Chapter 5

Standardization of 6G Wireless Communication Systems

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The fifth generation (5G) network promises to deliver enhanced mobile broadband (eMBB), ultra-reliability low-latency communications (URLLC) for mission-critical internet of things (IoT), and massive machine type communications (m-MTC) for massive IoT, aiming to drive the digital transformation in all industry sectors. Since the third generation partnership project (3GPP) published Release 15 in 2019, the first release of 5G new radio (NR) standard, 5G networks have started being deployed in many places in the world. Meanwhile, academia, industry, national and international regulators have started developing visions, identifying use cases, and specifying enabling technologies for 6G communications. Many white papers have been published, research programs started, forums and workshops organized, providing good references for the 6G standard development by 2030.

In this chapter, we will summarize the 6G vision, enabling technologies, and vertical use cases that are being discussed in the white papers, forums, and workshops. We will then provide an overview on the 6G standardization. The chapter is organized as follows. In Section 5.1, we summarize the 6G vision. In Section 5.2, the candidate enabling technologies are described. Section 5.3 presents the research initiatives, and Section 5.4 presents the 6G standardization process, including the regulation, the standard development organizations (SDOs), and industry forums. Finally Section 5.5 concludes the Chapter.

5.1 The 6G Vision

A number of 6G white papers have been published by industry companies, industry alliances, academic research centres, and public-private partnered research programs. Please see references [1] – [29]. This list is by no means exclusive. It keeps increasing and getting updated. However, there are good consensus and well-aligned views. In this section, we provide a quick summary of the 6G vision from these white papers.

Moving to 2030, the physical world, digital world, and human world will be even more seamlessly connected and interacted, creating brand new experiences in work, leisure, social activities, learning and study. Real-time fusion of the virtual and physical worlds, extended human senses and human world will further also accelerate the digital transformation in processes and practices in all industry sectors and public services. Digital twin, immersive extended reality (XR), tele-operation, industry 5.0, are some leading 6G use cases. Drive for sustainability, represented by the Sustainable Development Goals (SDGs) in the United Nations (UN) Agenda 2030 [31] also calls for 6G's contribution. Demands for communication anywhere, anytime, for anyone and anything, for intelligent digital transformation, form the core driver for 6G research and innovation.

The 6G research and technological innovation includes transmission technologies, network architectures, hardware and device technologies, softwarisation and open network, artificial intelligence (AI) integration, security and privacy of the system and information. 6G standards will ensure the inter-operability, backward compatibility with legacy and older generation systems such as 5G and 4G, and sustainable supply chain of 6G equipment, devices, and software.

5.2 The 6G Enabling Technologies

In this section, we describe the 6G enabling technologies to support the envisioned seamless integration of physical, digital, and human worlds. We focus on the following aspects: (1) machine as primary user, (2) AI as performance driver, (3) agile and software-defined everything (SDX) as necessity, (4) privacy, security, and resilience as warranty, and (5) sustainable networking and energy efficiency as baseline.

5.2.1 Machine as primary user

Among the three major applications for 5G, namely, eMBB, mMTC, and URLLC, URLLC is designed to support the mission-critical applications that require a very low latency and ultra-high reliability. The requirement for latency is down to 1 ms and the requirement for reliability is 99.999%. 6G will enable even more stringent latency and reliability performance to support more tactile internet (TI) applications [55][56].

In the highly connected physical, digital, and human worlds supported by 6G, the number of IoT-connected devices will continue to grow, and machines will become dominant users. Figure 5-1 shows the predicted number of IoT-connected devices by 2030 (source: Statista 2022, https://www.statista.com/statistics/), where 50 billion of such IoT devices is expected in year 2030. The URLLC-type of critical machine type communications will continue to increase, pushing for support of higher number of URLLC user volume, and higher area-average URLLC user capacity. We refer to this as *massive URLLC communications*. For example, in the coordinated fleet of robots or unmanned aerial vehicles (UAVs), the number of robots or UAVs can be large and URLLC communication is generally required. In smart factory supporting flexible and hyper-personalized manufacturing, the number of wireless-connected machines will increase at the manufacturing floor, and wirelessly-connected gadgets will become necessity for remote supervision, tele-operation, and digital twin. Massive URLLC communications has to be made available to support these operations.

In the 6G, URLLC is not only required in low data rate applications but also in some high data rate scenarios. The boundary between URLLC and eMBB will blur. For example, immersive XR is likely to be applied widely in many applications in the future. XR requires huge data rate and low latency, where the current 5G cannot support.

To enable massive URLLC communications in 6G, the following technical features are required.

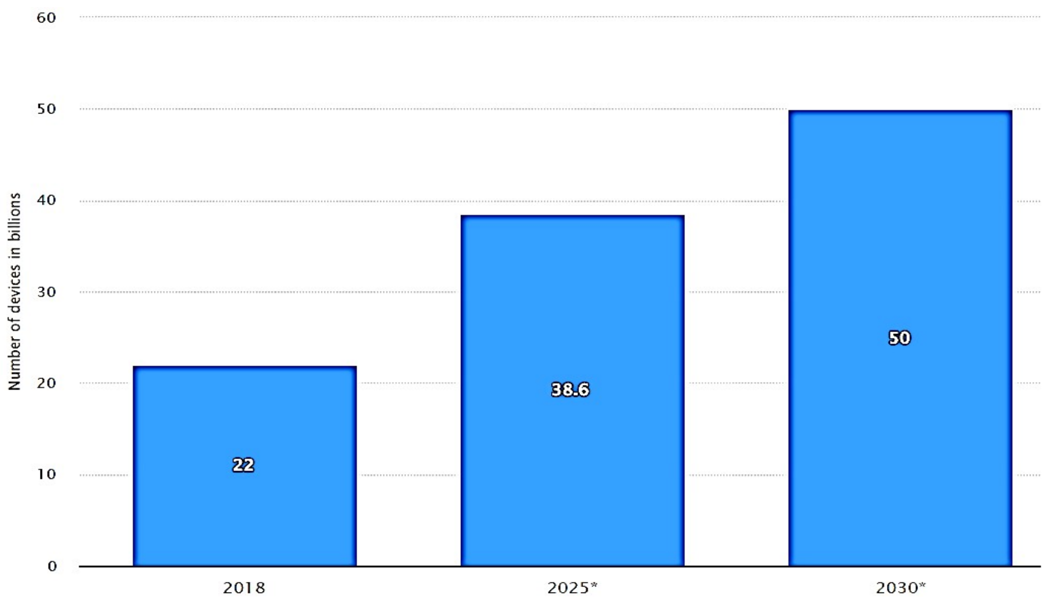

Figure 5-1 Predicted number of internet of things (IoT) connected devices (source: Statista 2022)

5.2.1.1 Flexible waveforms

In 6G networks, the number of connected devices is huge, and the traffic types and data rates of different devices and applications can be quite different. Some of them may generate periodical traffic, but many others may generate sporadic data. It is a big challenge to coordinate such a diversified and heterogeneous network. Especially the waveform and multiple access technologies need to be reinvestigated to meet the new requirements.

Currently the cyclic prefixed orthogonal frequency division multiplexing (CP-OFDM) is the dominate waveform. In OFDM, coarse time synchronization is required to avoid cross-interferences among users. However, it is difficult and resource hungry to maintain time synchronization, especially for low power devices with sporadic traffic. There are a few other waveforms that can relax the synchronization requirements, such as filter bank multi-carrier (FBMC), universal filtered multicarrier (UFMC), or generalized frequency division multiplexing (GFDM). However, their implementation complexity is higher than the OFDM. Waveforms like FBMC has also the long tail problem that is not suitable for short packet transmission [103].

In 6G, we also need to support many applications with high mobility such as vehicular-to-everything (V2X) and UAV communications. The high mobility induces high Doppler spread that makes the propagation channel fast-changing in time. If the channel changes significantly within an OFDM symbol, there will be large errors in OFDM demodulations. Recently, the orthogonal time frequency space (OTFS) modulation have been proposed to handle the high Doppler spread or fast time varying channel [45]-[47]. In OTFS, the signal is modulated in the delay Doppler domain, that is, it maps the time-varying multipath channel to the time-delay-Doppler domain. In references [46], the OTFS is compared with OFDM in high mobility scenarios, which show that OTFS can indeed have much better performance than OFDM at the expenses of more complicated receiver. There are still many unsolved issues in OTFS, which include the pilot design, the channel estimation, and the complicated equalization. The combination of the OTFS with other mature technologies such as multiple-input multiple-output (MIMO) also needs to be studied further.

One single waveform may not suit the need of all traffic types and applications in 6G while meeting the efficiency and sustainability requirements. But how to incorporate different waveforms in a harmonized system is a big challenge to address in 6G. Numerology, backward compatibility, hardware, software and network management, are some of the very important aspects in the design consideration.

5.2.1.2 Agile multiple access

Multiple access techniques are to manage how the spectrum and time resources are shared among multiple users. In 5G, the multiple access is mainly based on orthogonality among users. The orthogonality can be maintained with frequency separation by frequency division multiple access (FDMA), subcarrier separation by OFDM access (OFDMA), time separation by time division multiple access (TDMA), code division multiple access (CDMA), or combination of them. All these can be called orthogonal multiple access (OMA). The low implementation complexity of OMA is the main reason for its dominance in the past, although it is known to be sub-optimal based on Shannon's information theory [19]. In the coming 6G, non-orthogonal multiple access (NOMA) is likely to be adopted as another multiple access technique in coexistence with OMA. In NOMA, users can share the same spectrum at the same time, leading to higher spectral efficiency. The different channel conditions, quality of service (QoS) requirements, and power levels of users are used to decide on the multiple access scheme and demodulations. In recent year, the rate-splitting multiple access (RSMA) has been studied as a generalization of NOMA [19].

