting IMT-2030 capabilities.

4 POTENTIAL BUILDING BLOCKS OF 6G

While the exact building blocks of 6G will be known in coming years as the 3GPP progresses in developing 6G specifications, candidate building blocks and technologies can be determined by considering a vast body of 6G-related work carried out in the industry, academia, and SDOs. Figure 4.1 specifies six (coincidence!) categories of potential building blocks of 6G. These categories of 6G building blocks include (i) radio technologies, (ii) AI-native design, (iii) sustainability features, (iv) network architecture, (v) devices and applications, and (vi) component technologies.

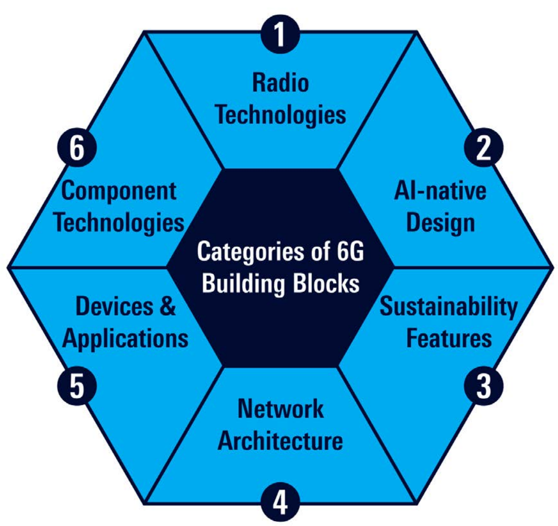


Figure 4.1: Key Categories of 6G Building Blocks

Radio Technologies

While 5G New Radio (NR) air interface is more complex than the 4G LTE air interface, 6G radio interface is likely to be even more complex than the 5G NR due to many newer radio technologies. These potential technologies include new radio waveforms and multiplexing and multiple access techniques, including Orthogonal Time Frequency Space (OTFS), peaking Frequency Shift Keying, and Non-Orthogonal Frequency Division Multiple Access (NOMA). Full duplexing may also be used in 6G. Section 5 describes waveforms and associated enhancements for 6G.

6G is expected to be sharing-native using a variety of spectrum sharing mechanisms. In addition to the typical sub-7 GHz Frequency Range 1 (FR1) spectrum and 24 GHz to about 70 GHz FR2 spectrum, 6G may use mid-band spectrum between 7 GHz and 24 GHz, sub-THz ranging from 100 GHz to 300 GHz, and THz spectrum ranging from 300 GHz to 3 THz. Section 6 describes spectrum considerations for 6G.

Several advanced antenna technologies are being explored for 6G. These technologies include Reconfigurable/Reflective Intelligent Surface (RIS), Massively Distributed MIMO, Cell-free MIMO, holographic beamforming, and Orbital Angular Momentum (OAM). Section 7 discusses potential antenna technologies for 6G.

Integrated Sensing and Communication (ISAC), also known as Joint Communication and Sensing (JCAS), is widely mentioned as one of the unique characteristics of 6G. ISAC utilizes radio signals to serve two purposes-communications and sensing. For example, a radio signal transports user traffic in support of communications. Additionally, a radio signal can be used to perform sensing, where a certain property is sensed to provide the sensing functionality. Sensing can detect objects' presence and characteristics to support applications such as weather and pollution monitoring, geofencing, gesture control, and health and security monitoring and guide activities such as RF optimization. Distributed sensing can be one of the important enables of ISAC. See Section 8 for more information on ISAC.

Examples of miscellaneous radio technologies for 6G include UE Cooperative Communications, Sidelink (SL), Non-terrestrial Networks (NTNs), mesh networks, and semantic communications. While SL and NTN have been comprehensively specified by the 3GPP in 5G and 5G-Advanced, they are expected to play an important role in 6G as well. Section 12 summarizes these miscellaneous radio technologies.

AI-Native Design

AI/ML can be used in an implementation-specific manner by an infrastructure vendor while designing a Self-Organizing Network (SON) algorithm or Network Data Analytics Function (NWDAF). O-RAN is another example of how intelligence can be incorporated into the design of RAN using RAN Intelligent Controllers (RICs). The 3GPP formally studied the use of AI/ML in NG-RAN in Release 18 and focused on the use cases of network slicing and Coverage and Capacity Optimization (CCO) for AI/ML usage in Release 19. More AI/ML use cases are expected to be introduced in 5G-Advanced. AI/ML is an afterthought in 5G and 5G-Advanced, where AI/ML is investigated for baseline architecture and protocol stacks.

In contrast, 6G is expected to be AI-native, where AI is incorporated into 6G beginning at the design stage. The NGA has defined the AI-native air interface as an air interface that uses AI as an integral component with characteristics such as autonomy, continuous learning, and near-real-time optimization [NGA_Radio2]. The autonomy aspect implies that AI enables the air interface to operate autonomously, making real-time decisions based on its knowledge of the network and user needs. Continuous learning means that the air interface continually learns from data, adapting to changing conditions and enhancing performance. Finally, the near-real-time optimization aspect refers to the situation where AI enables the air interface to optimize its operation in near-real-time, maximizing efficiency, reliability, and user experience.

6G may use what was learned from the AI/ML framework of 5G-Advanced. Classical signal processing may be augmented with ML-based signal processing. The classical receiver with distinct processing blocks, such as demodulation and decoding, may be replaced by a neural receiver. AI/ML may be exploited to optimize different aspects of the system, such as linearization of analog RF frontends and AI-driven optimization in radio resource management, network management, interference rejection, and in-device optimizations. Generative AI may play an important role in 6G wireless communications. Section 9 takes a closer look at the AI-native design in 6G.

Sustainability Features

Increased complexity of 6G compared to complex 5G will lead to increased energy consumption unless specific sustainability goals and features are defined for 6G. Performance metrics that quantify various aspects of sustainability need to be clearly identified. The devices and the networks need features or optimizations that contribute to sustainability. Technologies for a green radio network using time, frequency, spatial, and power domains would be important. Near Zero Energy (NZE) communications can be used for suitable devices. Device and network power-saving saving mechanisms developed in 4G and 5G can be used as a baseline and further enhanced in 6G. Renewable energy sources and circular economy principles can be exploited to make 6G eco-friendly. Furthermore, 6G can make other industries more sustainable. See Section 10 on how 6G can be more sustainable than previous generations of wireless technologies.

Network Architecture

While many novel technologies are expected to be considered for the 6G radio interface, network architecture in 6G may also undergo changes. The network generally consists of the radio network, the core network, and the services network, with support from a transport network to connect various network entities or network functions and suitable Operations, Administration, and Maintenance (OAM) systems to manage these radio, core, and services networks. Distributed cloud infrastructure would likely be used in 6G, going beyond that used for 5G. Security is likely to be further enhanced in 6G. To support lower end-to-end latency than 5G, edge computing along with air-interface enhancements would be critical.

New types of network architectures are expected to emerge in 6G. For example, 6G may introduce extreme networking, where special networks such as in-body and on-body networks are defined to support medical applications. Special industrial and in-vehicle networks may also be supported. See Section 11 for extreme networking-related discussions.

Devices and Applications

While the transformational aspect of 5G is still unfolding for commercial applications, 6G is expected to be even more transformational than 5G. As briefly discussed in Section 2, novel applications across multiple industries including entertainment, manufacturing, automotive/transportation, and healthcare are expected to benefit from the prowess of 6G. Examples of such applications include holographic displays, immersive video calls, AR/VR/XR headsets, and digital twins. New consumer and Industrial IoT devices would be needed to support such emerging applications.

Component Technologies

Advancements in component technologies are needed to build 6G devices and networks. Examples of these component technologies include semiconductor technology, RF circuits and subsystems, antenna systems, and displays [NGA_Roadmap]. For example, semiconductor technology will need to support radios with acceptable cost, range, power dissipation, and link margin characteristics. Candidate semiconductor technologies for 6G include silicon and III-V semiconductors. Suitable cost and performance tradeoffs and feasibility analysis would be required for the components of RF circuits and subsystems, including Analog-to-Digital Converters (ADCs), Digital-to-Analog Converters (DACs), Power Amplifiers (PAs), and Low Noise Amplifiers (LNAs). Antennas and subsystems such as filters, power amplifiers, and switches may need to be packaged in modules using novel packaging techniques. Advanced immersive displays in support of AR/VR/XR and immersive video calls are needed in 6G [NGA_ComponentTechnologies_Displays].

5 RADIO WAVEFORMS AND ASSOCIATED TECHNOLOGIES

6G radio interface is expected to be more complex than the radio interfaces of previous generations of cellular technologies. 5G NR consist of a vast number of newer radio technologies. A radio waveform plays an important role in the performance of wireless communications between a wireless device and the Radio Access Network (RAN). Section 5.1 discusses potential waveforms for 6G and associated techniques including multiplexing and multiple access, coding, modulation, and duplexing. The generation and analysis of a 6G waveform are described in Section 5.2.

5.1 Exploration of Novel Radio Waveform Techniques

Figure 5.1 summarizes candidate 6G radio waveforms and waveform-related techniques.

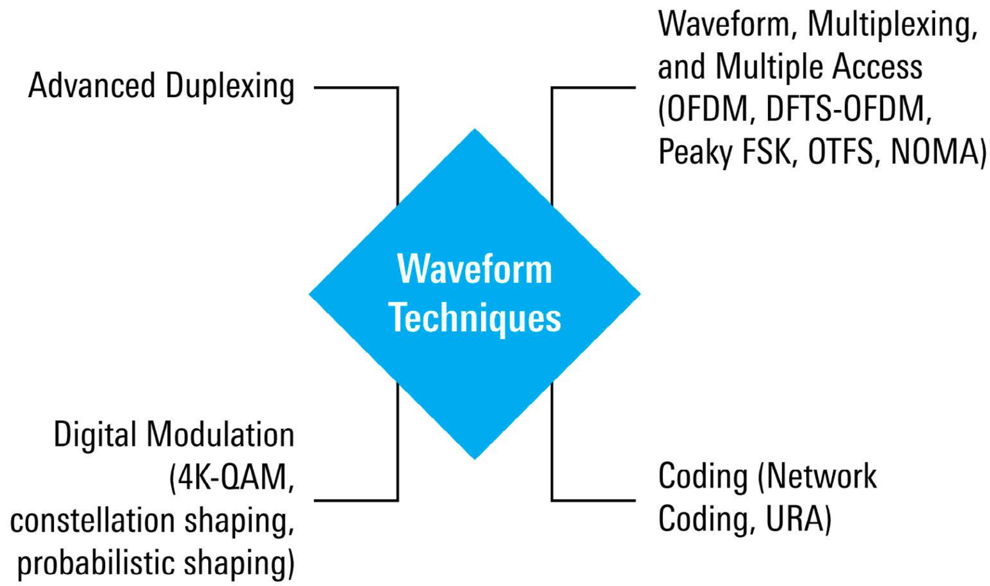


Figure 5.1: Novel Radio Waveforms and Related Technologies

A radio waveform carries information between the wireless device and the radio network. Furthermore, multiplexing and multiple access are highly dependent on the type of radio waveform. For example, 4G and 5G utilize the Orthogonal Frequency Division Multiplexing (OFDM) waveform on the air interface and use the multiple access technique of Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink. 4G LTE uses a modified version of OFDMA called Single Carrier- Frequency Division Multiple Access (SC-FDMA) in the uplink. SC-FDMA is also known as Discrete Fourier Transform – Spread OFDMA (DFTS-OFDMA). 5G supports both SC-FDMA and OFDMA in the uplink. OFDM is still one of the candidate waveforms for 6G. Examples of other candidate waveforms or multiple access techniques for 6G mentioned by the NGA include peaky Frequency Shift Keying (FSK), Orthogonal Time Frequency Space (OTFS), and Non-Orthogonal Multiple Access (NOMA). See Section 5.5.1 for discussions related to waveforms and multiple access technologies for 6G.

5G supports adaptive modulation with 1024-Quadrature Amplitude Modulation (1024-QAM) as the highest-order modulation scheme supported as of 3GPP Release 18. 6G may supper even higher order modulation schemes such as 4k-QAM. Constellation diagrams of modulation schemes may be transformed through techniques such as constellation shaping and probabilistic shaping. Section 5.1.2 describes modulation-related potential enhancements in 6G.

5G uses more effective techniques of Low-Density Parity Check (LDPC) and polar coding than turbo and convolutional coding used in LTE. These coding techniques are implemented at the physical layer of the radio interface protocol stack. Structured redundancy is added by such coding techniques to improve the error correction capability at the physical layer. Retransmissions by the protocols above the physical layer help achieve a low overall error rate on the radio interface. In cases where the physical layer coding and radio interface retransmissions above the physical layer are ineffective, network coding that operates above or at the top of the radio interface protocol stack can be quite helpful. Section 5.1.3 discusses network coding for 6G.

While Time Division Duplex (TDD), Frequency Division Duplex (FDD), and Half-FDD are widely used in LTE and 5G, a more advanced duplexing technique such a,s Full Duplex may be explored in 6G. Section 5.1.4 summarizes key considerations for such advanced duplexing.

5.1.1 Waveforms, Multiplexing, and Multiple Access

The 3GPP investigated several waveforms and multiple access techniques, including NOMA, prior to selecting OFDM/OFDMA for 5G specifications. Signal processing enhancements such as Weighted Overlap and Add (WOLA) were made to the OFDM waveform to increase the spectral emission characteristic of the OFDM waveform so that more subcarriers and hence more PRBs can be accommodated in the given channel bandwidth in 5G compared to LTE. In the end, 3GPP decided not to support NOMA in 5G.

While OFDM/OFDMA is expected to be a leading waveform candidate in 6G, peaky FSK, OTFS, low-complexity waveforms, and NOMA are often mentioned in the literature as candidate enhancements in 6G [NGA_Radio1].

Peaky FSK

When the SNR is very low, it may not be feasible to accurately quantify CSI. Hence, a signaling scheme that concentrates power in both time and frequency can perform well in low SNR situations. Impulsive FSK (I-FSK) is an example of a peaky FSH waveform that increases peak transmit SNR by using frequency-concentrated transmission with a low-duty cycle while maintaining the average SNR [NGA_Radio1]. The I-FSK signal is robust in challenging radio environments with high delay spread and Doppler spread and may perform better than OFDM in such environments. The I-FSK transmission resources are known to both the transmitter and the receiver.

In a variation of the I-FSK approach called Wideband Time Frequency Coding (WTFC), a peaky FSK waveform like I-FSK is used, but the exact transmission resources are known only to the transmitter [NGA_Radio1]. Hence, information can be encoded in the form of the exact resources used by the transmitter. For example, in one example of WTFC, if the transmitter uses a set A of resources, it implies that the transmit signal is carrying information X. Similarly, if the transmitter uses a different set B of resources, it implies that the transmit signal is carrying information Y.

OTFS

OTFS is a two-dimensional (2D) modulation scheme proposed by Hadani and others [OTFS_Hadani]. Integrated OTFS and equalization transform a fading and time-varying radio channel into a time-independent radio channel with a relatively constant channel gain during the transmit time interval. OTFS essentially transforms the time-varying radio channel into a 2D radio channel in the delay-Doppler (DD) domain. The DD channel model of OTFS is based on the framework originally developed by Bello [OTFS_Li].

The Wide-Sense Stationary Uncorrelated Scattering (WSSUS) channel model can be fully described by its response in either the time-frequency domain or the DD domain. The DD domain representation of a linear time-varying channel is given by

$$h(\tau,\nu) = \sum_{i=1}^{P} h_i \delta(\tau - \tau_i)\, \delta(\nu -$$

where P is the number of resolvable paths and hi, ⍰i, and vi are the channel coefficients, delays, and Doppler shifts corresponding to the ith path, respectively.

Each DD domain symbol corresponds to a delayed and phase-rotated pulse train in the time domain, where the symbol's location on the DD domain grid determines how the pulse train is delayed and phase-rotated in the time domain.

The approximately near-constant gain arises due to the spreading of information across the entire DD domain. Since a given DD domain symbol is spread into the time-frequency domain, it experiences fluctuations of the time-frequency channel response over an OTFS transmit time interval (TTI) or frame. OTFS is resilient to the Doppler spread. Due to the compact delay-Doppler radio channel representation, OTFS enables dense and flexible placement of reference signals. OTFS offers full diversity, enabling linear throughput scaling with the number of antennas regardless of the radio channel's Doppler shift. OTFS obviates the need for transmitters to adapt to the dynamic radio channel conditions.

OTFS modulates a given information symbol onto one of a set of 2D orthogonal basis functions that span the bandwidth and the TTI. OTFS can be viewed as generalized CDMA and OFDM, where OTFS transforms into CDMA when the basis functions are spreading codes and into OFDM when the basis functions are orthogonal subcarriers.

OTFS can be implemented using a suitable processing block in OFDM systems, as shown in Figure 5.2 [NGA_Radio1].

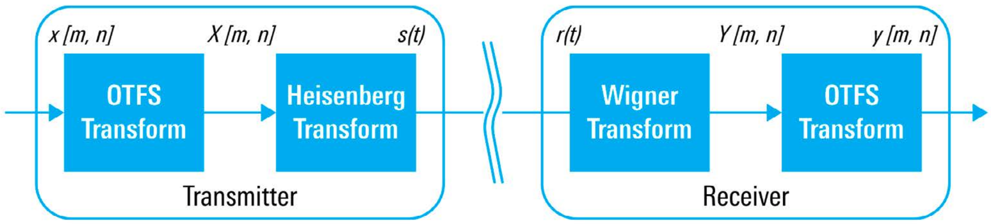


Figure 5.2: Example Implementation of OTFS

The received signal r(t) is given by

$$r(t) = \iint h(\tau, \nu) s(t - \tau) e^{j2\pi\nu(t-\tau)} \, d\nu \, d\tau$$

In Eq. (5.1), h(t) is complex baseband channel impulse response and s(t) is the input signal for the radio channel. The transmitter first maps the 2D delay-Doppler domain (where the information symbols reside) to the time-frequency domain through a combination of the inverse Symplectic Fourier transform and windowing. The transmitter then applies the Heisenberg transform (which is a generalization of the OFDM transform) to the time-frequency modulated signal to convert it into the time domain for transmission.

The receiver first performs the Wigner transform, which is the inverse of the Heisenberg transform. Next, it performs the OTFS transform to recover the information symbols.

OTFS systems can apply relatively simple channel estimation methods in the DD domain with a much smaller signaling overhead than traditional OFDM systems. In one channel estimation approach, a DD domain impulse (i.e., a reference signal symbol) together with guard spaces are used to estimate the channel. The embedded DD domain reference signal symbol is circularly convolved with the DD domain channel response. With integer delay and Doppler indices, there are P received reference signal symbols confined within the maximum delay and the maximum Doppler frequency. The DD domain channel parameters can be obtained by comparing each received and transmitted reference signal symbol.

The OTFS implementation shown in Figure 5.2 is referred to as Multi-Carrier OTFS, which is the most popular OTFS implementation. An alternative way to implement OTFS is Zak-OTFS. OTFS simplifies system operations and may significantly enhance performance in scenarios corresponding to high Doppler shifts, short packets, and large antenna arrays.

Low-complexity Waveforms

6G is expected to support diverse use cases. Some use cases may not have a high spectral efficient waveform with a high degree of linearity. Instead, a low-complexity waveform may be preferred by some use cases to reduce costs and energy consumption. Examples of low-complexity waveforms are Binary Phase Shift Keying (BPSK), Differential Phase Shift Keying (DPSK), and On-Off Keying (OOK) [NGA_Radio1].

In one example implementation, the cost of a digital transceiver chain can be reduced significantly using a low-complexity waveform, and each digital transceiver chain can have its own antenna even in massive MIMO scenarios [NGA_Radio1]. Example challenges include supporting very high data rates, mitigation of out-of-band emissions, suitable coding techniques, precoding and equalizer design, and non-linearity of the waveform, time-frequency synchronization, and reference signal design [NGA_Radio1].