The power based NOMA and code based NOMA have been studied extensively [19]. In the 5G standardization process, there were plenty of proposals on NOMA, although it is not adopted in the current 5G standard. Going forward, we have to reconsider the NOMA to cater for the massive connectivity with different QoS in the 6G. For this purpose, it is crucial to adopt a general framework for the standardization of NOMA in 6G systems such that the system maintenance cost is acceptable while keeping the spectral efficiency advantages and reasonable receiver complexity of the NOMA.

It is well known that ultra-low uplink latency is one of the most difficult tasks in URLLC [48]-[51]. Traditionally an uplink user needs to request the base station for the grant of transmission before emitting its signal. This "grant based" uplink in general cannot meet the delay requirement due to the time spent in the grant process [48],[49]. In recent years, "grant free" uplink schemes have been proposed to by-pass the grant process and allow an uplink user transmitting without a "grant" [48]-[51]. In 5G, some grant free uplink have already been adopted, like the semi-persistent scheduling (SPS) uplink [48]-[51] . There have been many researches on grant free uplink [48]-[51] . Among them, the contention based grant free uplink can overcome the resource wastage problem in SPS uplink [48], which can be treated as a modification and generalization of the SPS uplink to allow multiple users sharing the same spectrum and time. In contention based grant free uplink, any user in a group randomly chooses a resource in the pre-scheduled shared resources for uplink. In [48], a scheme called subband random sensing (SRS) grant free uplink is proposed. The SRS grant free uplink creatively combines the subband sensing, user grouping and random access, which allows a user sensing the unlicensed spectrum to use available sub-resources in a wideband and reduce collisions with other users. The new scheme overcomes the severe spectrum wastage problem of the SPS uplink in applications with sporadic traffic. Compared with the contention based grant free uplink, the new scheme achieves much lower collision probability.

The combination of the grant free with NOMA is promising, which can reduce handshaking time with grant free transmission, allow more users, and reduce the demodulation error rate [50],[51].

5.2.1.3 High-precision wireless time-sensitive network

Timing is critical in many applications like industrial automation, automatic driving, connected drones, tele-operation, etc, which are sometimes called time-sensitive applications. Here the timing has two different meanings:

(1) <u>Clock synchronization</u>: the clocks of the related users and devices must be synchronized to a certain degree of accuracy in order for them to coordinate in solving a common task. The clock synchronization accuracy is typically required to be below 1us. In some applications, the requirement even goes to nanosecond (ns) level. For example, for high precision localization with error below 30 centimeter (cm), the clock synchronization needs to be below 1ns, if the time difference of arrival (TDoA) based positioning algorithms are used [52]-[54].

(2) <u>Communication latency</u>. The time that takes to transfer a given piece of information from a source to a destination must be below a given threshold. Late arrival of the information will cause the information useless or even a disaster. In 5G, 5ms end-to-end latency is required in URLLC. This is not enough for many applications like tele-operation, XR, high speed UAV, automatic driving, etc [55]-[59].

Time-sensitive applications also relies heavily on the reliability of communication. In fact, the clock synchronization normally is based on exchanging clock information among the users.

Reliability of the information is critical. Latency is even more closely related to reliability. When a transmission has errors, it is normal to retransmit the packet in conventional communication protocols. However, for time-sensitive applications, retransmission is generally not useful, as the information may be already useless after the time limit. In recent years, in addition to the time delay, the age of information (AoI) has been used as another performance metric for network performance analysis [13]-[19].

There have been standards especially for the time-sensitive networking (TSN). One such standard is developed by the IEEE 802.1 Time-sensitive Networking Task Group [53]-[54]. It is designed to make Ethernet-based networks more deterministic. TSN was developed to provide a way to make sure information can travel from point A to point B in a fixed and predictable timeline [53]-[54]. There are two four components in the TSN: (1) clock synchronization; (2) latency; (2) reliability; (4) management. The latency requirement is dependent on the application. The clock synchronization is based on Precision Time Protocol (PTP), which are included in IEEE 802.1AS and IEEE 802.1ASRev [53]-[54]. Though not specifically considered in the TSN specification, AoI will be an important metric for analysis and design of time-sensitive networks.

Another related standard is the tactile internet (TI) being developed by the IEEE 1918.1 WG [57]. Traditionally, wireless communication was mainly used for content delivery (message, voice, file transfer, video streaming, and so on) and monitoring (information collection) applications [56]. In industrial networks, other information like touch, smell and taste are also important for real-time steering and controlling [56],[58]. Tactile Internet (TI), which was named in early 2014, is to transfer information as well as reproduce (or synthesis) stimuli (sight, hearing, touch, smell and taste) at the receiver. The IEEE 1918.1 WG has defined the TI as follows [57]: “A network (or network of networks) for remotely accessing, perceiving, manipulating, or controlling real or virtual objects or processes in perceived real time by humans or machines.” TI is projected to change the paradigm that enables wireless communication for real-time control and steering.

The goal of TI is that humans should not be able to distinguish between locally executing a manipulative task compared to remotely performing the same task across the TI. The results of machine-in-the-loop physical interactions will ideally be the same as if the machines were interacting with objects directly at—or close to—the locations of those objects. Figure 5-2 shows an example of remote balancing of a basketball through the TI [57]. TI conveys skills for balancing the basketball to the remote machine, and returns feedback of the current balance of the ball. The human must know the situation and react promptly. The reaction must be conveyed timely to the other end of the link. All these must be done before the basketball falls.

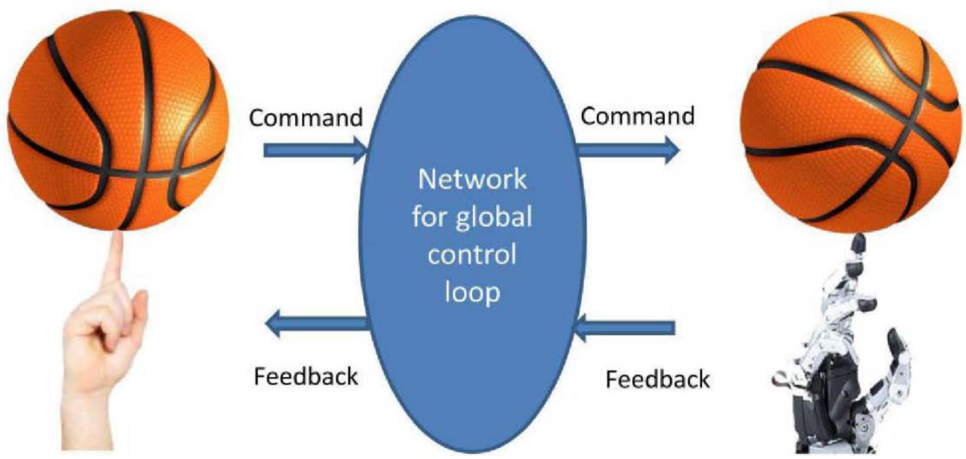

Figure 5-2 Remote balancing of a basketball through the TI [57]

Table 5-1 shows the latency and reliability requirements in some typical TI applications [56],[57].

ITU first observed the Tactile Internet as a new technology with potential impact on future standardisation and applications in ITU's Technology Watch in August 2014. IEEE launched its Digital Senses Initiative (DSI) in June 2015 to advance the technologies. Its purpose is to develop VR and AR standards to harmonise existing standards and develop new ones. It is projected to be finalized before 2022.

Table 5-1 URLLC Requirements in some typical applications

Use cases	**E2E Latency (ms)**	**Reliability (%)**	**Average data rate (Mbps)**
Teleoperation	1-20	99.999	1-100
Cooperative automated driving	1-50	99.99-99.999	1-40
Immersive virtual reality	1-50	99.99-99.999	1-100
Automotive (self driving, remote driving)	1-100	99.99-99.999	1-10
Internet of drones	2.5-50	99.99-99.999	1-100
Interpersonal communication	10-1000	99.99-99.999	1-600
Live haptic-enabled broadcast	12-18	TBD	Varying

5.2.1.4 Sensing-communication-computing-control convergence

Integrating sensing into the wireless communication eco-system has been actively studied recently [60]-[64], [14], [18]. For example, the IEEE 802.11 standardization committee has formed the IEEE 802.11 WLAN Sensing Topic Interest Group as well as the Study Group, respectively in September and November 2019 [60], which aim to incorporate wireless sensing as a new feature for next-generation Wi-Fi systems. Localization based on cellular network and signal is an established area. In 5G, there are a few enhancement features for the localization based on time, range and angles. One of the major enhancement in 5G localization is the newly added dedicated positioning reference signals in NR R-16: NR positioning reference signal (NR PRS) in the downlink and the sounding reference signal (SRS) in the uplink [2]. The downlink (DL) PRS is specifically designed to deliver the highest possible levels of accuracy, coverage, and interference avoidance and suppression. The DL PRS covers the whole NR bandwidth and over multiple symbols that can be aggregated to accumulate power. Each base station can then transmit the DL PRS in different sets of subcarriers to avoid interference. Moreover, it is possible to mute the PRS signal from one or more base stations at a given time according to a muting pattern, further lowering the potential interference. For use cases with higher transmission loss, for example, in macro cell deployments, the PRS can be also configured to be repeated to improve hearability.

However, such localization methods are mainly based on time difference of arrival (TDoA), signal strength, and angle of arrival (AoA). In recent years there is a trend to integrate radar sensing and wireless communication as one of the key technologies in future wireless systems [61]-[64], which is called joint radar and communication (JRC). With radar sensing, range, speed and angle can be detected at the same time with higher accuracy, which is hardly achievable by other type of sensing. Traditionally, radar and communication are separated in spectrum, hardware, and software. With the increasing usage of software defined radio and digital signal processing, the hardware and RF front-end for radar and communication tends to be similar. This makes the JRC practical. With many emerging applications, an integrated JRC using the same spectrum and sharing many hardware components will help alleviate the spectrum congestion and save the energy consumption.

Figure 5-3 illustrates two JRC applications [61],[62], where the figure at left shows a joint V2V communication and localization scenario: a vehicle sends useful information to another vehicle and uses the reflected signal to estimate the range and speed of the vehicle, while the right figure shows a joint video transmission and position/gesture detection scenario in VR/AR: the server transmits video to the persons and obtains the accurate position and gesture of the person using the reflected signal. Both applications need sensing and communication at the same time, where a JRC device can serve for the two purposes.

Instead of using the same waveform for simultaneous sensing and communications, a JRC system can also be realized by time-sharing the radar sensing and communication sessions by using dedicated radar and communication waveforms. Resource allocation and anti-jamming performance will be important design considerations [104],[105],[106].

In 6G, higher frequency like the THz band will be used and massive antenna arrays will be employed. These not only increase the communication throughput and reliability, but also create opportunities for very high accuracy environment sensing, where millimeter level localization and high resolution imaging can be achieved. The 6G context-aware intelligent networks will optimize the deployment, operation, and energy usage with information extracted from sensing and communication without human intervention.

However, it is still unclear how to design the joint sensing and communication system and maximize the overall benefit. There are still issues and difficulties to be addressed in the standardization of sensing in the 6G networks and infrastructures. These include joint waveform design, spectral sharing among sensing and communication, interference management, system design, hardware and software reuse, cost, and power consumption.

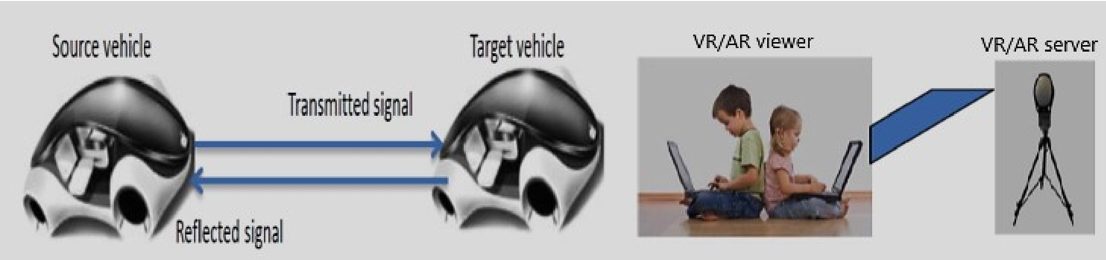

Figure 5-3 Example applications of joint radar and communication systems [61],[62]

In the 6G, distributed computation will be prevailing to achieve efficiency, privacy, security and low latency. The interaction of communication and computation requires an overall joint design for the dual functions. For real-time applications such as factory automation, remote power system control, fleet management of autonomous systems, tele-operation, etc., wireless networked control systems (WNCSs) call for an integrated communication-control design and optimization [107],[108]. It is envisioned that integrated sensing, communications, computing, and control will be an integral part of 6G, calling for research and technology innovation in network architecture, the various layers in the network, and the interface specification with the application domains.

5.2.2 Artificial intelligence (AI) as performance driver

There have been active research activities of making use of artificial intelligence (AI) to enhance the performance of communication systems and networks. For example, deep learning (DL) algorithms and neural network (NN) models can help mitigate the radio frequency circuit impairments and power amplifier (PA) non-linearity [109],[110],[111],[112], machine learning (ML) algorithms can learn the wireless channel characteristics for modulation and coding scheme (MCS) selection and link adaptation, DL models may help enhance the performance in user scheduling, resource allocation, dynamic spectrum management, and anomaly detection, etc [113][114]. These research activities have also pushed the advancement of AI algorithms development, e.g., reinforcement learning (RL), federated learning (FL), deep Q-learning, etc.

Driven by the great potential of performance improvement by AI, the various standard bodies have started various initiatives and activities to pave path for standard specification development of incorporating AI in networks. For example, in 2018, the European Telecommunications Standards Institute (ETSI) Experiential Networked Intelligence (ENI) Industry Specification Group (ISG) published a series of Group Specification documents, including the Proof of Concept Framework, terminology for main concepts in ENI, ENI requirements, use cases, etc [115]. In January 2019, the International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T)'s Focus Group on Machine Learning for Future Networks including 5G (FG-ML5G) published the "*Unified Architecture for Machine Learning in 5G and Future Networks*" [116]. It presents a set of architectural requirements, leading to specific architecture constructs needed to satisfy these requirements. Based on these constructs, a logical ML pipeline is discussed along with the requirements derived and its realizations in various types of architectures. Key architectural issues facing the integration of such an ML pipeline into continuously evolving future networks are also listed. Other standardization development organizations and industry alliances, including 3GPP, Linux Foundation [118], O-RAN alliance [100], etc., have also been developing framework to support the AI implementation in networks.

The above listed efforts are mainly focusing on how to enable AI in the 5G and future networks, after the 5G network standards have already been developed. Moving forward, we will see an even tighter and native integration of 6G with AI, in two aspects: (1) 6G network is defined to support AI of everything; (2) native AI enabled in 6G system and network. With this, not only the 6G system and network performance, but also the operation efficiency and user experience will be significantly enhanced. For infrastructure, increasingly automated deployment, configuration and management accelerates time-to-revenue as closed technology stacks give way to open, cloud-native architectures. For end user applications, the ability to anticipate customer needs and automatically deliver on constantly changing service level agreements simultaneously creates new, differentiated revenue streams while reducing operational costs.

There are remaining technical challenges and research issues to address for full adoption of AI in future networks, among which, explainability, controllability, robustness, training efficiency with small data set, privacy preservation, are some of them. Computation and energy-efficient implementation of AI models at the network edge (mobile edge computing, or MEC), the network server (cloud), and agile edge-cloud interaction for knowledge and data sharing will also remain a challenging research problem in 6G.

5.2.3 Agile and software-defined everything (SDX) as necessity

Softwarisation and open network will be more widely embraced in 6G, including both core networks (CNs) and radio access networks (RANs). Key initiatives include the open radio access network (O-RAN) alliance that aims to provide an open and intelligent RAN, the open network automation platform (ONAP) which develops a platform for network management and its automation through an open-sourced shared architecture. Open network opens more opportunities for new players to enter the market with lower barrier and for network operators more cost-effective options. New challenges in network security need to be addressed.

Open network makes software-defined networking (SDN) at CN and RAN a necessity. Moving to 6G, we will continue to see the usage of heterogeneous spectrums as in 5G. The spectrums in the lower frequency bands that could be deployed for 6G will be highly likely “re-farmed” from the earlier generation of wireless communication systems and other applications, while the higher frequency spectrum that has been less explored will be allocated for 6G. Sharing the license-exempted spectrums with software-defined cognitive radio-based solutions will also be an option. For system design efficiency and flexible spectrum access management, software-defined radio will continue to play an important role in 6G systems.

To overcome the radio wave propagation challenges especially in the high-band spectrum channels, large intelligence surface (LIS) [15]-[18] may make the concept of software-defined radio wave propagation environment a reality. It is therefore anticipated that software defined radio (SDR) to support heterogeneous spectrum access, software defined network (SDN) at both CN and RAN to support open networking and heterogeneous applications, and software defined environment (SDE) by reconfigurable LIS, will be essential elements in 6G.

5.2.3.1 Integrated terrestrial and non-terrestrial network for space-air-ground-sea coverage

It is generally recognized that pure terrestrial communication networks (TCN) cannot achieve ubiquitous, high-quality, and high-reliability services at anytime and anywhere, especially in coping with the upcoming trillion-level connections of IoT devices in remote areas [15]-[20]. Thus, it is necessary to integrate terrestrial and non-terrestrial network (NTN) to achieve worldwide connectivity and make various applications accessible. The integrated TCN and NTN brings space-air-ground-sea coverage via seamless access of satellite link, UAV communications, terrestrial wireless communications, and fibre-optical backbone networks. In the space-air-ground-sea integrated network, various networking technologies have their pros and cons in providing services, in terms of coverage, transmission delay, throughput, reliability, etc. Via effective inter-networking, different network segments can cooperate to support seamless service access and enhance service provision in a resource-efficient and cost-effective manner [19]. Specially, satellite communications can complement terrestrial networks for service access in areas with limited or no terrestrial network coverage (e.g., remote areas, disaster scenarios, and open seas). Meanwhile, the complementary properties of satellite link (wide coverage) and fiber-optical backbone (high data rate) can be considered as alternative backbone technologies to wireless backhaul. UAV communications can help to alleviate the terrestrial network burden and to enhance service capacity in congested locations with highly dynamic data traffic load. In addition, the satellites/UAVs with remote sensing technologies can support the reliable acquisition of monitoring data and assist terrestrial networks for efficient resource management and planning decisions [19].

However, compared to TCN, NTN will need much further advancement. There are still many issues in integrating the TCN and NTN for 6G, some of which are listed as follows [18]-[19].