NOMA

While orthogonal multiple access is the typical aim of OFDMA in LTE and 5G, it may not be feasible to ensure complete orthogonality in scenarios such as random access with no synchronized timing. Furthermore, NOMA can increase spectral efficiency significantly if the interference resulting from using the same time-frequency-space resources can be mitigated using advanced signal processing techniques. In one implementation, multiple UEs can transmit data using the same time-frequency-space[1] radio resources, and the Base Station can implement advanced Multi-User detection (MUD) to retrieve information for each user. NOMA is quite complex and needs to show a significant performance gain relative to orthogonal multiple access to justify its adoption in the 6G standard. AI/ML techniques may play an important role in enabling NOMA to achieve high-performance gains [NGA_Radio1].

5.1.2 Modulation

Below, we briefly discuss three candidate techniques for enhanced modulation schemes in 6G: high-order modulation, constellation shaping, and index modulation.

High-Order Modulation

A digital modulation symbol represents one or more bits. For example, a QPSK modulation symbol represents 2 bits, while a 1024-QAM modulation symbol represents 10 bits. A signal constellation diagram specifies the amplitude and phase of each possible modulation symbol for a given modulation scheme. Since a high-order modulation scheme has more closely spaced modulation symbols than a low-order modulation scheme, the probability of the receiver making a mistake in correctly identifying the received modulation symbol increases as the modulation order increases. Hence, a high SNR is required for the proper operation of a high-order modulation scheme. Modern wireless communication systems exploit adaptive modulation and change the modulation scheme based on the prevailing radio channel conditions.

A 4k-QAM modulation symbol represents 12 bits. Hence, if the SNR is very high, 4k-QAM can be used instead of 5G’s 1024-QAM modulation to increase the peak data rate by a factor of 1.2.

Constellation Shaping

Traditional signal constellation diagrams of modulation schemes utilize uniformly spaced modulation symbols. However, better performance may be realized if the constellation diagram is optimized. Two techniques of constellation optimization, constellation shaping, and probabilistic shaping, are briefly discussed below.

Constellation shaping leads to non-uniformly-distributed modulation symbols to approach the optimal channel input distribution of modulation symbols that maximizes the channel capacity under specific constraints such as the average power constraint and the peak power constraint [NGA_Radio1]. Bit-to-symbol mapping is also an important design consideration in constellation shaping. It influences the overall performance and complexity of the receiver. A shaping code may be used to define the bit-to-symbol mapping across multiple symbols. Constellation shaping could be achieved by geometric shaping, probabilistic shaping, or combined geometric and probabilistic shaping [NGA_Radio1].

Geometric shaping aims to design a suitable set of constellation points. Circular Amplitude and Phase Shift Keying (APSK) constellations are commonly utilized for geometric shaping. These signal constellation diagrams have several non-uniformly spaced amplitude levels. For a given amplitude level, multiple constellation points are uniformly placed on the corresponding circle. A significant shaping gain (e.g., 1.5 dB) can be realized by selecting suitable amplitude levels and a suitable number of constellation points on the circle. Probabilistic shaping aims to realize a target distribution of modulation symbols for a given signal constellation diagram. The optimal

[1] The same space resource in this context implies the same beam.

distribution of modulation symbols for a complex Gaussian channel consists of concentric energy levels with non-uniform probability [NGA_Radio1].

Examples of probabilistic shaping methods are trellis shaping, shell mapping, and probabilistic amplitude shaping [NGA_Radio1]. Trellis shaping utilizes a convolutional code as the shaping code to minimize the average power of the modulation symbols of the signal constellation diagram [Coding_Trellis]. Such processing results in a distribution that resembles a sampled Gaussian distribution. Shell mapping distributes the modulation symbols of the constellation diagram into shells associated with different average power levels [Coding_Shell]. A block code selects the shell indexes that minimize the average power of constellation symbols. Probabilistic Amplitude Shaping (PAS) [Coding_PAS] transforms uniformly distributed (input) bits into constellation amplitudes with a target distribution using a distribution matcher. The distribution matcher may be a fixed-length mapper or a variable-length distribution mapper.

Index Modulation
In a traditional modulation scheme such as QPSK and 64QAM, information is carried by a modulation symbol. Index modulation is an enhanced modulation scheme that carries information in the form of an index in addition to the typical information carried by a modulation symbol [Modulation_Index]. The index could be a subcarrier index for the OFDM waveform or antenna number in a MIMO system [NGA_Radio1]. Hence, the overall spectral efficiency could be higher for the index modulation scheme than the traditional modulation schemes. Consider a scenario where only one subcarrier is used to transmit each modulation symbol. In such case, additional information can be coded in the index of the subcarrier that is used to transmit information. The receiver thus extracts information from both the modulation symbol carried by the subcarrier and the subcarrier index used for transmission. Index modulation may be appropriate for IoT applications in 6G [NGA_Radio1].

Coding
5G uses LDPC and polar coding at the physical layer to add structured redundancy to correct bit errors at the physical layer. In certain challenging radio environments, the physical layer coding and radio interface retransmissions above the physical layer may not be able to recover the original information. In such environments, network coding can be exploited to achieve a low error rate between the UE and the RAN.

Network coding utilizes coded repair packets intelligently. Example network coding techniques include fixed and adaptive Sliding Window Random Linear Network Coding and Random Linear Network Coding [NetworkCoding1] [NetworkCoding2] [NetworkCoding3]. Such techniques utilize the knowledge about the radio channel to determine the window size of the number of packets to construct a coded packet. The amount of redundancy and error correction capability are considered to achieve a target balance between delay and throughput.

Network coding can be beneficial when the radio channel feedback is difficult to obtain or difficult to scale and when distributed network topologies such as small cells, Integrated Access and Backhaul (IAB), and Reconfigurable/Reflective Intelligent Surface (RIS) are deployed. Other potential benefits of network coding include simplified link adaptation, enhanced reliability, and reduced latency [NGA_Radio1].

Advanced Duplexing
LTE and 5G use duplexing techniques such as TDD, FDD, and Half-FDD. 6G may explore an advanced Full-Duplex technique. TDD utilizes different instants for transmission and reception. FDD utilizes different frequencies for simultaneous transmission and reception. Half-FDD utilizes different frequencies for transmission and reception but at different instants. In contrast to traditional duplexing techniques of TDD, FDD, and Half-FDD, Full Duplex simultaneously utilizes the same time-frequency resources for transmission and reception. Both the receiver portion of the transceiver and the transmitter portion of the transceiver use the same time-frequency resource. Hence, throughout can (theoretically) double. Furthermore, while using sensing-based frequency bands and unlicensed spectrum in conjunction with Full Duplex, listen-before-talk can be replaced by listen-and-talk, because the transceiver can cancel its own transmission while processing the received signal.

There are several possible applications of Full Duplex. Full duplex may be implemented only at the Base Station, only at the device, or both at the Base Station and the device. Furthermore, architectures that include relays may also utilize Full Duplex. In addition to Base Stations and mobile devices in terrestrial networks, the Customer Premise Equipment (CPE), UAVs, and NTN platforms (e.g., a satellite) may also utilize Full Duplex.

Simultaneous transmission and reception in Full Duplex leads to a significant amount of self-interference at the transceiver. Addressing self-interference is a non-trivial challenge for Full Duplex systems. Since such self-interference may not be eliminated completely, the receiver would need the ability to operate with a relatively high degree of interference compared to other duplexing techniques. Reflections from nearby objects can also add to such self-interference, further aggravating the interference situation. Cross-interference could also be non-negligible in Full Duplex; for example, a UE receiver may experience a significant interference from a nearby UE transmitter. The use of Full Duplex may result in increased interference within an operator's network and between networks of different operators. The performance gain of a Full Duplex system needs to be evaluated in the context of power efficiency and sustainability in 6G.

Several techniques can be explored to make Full Duplex a reality [NGA_Radio1]. The use of physically separated antenna panels may facilitate the implementation of Full-Duplex at low frequencies. For example, one antenna panel can be used for transmission, and another antenna panel can be used for reception. Beam-based separation may be feasible for Full Duplex at high frequencies (e.g., mmW, sub-THz, and THz frequencies). Hardware enhancements can also help mitigate interference in Full Duplex. Advanced interference cancellation techniques, including AI/ML-based techniques, can also be helpful in reducing interference in Full Duplex systems. Analog, digital, or hybrid analog and digital interference cancellation techniques can be explored for implementing a Full Duplex system. The suitability of techniques for mitigating interference in Full Duplex system depends on the deployment scenarios.

There are several challenges of a Full Duplex beyond self-interference management [NGA_Radio1]. As mentioned above, Full Duplex may influence co-channel interference between 6G and pre-6G cellular systems and adjacent channel interference, including interference within an operator's network and between two operators' networks. Furthermore, the coexistence of Full Duplex capable 6G transceivers and pre-6G transceivers is challenging. Interaction between user mobility and Full Duplex and the impact of non-linear hardware components on self-interference are other challenges.

5.2 6G Waveform Generation and Analysis

Evaluating candidate 6G waveforms requires coherent control of the entire signal chain: numerology definition, baseband generation, RF up/down-conversion, impairment injection, and standards-aligned analysis.

Generation workflow

1. Specify numerology (subcarrier spacing, CP length, slot/frame timing) for OFDM variants and non-orthogonal candidates (e.g., OTFS, peaky FSK, NOMA multiplexing maps).
2. Shape spectra via windowing or filtering to trade spectral confinement against time-domain dispersion.
3. Emulate channels and oscillators (phase noise, CPE) and front-end non-linearities to stress equalization and tracking loops.
4. Drive RF paths or sub-THz extenders with calibrated IQ to maintain repeatability across bandwidths approaching and exceeding 1 GHz.

Analysis workflow

- Perform synchronization and residual CFO/CPE correction, then compute per-RB EVM, constellation statistics, and SNR-EVM fit.
- Extract ACLR/SEM, occupied bandwidth, and spurious profiles for coexistence studies.
- For non-OFDM schemes, use ambiguity-function and delay-Doppler domain metrics to quantify resilience to dynamics and sensing utility.
- Close the loop with impairment sweeps (PA AM/AM, AM/PM; LO phase-noise masks) to establish sensitivity breakpoints for device specification.

This methodology enables apples-to-apples comparisons across candidate schemes and provides the hooks needed for later conformance-style limits.

6 SPECTRUM CONSIDERATIONS

Spectrum is the most important resource in a wireless communication system. A new generation of cellular communication technology typically uses new spectrum initially to avoid complications of re-farming of spectrum. Section 6.1 summarizes the potential new spectrum that 6G may utilize. Section 6.2 discusses key techniques for efficient spectrum sharing and management. The potential for dynamic spectrum access technologies in 6G is described in Section 6.3.

6.1 Spectrum Allocations and Availability

The 3GPP defined two frequency ranges (FRs) for 5G: (i) FR1 from 410 MHz to 7.125 GHz and (ii) FR2 from 24.250 GHz to 71.000 GHz, with FR2-1 covering 24.250 GHz to 52.600 GHz and FR2-2 covering 52.600 GHz to 71.000 GHz [3GPP_TS38.104]. Furthermore, the 3GPP defined FR2-NTN to support the Non-Terrestrial Network (NTN). FR2-NTN covers 17.300 GHz to 20.200 GHz for the downlink and 27.500 to 30.000 GHz for the uplink [3GPP_TS38.108]. While 6G may utilize 5G FRs, new spectrum may also be exploited by 6G. Figure 6.1 lists three new spectrum candidates that may be used in 6G. These spectrum ranges involve special challenges and may need different transceiver and antenna array architectures compared to FR1 and FR2.

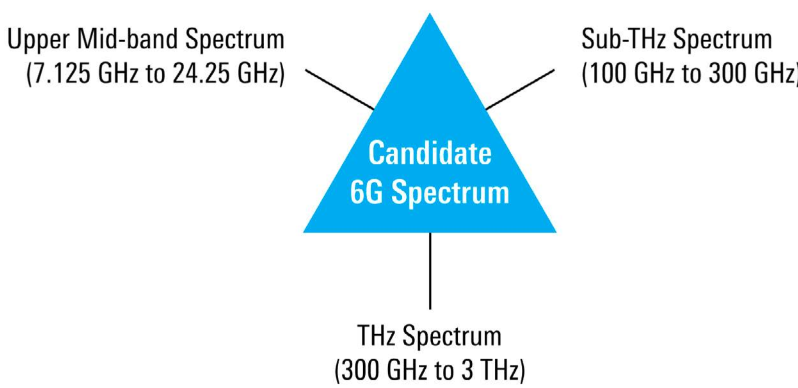


Figure 6.1: Potential New Spectrum for 6G

The upper mid-band spectrum, sub-THz spectrum, and THz spectrum are briefly discussed below.

Upper Mid-band Spectrum

For 6G, a mid-band frequency range from 7.125 GHz to 24.25 GHz may be used. The 3GPP has already started exploring this frequency range for 5G-Advanced and beyond. This frequency range is often referred to as FR3 [Samsung_FR3]. The International Telecommunication Union (ITU) has agreed to study the 7.1-8.4 GHz and 14.8-15.3 GHz for licensed mobile communications [ITU2023]. Additionally, the Federal Communication Commission (FCC) in the US has initiated a rulemaking process for the 12.7 GHz band ranging from 12.7 GHz to 13.25 GHz in July 2023 to transition some or all of the band for mobile broadband or other use [FCC2023].

Since FR3 is situated above FR1, it offers more spectrum compared to FR1 and can accommodate higher capacity and throughput compared to FR1. Furthermore, since FR3 is situated below FR2, it offers larger coverage due to smaller propagation path losses than FR2. Hence, FR3 can be considered a balance between capacity/throughput and coverage and is sometimes referred to as “golden spectrum” for 6G [Samsung_FR3]. FR3 can accommodate more antenna elements and enables finer beamforming compared to FR1. FR3 may also become popular due to lower cost fabrication technologies.

Sub-THz Spectrum and THz spectrum

Sub-Tera Hertz (THz) spectrum usually refers to the frequency range 100 to 300 GHz, while THz spectrum usually refers to the frequency range 300 GHz to 3 THz [NGA_Radio1]. The FCC has identified the frequency range from 95 GHz to 3 THz to facilitate development of new technologies as part of its Spectrum Horizons order [FCC_SpectrumHorizons]. Sub-THz spectrum and THz spectrum can potentially be used for short-distance and very high-speed communications (e.g., video transfer) and sensing.

Typical FR1 and FR2 systems use frequency oscillators to create RF signals from the baseband signals. Multiple approaches can be evaluated to generate sub-THz and THz signals [NGA_Radio1]. In the electronic approach, a sub-THz/THz signal is generated electronically similar to an FR1/FR2 signal, where a series of frequency multipliers that can double or triple the frequency of the input signal used to generate the target signal. An advantage of this approach is that the output power of Sub-THz/THz radios can be large, while disadvantages of this approach include low power efficiency and high phase noise. In the photonic approach, optical signals are down-converted to a suitable sub-THz and THz frequency. A photomixer can be used to multiply two optical signals with different wavelengths to generate a sub-THz/THz signal. Advantages of this photonic approach include low distortion and low phase noise. A disadvantage of this photonic approach is that the achievable transmit power is low. A third plasmonic approach is still in the early stage of development, where a THz signal is directly generated using plasmons and specific nanomaterials such as graphene. The advantages of the plasmonic approach include its compact design and low power consumption. A disadvantage is that the commercial realization of this approach may be beyond the target 6G timeline.

Sub-THz/THz transceiver design is certainly a challenge. Beams are expected to be narrower than narrow beams at millimeter wave frequencies, requiring advanced beam management to maintain a high-quality radio connection. RF propagation at these frequencies also needs to be understood. In particular, the near-field at these frequencies may be quite large, and near-field communications may occur frequently. For example, the far-field region may begin 400 m away from the transmitter at 1 THz [NGA_Radio1]. Compared to far-field propagation, near-field propagation is less predictable. Hence, suitable research is needed to design a sub-THz/THz system that can operate efficiently at sub-THz/THz frequencies.

6.2 Spectrum Sharing and Spectrum Management

New 6G services such as immersive video calls, holograms, and digital twins or replicas will require high data rates and hence large amount of spectrum. A large amount of unused spectrum is difficult to find at low frequencies. Hence, spectrum sharing and spectrum management are essential in 6G. Just like AI, spectrum sharing likely will be an essential element of 6G.

A comprehensive view of spectrum sharing methodologies can be found in [NGA_SAM]. Figure 6.2 summarizes types of spectrum sharing techniques [NGA_Radio1] [NGA_SAM]. 6G may use these techniques and/or enhanced versions of these techniques. A given deployment may use one or multiple techniques simultaneously.

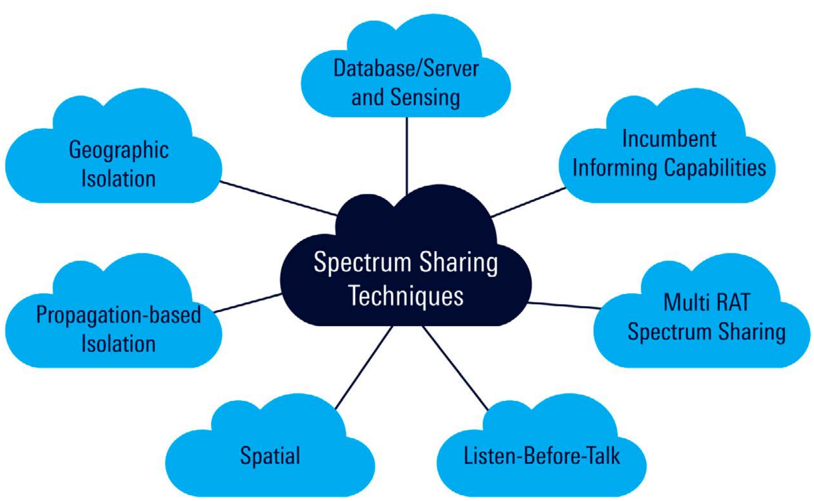


Figure 6.2: Spectrum Sharing Techniques

In the geographic isolation method, exclusion zones are created such that the secondary services do not use the shared spectrum in the exclusion zone. Only the primary service can use the spectrum in the exclusion zone. For example, in the Citizens Broadband Radio Service (CBRS) spectrum sharing, secondary services cannot use the CBRS spectrum in the geographic areas where the navy radars operate near the coastal areas.

In the database/server and sensing method, secondary users use a database/server to seek permission to use the spectrum. The CBRS spectrum sharing involves the use of a server called Spectrum Access System (SAS) that approves or rejects spectrum usage requests from secondary services. The SAS may utilize information from sensors when deciding whether to approve or reject spectrum access requests. In an enhanced version of the database method, a comprehensive Licensed Spectrum Coordination System (LSCS) can be designed to facilitate diverse and dynamic spectrum access transactions [NGA_SAM]. The LSCS aims to minimize unused licensed spectrum in each geographic area. The LSCS can support spectrum sharing at the Spectrum Management Area (SMA) level, which may be a city, a county, a market, a state, or a country. The LSCS enables a service provider to lend its spectrum to another operator based on space and time constraints, monetary considerations, or other incentives. Furthermore, an operator can let a commercial community service provider use spectrum and obtain financial incentives from the government. The LSCS can help address the urban-rural Digital Divide and accelerate Non-Public Network (NPN) or private (e.g., enterprise network) deployments.
In the temporal sharing method, spectrum is utilized by different services at different instants in the same geographic area. For example, a primary service such as a radar may not be using the spectrum all the time. Hence, a secondary service can use the spectrum when the primary service is not using the spectrum. A version of temporal sharing is Spatio-Temporal Dynamic Spectrum Sharing (ST DSS), where spectrum sharing occurs through the use of time periods or mitigation of interference using spatial techniques. The CBRS spectrum can be viewed as an example of temporal sharing method; the CBRS spectrum cannot be used by secondary users when the incumbent or primary radar system is operational.

In the Incumbent Informing Capabilities (IIC) method, the primary service informs a suitable database or server about the period when it is using or plans to use the spectrum so that other services do not use the spectrum during those periods. This method is especially useful when primary services do not transmit any signals but rather passively receive signals. In such scenarios, a secondary service does not use the spectrum in specific periods during which the primary service performs its signal reception.

In the Multi RAT[2] Spectrum Sharing (MRSS) method, two RATs or air interfaces can share the same spectrum through close coordination. For example, during a specific time interval (e.g., a 1 ms subframe), LTE can use the target spectrum, while 5G can use the same spectrum during another time interval. The 3GPP often uses the term Dynamic Spectrum Sharing (DSS) to refer to the feature that facilitates spectrum sharing between LTE and 5G. 3GPP 4G/5G DSS is one of the Open- Radio Access Network (O-RAN) use cases [Tripathi_O-RAN].

In the Listen-Before-Talk (LBT) method, a transceiver does not transmit (i.e., "talk") unless it finds the medium free based on observation (i.e., "listen") of the spectrum for any transmissions. This method is used for sharing of unlicensed spectrum between the Wi-Fi system and a 3GPP technology such as LTE-based Licensed Assisted Access (LAA). If the wireless medium is found to be busy, the transceiver waits for a random period to look for a future opportunity to transmit. 5G offers more flexibility by supporting various configurations compared to LAA.

In a spatial sharing method, transmissions may be restricted to specific 3D regions to enable spectrum sharing. For example, the spectrum may be shared between a Terrestrial Network (TN) and a Non-Terrestrial Network (NTN) by restricting the TN emissions above the horizon and in the direction of the NTN receivers.

In a propagation-based isolation method, the spectrum is shared between two systems by utilizing isolation provided by propagation mechanisms. For example, by restricting the maximum transmit power levels and exploiting the penetration losses between the outdoor and indoor systems, spectrum can be shared between an outdoor NTN and an indoor TN [Chintalapati2024].

[2] RAT stands for Radio Access Technology. 4G Long Term Evolution (LTE) and 5G are examples of RATs.

With the rising importance of AI/ML in 6G, AI/ML-based spectrum sharing can be exploited in the radio network. The O-RAN framework can be used to facilitate spectrum sharing, where Non-Real-Time RAN Intelligent Controller (Non-RT RIC) and Near-Real-Time RIC (Near-RT RIC) are utilized to enable spectrum sharing. A suitable rApp in the Non-RT RIC and a suitable xApp in the Near-RT RIC can process relevant measurements and manage radio resources to realize effective spectrum sharing. Spectrum sharing among co-licensees can improve the overall utility of spectrum. RAN sharing or infrastructure sharing in general may facilitate spectrum sharing among co-licensees [NGA_Radio1]. A variety of factors such as deployment type (e.g., indoor vs. outdoor), QoS, and user behavior (e.g., mobility and channel state information) may be used by context-aware spectrum sharing to enhance effectiveness of spectrum sharing [NGA_SAM].

7 ADVANCED ANTENNA TECHNOLOGIES

Advanced antenna technologies can significantly increase spectral efficiency, cell throughput, user throughput, and reliability. While commercial 4G LTE and 5G networks have been making use of multiple antenna techniques such as spatial multiplexing and beamforming over the past few years, 6G may use more advanced antenna technologies. Spatial multiplexing involves the transmission of different streams of information or layers from different transmit antennas using the same time-frequency resources. Beamforming involves focusing energy on a target direction to increase Signal-to-Noise Ratio (SNR) and Signal-to-Interference plus Noise Ratio (SINR). Types of beamforming are digital beamforming, analog beamforming, or hybrid digital and analog beamforming.

Figure 7.1 lists examples of new antenna technologies that may be utilized in 6G. These technologies include the Reconfigurable/Reflective Intelligent Surface (RIS), massive distributed Multiple Input Multiple Output (MIMO), cell-free MIMO, holographic beamforming, and orbital angular momentum (OAM).

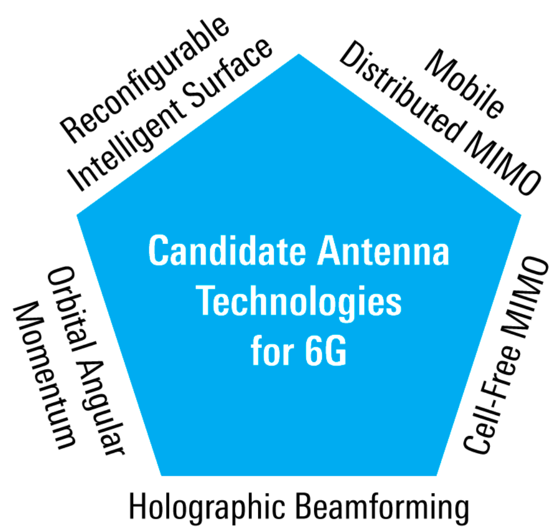


Figure 7.1: Candidate Advanced Antenna Technologies for 6G

Sections 7.1 through 7.5 describe key concepts of advanced antenna technologies specified in Figure 7.1.

7.1 Reconfigurable Intelligent Surface

A Reconfigurable Intelligent Surface (RIS) is also known as Reflective Intelligent Surface, Intelligent Reflective or Reconfigurable Surface, Smart Surface, or Large Intelligent Surface (LIS) [Liu21].

Figure 7.2 illustrates an example implementation of the RIS [NGA_Radio1].

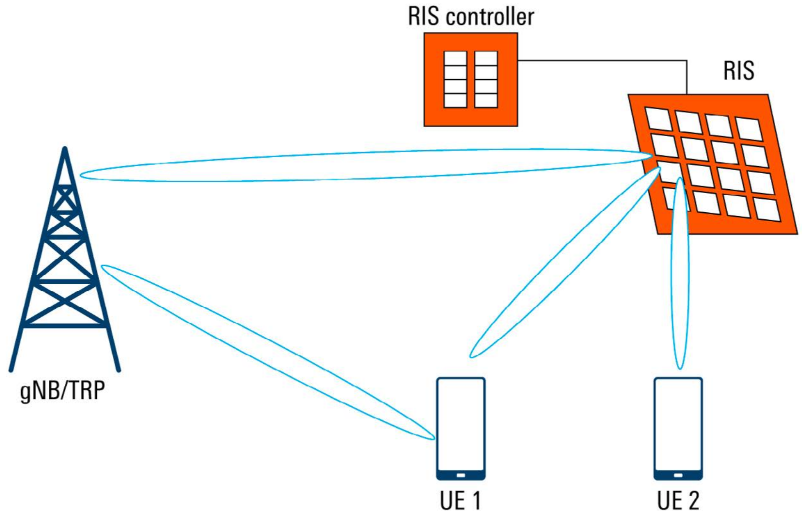


Figure 7.2: RIS: An Example Implementation

While traditional antenna techniques aim to realize their operational goals to the extent possible for the given propagation radio environment, the RIS modifies the properties of the radio propagation environment itself. For example, in Figure 7.2, the RIS creates an additional propagation path between the transmitter and the receiver so that the receiver experiences a stronger signal compared to the Non-Line-of-Sight (NLOS) scenario when the RIS is absent.

A RIS may be created by designing unit cells on a metasurface. In general, properties of unit cells can be modified through one or more mechanisms such as reflection, refraction, diffraction, focusing, refraction,

collimation, and modulation. A RIS may exploit operations such as waveguide, refraction, and reflection [Liu21]. A waveguide RIS utilizes waveguide-fed metasurfaces. The elements in the metasurface can be viewed as uncoupled magnetic dipoles, where the magnitude of a dipole's signal is proportional to the product of the reference wave and each dipole's polarizability. The waveguide RIS can create a beam by tuning the polarizability of diploes. Compared to conventional antenna arrays, the compact waveguide metasurface occupies less space and can transmit towards wider angles. Refracting and reflecting RISs are alternatives to the waveguide RIS. A RIS may be active or passive, although a passive RIS is most commonly discussed in the literature.

A RIS can be categorized from various perspectives, such as structure, power source or location, and tuning mechanism [Liu21]. From the structure perspective, a RIS can be realized by using metamaterials or patch arrays. Metamaterial-based RISs are often referred to as metasurfaces. From the power source or location perspective, a RIS can be designed to work as reflecting/refracting surfaces between the BS and the user or waveguide surfaces operating at the BS. From the tuning mechanisms perspective, a RIS can be reconfigured electrically, mechanically, or thermally. From the energy consumption perspective, a RIS can be categorized as passive-lossy, passive-lossless, or active.

A passive RIS can also be divided into three categories based on the degrees of reconfigurability and intelligence [NGA_Radio1]. In a pre-configured RIS, the directions of reflected signals are static and pre-determined. Such a RIS is suitable for static transmitter and receiver locations and can be used to fill in coverage holes in indoor and outdoor deployments. In a partially configured RIS, a set of preconfigured reflection patterns is defined, and coverage is improved compared to that of a preconfigured RIS. In the fully reconfigurable RIS, the RIS has a high degree of reconfigurability and dynamically adapts to sensed channel information.

A RIS can be utilized in a variety of use cases. These use cases include coverage extension, enhanced spectral efficiency, positioning, integrated sensing and communication, wireless power transfer, UAV-mounted RIS, and physical layer security [NGA_Radio1].

A RIS offers potential benefits such as ease of deployment, increased spectral efficiency, environmental sustainability, wide applicability, and low cost [Liu2021] [Wu2020]. RISs can be deployed on a variety of structures such as buildings, indoor walls, aerial platforms, roadside billboards, highway poles, vehicle windows, and even pedestrians' clothes [Liu21].A RIS increases spectral efficiency by modifying the radio channel and creating virtual line-of-sight (LoS) links between the base stations and mobile devices to increase the overall SINR. A RIS can be designed using passive elements. A passive RIS can shape the incoming signal by controlling the phase shifts of reflecting RIS elements instead of employing a power amplifier. Since a passive RIS does not use power amplifiers, it consumes less energy and, hence, is more environment-friendly compared to active solutions such as relays and repeaters. A RIS is not confined to a specific waveform or multiple access technique; it can be applied to 4G, 5G, and 6G technologies. Since a passive RIS utilizes passive elements, it does not require RF chains for processing, reducing the overall cost compared to the solutions using numerous RF chains.

RIS deployments need to consider numerous factors, including low-cost hardware designs, configurations of controllable RIS elements, CapEx and OpEx, site acquisition, and visual impact [NGA_Radio1].

A RIS also poses a few challenges [NGA_Radio1]. A RIS architecture needs to be properly designed and fabricated. To facilitate simulation-based performance evaluation of a RIS-enabled system, accurate modeling of the RIS is needed. The degree of RIS reconfigurability is another challenge. Frequency selectivity needs to be thoroughly investigated. Integration of RISs with existing and/or new infrastructure needs to be analyzed, and deployment guidelines need to be developed. Mechanisms to ensure security, privacy, and resilience in RIS-assisted systems needs to be defined. Control mechanisms of the RIS need to be worked out. Also, a major challenge is identifying the channel between the RIS and the target user to set the parameters of the RIS. Finally, the commercial viability of a RIS-based system needs to be determined.

7.2 Massively Distributed MIMO

A typical 5G gNB utilizes an antenna structure that provides radio coverage in a given sector. For example, as shown in Figure 7.x, one antenna structure could provide 120° azimuth coverage in each sector, and three such antenna structures enable the gNB to provide 360° radio coverage. The 3GPP has recently defined support for multiple Transmission/Reception Points (TRPs) that provide radio coverage in the target sector but can be placed away from the baseband processor of the gNB. Suitable signals are transported between the baseband processor of the gNB and TRPs. In an example implementation, a UE can receive its traffic from two TRPs. Massively distributed MIMO uses a large number of antenna structures distributed throughout the sector, as shown in Figure 7.3.

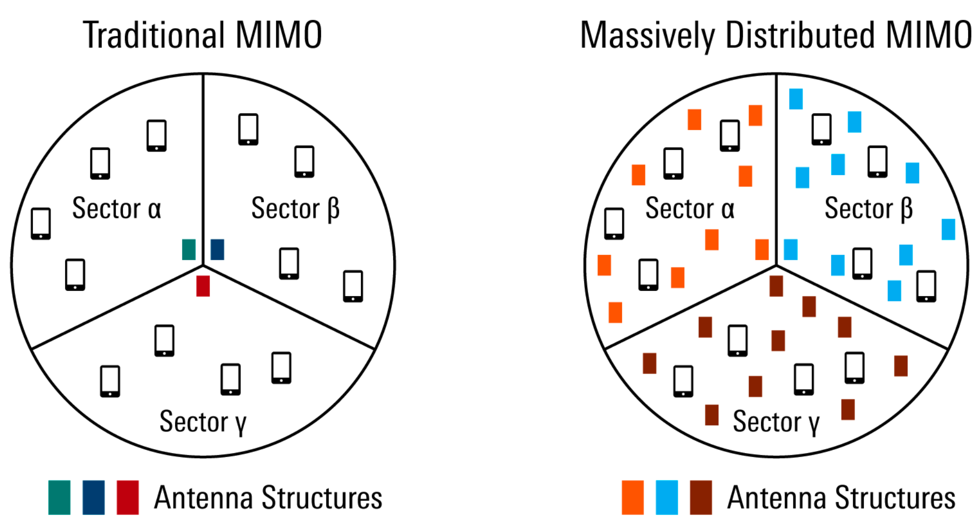


Figure 7.3: Traditional MIMO and Massively Distributed MIMO

Since these structures are much closer to UEs compared to the gNB location, both the downlink SINR and the uplink SINR and, subsequently, the downlink throughput and the uplink throughput are higher compared to a non-distributed MIMO system. One challenge with massively distributed MIMO is the need for a suitable backhaul between the base station's baseband processor and distributed MIMO structures.

Note that MD-MIMO can be realized in a traditional cell-based MIMO or cell-free MIMO. While the literature often mentions single-antenna Access Points (APs) for Cell-Free MIMO (CF-MIMO), there is no inherent constraint in CF-MIMO that prevents the use of massive MINO antennas at APs.

7.3 Cell-Free MIMO

In the traditional RAN, a service area is divided into distinct geographic areas called cells. A user device exchanges user traffic using a dedicated radio connection with a cell. One Base Station controls one or more cells. In scenarios such as multi-Transmission/Reception Point (TRP) transmissions, a user device can exchange user traffic with multiple cells. In the case of Carrier Aggregation in a given geographic area, each carrier frequency used by the user device is also considered a serving cell.

Cell-free MIMO (CF-MIMO) or user-centric MIMO involves clustering of TRPs for the user device, where the user device exchanges user traffic with a cluster of TRPs. Figure 7.4 illustrates an example architecture of CF-MIMO, where Access Points (APs) are clustered per UE, and a Central Processing Unit (CPU) interacts with and manages a set of APs [Björnson]. (equivalent to TRPs). The traditional Base Station functions are distributed between the AP and the CPU.

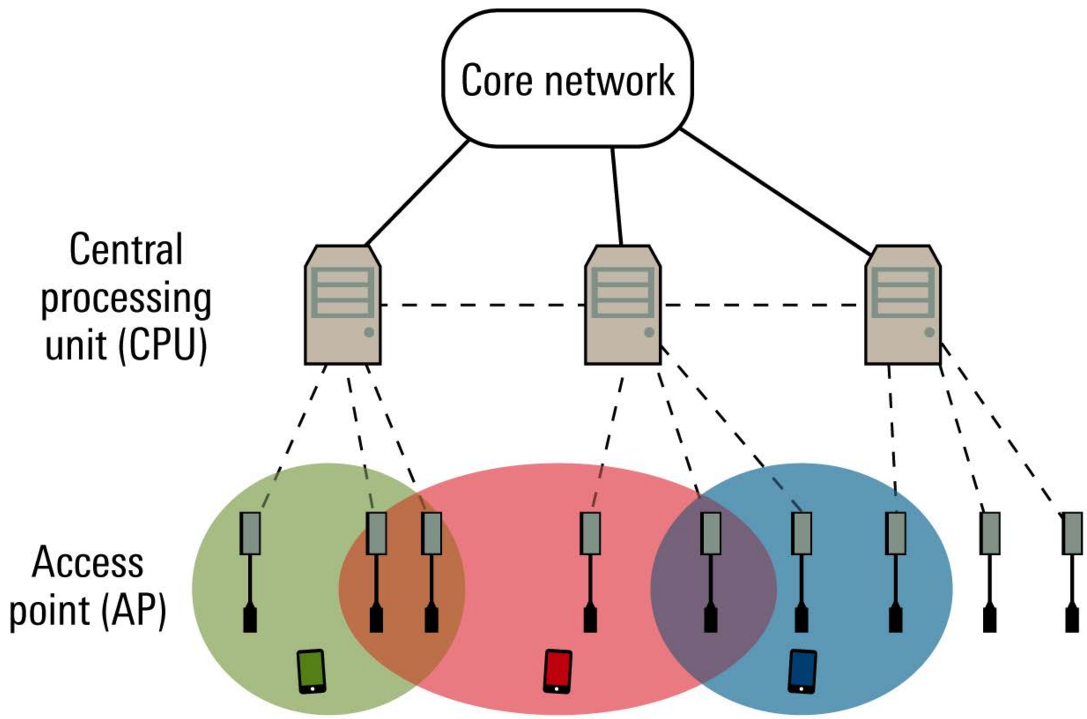


Figure 7.4: Cell-Free MIMO: An Example Configuration

While a traditional RAN focuses on cells and extensive cell-specific processing, cell-free MIMO focuses on the user. As the user moves from one location to another, the cluster of TRPs is dynamically modified.

Several types of CF-MIMO systems have been mentioned in the literature. In one CF-MIMO implementation, numerous single-antenna Access Points (APs) are distributed in a given service area, and these APs are connected to a central processing unit (CPU) via wireline backhaul. The number of APs is assumed to be significantly larger than the number of user devices being served.

Different degrees of cooperation between APs and the CPU have been proposed. In one approach, both uplink pilot signals and data received at APs are sent to the CPU, and the CPU performs channel estimation and coherent combining of data. In another approach. each AP performs channel estimation and provides channel estimates and decided data to the CPU, and the CPU combines the user data using techniques such as simple averaging or channel estimation-based weighted averaging to decide the user data.

Example challenges of CF-MIMO include clustering, mobility, propagation delays, the need for coordination among TRPs, and the need for RF planning and design methodologies [NGA_ Radio1]. The dynamic creation of a user-specific cluster for user traffic exchange is an important research area. Furthermore, mobility management for the user device in connected, inactive, and idle mode must be designed. There could be significantly different propagation delays between the user device and TRPs, requiring suitable coordination strategies among the TRPs for data transmissions. Additionally, TRPs would need the ability to communicate with one another about overall resource management, including the device configurations. Traditional RF planning and design methodologies must be modified to ensure an effective cell-free RAN.

CF-MIMO has the potential to outperform traditional cell-centric RAN. For example. CF-MIMO is shown to have higher spectral efficiency than alternatives such as a macrocellular network and small cells.

7.4 Advanced Massive MIMO

In a typical MIMO-based 5G RAN with integrated Base Stations, each Base Station manages a certain number of cells (e.g., three 120 degree sectors or cells). Each sector or cell may utilize a massive MIMO antenna with a large number of transmit/receive (TRX) chains such as 64 TRX chains at low or mid frequency bands, where each TRX chain includes components such as ADC/DAC, frequency oscillator, power amplifier, and filter and connects to an antenna element. In the MIMO antenna transceiver for the mmW spectrum, the number of TRX chains is small, but the total number of antenna elements is large (e.g., 512 or 1024 antenna elements). The antenna elements for the mmW system are often grouped into subarrays (e.g., four subarrays), and each subarray connects to a TRX chain. For both mmW band systems and non-mmW systems, the total number of baseband signals corresponds to the number of TRX chains. Furthermore, the use of cross-pol antenna elements is quite common in commercial 5G networks.

An advanced mMIMO (A-mMIMO) antenna array or giga MIMO is expected to use more antenna elements than a typical 5G mMIMO antenna array. For example, an A-mMIMO antenna array in 6G may have more than 4,000 antenna elements.