- *Architecture design for integrated TCN and NTN:* Design of an architecture with no distinction between TCN and NTN elements that can be therefore orchestrated to provide cost-efficient network configuration by dynamically moving functionality creating a flexible network topology. Three main enablers need to be developed, namely, softwarization of the NTN, virtualization, and disaggregation.
- *Satellite/UAV constellation with hierarchical design:* Hierarchical constellations will consist of nodes flying at different altitudes and communicating among them through horizontal inter-node links, i.e., among nodes at the same altitude, and vertical inter-node links, i.e., among nodes flying at different altitudes, or terrestrial nodes.
- *Smart NTN with computing and storage in the sky:* Flying nodes will become smart edge nodes of the 6G network. Processing, storage, and communication in the sky needs to be enabled in support of the realization of non-terrestrial clouds and space information networks (SIN).
- *Resource optimization with infrastructure as a resource:* Beyond the bandwidth, time, power, and space dimensions, resource optimization needs to address the infrastructure itself as a resource to be configured according to the service requirements.
- *Dynamic spectrum management, coexistence and sharing:* Dynamic spectrum coexistence and sharing between the terrestrial and NTN segments, as well as among the different layers of the architecture, e.g., geosynchronous equatorial orbit (GEO) and Non-Geostationary-Satellite Orbit (NGSO) nodes, space- and air-borne nodes, need to be developed.

- *New spectrum for NTN beyond THz:* The use of new spectral bands use, up to optical communications, needs to be investigated, in close collaboration with the terrestrial counterpart. This includes the characterization of propagation conditions and development of channel models encountered by the NTN elements both in inter-node communications and in non-terrestrial to terrestrial communications.

- *Radio access technologies with flexibility and adaptability:* Waveform design shall jointly address the non-terrestrial and terrestrial channel characteristics, such as Doppler effects introduced by the NGSO nodes, the delay, and latency aspects of the higher altitude nodes, and the need for efficient support of channel estimation. The integrated access network needs also to support discontinuous backhauling in scenarios where a flying base station cannot assume a continuous connection to the core network, e.g., in Low Earth orbit (LEO) or Very Low Earth orbit (vLEO) incomplete constellations.
- *NTN components with beyond current technologies:* Software-defined payloads, new antenna design and technologies, and new components at THz and beyond.
- *AI for exploitation of NT dynamics:* Autonomous and intelligent network management system shall be appropriately developed, exploiting the predictable dynamics component of the NT segment.

5.2.3.2 Large reconfigurable intelligent surface

Large Reconfigurable Intelligent Surface (RIS) or Intelligent Reflecting Surface (IRS) has been proposed as a promising technology for wireless communication [15]-[20]. RIS is two-dimensional surface made by electromagnetic metamaterials that is used as a relay to reflect the RF signal. The metamaterials for RIS have unique electromagnetic properties, such as, negative refraction, perfect absorption, and anomalous reflection/scattering. In a large size RIS, there are many subwavelength-sized structural elements, where each element can controlled independently. The distinct feature of RIS is its adjustable reflection coefficient of each element: the phase of the reflected signal by an element can be electronically tuned to a given value. By adjusting the reflection coefficients of elements, the reflected signals from different elements will be focused on a given direction or point. This makes the RIS similar to the MIMO, but with less power consumption and cost. RIS can be used for enhancing the localization in the 6G, where the fixed RIS reflectors can be treated as additional anchors in the positioning process [19],[20]. A special advantage of RIS in localization is the capability of positioning via trilateration without relying multiple base-stations [19]. There have been demonstrations on the RIS for enhancement of communication at different environments, which has shown notable performance gains.

However, currently the number of states of the adjustable phases is limited due to constraints on material and technology. In most of the current used RIS, the number of adjustable states is only 4, which reduces the achievable performance in practice. The evolving of the material and manufacturing technologies may solve the problem and make the RIS more powerful. Other than the hardware performance and cost, there are a few major difficulties for using RIS in a real system: (1) Estimation of the channels from transmitter to elements of RIS and RIS elements to the receiver. (2) Added overhead due to additional pilots for channel estimation, signalling and controlling of the RIS.

5.2.3.3 Heterogeneous spectrum access and management

In 6G, there are vast different applications. These different applications need different spectrum properties. Overall, the large number of applications and massive number of users require huge spectrum. Figure 5-4 shows the possible spectrum for 6G. Other than the spectrum used in 5G, it is estimated that tremendous spectrum is needed in the terahertz band (0.3 THz to 3 THz, wavelength range 1 mm to 100 μm) and VLC band (400–790 terahertz, wavelengths from about 380 to about 750 nanometers) [65],[66].

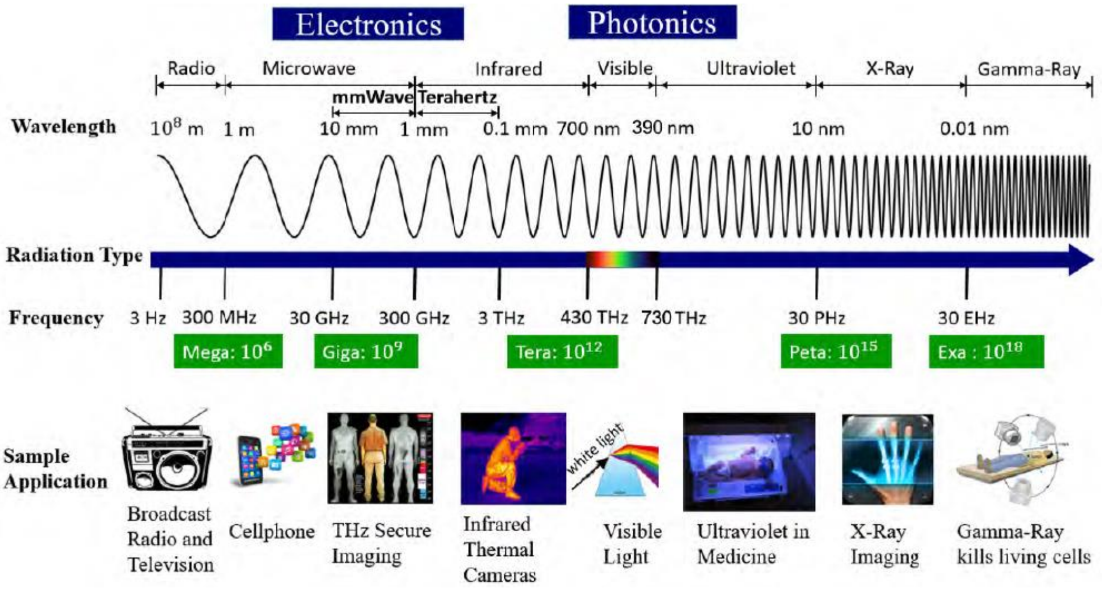

Figure 5-4 Potential radio frequencies for 6G

The newly added frequency for 6G is likely to start from around 90GHz, which is called 6G frequency [65],[66]. The band classification and rectangular waveguide (WR) sizes of the 6G frequency are shown in Table 5-2 [67]. The FCC has opened up experimental 6G spectrum licenses in 2019. Through its rules, the FCC will give innovators a 10 year license to experiment with new 6G products and services. The spectrum, once thought of as useless, could offer super high speed internet service for data intensive applications, such as super high resolution imaging and sensing applications.

Different spectrums have different regulations [65],[66]. Two requirements are commonly found in regulations: (1) Occupied channel bandwidth (OCB). The OCB requirement is expressed as the bandwidth containing 99% of the power of the signal and shall be between 80% and 100% of the declared Nominal Channel Bandwidth. (2) Maximum Power Spectral Density (PSD). The regulations are also different at different countries/regions. For example, both these requirements are enforced for 5 GHz carriers according to ETSI 301 893, while only the maximum PSD requirements are enforced in the US regulation for 5GHz. Maximum PSD requirements exist in many different regions. For most cases the requirement is stated with a resolution bandwidth of 1 MHz. For example, the ETSI 301 893 requires 10 dBm/MHz for 5150-5350 MHz. The implication of the PSD requirement on the physical layer design is that, without proper designs, a signal with small transmission bandwidth will be limited in transmission power. This can negatively affect coverage. That is, the maximum PSD requirement is a binding condition that requires changes to UL transmissions in unlicensed spectrums. How to regulate the terahertz band for 6G is still an open question, which must be done before the 6G standardization.

Table 5-2 The band classification and rectangular waveguide (WR) sizes of 6G frequency

Band	**Frequency**	**WR-Size**
F	90 GHz-140 GHz	WR-8
D	110 GHz to 170 GHz	WR-6
G	140 GHz to 220 GHz	WR-5
G	170 GHz to 260 GHz	WR-4
G	220 GHz to 325 GHz	WR-3
Y	325 GHz to 500 GHz	WR-2
Y	500 GHz to 750 GHz	WR-1.5
Y	750 GHz to 1100 GHz	WR-1
	up to 3000 GHz (3 Terahertz)	

Although the new spectrum bands such as THz and VLC bands could possibly provide large bandwidth for 6G for very high data rate transmission, low frequency bands (for example, sub-6 GHz band) is essential to provide communication services with low cost, broad coverage, and massive access support. Dynamic spectrum access or cognitive radio is needed to support spectrum sharing and accessing intelligently for both licensed and unlicensed bands. There could be a few spectrum access and management schemes in the 6G [15]-[20].

- *Centralized spectrum management:* This has been partially used in 5G to adjust the spectrum allocation in different network slices. The scheme needs to set up a database to indicate the spectrum availability, and a centralized management unit to dynamically authorize the spectrum use and update the spectrum availability information. The major issues of this scheme are the requirement of real-time information and future traffic prediction of the network. If the network dynamics is high, it is very difficult to acquire the real-time information and predict the future traffic. It is also a challenging for the optimization algorithm. As the number of network slices and the range of spectrum bands are large, the optimization algorithm may run long time and cost a lot of energy.

- *AI for dynamic spectrum access:* Fast capturing/learning the network state and predicting the future traffic are the key enablers for efficient dynamic spectrum access. Unsupervised learning, like the deep reinforcement learning (DRL), could be used to tackle these challenges. In recent years, we have seen a boom of AI research in the wireless networks. It is expected to see wide usage of AI in various aspect of 6G. However, it is still not crystal clear how important the role of the AI is, as the reliability and interpretability of AI are still not well understood.
- *Spectrum sharing in unlicensed bands:* Use of unlicensed bands is already implemented in the 5G [15]-[20]. For example, 5G has defined the standard NR unlicensed to use the unlicensed spectrum including the ISM bands in the 2.4GHz and 5.9GHz. In the 6G, this trend will continue. Further enhancement will be introduced in 6G for smart access schemes to avoid cross-interferences among different networks that are sharing these license-exempted bands, including Wi-Fi, LTE, 5G NR, and 6G. In addition to the ISM bands, there may be other traditionally licensed bands for legacy systems that will be freed for spectrum sharing in the future.

The 6G standards and protocols will need to coordinate the dynamic spectrum access in licensed, unlicensed, license-assisted, or tiered-access bands for heterogeneous usage.

5.2.3.3 Open network

In 6G, there will be a vast number of use cases with different requirements and network structures, which provide both public and private smart networks and services with higher degree of flexibility and functionality. To efficiently run such a complicated system, there are a few criteria on the network management. (1) The overall architecture complexity of the network layers and system functions should not be increased with the increased flexibility and functionality. (2) The visible complexity to the user/developer/app needs to be reduced such that the final user, the developer and the app can use simple primitives with clear features and error conditions, without constraining the flexibility and the features. Toward this end, the network needs to be softwarised with full support of cloud-native architecture and service-based architecture (SBA), as well as software and hardware disaggregation.

In recent years, open network design is becoming more and more popular to enhance user selection and interoperability of multiple vendors' equipment and protocol stacks. In open network, commodity hardware and open standards are adopted, which enables the network compatibility in both hardware and software, expandability and extendibility. With open network design, network designers and administrators can benefit from flexible hardware and software components without having to worry about relying on a single vendor, which helps improve the cost efficiency and network configurability. Open network will also facilitate more flexibility and open innovation, and allow more industry players to support the expansion of network infrastructure in future network.

There have been a number of initiatives to develop more open and interoperable open networks, both in RAN and CN. There are a number of challenging issues to address to further develop the open network in 6G.

Software defined network (SDN) is one aspect of open networks, which enables more flexible and agile network control. SDN enables enterprises and service providers to respond quickly and adapt to changing business requirements. Taking advantage of SDN principles, open network adds the use of open source platforms and defined standards in the production of networks. In 6G, open network design will need to be considered in different aspects. Firstly, the network architecture should be open, so that with network virtualization, the required serving network or network slicing for any vertical application can be generated on the top of the shared physical infrastructure. Meanwhile, the interface should be open to supporting the interoperability of different participants and the flexible schedule of virtualized network elements.

It is important to develop the 6G open network platform and open interface to support the interconnection and interoperability of different vendors and share the physical infrastructure and the construction of the supplier ecosystem of mobile networks [15]-[20]. Based on an open network platform/interface, 6G will support service-driven network slicing management as needed, which enables service providers and vertical industries to deploy new services quickly. White box hardware with universal processor architecture will be developed for the open network platform, based on which service providers can customize the required network functions by software definition. SDN and Network Function Virtualization (NFV) will be used to generate the required network slicing flexibly. The decoupling of hardware and software, and SDN/NFV provide a flexible and fast way to support various service innovations in 6G. Moreover, since 6G will converge with more and more vertical industries, the ownership of physical infrastructure may belong to not only mobile operators but also various vertical industries. Therefore, open network/interface designs and standardization become urgent in 6G.

With network openness, not only the network management will be flexible, but also computing and caching resources at different nodes can be fully scheduled and utilized by various mobile edge applications to improve user experiences. But it should also be noted that with the increasing openness of the network, the security problem will be more prominent in the future network.

5.2.4 Privacy, security, and resilience as warranty

As the 6G network is envisioned to seamlessly connect the physical, virtual, and human worlds, vast amount of information will be collected and traversed in the 6G network. In-network computing as discussed in earlier sections, for example, at the MEC and other network nodes, will derive insights on industrial and business processes, personal work and life styles, social relations, for actionable controls. Networked close loop control will be an essential function of 6G, leading to significant increase of command and control packets/traffics in 6G networks. The 6G network therefore introduces new potential security vulnerabilities and opens to a much wider security threat landscape and design challenges than legacy 4G and 5G networks, calling for new enabling technologies for security protection, privacy preservation, and resilience. The 6G vision would only be successfully realized if security, privacy, and resilience could be designed to support the new requirements arising from the real-time interconnected and interactive physical, virtual, and human worlds.

There are multi-folds of challenges and potential technologies in security, privacy, and resilience design in 6G networks. While the traditional security threats such as denial of service (DoS) attacks, eavesdropping, replay attacks, physical attacks, malware applications, hardware tampering, will remain important in 6G, new challenges and issues arise. The automatization and softwarisation of the 6G network makes the network security much more complicated than that in the 5G network. The system is not only vulnerable to direct cybersecurity attacks, but also easily affected by the misbehaviours of automatized functionalities. The 6G security standardization will need to address these new challenges. We discuss a few in the following.

- Guaranteeing the dependability and trustworthiness of the system will be one of the major challenges. Solutions such as zero-touch micro-segmentation and slicing needs to be guaranteed, and distributed AI/ML functions and models need to be hardened to avoid malfunctions and cyberattacks and guarantee their trustworthiness and security, for example, to avoid model poisoning and membership inference attacks in federated-learning distributed architectures.
- Security quantification in a 6G context should deal with complexity and fragmentation, and mandates the exploration of mechanisms to identify, evaluate, certify, and monitor the level of security. Based on such quantification, trust can be given to providers and

services, enabling the growth of the sector by answering the diversity of demands from mass market to specific business to business (B2B) verticals.

- Despite commonalities with other digital services, some data centric or green issues remain a specific challenge for 6G systems. As such, human centric privacy, relevant trustable AI, orchestrated operations across parties, impact and sustainability of solutions will be key to shape an acceptable digital future enabled by 6G.
- The research for security solutions will also need to take into consideration the performance, ease of management and energy consumption, when targeting to guarantee the security and trustworthiness of 6G telecom and service/application platforms.

New and emerging technologies and innovations will need to be incorporated in 6G to address the above security and privacy challenges. We give a few examples here. (1) security protocols at different network layers in the architectural framework, which has been decomposed into four segments in [68], namely, platform, functions, orchestration and specialization. Each segment is presented with its own security and privacy challenges, while their integration and interaction opens new threats; (2) security key acquisition using physical layer (PHY) information, referred to as physical layer security (PLS) [118][119], quantum key distribution (QKD) [120]; (3) inter-network security in terrestrial/non-terrestrial integrated space-air-ground-sea communications; (4) privacy-preserving communications and computing; (5) use of distributed ledger technologies (DLT); (6) use of AI for threat analysis and prevention, attack and anomaly prediction, detection, attribution, and mitigation; (7) security threats and counter-measures in 6G-supported vertical domains. More detailed discussions on 6G security and privacy may be referred to [69][70] and references therein.

There is a very active standardization and project landscape in the security domain. A number of research projects and standardization efforts have been kicked off by ITU-T FG-ML5G [116], ETSI ISG ENI [115], 3GPP, National Institute of Standards and Technology (NIST). These initiatives will impact the 6G security standards.

5.2.5 Sustainable networking and energy efficiency as baseline

With the emerging of 5G technology and its rapid deployment progress, [71] estimated that about 15% of the total global carbon dioxide (CO_2) emission would be from the information and communication technology (ICT) sector by the end of 2020. Moreover, RAN takes about 57% of the total network energy consumption. With a better energy efficiency of 5G than its predecessors, the RAN energy consumption will reduce to 50.6% by 2025 with 5G to gradually replace 3G and 4G networks [72]. Nevertheless, the ultra-dense deployment, the extremely large data traffic volume, the increased functionalities of sensing, computation, and the tens of billions of devices to be connected by 6G, makes the energy consumption reduction and energy efficiency enhancement a very important area in 6G design. Sustainable network will need be delivered as a baseline for 6G to support the Sustainable Development Goals (SDG) [73].

To address the energy consumption in 6G, an energy-efficient RAN will be critical. Based on the GSMA report [74], RAN accounts for 73% of total energy consumption of a mobile network operators (MNO), and the energy consumed at base stations in the cellular network can be up to 77% [74]. Vodafone reported in [75] that cellular base station sites consume 73% of total energy in its cellular network. These numbers clearly indicate that reducing the energy consumption at the cellular base stations will potentially lead to significant improvement on energy efficiency of the whole system.

Figure 5-5 shows the energy consumption breakdown at a basestation site [76]. Although the percentage may vary according to proprietary settings of MNOs and original equipment manufacturers (OEMs), the main network equipment, consisting of radio frequency (RF) processing unit, baseband unit (BBU) and main control, requires the largest amount of energy. The radio processing unit requires 40% of the total energy consumption at the basestation, and the high power amplifier (HPA) consumes most of the energy at the radio processing unit. For 5G network using massive multiple-input multiple-output (mMIMO), the energy consumption can be broken down to two major parts: antenna unit and BBU, in which the antenna unit requires about 90% of the total energy consumption. HPA efficiency has been indicated as a key component of network energy efficiency during 3G/4G era [121][122]. However, HPA efficiency has been improved over the time, in which Doherty PA architecture with envelope tracking and Gallium Nitride (GaN) semiconductor material have been introduced, resulting in HPA efficiency of more than 50% [77]. On the other hand, it is observed that energy consumption at the base station varies with the traffic load and signal transmission regularity, i.e., the base station has less signal to transmit during low-load period, and accordingly consumes less energy than high-load period. For each basestation, full load has been shown to achieve optimal energy efficiency [123].