The A-mMIMO system enables high-gain pencil beams, significantly increasing the SINR. The A-mMIMO system may use new midland spectrum from 7 GHz to 24 GHz, sub-THz spectrum (e.g., 100 GHz to 300 GHz), or THz spectrum.

Beam management, reference signal design, massive data transport, and mobility management are important research areas for A-mMIMO systems. Note that A-mMIMO can be realized in traditional cell-based or cell-free RAN.

7.5 Holographic Beamforming

Holographic beamforming (HBF) utilizes optical holography principles to create beams. Holographic beamforming can be viewed as a candidate approach to create beams just like an active antenna array, or a massive MIMO antenna array can be used to create beams.

Figure 7.5 illustrates one potential approach to implement holographic beamforming for a Time Division Duplex (TDD) system [Pivotal_HBF]. A Transmit/Receive (T/R) switch facilitates switching between the transmit operation and the receive operation. For the transmit operation, external power amplifiers drive passive HBF antennas. For the receive operation, the RF signals received by the HBF antennas in specific beams undergo low noise amplification.

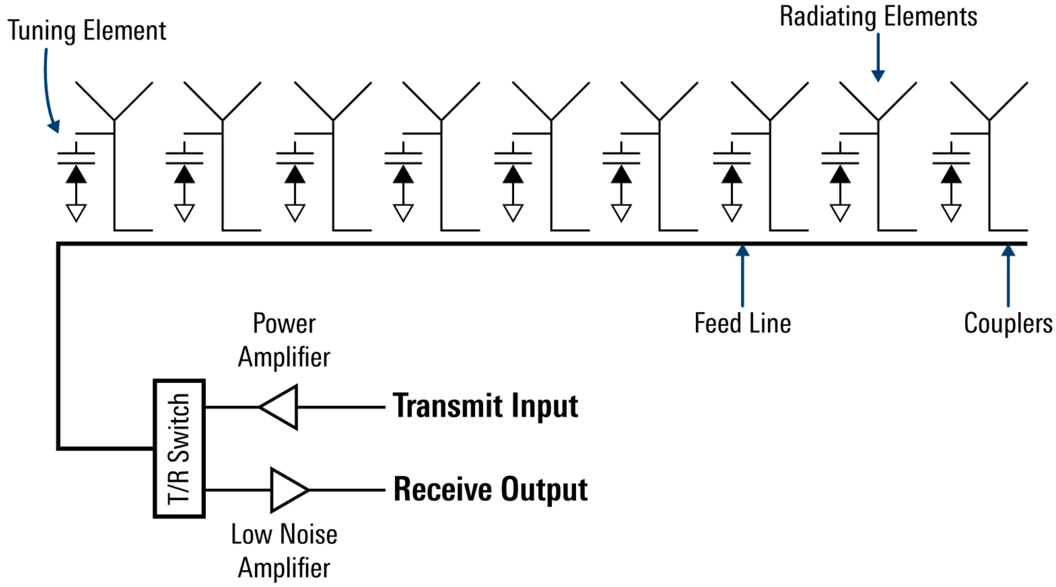


Figure 7.5: Holographic Beamforming: An Example Implementation

The HBF antenna utilizes feed lines for rows of radiating antenna elements. Figure 7.5 shows one feedline for a row of radiating antenna elements. One tuning element is used per radiating antenna element. The tuning element provides controllable capacitance that can alter the amplitude and phase of the signal at the associated radiating antenna element. A varactor can be used as the tuning element in an example implementation. Other fabrication methodologies include PIN diodes and liquid crystals [Deng_RHS].

In an example implementation, the HBF antenna utilizes an RF port in the center of the backside of the antenna. The RF port connects to an RF distribution network. For the transmit operation, a traveling RF wave called the reference wave propagates from the central feed point toward the edges in all directions by following the RF distribution network. The overall goal of the HBF antenna is to transform the reference wave into the object wave that corresponds to the desired beam pattern. This transform occurs through a hologram, which corresponds to the impedance pattern of the tunable elements. The hologram can be viewed as a structure that transfers energy from the reference wave to the object wave [Pivotal_HBF].

Modification of the DC bias of the varactor changes the impedance seen by the reference wave at each element. The required overall impedance pattern of the HBF antenna can be viewed as a hologram. It can be calculated based on the available reference wave and the desired object wave associated with the target beam pattern. Two different holograms corresponding to two different overall impedance patterns imply two different beams. A beam can be steered in different directions by changing holograms (or, equivalently, impedance patterns). Note that the same beam pattern exists in the transmit operation and the receive operation.

The HBF antenna is also known as Reconfigurable Holographic Surface (RHS). The HBF antenna or the RHS can also be viewed as a leaky antenna, where RF energy is leaked into free space for radiation. Potential benefits of holographic beamforming include lower weight, lower cost, thinner design, and low power consumption compared to active antenna arrays. Example drawbacks include an increased number of antenna elements and higher design complexity compared to active antenna arrays. Examples of RHS challenges include beamforming control algorithms, need for hybrid holographic beamforming, serial or sequential feeding, channel estimation, and hardware implementation [NGA_Radio1].

7.6 Orbital Angular Momentum

Orbital Angular Momentum (OAM) is the property of an electromagnetic wave that describes the helical phase pattern of a wavefront. An OAM mode indicates the amount of phase front twisting. In theory, different OAM modes are spatially orthogonal. Simultaneous transmission of information on multiple orthogonal OAM modes increases spectral efficiency. In practice, multiplexing gains are achievable for short distances under line-of-sight propagation conditions and alignment of the transmit antenna array and the receive antenna array. Hence, OAM is principally suitable for fixed point-to-point transmissions such as fronthaul and backhaul transmissions.

Figure 7.6 illustrates a simplified example implementation of OAM-based communication system, which exploits multiplexing in a Uniform Circular Array (UCA) to increase the data rate [NGA_Radio1].

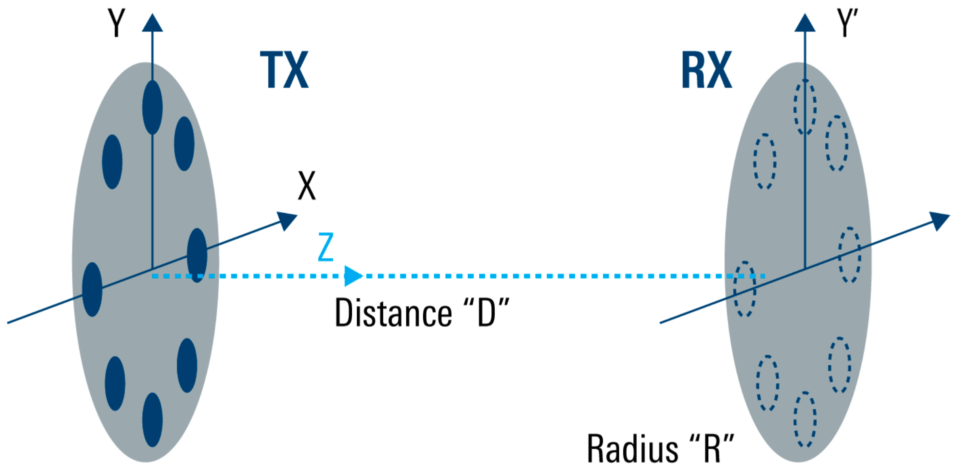


Figure 7.6: Multiplexing with Orbital Angular Momentum: An Example Implementation

Numerous omni or directional antennas are placed on a circle at equal angles at the transmit antenna array and the receive antenna array. At the transmit antenna array, different modes are created by applying different counterclockwise rotations. At the receive antenna array, a reciprocal clockwise rotation is applied. The overall gain corresponds to the signal power after signals are combined at the receiver. Mode 0 corresponds to the case where all antennas are in phase. Higher modes become unusable for long distances (e.g., a few hundred meters for a 0.3 m antenna array radius). Different modes experience the maximum gain at different distances.

8 INTEGRATED COMMUNICATION AND SENSING

A cellular communication system typically focuses on wireless communication between a wireless device and a radio network. A radar system usually focuses on sensing. Sensing is a process of determining characteristics of an object (e.g., presence, shape, position, and/or velocity) or an environment (e.g., interference in a spectrum band or a weather event such as rain). Integrated Sensing and Communication (ISAC) utilizes a common framework to support both communication and sensing. While the 3GPP has already started studying ISAC as part of 5G-Advanced, ISAC is likely to become one of the key technologies in 6G. Section 8.1 provides a brief introduction to sensing and ISAC. Section 8.2 describes use cases enabled by ISAC. Section 8.3 discusses ISAC technologies. ISAC research trends are summarized in Section 8.4.

8.1 Sensing and ISAC: A Brief Introduction

In a sensing system, a sensing transmitter sends out a sensing signal (radio transmission), and a sensing receiver receives the sensing signal [3GPP_TR22.837]. Figure 8.1 illustrates two types of generic sensing, mono-static sensing and bi-static or multi-static sensing.

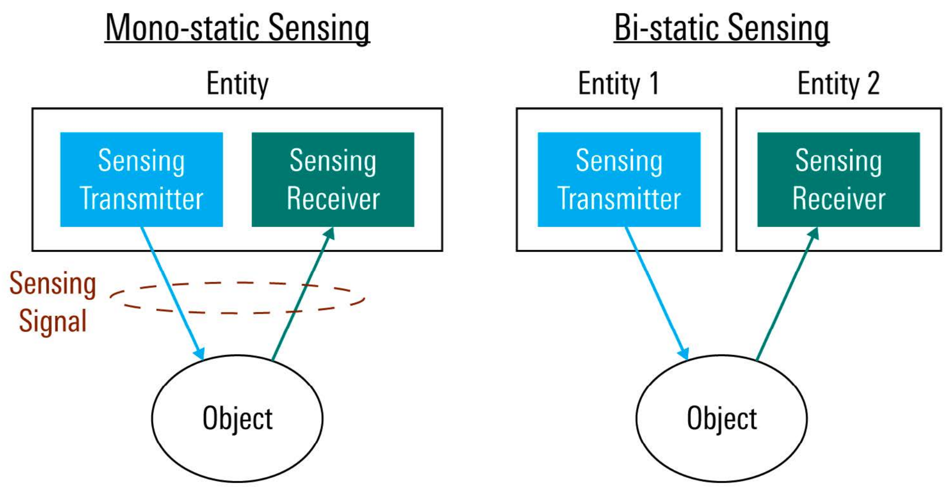


Figure 8.1: Types of Sensing

In mono-static sensing, the same entity includes both the sensing transmitter function and the sensing receiver function. In contrast, in bi-static sensing, the sensing transmitter and sensing receiver functions reside in different entities. In generic multi-static sensing, multiple entities participate in sensing. Hence, bi-static sensing can be viewed as a special case of multi-static sensing.

In the context of a mobile wireless network, referred to as a perceptive mobile network (PMN) in [Liu_2022], multiple sensing topologies can be defined: downlink mono-static sensing, uplink mono-static Sensing, downlink bi-static sensing, uplink bi-static sensing, and distributed/networked sensing [Liu_2022]. Figure 8.2 illustrates these sensing topologies.

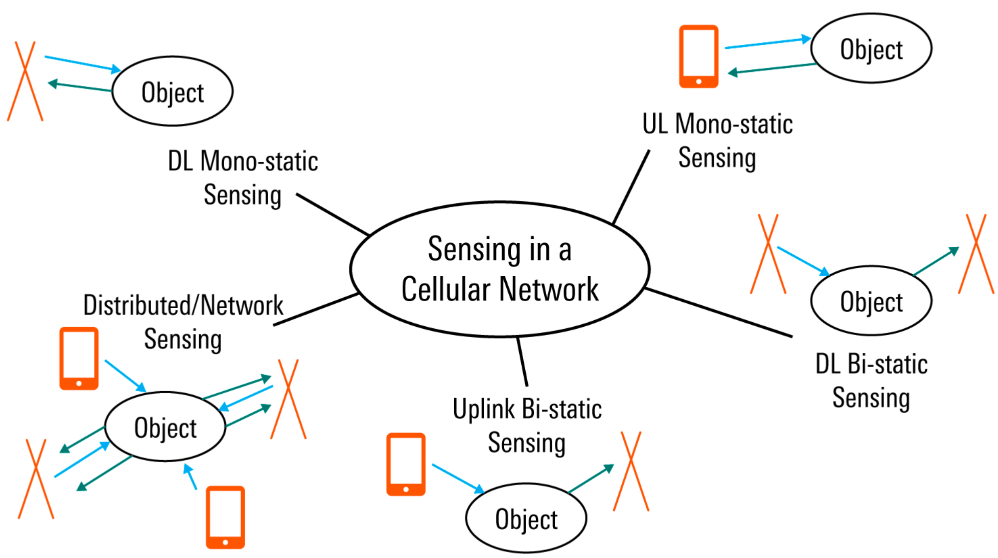


Figure 8.2: Types of Sensing in a Cellular Communication Network

Downlink Mono-Static Sensing

In this method, the base station is the entity that acts as both a sensing transmitter and a sensing receiver. As a sensing transmitter, the base station transmits sensing signals in the downlink. The sensing signals are reflected from the object(s) in the environment. The base station, as a sensing receiver, processes the reflected downlink sensing signals. A typical base station in a cellular system does not process the downlink signals. However, in this downlink mono-static sensing method of an ISAC system, the base station processes reflected downlink sensing signals in addition to processing regular uplink communication signals.

Uplink Mono-static Sensing

This method utilizes the uplink signals for sensing. In this method, the UE is the entity that acts as both a sensing transmitter and a sensing receiver. As a sensing transmitter, the UE transmits sensing signals in the uplink. The sensing signals are reflected from the object(s) in the environment, and the UE acting as a sensing receiver processes the reflected uplink sensing signals. Note that a typical UE in a cellular system does not process the uplink signals. However, in this uplink mono-static sensing method of an ISAC system, the UE processes both the reflected uplink sensing signals and regular downlink communication signals.

Downlink Bi-static Sensing

In this method, downlink sensing signals are used with the sensing transmitter and the sensing receiver is implemented in a different entity. In one implementation approach, a base station, as a sensing transmitter, transmits sensing signals in the downlink. The downlink sensing signals are reflected from the object(s) in the environment. A different base station, as a sensing receiver, processes the reflected downlink sensing signals. This second base station processes reflected downlink sensing signals in addition to processing regular uplink communication signals received from the UEs that it serves.

Uplink Bi-static Sensing

In this method, uplink sensing signals are used with the sensing transmitter, and the sensing receiver is implemented in different entities. A UE, as a sensing transmitter, transmits sensing signals in the uplink. The uplink sensing signals are reflected from the object(s) in the environment. In one implementation approach, a base station acts as a sensing receiver and processes the reflected uplink sensing signals.

Distributed/Networked Sensing

This method utilizes multiple sensing transmitters and receivers. Both the base station and the UE can act as a sensing transmitter, and both the base station and the UE can act as a sensing receiver. This flexible multi-static sensing method requires coordination among multiple entities to achieve effective sensing.

8.2 ISAC Use Cases

ISAC enables a variety of innovative use cases. Figure 8.3 summarizes the use cases identified in [Liu_2022] and [3GPP_TR22.837].

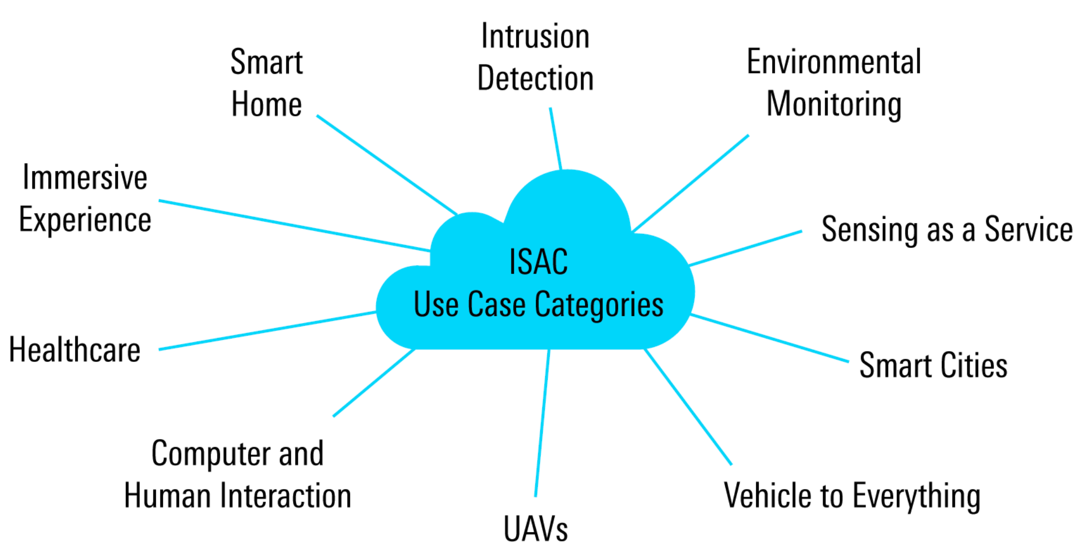


Figure 8.3: ISAC Use Case Categories

Specifically, the following use cases are mentioned in [Liu_2022] are classified into following use case categories: smart manufacturing (including industrial IoT), environmental monitoring, sensing as a service (including remote sensing), smart home, human computer interaction, and vehicle to everything. The 3GPP has identified more than thirty use cases, which have been grouped here in the following use case categories here: intrusion detection, environmental monitoring, sensing as a service, smart cities, vehicle to everything, smart manufacturing, UAVs, computer and human interaction, healthcare, and immersive experience. A given use case could potentially be classified into more than one use case category.

- **Intrusion Detection.** Example use cases include intruder detection in a smart home, pedestrian or animal intrusion detection on a highway, intruder detection in the surroundings of a smart home, railway intrusion detection, and detection of UAVs, vehicles, and pedestrians near smart grid equipment.
- **Environmental Monitoring.** This category includes rainfall monitoring, weather prediction, pollution monitoring, and insect monitoring.
- **Sensing as a Service.** Example use cases include mobile crowd sensing, tourist spot traffic management, protection of sensing information, creation and management of sensor groups, sports monitoring, channel knowledge map construction, and cooperative localization and imaging.
- **Smart Cities.** This category includes use cases such as flooding in smart cities, parking space determination, and public safety search and rescue or apprehension.
- **Vehicle-to-Everything (V2X).** Examples of use cases are sensing assisted automotive maneuvering and navigation, sensing at crossroads with or without obstacle, accurate sensing for automotive maneuvering and navigation service, sensing of vehicles for Advanced Driving Assistance System (ADAS), sensing for automotive maneuvering and navigation service when not served by the RAN, blind spot detection smart manufacturing, automated guided vehicle (AGV) detection and tracking in factories, Autonomous Mobile Robot (AMR) collision avoidance in smart factories, and integrated sensing and positioning in a factory hall.
- **UAVs.** This category includes UAV flight trajectory tracing, network-assisted sensing to avoid UAV collisions, and sensing for UAV intrusion detection.
- **Computer and Human Interaction.** Example use cases are coarse gesture recognition for application navigation and immersive interaction, head activity recognition, general gesture recognition, arm activity recognition, and keystroke recognition.
- **Healthcare.** The use cases for this category cover contactless sleep monitoring service, health monitoring at home, and service continuity of unobtrusive health monitoring.
- **Immersive Experience.** This category has use cases such as seamless XR streaming and immersive experiences based on sensing.
- **Smart Home.** Examples of use cases for this category are sensing-aided wireless charging, human proximity detection, spatial-aware control of instruments such as lights and fans, and fall detection.

8.3 Key ISAC Technology Areas

Two key technology areas for ISAC are the sensing architecture and the signal processing [NGA_Radiop1] [Liu_2022].