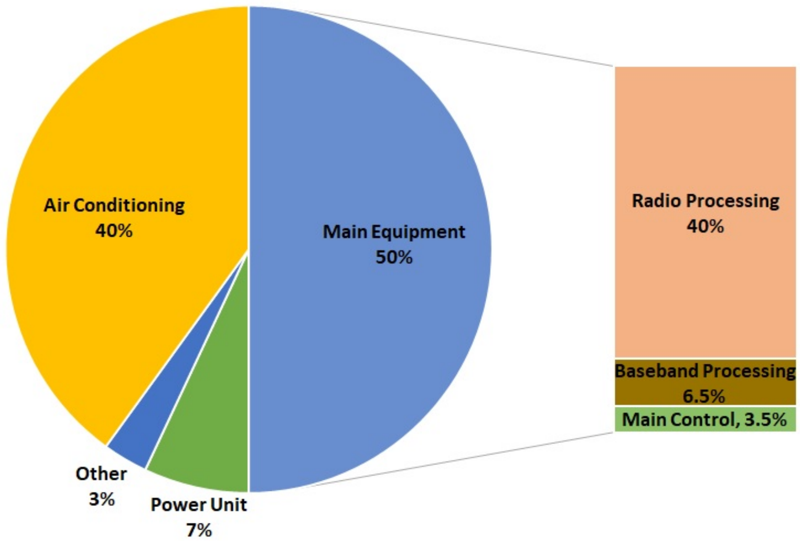

Figure 5-5 Energy consumption breakdown at the base station (brought from NGMN report [76])

A 10% energy consumption reduction target had been set from 4G system when the concept of 5G system was introduced. For 6G system, although the exact target number has not been determined yet, a more ambitious target is expected following the SDG. According to ITU, the ICT sector has committed to reduce the greenhouse gas emissions by 45% from 2020 to 2030 [78], while the North American ICT sector are encouraged to achieve net-zero greenhouse gas emission by 2040 [79]. The efforts to reduce network energy consumption in 6G network can be discussed as an end-to-end perspective, including: (1) specifications and designs from data transmission, signaling, network architecture, to AI-driven methods; (2) power efficiency improvement at device-level and site-level, e.g. air conditioning and cooling system; (3) energy harvesting and circular energy; (4) ecosystem and regulatory aspects. As this chapter is on the standardization of 6G communication systems and networks, we will discuss the potential enabling technologies related to system and network specifications, designs, and AI-driven solutions [76], [80]-[82].

5.2.5.1 Specifications and designs

In aspects of signal transmission and network operation, 3GPP has introduced the following energy saving techniques in its 5G NR interface.

- *Massive MIMO transmission:* Massive MIMO is introduced at the base station by equipping with antenna arrays, consisting of large number of antenna elements [83]. With well-optimized signal transmission at each antenna element, massive MIMO improves spectral efficiency by allowing simultaneous transmission across multiple user equipment (UE). At the same time, energy efficiency is also improved via beamforming, in which the wireless signal from base station is delivered by a narrow beam directly to a designated UE, and accordingly improves the received signal quality and extends the network coverage.

  As an evolution path to 6G system, introducing more antenna elements at the basestation will enable more radio processing chains and hence increase the total energy consumption. It is therefore to analyse the trade-off between performance gain and energy consumption to develop the massive MIMO specification in 6G systems.

  In addition to the single and centralized adaptive antenna array architecture, a distributed antenna system (DAS) can be deployed by placing the antenna elements at different locations in the network coverage area [84], [85]. The antenna elements are connected via optical fiber cable as a fronthaul link, as well as with the central control unit (CCU) and central BBU. Large-scale DAS has been shown to deliver better energy efficiency than centralized massive MIMO [124] due to the advantage of more effectively overcoming the radio wave propagation loss and at the same time enjoying the beamforming gain. 3GPP and a few other standardization bodies and alliances, e.g., O—RAN, have been developing specifications for DAS implementation in 5G and beyond 5G networks.

- *Lean carrier design:* Lean carrier design refers to a design to minimize transmission of broadcasting and reference signals when they are not necessary, e.g. when the traffic load is low and/or when the users have low mobility, instead of the "always on" transmission in 4G system [86]. This can be done in various approaches, for example, increasing the signal cycle, introducing flexibility in reference signal setting, turning the broadcast channel off, etc. In 5G system, the increasing of signal cycle, in particular the cell synchronization signal (SS) which is broadcasted from the base station to provide cell information to new users, can be up to 160 ms, i.e. 8-times the original cycle. The use of lean carrier design saves energy from both the signal transmission and the hardware operation, as some hardware can be switched off during the transmission cycle, as shown in Figure 5-6 [87]. It is expected that the same technique will still be available in 6G system, with an addition of flexibility to various use cases, e.g. different user mobility and network density.
- *Improved sleep mode*: Sleep mode and its operation are designed under the similar concept to lean carrier, i.e., switching off some of network equipment when the traffic load is low, or when there is no data to transmit [87]. With the recent development in network equipment, most of the hardware can be switched on/off in sub-second granularity level without requiring transition time. Therefore, the improved sleep mode is proposed in order to reduce the energy waste during the low-load and the no-transmission period, even when the gap is very short at sub-second level, as shown in Figure 5-7.

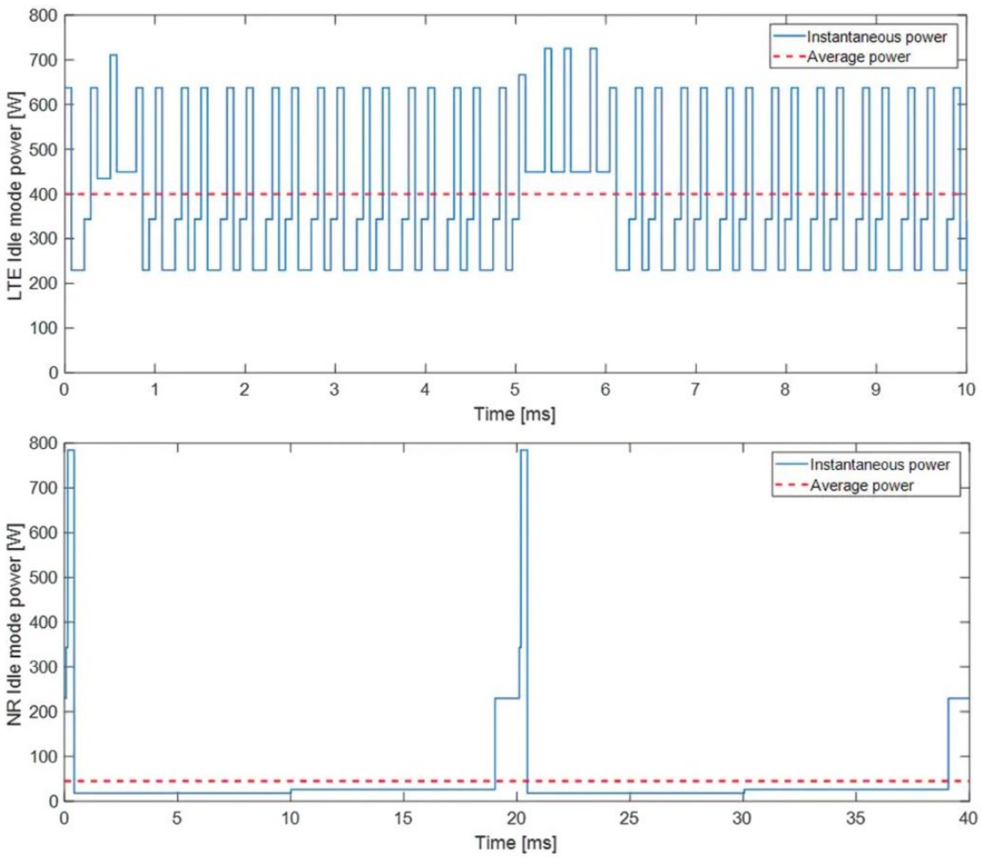

Figure 5-6 Power consumption comparison due to signal transmission for 4G (top) and 5G with lean carrier design and reduced SS transmission (bottom) (brought from Ericsson blog [87])

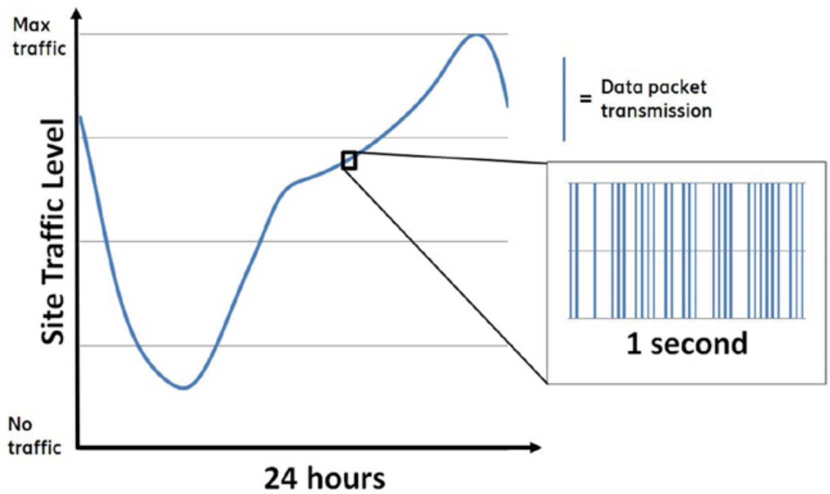

Figure 5-7 Gaps in data packet transmission (brought from Ericsson blog [87])

The improved sleep mode is now being studied and will be introduced in the next release of 3GPP standards (expected to be Release 18). Four levels of sleep modes, with different minimum sleep durations, are being investigated as follows [88].