ISAC Architecture

The ISAC architecture corresponds to a sensing topology. As identified in Section 8.1, candidate sensing topologies include downlink mono-static sensing, uplink mono-static Sensing, downlink bi-static sensing, uplink bi-static sensing, and distributed/networked sensing. Since mono-static sensing requires the full duplex capability (which is quite complex to realize in practice), bi-static or multi-static sensing may be preferred to ease implementation. Furthermore, since the base station has more RF power, more processing power, and more space available compared to a UE, placing the sensing receiver at a base station instead of a UE may yield better performance and may be more practical. The use of downlink signals for sensing may be better than the uplink signals because the downlink signals can be much stronger than the uplink signals. Note that the reflected signals received at the sensing receiver can be quite weak due to the propagation path loss between the sensing transmitter and the object and the propagation path loss between the object and the sensing receiver. Hence, a stronger transmit signal would be preferable to a weaker transmit signal to ensure a detectable sensing signal at the sensing receiver.

ISAC Signal Processing

A typical communication system can focus on optimization of communications, and a typical radar system can focus on sensing optimization. However, an ISAC system needs to meet the communications performance targets as well as sensing performance targets. Examples of communications related key performance indicators (KPIs) are throughput, latency, accessibility, retainability, and mobility. Examples of sensing related KPIs are accuracy of positioning estimate, accuracy of velocity estimate, confidence level, sensing resolution, missed detection probability, false alarm probability, maximum sensing service latency, and refreshing rate. Possible design conflicts may arise in achieving desired communications and sensing KPIs.

The waveform needs to be designed properly to serve both communication and sensing needs. Furthermore, the waveform should have adequate flexibility to achieve the required tradeoffs between the communication and the sensing performances. The resources in time, frequency, and spatial domains need to be allocated properly to the communication and sensing services. The system needs efficient and flexible multiplexing and resource sharing for these two services.

While the conventional OFDM waveform can still be a good choice for ISAC, the 3GPP may also consider other waveforms, such as OTFS, for ISAC in 6G. The chosen ISAC waveform may need to support large channel bandwidths to achieve a target sensing resolution. Finally, AI/ML techniques could be applied to facilitate ISAC operations such as object detection.

8.4 ISAC Research Directions

The NGA has identified several research directions for ISAC [NGA_Radio1]. In mono-static sensing, the same entity, such as a base station, acts as a sensing transmitter and a sensing receiver. Hence, such a base station needs to support the full-duplex operation, which is extremely challenging because of the need to isolate transmission and reception in the same equipment and implement self-interference cancellation. The system needs to have adequate flexibility to support various frequency bands (e.g., higher bands for a finer sensing resolution and lower bands for reliable coverage), sensing numerology, and frame structure, to achieve target design trade-offs. Furthermore, as mentioned in Section 8.3, a base station may need to implement a downlink receiver in addition to the regular uplink receiver. Additionally, typical sensing systems assume line-of-sight propagation, which is extremely challenging to guarantee in a typical cellular network deployment. Hence, the ISAC system needs to have a robust design to enable sensing in the non-line-of-sight propagation conditions. Accurate radio channel models must be developed to design an effective ISAC system. When distributed sensing is used, timing synchronization would need to be considered for accurate sensing. Application of distributed spectrum sensing may also be considered by OSAC. ISAC may probe the environment to determine best propagation paths for communication. Furthermore, ISAC may exploit O-RAN to realize sensor-aided communications.

8.5 Testing Direction for ICAS Systems

ICAS merges communications KPIs with sensing figures of merit. Test strategy must therefore evaluate both domains concurrently and quantify their coupling.

Recommended directions

- **Dual-domain KPI matrix:** Measure throughput, BLER, latency, and positioning error alongside radar metrics such as range/velocity accuracy, probability of detection/false alarm, sidelobe levels, and resolution. Report Pareto fronts as sensing duty factor or power allocation varies.
- **Waveform co-existence:** Validate multiplexing of comm and sensing either in time, frequency, or code. Characterize the impact of sensing sidelobe control on ACLR/SEM and of comm PAPR on sensing dynamic range.
- **Channel realism:** Combine non-LOS multipath channel emulation with moving target simulators to stress joint estimators under realistic Doppler and clutter.
- **O-RAN/edge hooks:** Exercise split architectures where sensing features are exported to higher layers for resource orchestration; verify latency budgets for near-real-time ICAS adaptivity.
- **Calibration & traceability:** Define calibration steps for group delay, phase coherence, and timing that remain valid across multi-GHz bandwidths and sub-THz carriers so sensing outputs remain metrologically sound.

This ensures ICAS proposals are benchmarked on the actual trade space they must navigate rather than isolated, idealized KPIs.

9 AI-NATIVE RADIO INTERFACE

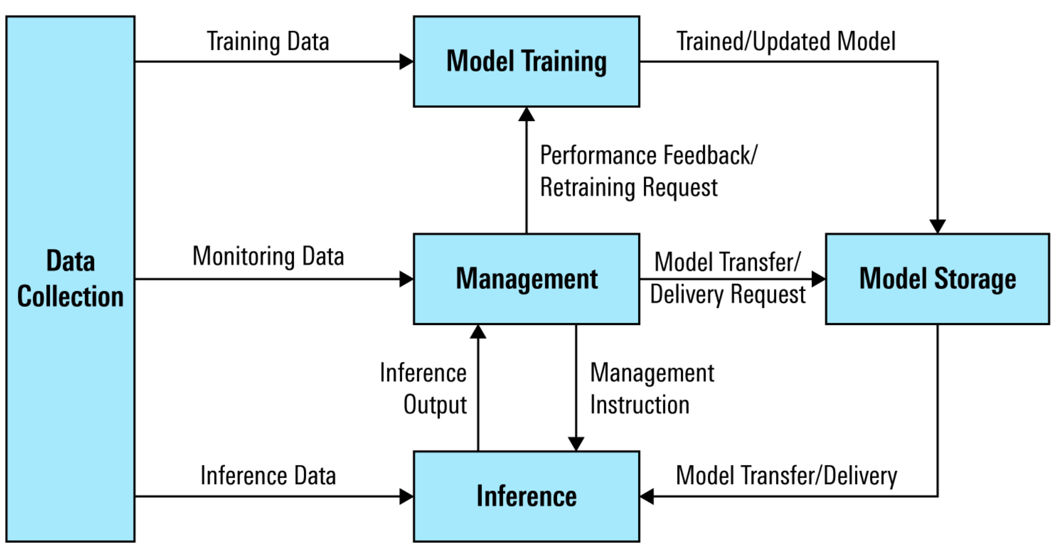
Organizations such as the 3GPP and the O-RAN ALLIANCE utilize the existing 5G system as a baseline and add AI capabilities. In contrast, 6G aims to use AI from the design stage itself. In other words, 6G aims to be AI-native. AI/ML is expected to be utilized throughout the 6G system, such as the communication device, radio network, core network, and services network. This section focuses on applying AI to the 6G radio interface.

Section 9.1 illustrates the AI/ML framework defined by the 3GPP for 5G-Advanced, which may be used as a baseline framework in 6G. Furthermore, Section 9.1 mentions the role of generative AI in 6G wireless communication. Examples of AI-driven optimization in radio resource management, including AI/ML use cases identified by the 3GPP in Release 18 and Release 19, are given in Section 9.2. Section 9.3 describes how classical signal processing can be augmented with ML-based signal processing in 6G. Section 9.4 discusses AI/ML-based linearization of analog RF frontends. Testing of a neural receiver using AI/ML models is narrated in Section 9.5. Section 9.6 summarizes challenges in implementing AI in real-time communications. Finally, an overview of research areas for the AI-based radio interface in 6G is given.

9.1 AI-Native Radio Interface: A Brief Introduction

The envisioned AI-native radio interface includes AI as an integral component of the air interface and is characterized by autonomy, continuous learning, and near-real-time optimization [NGA_Radio2]. 3GPP has begun incorporating AI/ML in 5G-Advanced with an initial study carried out in Release 18 and normative specifications starting in Release 19. Specifically, AI/ML in the NG-RAN aims to enhance network performance and user experience by analyzing the collected data autonomously [3GPP_TS38.300]. An NG-RAN node (i.e., a gNB) may obtain data from neighboring NG-RAN nodes and/or UEs. The AI/ML algorithms and models themselves are beyond the scope of the 3GPP specifications. The 3GPP may support two deployment scenarios [3GPP_TS38.300] [3GPP_TS28.105]. In one deployment scenario, AI/ML model training occurs in the OAM, and AI/ML model inference occurs in the NG-RAN node. In another deployment scenario, both the training AI/ML model and the inference AI/ML model occur in the NG-RAN node. An NG-RAN node may be configured to report information such as predicted resource status, UE performance feedback, measured UE trajectory, and energy cost [3GPP_TS38.300].

Figure 9.1 illustrates a functional framework studied by the 3GPP for AI/ML-based NR air interface [3GPP_TR38.843]. The 3GPP may use this framework as a baseline in 6G. Key functions of this framework are Data Collection, Model Training, Management, Inference, and Model Storage, and are described below.



. Figure 9.1: 3GPP-studied Functional Framework for AI/ML based NR Air Interface

Data Collection

The Data Collection function provides input data to other functions, including Model Training, Management, and Inference. Three types of data can be envisioned, training data, monitoring data, and inference data. The training data is the input data for the AI/ML Model Training function. The monitoring data is the input data for the management of AI/ML models or AI/ML functionalities. The inference data is the input data for the AI/ML Inference function.

Model Training

The Model Training function involves AI/ML model training, validation, and testing. Model performance metrics may also be created for use in the model testing procedure. The Model Training function may perform data preparation tasks such as data pre-processing and cleaning, formatting, and transformation based on the type of training data provided by the Data Collection function. This function also delivers trained, validated, and tested AI/ML models or updated AI/ML models to the Model Storage function.

Management

The Management function manages the overall operations, such as selection, deactivation/switching, and fallback, and monitors the performance of AI/ML models or functionalities. This function ensures that suitable inference occurs based on data received from the Data Collection and the Inference functions. This function utilizes the management instruction as input to manage the Inference function. The management instructions may include instructions on selection, deactivation, switching of AI/ML models or AI/ML-based functionalities, and fallback to non-AI/ML operation. Furthermore, this function uses a model transfer/delivery request to the Model Storage function to request model(s). The Management function may send Performance Feedback or Retraining Request to the Model Training function to provide information needed as input for model retraining or updating.

Inference

The Inference function receives the input from the Data Collection function, applies AI/ML models or AI/ML functionalities, and generates outputs. The Inference function may perform data preparation tasks such as data pre-processing and cleaning, formatting, and transformation based on the type of training data provided by the Data Collection function. The inference output is used by the Management function to monitor the performance of AI/ML models or AI/ML functionalities.

Model Storage

This function stores trained or updated models that can perform the Inference function. It uses Model Transfer/Delivery to provide an AI/ML model to the Inference function.

Generative AI

Generative AI has garnered significant attention from researchers for an AI-Native Air Interface. Example application areas of generative AI include wireless channel modeling, MIMO detection, constellation shaping, and channel-agnostic communication systems [NGA_Radio2]. While generative AI has good potential, there are several challenges that need to be addressed. For example, both training and inference are expected to be complex. Since generative AI models can create new instances by learning the distribution of training data, it is important to generate precise samples for training.

9.2 AI-Driven Radio Resource Management

An AI-native interface can be applied to various use cases in support of AI/ML-assisted radio resource management as mentioned in Figure 9.2 [NGA_Radio2] [3GPP_TR38.843]. These use cases include Channel State Information (CSI) feedback, beam management, MIMO symbol detection, constellation design, transceiver impairments, ISAC enhancements, positioning accuracy enhancements, neural-based receiver, and channel estimation reference signal design. Among these use cases, the 3GPP has identified CSI feedback enhancement, beam management, and positioning accuracy enhancements in [3GPP_TR38.843].

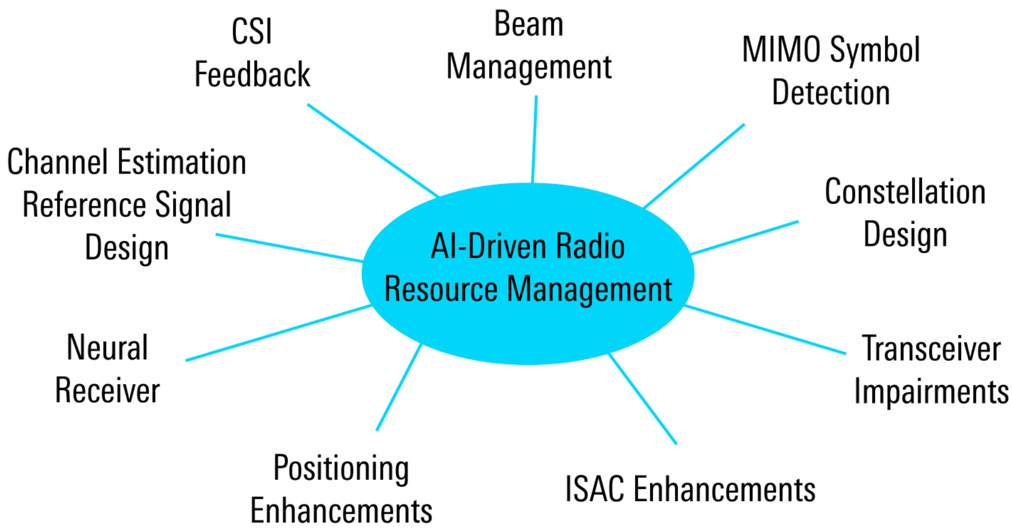


Figure 9.2: AI-Driven Radio Resource Management

Channel State Information (CSI) Feedback

6G is expected to be much more complex than 5G. MIMO architectures such as gigantic MIMO with numerous antenna elements, and massively distributed MIMO lead to CSI feedback that requires high overhead. AI/ML can potentially be applied to directly learn low-dimensional CSI representations, and two-sided AI/ML models for joint UE-side compression and base station-side reconstruction can be exploited [NGA_Radio2].

Beam Management

At high carrier frequencies such as the mmW band, sub-THz band, and THz band, narrow high-gain beams are required to overcome large propagation path losses and achieve a high SINR. However, in these situations, there is a large overhead in acquiring and maintaining UE-specific optimal beams. AI/ML can be utilized to manage beams and maximize throughput through intelligent means such as Modulation and Coding Scheme (MCS) prediction, blockage reduction, and codebook [NGA_Radio2].

MIMO Symbol Detection

As higher-order MIMO becomes more prevalent, detecting MIMO symbols reliably becomes a challenge. Indeed, Maximum likelihood detection and equalization could become quite complex in 6G. To address this complexity, AI/ML can be applied to achieve a target tradeoff between the complexity and the performance of the MIMO symbol detection algorithm. In a data-driven approach, neural networks are used to detect MIMO symbols directly. In contrast, in a model-driven approach, neural networks are integrated into existing algorithms [NGA_Radio2].

Constellation Design

Signal constellations with uniformly spaced modulation symbols are commonly used in 5G. However, a non-uniform signal constellation could provide better performance at the cost of increased complexity and processing requirements. Designing non-evenly spaced and/or non-uniformly distributed signal constellations for various radio channel conditions is non-trivial. Hence, AI/ML can be exploited to determine optimal signal constellations that increase spectral efficiency in different radio channel conditions [NGA_Radio2]. Such signal constellation design may be changed dynamically.

Transceiver Impairments

Some components in the transceiver may be non-linear. Furthermore, some components may create impairments. Non-linearities and impairments can degrade the achievable performance. AI/ML can be explored to address such non-linearities and impairments so that high reliability and spectral efficiency can be achieved through intelligent processing despite the inherent transceiver challenges in 6G [NGA_Radio2].

ISAC Enhancements

Sensing typically assumes line-of-sight (LOS) propagation environment. Hence, in a realistic non-LOS propagation environment, sensing accuracy can be quite poor in an ISAC system. It is possible to exploit AI/ML to enhance sensing performance in a non-LOS radio environment. Indeed, when accurate sensing is achieved, sensing can be leveraged to enhance the utilization of communication-related radio resources [NGA_Radio2].

Positioning Accuracy Enhancements

Positioning errors can be large in challenging environments such as non-LOS propagation environments. The 3GPP has been aiming for high-accuracy positioning in several use cases, including automated factories and dense urban environments. AI/ML can be exploited to enhance the positioning accuracy [NGA_Radio2].

Neural-Based Receiver

A typical receiver consists of distinct processing blocks such as channel estimation, demodulation, and decoding. As the physical layer becomes more complex, the receiver's complexity increases. One or more processing blocks can be replaced with a neural network. Indeed, in the extreme case of a neural receiver, the entire receiver pipeline could be replaced with a neural network [NGA_Radio2].

Channel Estimation Reference Signal Design

Coherent demodulation is widely used in modern communication systems. Coherent demodulation requires an efficient reference signal design. If too few radio resources are used for the reference signal, channel estimation performs poorly. In contrast, if too many radio resources are used for the reference signal, the overhead increases. Hence, a balance needs to be achieved by the reference signal design. It is possible to substitute a fixed design of reference signals with an intelligent and adaptive design created by AI/ML. Indeed, AI/ML can exploit offline datasets and make dynamic adjustments to the reference signal design. AI/ML can also support high-dimensional and nonlinear radio channel representations [NGA_Radio2].

9.3 Augmenting Classical Signal processing with ML-based Signal Processing

Hybrid design principle. Combine model driven blocks with data driven learners where classical methods are brittle or computationally prohibitive. Examples: learned MIMO detectors that warm start sphere decoding; neural channel estimators that adapt pilot density on the fly; learned beam management policies using side information from sensors.

Where ML helps:

- MIMO detection: replace hard decision stages with lightweight DNNs or plug in unfolded networks to reduce complexity while preserving near ML performance.
- Constellation shaping: use ML to adapt non uniform constellations to channel state and PA constraints for spectral efficiency gains.
- Transceiver impairment mitigation: compensate PA memory effects, IQ imbalance and LO phase noise with learned inverse models integrated post equalizer.
- ISAC enhancement and positioning: fuse sensing returns to improve link adaptation and refine UE positioning in NLOS.

Deployment constraints. Enforce latency, memory and energy budgets; quantize models for on device inference; implement fallback to classical algorithms; define lifecycle hooks for online monitoring, drift alarms and retraining.

9.4 AI/ML-based Linearization of Analog RF Frontends

Problem. Sub THz and wideband FR3 radios suffer strong nonlinearity and memory effects. Classical DPD using memory polynomials/Volterra models can struggle across multi band, high PAPR, and thermally drifting conditions.

ML aided DPD. Train neural predistorters (feed forward or LSTM) on captured I/Q, using indirect learning or closed loop architectures. Condition models on temperature, frequency, and output back off; include uncertainty aware loss to avoid overfitting. For multi user/multi carrier signals, add cross term features capturing inter band coupling.

Test plan. Sweep bandwidth, waveform type and PAPR; measure EVM, ACLR, NPR, AM/AM and AM/PM, and efficiency. Validate model stability under device aging and supply droop. Compare inference latency against TX pipeline budget and quantify fallback to polynomial DPD under watchdog triggers.

9.5 Testing of a Neural Receiver using AI/ML Models

Objective. Establish a repeatable bench to qualify neural receivers that replace parts or all of channel estimation, equalization and decoding.

Test artifacts. Curate datasets spanning standardized channel models plus hardware captured impairments (phase noise, IQ imbalance, PA compression). Maintain train/val/test splits with no scene leakage; log seeds and hyperparameters for reproducibility.

Metrics. BLER/throughput vs. SNR and mobility; generalization to unseen channels; robustness to distribution shift; calibration of soft outputs; compute/latency/energy profiles; resilience under adversarial perturbations; graceful fallback behavior.

Procedures:

1. Pre silicon: inject synthetic channels and impairments, run HIL with vector instruments as channel/impairment sources.
2. Post silicon: OTA in anechoic and reverberation chambers; measure coexistence with legacy receivers.
3. Lifecycle: monitor drift, trigger model updates via MLOps hooks; verify bit exact model portability across toolchains and quantization levels.

9.6 AI-Native Radio Interface for 6G: Challenges and Research Areas

While an AI-native air interface has the potential to revolutionize the air interface, several challenges need to be addressed. Furthermore, research is needed in several areas to realize the full potential of the AI-native air interface in 6G. Details of these challenges and research areas are available in [NGA_Radio2] and are summarized below.

Challenges for the AI-Native Radio Interface

Key challenges include Lifecycle Management (LCM) of AI/ML Models, Test and Interoperability Challenges.

Lifecycle Management (LCM) of AI/ML Models.

New challenges emerge when AI models in an AI-native air interface are deployed. In one approach, AI/ML models are trained in the network and sent to UEs for use. The model information needs to be transferred using precious radio resources. In particular, when models require two-sided communication (i.e., between the device and the network), the amount of information to be carried over the resource-constrained radio interface increases. To address this information transfer challenge, effective and secure methods for deploying and updating AI models would be needed in 6G.

Another challenge is that the 6G system needs to ensure that UEs can run the transferred AI/ML models. To address this challenge, in one approach, the network could check the model structure for compatibility with target UEs. In another approach, UEs could inform the network about their model capabilities and compatibility. In a more elaborate approach, the UE may inform the network about its AI/ML capabilities, such as supported instructions, library licenses, and available resources.

Testing and Interoperability Challenges

The advent of AI-native air interface leads to testing and interoperability challenges. These challenges are described in [NGA_Radio2] and summarized next.

Two major types of testing are conformance testing and performance testing. Conformance testing helps ensure compliance with relevant specifications and interoperability requirements. In contrast, performance testing ensures that the product's performance meets the minimum performance levels defined by relevant specifications.

For conformance testing [NGA_Radio2], one challenge is specifying any required interfaces and creating procedures for AI-native air interfaces (e.g., triggering monitoring reports). Another challenge is that new protocols and methodologies are needed to evaluate different LCM aspects of AI/ML functions. For example, over-the-air (OTA) updates of AI/ML models may need to be tested. Furthermore, there could be interdependence between multiple AI/ML models.

One challenge for performance testing [NGA_Radio2] is that suitable data sets must be defined and generated to enable standardized testing. Furthermore, relevant KPIs and pass/fail criteria for AI/ML-based functions. Additionally, testing needs to determine if specific input parameters or data generate predictable outputs that can be used to assess pass/fail for the AI/ML functions. Accuracy in monitoring reports and outcomes also needs to be defined.

New interoperability-related challenges emerge when two-sided models are used, and different vendors have developed these two sides of the models. For example, the UE side may be performing compression, and the network side may be performing decompression using a joint AI/ML function. A trade-off between reference and proprietary implementations also needs to be considered.

To enable standardized testing, methodologies for generating data sets for training/learning, validation, and testing are needed. The overall certification process would likely need to be updated. For example, 3GPP conformance specifications are utilized by the Global Certification Forum (GCF) and Personal Communications Service (PCS) Type Certification Review Board (PTCRB) for mobile device certification. PCS stands for Personal Communications Service. To facilitate testing of an AI-native air interface, updates to testing procedures followed by GCF and PTCRB would need to be made. Separate testing procedures may be needed for proprietary implementations.

Research Areas for the AI-Native Radio Interface

Examples of research areas for the AI-native radio interface include (i) generalizability and specialization in AI/ML models, (ii) role of AI/ML in next-generation networks, (iii) synergizing efficient data-driven AI with domain expertise, (iv) green AI frameworks, and (v) responsible and explainable AI [NGA_Radio2]. These areas are discussed in [NGA_Radio2] and briefly summarized here.

Generalizability and Specialization in AI Models.

Generalizability is the ability of AI/ML models to perform well on unseen data (NGA_Radio2). However, this generalizability is challenging to achieve in a wireless system because of the dynamic nature of the radio channel and the availability of reliable and relevant training data. Research is needed to enhance generalizability. For example, there is a need to generate a suitable training dataset that reflects diversity of real-world radio channel environments. The use of regularization techniques and suitable constraints could enhance robustness of the AI/ML based algorithms. Furthermore, causal relationships within the dataset could be exploited to improve generalizability. The use of a set of specialized AI/ML models instead of one large model could be investigated, where each model .is customized for a specific scenario or configuration.

Role of AI/ML in Next-Generation Networks.

While AI/ML can revolutionize 6G, research is needed to determine its specific role. The performance of an AI/ML algorithm needs to be quantified against a traditional algorithm by considering suitable KPIs that reflect various perspectives such as performance improvement, complexity, computational requirements, and energy requirements. Without suitable datasets, AI/ML algorithms cannot be expected to perform well. Datasets are often proprietary, further complication the design and testing of AI/ML algorithms.

Synergizing Efficient Data-Driven AI with Domain Expertise.

Data plays a crucial role in the design of the AI-native air interface. Comprehensive and high-quality data that reflects realistic scenarios is important for the training of AI/ML models. Such data enables the convergence of the AI/ML model. It may be quite costly to acquire data for some functions, especially at the physical layer and other layer 2 of the radio interface protocol stack, due to a large amount of data generated in case of a system with numerous time-frequency resources and short symbol times and transmit time intervals. Research is needed to increase the efficiency of data acquisition. In some scenarios, suitable data augmentation is needed if data is missing or inadequate. Furthermore, datasets may be a function of the use case. Active learning strategies that prioritize informative training data could be explored in 6G. Furthermore, it may be necessary to integrate domain knowledge with data-driven AI/ML algorithms.

Green AI Frameworks.

AI/ML has good potential to outperform traditional non-AI/ML algorithms for the AI-native radio interface. However, there are concerns about the energy consumption and carbon footprint of advanced AI/ML models. Since 6G emphasizes sustainability as one of the important goals, energy efficiency becomes an important consideration. Research is needed to reduce the overall computational complexity and increase the energy efficiency of AI/ML models. Both the device and the radio network need to be energy efficient. Energy efficiency becomes even more important for wireless devices because these devices have much less power availability and processing abilities compared to the radio network. 6G could explore methods such as model compression, pruning, and low-precision inference to reduce memory and computational power requirements. Knowledge distillation could potentially utilize simpler AI/ML models while minimizing performance degradation. Furthermore, research in AI methods such as Spiking Neural Networks (SNNs) and hyper-dimensional computing could help enhance energy efficiency.

Responsible and Explainable AI.

Like many other domains, transparency is quite important for the AI-native air interface. Stakeholders need to have confidence in the trustworthiness and fairness of AI/ML algorithms. In general, typical AI/ML models such as deep neural networks (DNNs) lack transparency and are often treated as a black box. Research is needed on Explainable AI (XAI) to clearly explain the functioning of the AI/ML model. The causal learning method improves interpretability by pointing out causal relationships in the decisions made by an AI/ML model. XAI can be exploited to meet ethical, societal, and regulatory expectations.

10 GREEN NETWORKS AND DEVICES

Sustainability is one of the important objectives for 6G. For example, the ITU has specified sustainability as one of the four overarching aspects of IMT-2030 [ITU_IMT-2030_Framework]. Furthermore, the NGA has also identified sustainability as one of the six audacious goals for 6G [NGA_Roadmap_2022].

Section 10.1 discusses sustainability from the perspective of 6G, sustainability goals, and performance metrics. Candidate technologies for a green radio network are described in Section 10.2. The concept of Near Zero Energy (NZE) communications is introduced in Section 10.3. The device aspect of sustainability in the form of device power savings is addressed in Section 10.4.

10.1 Sustainability, Indicators, and KPIs

6G could become sustainable by providing energy-efficient networks and devices, implementing circular economy principles, and reducing its environmental impact on materials, water, land, and air [NGA_Roadmap_2022]. Sustainable 6G can reduce its carbon footprint. Reduced energy consumption and increased usage of renewable energy sources are important in 6G. 6G can also help other verticals become sustainable. Climate change related key challenges include global temperature increase and biodiversity loss, and the path toward more sustainable 6G spans the full life cycle of ICT technologies, which includes material sourcing and mining, manufacturing, supply chain, operation and maintenance, and waste management [NGA_Sustainability_2023].

The ITU has issued guidance to ICT sector organizations on setting net-zero targets and strategies to achieve decarbonization toward achieving net-zero emissions. Note that net zero carbon dioxide emissions correspond to the point when "anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period" [NGA_Sustainability_2023]. Example decarbonization strategies include "(i) operating energy-efficient network (e.g., power saving features, alternative energy supply, consolidation and virtualization, and free cooling and location optimization), (ii) efficiency in buildings and services (e.g., monitoring solutions for efficient buildings, focus on energy conservation measures, alternative mobility concepts, and video conferencing and audio conferencing), (iii) alternative energy (e.g., self-production of renewable energies, purchasing renewable energy, energy supply innovation), (iv) application of the circular economy principles (e.g., eco-design of products and services, reuse of network equipment, optimizing the life cycle and end-of-life of customer products and services, and selling repairable products)" [NGA_Sustainability_2023].

Figure 10.1 shows five key sustainability impact categories identified by the NGA for a sustainable 6G ecosystem. These categories include (i) energy, (ii) greenhouse gas (GHG) and other emissions, (iii) water footprint, (iv) reuse, recycle and refurbish, and (v) land and biodiversity [NGA_Sustainability_2023].

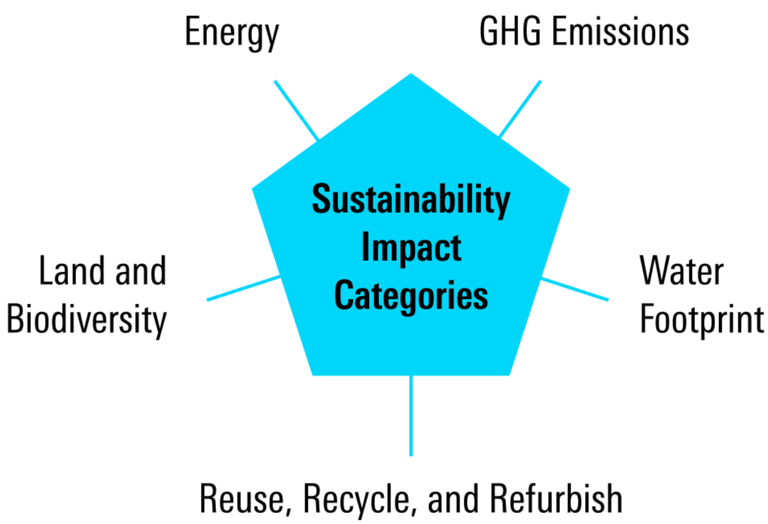


Figure 10.1: Sustainability Impact Categories

Important energy-related topics include Energy consumption, energy efficiency, renewable energy usage, and sources. GHGs trap heat in the atmosphere. Examples of GHSGs are carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride. Emissions of the GHGs need to be tracked. Water footprint needs to consider withdrawal or extraction from sources, consumption, discharge, and efficiency of reuse. Reusing, recycling, and refurbishing help reduce waste. To minimize the impact on land and biodiversity, the sustainable use of terrestrial ecosystems is desirable. Specifically, the 6G ecosystem addresses the impact on land and biodiversity caused by data centers, cell sites, network equipment, manufacturing facilities, and access and easements for backhaul and metro-area networks.

Suitable key performance indicators (KPIs) related to these sustainability impact categories need to be defined and tracked to quantify the progress toward sustainability goals. Furthermore, these sustainability impact categories need to consider the building blocks of the 6G ecosystem including the end user communication devices (e.g., smartphones, AR/VR headsets, and IoT devices), RAN, core network, centralized and edge clouds or data centers, and supply chain and manufacturing processes (i.e., the processes that transform raw materials into finished products and deliver these products to customers).

Examples of sustainability KPI metrics discussed in [NGA_KPI_Assessment_2023] are mentioned below.

- **Energy.** Energy-related metrics include total energy consumption, power usage effectiveness, energy reuse factor, renewable energy factor, renewable energy consumption, energy consumption per customer (e.g., operator), and energy intensity.
- **GHG and other emissions.** Relevant metrics for emissions are GHG emissions, location-based and market-based carbon intensity, carbon usage effectiveness, and carbon intensity.

- **Water footprint.** Related metrics are total site water usage, total source water usage, and water usage effectiveness.
- **Reuse, recycle, and refurbish.** The metrics relevant to water footprint are total waste generated, waste landfilled and diverted, waste diversion rate, and percentage recycled hardware.
- **Land and biodiversity.** Relevant metrics include total land occupation to support the product/system, proportion of land degraded over total land area, and mean species abundance (MSA).

The pathway to net-zero emissions needs to consider scope 1, scope 2, and scope 3 emissions. Scope 1 emissions are within direct operational control, scope 2 emissions are indirect emissions from the generation of purchased electricity, and scope 3 are emissions from products during manufacturing and transportation (Scope 3) [NGA_Evolution_Sustainability_2023]. The three pillars of sustainable 6G identified in [NGA_Evolution_Sustainability_2023] include observability, choice, and circular economy. Observability of sustainability KPI metrics involves observing indicators in near real time. Choice enables end users to select one or multiple sustainability options to achieve a target tradeoff among KPI metrics. Circular economy makes use of the nine Rs, such as rethink, refuse, reduce, reuse, repair, refurbish, remanufacture, repurpose, and recycle, to realize sustainability.

- **RAN-specific KPIs.** In a wireless system, the RAN consumes a significant amount of energy. The RAN consumes more than 73% of the energy used by a Communications Service Provider (CSP) [NGA_Radio2]. Climate control and the base station configuration contribute to RAN's energy performance. Several RAN-specific sustainability KPIs specified in [NGA_Evolution_Sustainability_2023] are briefly introduced below.
- **DV_T/EC_T** is the ratio of the total data volume (DVT) of the UP data in bits to the total RAN energy consumed (ECT) in kilowatt hours (kWh). It indicates the RAN's energy efficiency in delivering services to users.
- **Site Energy Efficiency (SEE) or Power Usage Efficiency of RAN (PUER).** It is the ratio of the energy used by the RAN equipment for tasks such as communications, computing, and sensing and the total energy usage in the RAN site. This KPI indicates how much energy is used to support the core functions of the RAN compared to overhead, such as cooling.
- **Energy Re-use Effectiveness (ERE).** It is the ratio of re-used energy by facilities, external to the ICT/base station site, to the total energy consumption of the ICT/base station site. Note that the heat generated by the base station site can potentially be reused to heat water, facilities within the ICT/base station site, and other commercial or residential sites.
- **EC_N/DV_T.** It is the ratio of the total RAN equipment energy consumed (ECN) in kWh and the total data volume (DVT) of the UP data in bits during a given reporting period. It is the inverse of DVT/ECT.
- **P_R.** It is the percentage of energy from renewable sources of the total energy used in RAN. It indicates how much energy is obtained from renewable energy sources.
- **UE_{ACT}/EC_T** is the ratio of the average number of UEs (UEACT) or connections and the total energy consumed (ECT) during a given data collection period. It indicates the RAN's energy efficiency in serving users.
- **A/EC_T.** It is the ratio of area A (in square meters) that has a signal strength[3] of -110 dBm or better, and the total energy consumed (ECT). It indicates the overall energy efficiency of the RAN in serving a given geographic area with a certain coverage quality.
- **Physical Resource Block occupancy (PRBO)** is the ratio of the number of PRBs utilized to the total number of PRBs. It can be measured on a per-carrier or per-cell level.
- **EC_T/N_S.** It is the ratio of the total energy consumed (ECT) and the number of subscribers served NS during a given period. It is an indicator of energy consumption per subscriber and is expressed as kWh per customer. Energy Consumption Total (ECT). It is the sum of ECN and ECs, where ECN is EC of network nodes (including X-haul) and ECs is the energy consumption by non-network nodes such as cooling.
  Energy Consumption Total (ECT). It is the sum of ECN and ECs, where ECN is EC of network nodes (including X-haul) and ECs is the energy consumption by non-network nodes such as cooling.

Product Circularity KPIs

A circular economy aims to keep products, components, and materials at their highest utility and value while reducing waste [NGA_Evolution_Sustainability_2023]. The United Nations Environment Program (UNEP)'s circular economy approach utilizes the reduce-by-design principle and value retention processes. The NGA has specified circularity indicators of a product for three categories [NGA_Evolution_Sustainability_2023]. These indicators

[3] This signal strength can be viewed as equivalent to Reference Signal Received Power (RSP) used in LTE and 5G.

can determine the circularity of an integrated base station or components of a disaggregated base station. The indicators for all three categories are listed below.

- **Category 1: Product Durability (PD).** Relevant circularity indicators include software and data support, scratch resistance, maintenance support, robustness, battery for portable ICT goods, and data security.
- **Category 2: Equipment-level ability to recycle, repair, reuse, and upgrade.** Relevant circularity indicators include fasteners and connectors, diagnostic support, material recycling compatibility (plastic parts and metal parts), recycled/renewable plastics, recycled metals, material identification, hazardous substances, critical raw materials, packaging recycling, and technical performance product mass-based material efficiency.
- **Category 3: Manufacturer-level ability to recycle, repair, reuse, and upgrade.** Relevant circularity indicators include the service offered by manufacturers, spare parts distribution, spare parts availability, disassembly information, collection and recycling programs, and environmental footprint assessment knowledge available to improve the equipment material efficiency.

Additional examples of circularity KPIs are the repairability index and recycling rate [NGA_Evolution_Sustainability_2023]. The repairability index rates products and components based on their ease of repair and considers factors such as spare parts availability, disassembly simplicity, and repairability documentation. The recycling rate is the percentage of materials from decommissioned infrastructure that are recycled or reused in the production of new components.

Overall Environmental Sustainability Indicators for 6G

The NGA has identified **sustainability indicators** from the perspectives of **observability, choice,** and **circular economy** [NGA_Evolution_Sustainability_2023]. These indicators are briefly mentioned below.

Observability Indicators

Enhanced observability enables accurate and reliable recording and reporting of environmental sustainability metrics. Observability-related indicators are Renewable Energy Ratio (RER), Grid Dependency Ratio (GDR), Carbon Intensity of Energy (CIE), Energy Efficiency Index (EEI), Peak Load Efficiency (PLE), Dominant Energy Source (DES), and Energy Storage Efficiency (ESE) [NGA_Evolution_Sustainability_2023]. RER is the ratio of the renewable energy consumption (i.e., the energy consumed by the network element or domain from renewable sources) and the total energy consumption by the network element. RER indicates the proportion of energy that is derived from renewable sources. GDR is the ratio of total energy consumption by the network element to grid-sourced energy consumption by the network element. GDR quantifies the reliance of the network element on the external power grid. CIE is the ratio of carbon dioxide emissions to the total energy consumption for the network element. CIE quantifies the impact of the network element on CO2 emissions. EEI is the ratio of the network element's useful energy output and the network element's energy input. EEI quantifies how efficiently the network element converts energy input into useful energy output. PLE is the ratio of the energy input during peak load and the useful work output during peak load. PLE quantifies the energy efficiency of the network element during periods of high demand. DES is the consumption from an energy source with the highest input by the network element to the total energy consumption by the network element. DES quantifies how much reliance the network element has on the single highest energy source. ESE is the ratio of energy input for storage and useful energy output from storage. ESE quantifies the effectiveness of energy storage systems associated with the network element.

Choice Indicators

These indicators quantify the environmental impact of different service configurations, which can be displayed on a dashboard. Example KPIs include Sustainability Impact Index, Green Service Performance Index, User Sustainability Profiles, Renewable Energy Usage Percentage, and Energy-saving analytics (while accepting QoS-Sustainability Balancing). Sustainability Impact Index quantifies the environmental impact of a given service configuration. Green Service Performance Index is a composite index that considers traditional performance metrics (e.g., throughput and latency) and sustainability metrics to provide a holistic view of service quality. User Sustainability Profiles categorize users within predefined profiles related to sustainability goals and metrics. Renewable Energy Usage Percentage quantifies the proportion of energy obtained from renewable sources. Energy-saving analytics quantify the energy savings realized due to the downgrade of QoS.