Table 5-3 Sleep mode level comparison [88].

Level of Sleep	**Level 1(4G like)**	**Level 2**	**Level 3**	**Level 4**
Sleep time (minimum duration)	71 μs	1 ms	10 ms	Approx.. 1 s
Sleep depth (components to switch off)	PA	PA & some RF components	PA & some RF, BB components	PA & some RF, BB components

(a) 1st level sleep mode – This level refers to the deactivation of HPA for the duration of at least 71 μs, similar to micro discontinuous transmission (μDTX) in 4G network.

(b) 2nd level sleep mode – This level refers to the deactivation of some of base station components, mostly in the RF units for at least 1ms, i.e. one transmission time interval (TTI).

(c) 3rd level sleep mode – This level deactivates more components in RF and some of digital baseband units, in which the deactivation duration is at least 10 ms, i.e. one frame.

(d) 4th level sleep mode – This level targets at the deactivation duration of approximately 1s. Most of the components at the base station can be switched off. It is worth noting that the 4th level sleep mode has a longer duration than the maximum SS broadcasting cycle, hence implementation of this sleep mode should be supported with alternative offloading solutions, e.g. microcell switch off with traffic offloading to macrocell, in order to prevent from any connectivity loss.

The above sleep mode levels are used as design principle to offer several approaches to switch off, or shutdown, the following network and radio resources.

(a) Symbol shutdown – This is similar to lean carrier design, which is to minimize any unnecessary signal transmission, especially the cell synchronization signal and beam sweeping. This can reduce the energy consumption at the RF unit, especially the HPA.

(b) Channel shutdown – Channel shutdown refers to silencing the base station with multiple channels, by switching off the RF components with respect to channels having low traffic, expecting 10-20% of energy saving.

(c) Carrier shutdown – 5G offers flexible radio resource management, in which the whole signal bandwidth can be separated to bandwidth parts (BWP). With multi-layer heterogeneous network deployment, it is possible to switch off the capacity-layer bands, e.g., high-frequency and large-bandwidth bands, while maintaining the coverage-layer bands, e.g. low-frequency and long-coverage bands.

There are also several techniques similar to the above-mentioned approaches aiming to reduce the energy consumption under low-load conditions, e.g. cell zooming and adaptive transmit power control. In addition, since the massive MIMO has been introduced in 5G network, several OEMs and MNOs are studying approaches to reduce energy consumption at the antenna arrays, including switching off some of RF chains at the array or using sparse antenna arrays [89].

It is obvious that sleep mode and network resource switch-off will continue to be studied and developed for adoption in 6G. However, switch-off technique also leads to drops of quality of services (QoS), which needs to be carefully managed when there are mission-critical services. It is important to take into account the service quality and energy consumption trade-off and ensure the required QoS for all users while driving for better energy efficiency. In addition, other emerging technologies in antenna, circuit, network architecture, etc., need to be considered holistically for an energy-efficient and sustainable 6G.

5.2.5.2 AI-driven solution

With the rapid growth of computational power and computational resource, data collection and storage, and neural network development, AI is being introduced in various fields, including wireless communications. Wireless network design is usually based on optimization, dealing with multiple factors including the network load, available resources, user priority, required QoS, channel conditions, and the overall network performance metrics such as reliability, capacity, and energy efficiency, etc. It is not possible to solve the wireless network optimization at full-scale. ML and DL has been actively studied to drive the network energy efficiency performance.

Several industry standards are focusing on integrating ML and AI for energy efficiency [90]-[93]. In particular,

- ETSI Zero-Touch Network and Service Management (ZSM)
- ITU-T Focus Group on AI for Environmental Efficiency
- 3GPP TS 29.520, 5G Systems; Network Data Analytics Service
- O-RAN AI/ML in RAN Intelligent Controller

ML and AI may introduce energy saving, but also incurs energy consumption due to its computational load. We discuss both aspects in the following.

- *Energy consumption reduction through AI/ML:* Energy consumption reduction across multiple base stations, ranging from hundreds to thousands, is a large-scale optimization problem, which is difficult to solve under time and resource constraints. Within the past recent years, there are studies and experiments of using AI/ML for energy saving, in which the energy saving policies may be based on signal processing, sleep mode setting, or other approaches such as integration with renewable energy resources. Some examples of these works are listed below:

    - AI/ML for optimizing RAN operation and energy flows among power grid and renewable energy resource [94], where the ML can provide 10-40% of energy saving
    - AI/ML for automated network operation, resource management, and QoS assurance [95]-[96]
    - Power consumption monitoring, analytics and predictions for service assurance to optimize the placement of network functions, utilizing 3GPP defined Network Data Analytics Function (NWDAF) and network slicing [92]
    - UE location tracking and trajectory prediction, then optimizing sleep mode policy and data traffic offloading across multiple base stations [97]
- *Energy consumption of AI/ML:* Energy consumption of an AI/ML model is not negligible since it requires computational resource to run the sophisticated neural networks, especially when some application needs to call the ML function frequently, e.g. every 100 ms. Moreover, energy consumption during model training may need to be taken into account as well, although it is an offline process, due to the following reasons:

  (a) Energy consumption for one-time model training is relatively large, requiring long-time training with large amount of input data, and sometimes requiring high performance computer. Furthermore, those processes produce greenhouse gas and contribute to the expenditures of either OEMs or MNOs.

  (b) Some applications may need periodic model re-training, such as once a month, to ensure its functionality and to be adaptable for changes in environment.

It is therefore important to take a systematic and holistic evaluation ML/AI-based methods, similar to other energy-efficient approaches. However, there is limited work on the energy consumption assessment of AI/ML models. [76] has proposed a method to account for the energy consumption by taking into account the AI model parameters and the computational platform. To support the standardization efforts, more research is needed to establish a systematic approach and cover the various key factors.

5.3 Selected 6G Research Initiatives

There has been strong momentum and strong funding support in 6G research since 2019. The European Union (EU), China, Korea, Japan, and the United States are leading the activities.

5.3.1 European Union

EU has initiated many beyond 5G and 6G research projects, as summarized in Figure 5-8, courtesy of 6G World. Among them, the European Commission's 6G flagship initiative Hexa-X funded by EU Horizon 2020, the Finnish 6G Flagship hosted by the University of Oulu, have received much attention.

- *Hexa-X (https://hexa-x.eu/)*: Kicked off in December 2020, Hexa-X brings stakeholders including network vendors, communication service providers, verticals, technology providers, and European communications research institutes, aiming to create unique 6G use cases and scenarios, developing fundamental 6G technologies and defining a new architecture for an intelligent fabric to integrate the key 6G technologies.
- *6G Flagship (http://6gflagship.com)*: 6G Flagship is a Finnish initiative under the Academy of Finland, a governmental funding agency. Coordinated by the University of Oulu, it is among the world's first 6G research initiatives. Envisioning a data-driven future society enabled by near instant and unlimited wireless connectivity, it brings ecosystem players in 6G research, development, and innovation and aims at creating new business opportunities as well as implementing the UN's SDGs and major societal challenges. Its published white papers have been providing useful references in various aspects of 6G.

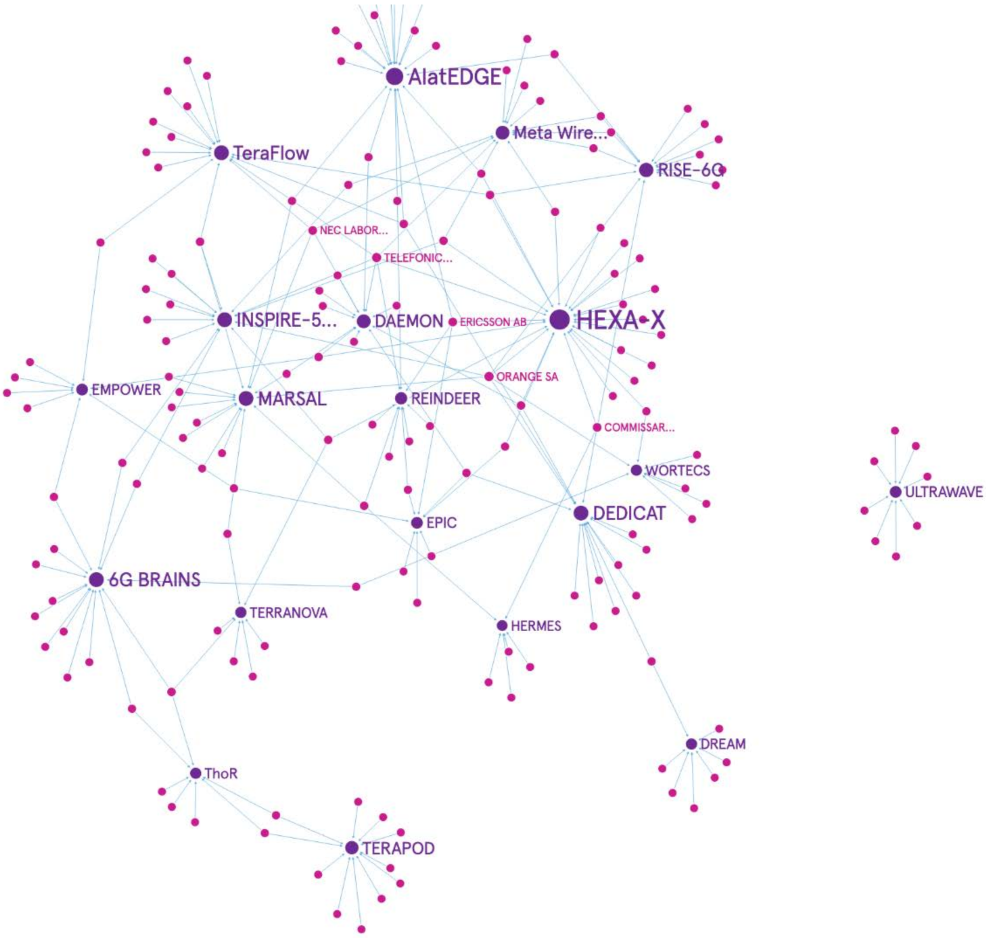

Figure 5-8 Interactive Graph of EU-Funded 6G Initiatives (Source: https://www.6gworld.com/exclusives/the-ultimate-6g-research-network-graph/)