AI/ML can be exploited to recommend service configurations that help realize target sustainability goals. KPIs related to AI/ML sustainability recommendations include Sustainability-Personalized Service Recommendations Effectiveness and Energy Efficiency Improvement from AI Optimization.

"Sustainability-Personalized Service Recommendations Effectiveness" quantifies the effectiveness of AI-driven recommendations in aligning services with user goals based on the acceptance of such recommendations by the user. "Energy Efficiency Improvement from AI Optimization" quantifies the improvement in energy efficiency realized through AI-driven optimizations relative to a baseline configuration.

Circular Economy indicators quantify the environmental impact of products during their lifecycle. The product circularity KPIs mentioned earlier in the section are examples of circular economy indicators.

10.2 Section 10.2 Technologies for a Sustainable 6G Network

The manufacturing of the RAN and the UE inherently has a certain carbon footprint. The degree of circularity influences the net effect on the carbon footprint. A carbon footprint associated with the operations is influenced by energy consumption and the amount of regenerative energy used.

Figure 10.2 shows NGA-identified factors that can contribute to making a 6G network sustainable [NGA_Radio2].

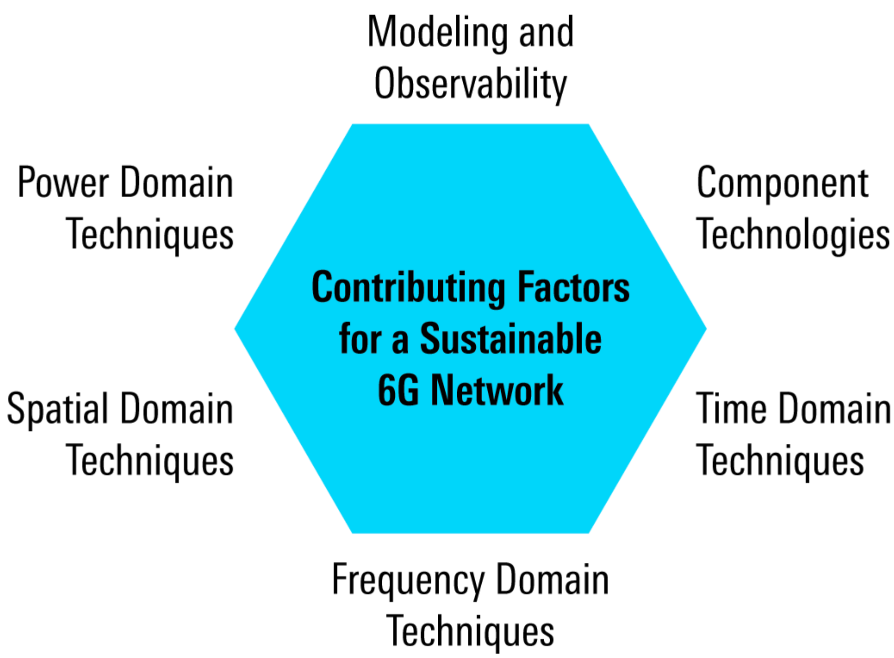


Figure 10.2: Factors Contributing to a Sustainable 6G Network

Modeling and Observability

While the traditional system design of a cellular system considers factors such as capacity, throughput, latency, and coverage reliability, new considerations for sustainability are also needed in 6G. Suitable modeling of the impact of various design choices on sustainability-related metrics or indicators is needed [NGA_Radio2]. Relevant KPIs need to be defined so that the designs can be evaluated using such sustainability KPIs. Standardization of sustainability KPIs is desirable. Both traditional KPIs and sustainability KPIs should be evaluated while performing R&D and selecting technologies or features for standardization. Observability of sustainability metrics and KPIs mentioned in Section 10.1 is important to evaluate the ability of 6G to realize sustainability goals.

Component Technologies

As mentioned in Section 10.1, the RAN consumes a vast majority of the energy used by a cellular network. Furthermore, the RF power Amplifier (PA) consumes most of the energy within the RAN. The PA efficiency degrades as the carrier frequency increases (e.g., from sub-7 GHz to mmW or from mmW to sub-THz/THz). Additionally, the need for extreme massive MIMO systems in 6G leads to increased RF PA requirements. If the

RF PA is made efficient, energy consumption can be reduced accordingly. AI/ML algorithms can be exploited to realize intelligent digital pre-distortion (DPD) to increase the efficiency of the RF PA. Furthermore, Gallium Nitride (GaN)-based PA technology for RF frequencies above 2.5 GHz can increase energy efficiency.

If other components, such as the physical layer processor, digital front-end (DFE), transceiver, analog front-end, filters, and antennas, are also made more energy-efficient, the overall RAN can become greener [NGA_Radio2]. Integrating digital logic, internal memory, and a central processing unit (CPU) into a system on Chip (SoC) implementation can help reduce power consumption and eliminate power consumption resulting from inter-module information exchanges. Furthermore, integrating the antenna with the filter unit can reduce insertion loss. Additionally, well designed board layout and heat sinks can contribute to energy efficiency in 6G.

Time Domain Techniques

Examples of time-domain techniques that can save energy include SSB/SIB-less transmission adaptation and micro-discontinuous transmission (micro-DTX) [NGA_Radio2]. When the loading is low or medium, intelligent adaptation of SSB/SIB-less transmission can reduce energy consumption. Micro-DTX involves moving analog components into the micro-sleep mode in the absence of data transfer. Note that there are more opportunities for micro-DTX when the loading is light.

Frequency Domain Techniques

To reduce energy consumption, frequency domain techniques such as frequency resource selection, agile carrier bandwidth part selection, and intelligent carrier aggregation can be exploited [NGA_Radio2]. Resource blocks within the channel bandwidth can be adapted based on radio channel conditions, and loading can reduce energy consumption. Different carrier bandwidth parts can be intelligently and quickly activated or deactivated. Similarly, selected carriers can be activated or deactivated based on radio channel conditions and user traffic. UE-assisted management of these frequency domain techniques can lead to increased energy savings.

Spatial Domain Techniques

The RAN can deactivate some transceivers to save energy for spatial domain processing. At the same time, the RAN can continue to realize a beamforming gain by keeping the antenna elements connected to such disabled transceivers active. Reference signals may still be transmitted to ensure reliable acquisition of comprehensive channel state information (CSI). Alternatively, CSI can be estimated based on the physical parameters of the radio channel (e.g., the angle of departure and multipath delays) that are independent of the spatial domain configuration of the base station.

In another technique, energy consumption of RF PAs can be reduced by dynamically and intelligently muting specific antenna elements and associated corresponding PAs and DFEs.

Power Domain Techniques

Power domain techniques can be used to influence the operation of the RF PA to save energy. As discussed earlier in this section, the RF PA has a considerable influence on the overall energy consumption in the RAN. In one power domain technique, the RF PA's output power is adapted to the network loading to realize significant energy saving. Accurate estimation or prediction of network loading and the overall network status can facilitate adaptation of the RF PA power.

Another power domain technique that mitigates the nonlinear impairments of the RF PAis digital pre-distortion and/or digital post-distortion techniques. Digital predistortion exploits internal RF feedback at the transmitter to address the non-linear distortion introduced by the RF PA, enabling the RF PA to operate in the traditionally non-linear region without causing much distortion in the transmit signal. Digital post-distortion removes distortion in the received signal through suitable post-processing at the receiver (i.e., the UE in case of the downlink transmission). Suitable adjustments to the spectral mask for the out-of-band emissions may be needed.

10.3 Near-Zero Energy (NZE) Communications

What is NZE Communication?

NZE communication utilizes low-power devices that are powered by ambient energy sources such as sunlight, thermal, or RF energy sources [NGA_Radio2]. These devices typically tend to be IoT devices. The NZE devices may store harvested energy in components such as capacitors or rechargeable batteries, or directly use harvested energy to perform tasks such as sensing and communications. Both the 3GPP and the IEEE have carried out studies on NZE devices. NZE communication facilitates the development of a sustainable and cost-effective IoT ecosystem.

NZE devices can be classified as active or passive based on their signal generation method [NGA_Radio2]. Active NZE devices harvest ambient energy and transmit using active circuit components such as a power amplifier. In contrast, passive devices utilize backscattering activation or illumination signal instead of active transmission components. Active devices typically have a longer range than passive devices. Passive devices modulate information over the reflected signal. In the monostatic configuration, both the activator in the transmitter and the reader device in the receiver are in the same entity. In the bi-static configuration, the activator in the transmitter and the reader device in the receiver are different entities. Passive devices may or may not have a battery. Radio Frequency Identification (RFID) Tags are examples of passive devices.

NZE devices have numerous use cases. The NGA has classified them into five categories based on their application types and functionalities [NGA_Radio2].

- **Category 1 NZE Devices.** NZE devices can serve as an ID or a numerical value indicator. There is a unique ID for a type, object, or person. Example use cases include (i) the use of a type or serial number for inventory control in smart warehousing, (ii) the use of a product ID and value for automated check-out at a point of sale, (iii) the use of ID for entry or access control to ensure safety, and (iv) medical equipment inventory in health care.
- **Category 2 NZE Devices.** These NZE devices perform measurements. They can measure, record, and report temperature, humidity, toxic gas, sound, voltage level, and weight. Example use cases include (i) Heating, Ventilation, and Air Conditioning (HVAC) control and carbon monoxide (CO) detection in smart buildings, (ii) transportation of containers or packaging of temperature sensitive goods in cold chain management, (iii) temperature-sensitive production line and worker protection in smart manufacturing, (iv) greenhouse in smart agriculture, (v) warehousing, (vi) mining, (vii) submarines or aircraft/space shuttles, (viii) airtight facilities/labs, (ix) remote monitoring of power quality in smart grids, and (x) cargo weight tracking in transportation.
- **Category 3 NZE Devices.** These devices indicate the presence of certain substances. Example use cases include (i) CO or radon gas alarm systems in smart homes, (ii) emergency vehicle control in transportation, (iii) fall detection in health care, (iv) automatic lighting in smart homes, and (v) quality control for photo resistant packaging in smart manufacturing.
- **Category 4 NZE Devices.** These devices use a beacon for presence and location. The beacon may respond to a read trigger and may convey ID, coordinates, and other information relevant to the application. Example use cases include (i) buoy for maritime, (ii) environmental land-marking, (iii) UAV route control in smart manufacturing, and (iv) drone guiding-assist system.
- **Category 5 NZE Devices.** These devices perform switching to act as a trigger for a more complicated system. Conveyor control in smart manufacturing is an example use case.

Motivation for NZE Communications

NZE communications can help reduce the carbon footprint. While the energy consumed by a single device is quite low compared to the energy consumed by a base station, the total energy consumption for a vast number of devices could be significant. Hence, using renewable sources in hundreds of millions of NZE communication IoT devices could significantly reduce the cumulative energy consumption. Note that NZE communications can also be applied to higher-tier devices and networks to make them more sustainable.

Figure 10.3 shows both device-side and network-side technology enablers for NZE communications. For details of these technology enablers, see [NGA_Radio2].

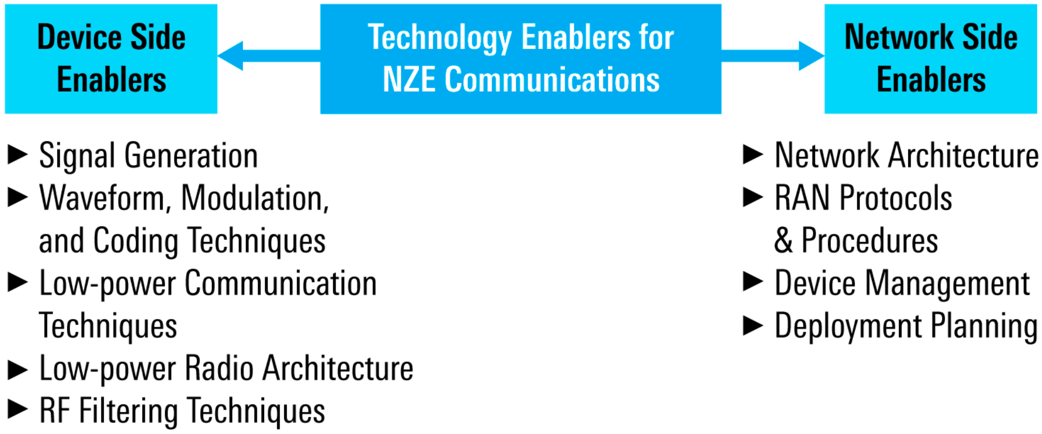


Figure 10.3: Technology Enablers for NZE Communications

Device Side Technology Enablers of NZE Communications

- **Signal Generation.** As mentioned earlier, an active NZE device can generate a signal internally using an active component, and a passive NZE device uses backscattering of an externally generated signal. When the signal is generated externally, the NZE device receives an unmodulated carrier wave and performs processing such as modulation (e.g., ASK or PSK), encoding, and reflection as a backscatter signal. When the signal is generated internally, an active component such as a PA is utilized.
- **Waveform, Modulation, and Coding Techniques.** These techniques play a key role in reducing the power requirements and complexity of NZE devices. For example, they influence the processing and power requirements of the baseband processor in the NZE device. Furthermore, these techniques affect achievable coverage. For simplicity, an alternative to the OFDM waveform may be explored in 6G. Simple modulation techniques include ASK and PSK. Manchester coding is a simple coding technique.
- **Low-power Communication Techniques.** Components that support communications and device-specific functions, such as sensing, need to minimize power consumption. For example, the RF circuitry, the baseband processor, and device-specific functionalities such as sensors and memory need to minimize their power consumption. Duty cycles and efficient wake-up procedures requiring low-complexity processing are important for active NZE devices. Increasing energy harvesting efficiency is also an important consideration.
- **Low-power Radio Architecture.** NZE devices need to be designed with a low-power radio. In one option, a low-power RF envelope detector can be used with an amplitude-based waveform. In another option, a zero-IF architecture converts the received RF signal to a baseband signal, which is processed by the baseband transceiver components to reduce power consumption.
- **RF Filtering Techniques.** While some NZE devices may not have adequate RF filtering, it is feasible to employ low-cost selective RF filtering techniques to enhance the communication performance of NZE devices at the cost of increased complexity. Such filtering techniques can mitigate interference and enhance performance. There is also a potential for spectrum sharing, where NZE communications and traditional cellular systems can co-exist harmoniously.

Network Side Technology Enablers of NZE Communications

- **Network Architecture.** Various enhancements to the network architecture are feasible to support NZE communications. For example, different network topologies could be explored for NZE communications. In one topology option, bi-directional communication between an active NZE device and a 6G BS is feasible. Furthermore, backscattering communication is feasible if a 6G BS is deployed near passive NZE devices. In another topology option suitable for constrained NZE devices, intermediate or assisting nodes (e.g., a UE, a repeater, or an IAB-node) are used between an NZE device and a 6G BS. Such nodes process complex protocols and procedures on behalf of NZE devices. A new network entity dedicated to NZE communications service may be introduced in the core network. This entity can process a vast number of NZE devices. Furthermore, this entity may need to support enhancements to typical device-core network procedures such as subscription management, authentication/authorization, tracking, and charging for NZE devices.

- **RAN Protocols and Procedures.** Due to the need to support low-complexity and low-performance NZE devices, RAN protocols and procedures may need to be simplified. For example, network slices dedicated to NZE communication services may be needed to support NZE devices with relaxed QoS requirements. Enhancements to the random-access procedure would likely be needed to support many NZE devices trying to access the 6G RAN. When suitable RF filtering is not available in an NZE device, interference mitigation techniques may be needed to protect such NZE devices. Techniques such as dynamic power boosting and allocation of large guard bands through dynamic scheduling could be exploited to mitigate interference. Paging and mobility management may also need to be simplified to accommodate low-complexity NZE devices. For example, instead of continuous tracking of all NZE devices, use case-based mobility management may be carried out, where mobility is tracked only when needed (e.g., only when an NZE device is in a smart warehouse and not when it is outside the warehouse).
- **Device Management.** Device management for NZE devices may be different compared to non-NZE devices due to their low-complexity and low-performance . These devices may or may not maintain the context information throughout their connection with the network (e.g., information related to the radio connection such as information about bearers). The network may need to track certain context information under such constraints. A new entity such as NZE Application Function (NZAF) may be introduced to manage NZE devices. The NZAF may store suitable information for a vast number of NZE devices.
- **Deployment Planning.** NZE devices require special deployment planning. For example, when intermediate or assisting nodes are deployed to facilitate reliable communications for NZE devices, locations and radio configurations of such nodes need to be determined.

10.4 Device Power Savings

As highlighted earlier in this section, energy consumption of the network is much higher than energy consumption of a device. However, when a massive number of devices are considered, total energy consumption of all devices may no longer be negligible. Hence, device power saving techniques are important for a sustainable 6G system. Additionally, reduced power consumption in a device increases the battery life and reduces the frequency of charging.

In addition to time domain techniques such as Discontinuous Reception (DRX), 6G may exploit new power saving mechanisms [NGA_Radio2]. In one mechanism, a dual-radio architecture with a main radio for data transmission and reception and a low-power radio for other tasks may be used. The low-power radio can help save power through relaxed measurements and wake-up monitoring of paging messages. In another mechanism, a low-complexity waveform such as On-Off Keying (OOK) may be used for wake-up signaling. A yet another mechanism utilizes a suitable policy so that the device does not consume a significant amount of power while operating in an integrated network consisting of 3GPP-based terrestrial and non-terrestrial networks, as well as non-3GPP networks.

A frequency-domain mechanism selects suitable carrier bandwidth in a channel and suitable carrier frequencies in Carrier Aggregation to reduce power consumption.

A spatial domain mechanism at the device opportunistically utilizes fewer antenna ports or MIMO layers so that the total amount of power is reduced.

A network architecture mechanism uses sidelink communications or a mesh network instead of the UE-Base Station connectivity to reduce the distance between the UE and the radio node to reduce the amount of transmit power needed to close the radio link.

11 EXTREME NETWORKING

A 6G network is expected to be a network of networks, including terrestrial, aerial, non-terrestrial, in-factory, in-vehicle, in-body, and on-body networks. Extreme networking is characterized by extreme performance requirements, such as much higher reliability than 5G and much lower latency than 5G. Extreme networking can play a key role in special networks such as in-factory, in-vehicle, in-body, and on-body networks.

Section 11.1 gives examples of use cases and associated performance requirements of extreme networking. Trends and challenges of extreme networking are summarized in Section 10.2.

11.1 Use Cases and Performance Requirements of Extreme Networking

Figure 11.1 lists use cases of extreme networking. These use cases are in-factory network, in-vehicle network, in-body network, and on-body network. See [NGA_Radio2] for details of these use cases and associated performance requirements.

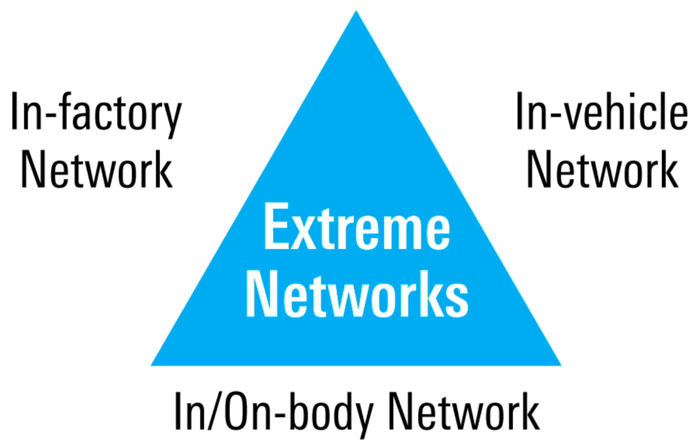


Figure 11.1: Use Cases of Extreme Networking

In-factory Network

While 5G could meet some of the requirements of an in-factory network, 6G can meet more requirements than 5G. Example use cases include (i) motion, torque, and force control, (ii) cooperative robots, and (iii) wired-to-wireless link replacement. Example KPIs for the motion, torque, and force control use case include reliability and service availability of 8 nines, maximum E2E 2-way latency of 0.5 ms, survival time of 0.5 ms, and motion-control relative movements of 72 km/h [NGA_Radio2]. Example KPI requirements for the cooperative robots use case are synchrony of 700 ns for the wireless portion and reliability and service availability of less than 8 nines. Example KPI requirements for the wired-to-wireless link replacement use case include the data rate of less than 1 Gbps and reliability and service availability of less than 8 nines.

In-Vehicle Network

Traditional in-vehicle networks rely on wired infrastructure to support Local Interconnection Network (LIN) and Controller Area Network (CAN). The LIN and the CAN help manage typical functions, including door lock activation, powertrain and body control domain, on-board diagnostics, braking, direction control, and security systems. These functions have different requirements: simplicity, low cost, reliable error handling, low latency, and fault tolerance. Furthermore, the in-vehicle network must support the emerging Advanced Driver Assistance System (ADAS) functions such as collision warning and intervention and driving control assistance.

6G can replace the wired infrastructure with wireless infrastructure to reduce weight and cost by using its expected capabilities, such as time-sensitive networking (TSN), having high throughput, low latency, high reliability, and accurate end-to-end synchronization. A 6G-based in-vehicle network may need to support KPI requirements such as the number of vehicles involved ranging from 50 to 100, the data rate ranging from less than 10 Mbps for control to less than 10 Gbps for ADAS, service reliability and availability ranging from 99.9999% to 99.999999%, and a latency of about 54 μs [NGA_Radio2].

In-body and On-body Networks

Implanted or ingestible sensors and actuators, often called in-body nodes, can create a network to enhance, monitor, and track the health and functionality of human organs [NGA_Radio2]. These in-body nodes may communicate with one another, on-body sensors, or body control units, or a nearby node outside of the human body, such as a wireless device. Furthermore, these nodes often have certain material requirements to avoid toxicity or foreign agent reactions. Additionally, due to the restricted space and human body safety constraints, these nodes may have limitations on power emissions, power consumption, battery life, and size. Example KPI requirements for such in-body networks include a battery life ranging from a few months to a few years, data rates ranging from 1 kbps to less than 10 Mbps, high service availability and reliability requirements, and high security and privacy requirements. Compared to in-body networks, on-body networks may require higher data rates and lower latency, but more relaxed battery-related requirements.

11.2 Section 11.2 Research Directions for Extreme Networking

Several research directions identified in [NGA_Radio2] are briefly summarized below.

Physical Layer Enhancements

If an OFDM-based waveform is used, wider subcarrier spacing, such as 480 kHz or 960 kHz,will enable the 6G system to realize very low latency. Furthermore, since a smaller CP value can be utilized for short range communications, the spectral efficiency also improves.

A high order modulation scheme such as 4096QAM may be feasible due to high SINR achievable for short distances in in-vehicle and in/on-body networks.

MAC Layer Enhancements.

Configured scheduling can be applied to reduce latency. For example, the Base Station can specify the resource allocation once via signaling such as RRC signaling and such allocation can be used by the UE at the periodicity specified by the Base Station.

Architectural Considerations

Architectural enhancements are needed to manage radio resources for both the macro/micro network and special subnetworks (e.g., in-vehicle and in/on-body networks). Distributed or centralized resource allocation approaches will be to minimize interference and maximize resource utilization. In distributed resource allocation, each subnetwork allocates resources autonomously. In centralized resource allocation, channel measurements are conveyed from the subnetwork to a network node, and the network node allocates resources. Each way has its own merits.

12 MISCELLANEOUS RADIO TECHNOLOGIES

Features such as the sidelink and the NTN, previously used in 5G, may be enhanced in 6G. Additionally, new technologies such as UE cooperative communications and semantic communications could be explored in 6G.

Section 12.1 discusses sidelink and mesh networking related enhancements. Section 12.2 summarizes the role of the NTN in 6G, along with potential enhancements in 6G. Section 12.3 describes innovations related to UE cooperative communications. Finally, Section 12.4 introduces the concept of semantic communications.

12.1 Sidelink and Mesh Networking Enhancements in 6G

The downlink refers to the radio link from the BS to the UE, the uplink refers to the radio link from the UE to the BS, and the sidelink (SL) refers to the radio link between two UEs. The sidelink enables the direct transfer of user traffic between the UEs without the user traffic traveling through the BS and the core network. The direct communication enabled by the sidelink is helpful in various scenarios, such as public safety and Vehicle-to-Everything (V2X) communications. Sidelink and mesh networks can facilitate applications requiring high data rates, but user devices are far from distant base stations. In such cases, nearby mesh nodes or devices can provide good-quality radio links to the devices due to relatively shorter distances. The sidelink may also reduce power consumption and increase spectral utilization. 6G may introduce enhancements to the sidelink in one or more areas briefly mentioned next. See [NGA_Radio2] for details of these enhancements. While a mesh network could be created using a network architecture such as the Integrated Access and Backhaul (IAB), the focus here is on the SL-based mesh network.

The SL-based mesh network may utilize a different physical layer waveform than the DL/UL waveform so that the new waveform is optimal for relatively short distances. The discovery and peer selection procedures may be enhanced for multi-hop scenarios so that both close and far away devices can offer a direct or an indirect path to the destination. To reduce link setup delays in a multi-hop scenario, a faster mobility or link establishment procedure may be defined. A routing procedure that is simple and yet effective may be considered, and the impact of UAV UEs on routing should also be considered. A load-balancing mechanism may be developed to distribute the overall load in the system. Furthermore, the interaction of the SL-based mesh network with frameworks such as IAB, smart repeater, NTN, Wi-Fi, and Bluetooth should also be investigated to design an effective mesh network. Efficient synchronization across multiple devices in a multi-hop scenario must be designed to reflect different propagation delays in a multi-hop system. Support for a large number of low-capability and power-constrained devices may be required. Intelligent radio resource allocation approaches may be evaluated to ensure high spectral efficiency. There could be enhanced beam management opportunities in the higher frequency bands, such as mmW and sub-THz bands. A cross-band SL-based mesh network may be utilized, where a lower frequency band is used to connect the BS and a relay node (which could be located inside a building), and a higher frequency band is used between the relay node and a nearby UE. The overall power efficiency can be further enhanced through enhanced Discontinuous Reception (DRX), especially for low-capability UEs. Network coding for a mesh network could be explored in 6G to improve the overall efficiency of data transmission. Both hop-by-hop and end-to-end security must be supported for a secure SL-based mesh network.

12.2 Non-Terrestrial Network

A Non-terrestrial Network (NTN) is critical in 6G to meet the 6G usage scenario of ubiquitous connectivity, which involves serving uncovered or scarcely covered geographic areas such as rural, remote, and sparsely populated areas. The ITU has also defined "connect the unconnected" as one of the overarching aspects of 6G. Since the cost-effective deployment of the terrestrial Base Stations and the associated transport network is not feasible in remote and sparsely populated areas, the NTN is an attractive alternative. Furthermore, only an NTN is a practical solution to provide maritime coverage. In summary, the NTN is expected to play an essential role in 6G in ensuring ubiquitous connectivity.

In addition to basic connectivity, the NTN can also provide an additional benefit of resilience by providing a method of communication in addition to terrestrial communications. In case the terrestrial network is partially damaged or destroyed, the NTN can provide communications. In another possibility, a device can simultaneously connect to a terrestrial network and an NTN for enhanced performance by utilizing radio resources of both networks.

While the NTN was introduced by the 3GPP in Release 17, it is expected to be more prevalent in the 6G time frame. Both transparent NTN payload and regenerative NTN payload are expected to be supported in both 5G and 6G.

Several NTN enhancements for 6G discussed in [Tripathi_2025] are briefly summarized below. These candidate enhancements include regenerative payload-related architectural enhancements, spectrum sharing, security, and multi-constellation connectivity.

- **Regenerative Payload.** The 3GPP has defined an NTN with a transparent NTN payload in Release 17 and 18. A transparent NTN payload, also called a bent pipe architecture, means that the Base Station functions are carried out on the ground, and the NTN platform, such as a satellite or high-altitude ballon, acts as a repeater between the UE and on-the-ground Base Station. A regenerative payload means that some or all Base Station functions (e.g., baseband and RF functions) are carried out by the NTN payload residing on the NTN platform. An NTN with a regenerative NTN payload is necessary to provide global coverage. 6G needs to address challenges such as optimal routing of user-specific information on Inter Satellite Links (ISLs). Research is also needed to explore advanced antenna configurations to facilitate high-performance NTN for a smartphone UE.

- **Spectrum Sharing.** A large amount of spectrum is necessary to achieve high capacity and throughput in a TN and an NTN. Hence, if spectrum is shared between a TN and an NTN, more spectrum becomes available to both networks. Preliminary analysis indicates that it is feasible for a low-power indoor TN and an NTN to share the same spectrum [Tripathi_2025].
- **Multi-Constellation Connectivity.** 5G supports mobility between a TN and an NTN. 6G can enhance TN-NTN interworking to balance loading between a TN and an NTN and transfer data using both a TN and an NTN simultaneously.

12.3 UE Cooperative Communications

The UE cooperative communications can be viewed as a comprehensive framework for collaboration among UEs for better performance for a single device communicating with the radio network. Figure 12.1 illustrates a candidate architecture to realize UE cooperative communications. See [NGA_Radio2] for examples of candidate architectures for UE cooperative communications.

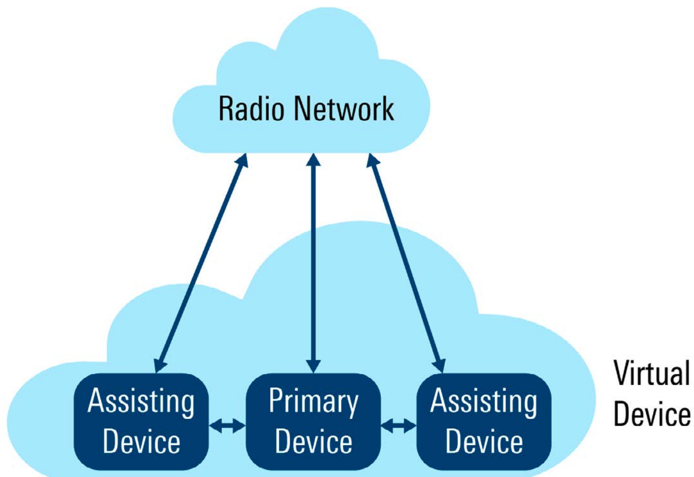


Figure 12.1: UE Cooperative Communications

In UE cooperative communications, multiple UEs together form a virtual device or UE that appears as a single device/UE to the network. The capabilities and resources of the UEs that form the virtual UE are utilized to enhance the overall performance of one or more devices. In Figure 12.1, the primary device is the device currently interested in exchanging user traffic with the network. Examples of assisting devices include a smartphone and Customer Premise Equipment (CPE). The primary device and the assisting device may communicate with each other using a 3GPP or non-3GPP technology. There are multiple scenarios where the UE cooperative communications can be exploited. In one scenario, antennas from the primary device and the assisting devices are combined to support a higher-order MIMO technique to enhance throughput.

12.4 Semantic Communication

In a typical communication system, information, such as video is represented by bits, and the wireless network aims to transport these bits to meet the QoS requirements of the applications. For example, a voice codec or vocoder converts speech into bits, and an H.264 video codec converts a video into bits. These voice and video bits are transported between the device and the radio network with the help of a radio interface protocol stack. Semantic communication transports the semantics or meaning of the information to be conveyed instead of the information itself. Semantic communication involves delivering the meaning or interpretation of the message instead of the message itself. For example, instead of sending the photo of “A kid is riding a bicycle,” semantic communication transports the interpretation information representing the photo. Figure 12.2 illustrates key components of an example semantic communication system; see [Shi_2021] for system details.

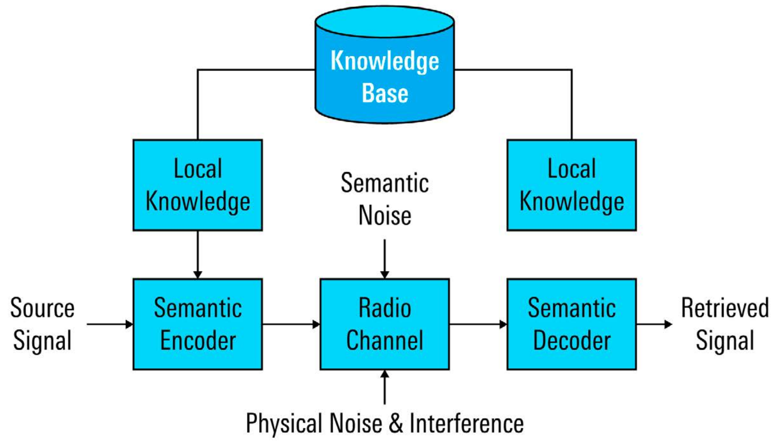


Figure 12.2: Semantic Communication

The semantic or source encoder detects and extracts semantic content or meaning of the source signal and reduces or removes any irrelevant information. For example, the encoder identifies the entities in the source image (i.e., the image that needs to be transmitted) based on the local knowledge enriched by a knowledge base. It infers a possible relationship among the entities according to a common world model.

The semantic decoder interprets the semantic information sent by the source/transmitter and retrieves the source signal in the form that is usable by the destination user. The decoder determines if the semantic information retrieval is successful or not.

Semantic noise can be viewed as the noise or disturbance introduced during the overall communication process that causes misunderstanding and incorrect interpretation of the semantic information. Semantic noise may occur in processes such as encoding, data transportation, and decoding.

The knowledge base contains knowledge that can be exploited by the encoder and the decoder to enrich the local knowledge at the encoder and the decoder and facilitate encoding and decoding.

Potential benefits of semantic communication include improved communication efficiency and reliability, enhanced quality of experience for human-oriented services, and protocol/syntax-independent communication [Shi_2021]. Since semantic communication transmits the meaning of the source signal instead of the source signal itself, it consumes fewer communication resources. For example, the transmission of speech summary consumes significantly fewer radio resources compared to full speech. Furthermore, reliability can also be improved since the decoder could potentially infer corrupted or missing parts of the speech summary. With the use of semantic-related side information such as context and intention of users, the semantic error can be reduced. Note that semantic error is the difference between the meaning of the source signal and the meaning of the retrieved signal. The human experience may be enhanced because the main goal is to deliver the intended meaning. Since semantic communication is independent of protocol or syntax, it allows for a more robust and upgradeable or evolution-friendly communication framework for future wireless systems.

Realization of semantic communication faces several challenges [Shi_2021]. One challenge is that semantic information can be quite difficult to detect, extract, and represent due to various factors such as its dependence on the background, personality, interaction history, semantic ambiguity, and nuances. Furthermore, significant amounts of computing power and storage space are required to detect and extract semantic information, including object classification, knowledge entity recognition, and relation inference. Additionally, a large number of labeled training data samples are needed. Also, certain aspects of semantic information, such as knowledge relations, properties of objects, and implicit meaning of statements are difficult to represent. Data and privacy protection are also needed. Collaborative training of a shared knowledge model is also an important challenge.

13 CONCLUSION

Compared to all predecessor generations of cellular communications, 6G is expected to serve a much more comprehensive set of use cases, including the user cases that reflect significant contributions to society and the environment. 6G is also anticipated to be more flexible and complex than previous generations of cellular technologies. The ITU has identified services and performance targets for 6G in the form of target IMT-2030 requirements. The ITU extended the three usage scenarios of 5G and introduced three more usage scenarios for 6G. The eMBB usage scenario of 5G is extended to Immersive Communication for 6G, the mMTC usage scenario of 5G is extended to Massive Communication for 6G, and the URLLC usage scenario of 5G is extended to HRLLC for 6G. Three new 6G usage scenarios are Ubiquitous Connectivity, Integrated AI and Communication, and Integrated Sensing and Communication. The ITU has also defined enhanced capabilities for 6G (IMT-2030) compared to 5G (IMT-2020), such as., higher peak data rate and lower latency, as well as new capabilities for IMT-2030, such as sensing capabilities, AI capabilities, and sustainability.

This paper has determined candidate building blocks and technologies by considering a vast body of 6G-related work carried out in the industry, academia, and SDOs. These categories of 6G building blocks include (i) radio technologies, (ii) AI-native design, (iii) sustainability features, (iv) network architecture, (v) devices and applications, and (vi) component technologies.
6G may include enhancements to waveforms and associated techniques, including multiplexing and multiple access, coding, modulation, and duplexing. Examples of candidate waveforms or multiple access techniques for 6G mentioned include OFDM, peaky FSK, OTFS, and NOMA. 6G may exploit a high-order modulation, constellation shaping, and index modulation. 6G may also explore full duplex.

While 6G may reuse 4G and 5G spectrum, it may also use upper mid-band spectrum (e.g., 7 to 24 GHz), sub-THz spectrum (e.g., 100 GHz to 300 GHz), and THz spectrum (e.g., 300 GHz to 3 THz). To support high data rates associated with applications such as immersive video calls, holograms, and digital twins or replicas, a large amount of spectrum is needed. Since a large amount of unused spectrum is difficult to find, especially at low frequencies, dynamic and efficient spectrum sharing and management are essential in 6G. 6G may be spectrum sharing-native, like AI-native.

New candidate antenna technologies that may be explored in 6G include RIS, massively distributed MIMO, cell-free MIMO, holographic beamforming, and OAM.

While the 3GPP has already started studying ISAC as part of 5G-Advanced, ISAC is likely to become one of the key technologies in 6G. ISAC utilizes a common framework to support both communication and sensing. Monostatic sensing and bistatic or multistatic sensing can be exploited. Examples of sensing topologies include downlink monostatic sensing, uplink monostatic sensing, downlink bistatic sensing, uplink bistatic sensing, and distributed/networked sensing. The 3GPP has identified more than thirty use cases, which can be grouped in the following use case categories: intrusion detection, environmental monitoring, sensing as a service, smart cities, vehicle-to-everything, smart manufacturing, UAVs, computer and human interaction, healthcare, and immersive experience. Two key technology composing ISAC are the sensing architecture and the signal processing algorithms.

The AI-native radio interface includes AI as an integral component of the air interface and is characterized by autonomy, continuous learning, and near-real-time optimization. A functional framework studied by the 3GPP for AI/ML-based NR air interface includes functional blocks such as Data Collection, Model Training, Management, Inference, and Model Storage. An AI-native interface can be applied to various use cases such as CSI feedback, beam management, MIMO symbol detection, constellation design, transceiver impairments, ISAC enhancements, positioning accuracy enhancements, neural-based receiver, and channel estimation reference signal design.

6G could become sustainable by providing energy-efficient networks and devices, implementing circular economy principles, and reducing its environmental impact on materials, water, land, and air. Reduced energy consumption and increased usage of renewable energy sources are important in 6G. 6G can also help other verticals become sustainable. Five key sustainability impact categories identified by the NGA for a sustainable 6G ecosystem include (i) energy, (ii) greenhouse gas (GHG) and other emissions, (iii) water footprint, (iv) reuse, recycle and refurbish, and (v) land and biodiversity. Factors contributing to a sustainable 6G network are modeling and observability, component technologies, time domain techniques, frequency domain techniques, spatial domain techniques, and power domain techniques.

A 6G network is expected to be a network-of-networks, including terrestrial, aerial, non-terrestrial, in-factory, in-vehicle, in-body, and on-body networks. Extreme networking is characterized by extreme performance requirements, such as much higher reliability and lower latency than 5G. Extreme networking can play a key role in special networks such as in-factory, in-vehicle, in-body, and on-body networks.

Features such as the sidelink and the NTN, previously used in 5G, may be enhanced in 6G. Additionally, new technologies such as UE cooperative communications and semantic communications could be explored in 6G.

6G is expected to significantly expand the utility of wireless systems by making various verticals more efficient or facilitating their growth. Conscious efforts are required to enable the expansion of 6G into verticals. Furthermore, collaboration among stakeholders is needed to make 6G and 6G-influenced industries more sustainable. Collaboration among stakeholders will make 6G a transformational cellular technology.

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