5.3.2 United States of America

In October 2020, the Alliance for Telecommunications Industry Solutions (ATIS) announced the launch of the Next G Alliance (NGA), an industry initiative to advance North American mobile technology leadership in 6G and beyond. The NGA will encompass the full lifecycle of research and development, manufacturing, standardization and market readiness, aiming to establish North American preeminence in the 5G evolutionary path and 6G development. It has three strategic focus:

- Develop a 6G national roadmap that addresses the changing competitive landscape and positions North America as the global leader in R&D, standardization, manufacturing and adoption of Next G technologies.

- Align the North American technology industry on a core set of priorities that will steer leadership for 6G and beyond to influence government policies and funding.

  Identify and define the early steps and strategies that will facilitate and lead to rapid commercialization of Next G technologies across new markets and business sectors and promote widescale adoption, both domestically and globally.

Since its launch, NGA has kicked off a number of working groups to execute its mission, and has released its white paper recently in February 2022 [79].

5.3.3 China

China's government activity on 6G is led by the Ministry of Science and Technology (MOST) and Ministry of Industry and Information Technology (MIIT), and government-industry coordination occurs through "IMT-2030 (6G) Promotion Group". The "IMT-2030 (6G) Promotion Group" published its white paper on "6G Vision and candidate technologies" in June 2021, listing the following use cases:

- Immersive Cloud XR
- Holographic Communications
- Sensory Interconnection
- Intelligent Interaction
- Communication for Sensing
- Proliferation of Intelligence
- Digital Twins
- Global Seamless Coverage

Ten candidate 6G technologies have also been highlighted:

- New network with native AI, including new air interface and new network architecture with native AI

- Enhanced wireless air interface technologies, including basic physical layer technologies, ultra-massive MIMO, and in-band full duplex
- Wireless transmission technologies on new physical dimensions, such as reconfigurable intelligent surface, orbital angular momentum (OAM), intelligent holographic radio (IHR)
- Terahertz and visible light technologies
- Integrated communications and sensing
- Distributed autonomous network architecture
- Deterministic network
- Computing-aware network
- Integrated terrestrial and non-terrestrial network
- Native network security based on multi-lateral trust model

Research and development projects have also been started as part of the national initiative.

5.3.4 Japan

Japan established the "Beyond 5G Promotion Consortium" in December 2020 under the Ministry of Internal Affairs and Communications as the hub of 6G activities. The "Beyond 5G Promotion Consortium" aims to achieve the early and smooth introduction of Beyond 5G and to strengthen the international competitiveness of Beyond 5G in order to realize the strong and vibrant society expected in the 2030s. The Consortium consists of the General Assembly and its subordinate committees, the Planning and Strategy Committee and the International Committee, with the Planning and Strategy Committee focusing on the study of comprehensive strategies to promote Beyond 5G and preparation of Beyond 5G White Paper, while the International Committee focusing on identifying international trends for promoting Beyond 5G and international dissemination of the status of Japan's efforts.

5.3.5 Korea

The Ministry of Science and ICT ("MSIT") of Korea announced its "6G R&D Implementation Plan" in June 2021, which includes the following three goals (https://www.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&pageIndex=9&bbsSeqNo=42&nttSeqNo=517&searchOpt=ALL&searchTxt):

- Secure next-generation key original technologies
- Gain dominance in international standards and patents
- Lay the foundation for 6research and industry

5.4 The 6G Standard Development

To create an international 6G standard, a number of organizations will be involved: standard developing organizations (SDOs), regulatory bodies and administrations, and industry forums.

5.4.1 Standard Developing Organizations (SDOs)

3GPP is a global SDO from seven regional and national SDOs in Europe (ETSI), Japan (ARIB and TTC), the United States (ATIS), China (CCSA), Korea (TTA), and India (TSDSI). 3GPP has created the technical specifications of 2G (GSM), 3G (WCDMA/HSPA), 4G (LTE), and 5G (NR), and is expected to create the 6G technical specification. The technical specifications are essential for industry to produce and deploy standardized products and provide interoperability among those products.

- *Release (Rel-) 17:* Rel-17 (the third release of 5G specifications) is expected to be the enhanced version of previous releases, in particular offering low-latency communication. However, the standard development has been under pressure due to COVID-19 restrictions. The RAN1 physical layer specifications development was initially targeted to freeze by December 2021. Then the Stage 3 freeze (RAN2, RAN3, and RAN4) would follow with the initial targeted time line of March 2022, and the ASN1 freeze and the completion of performance specifications by September 2022.

- *Rel-18 and the start of work on 5G-Advanced:* During the Rel-18 planning process, some capacity of the working group's effort will be kept in reserve for workload management and to meet late, emerging critical needs arising from commercial deployments. The 3GPP had finalized its key topics to be studied and developed in Rel-18 in December 2021, in which the full list can be found in [98]. Below are the interested topics for R&D perspective and further studies:
    - Evolution for downlink MIMO, including enhancement for channel state information (CSI) and multi-TRP handling
    - Uplink enhancement, which strongly needs to be considered (i.e., the previous releases mainly focused on downlink improvement)
    - Mobility enhancement, especially for high-frequency band (FR2)
    - Reduced Capacity (RedCap) device and specification development for UE which does not require high network performance but cost-effective, including power saving enhancement
    - Non-terrestrial network (NTN), following the first version in Rel-17, including IoT aspects
    - Expanded and improved positioning
    - Evolution of duplex operation, with cross-link interference management
    - AI/ML for air interface and next-generation RAN, starting from use cases and KPI determinations
    - Network energy saving
    - Additional and open topics, such as carrier aggregation and dual-connectivity enhancement, flexible spectrum integration, RAN support beyond 52.6 GHz, reconfigurable intelligent surface (RIS), unmanned aerial vehicle (UAV) and high altitude platform system (HAPS)

The Rel-18 work/study items will be examined over 18 months, starting from the first half of 2022.

5.4.2 Regulatory bodies and administrations

The government-led regulatory bodies and administrations are responsible for setting regulatory and legal requirements for selling, deploying, and operating mobile communication systems and other related products. They have two important tasks:

- *Spectrum regulation:* control spectrum use and set licensing conditions for the mobile operators that are awarded licenses to use parts of the *radio frequency (RF)* spectrum. Spectrum regulation is handled at multiple levels: national level, regional level, and global level. There are three regional bodies, namely, Electronic Communications Committee (ECC) under the European Conference of Postal and Telecommunications Administrations (CEPT) for Europe, Inter-American Telecommunication Commission (CITEL) for the Americas, and Asia-Pacific Telecommunity (APT) for Asia. The global regulatory body is the International Telecommunications Union (ITU). Spectrum regulation specifies the services each spectrum is to be used for, and the limits of allowed and unwanted emissions.
- *Regulatory certification and type-approval:* This is to ensure devices, base stations, and other equipment are type-approved and meet the relevant regulation.

5.4.3 ITU

ITU is a specialized agency of the United Nations (UN) responsible for all matters related to information and communication technologies. ITU is preparing high-level performance statements for 6G systems in a form of the International Mobile Telecommunications 2030 (IMT-2030). This is expected to be an iterative and joint effort with SDOs and industry forums. In particular, the following study groups and entities in ITU play active roles in the making of 6G standard.

- *The ITU-T Future Networks Study Group SG13:*

SG 13 is responsible for developing the requirements and architecture of Future Networks. It considers candidate ideas for IMT-2030 requirements [3], including, but not limited to, network slicing, machine learning, and quantum key distribution. In particular, the Focus Group (FG) on Technologies for Network 2030 (FG-Net2030) in SG 13 is working on a new network vision for 2030 [3]. FG-Net2030 published the white paper [10], focusing on the "non-radio-related" aspects of future network capabilities for the year 2030 and beyond. It has also published [8], specifying the network architecture framework.

- *ITU-R:*

ITU-R is the radio communications sector of the ITU. ITU-R is responsible for ensuring efficient and economical use of the RF spectrum by all radio communication services. The different subgroups and working parties produce reports and recommendations that analyze and define the conditions for using the RF spectrum. The quite ambitious goal of ITU-R is to "ensure interference-free operations of radio communication systems," by implementing the Radio Regulations and regional agreements. The Radio Regulations is an international binding treaty for how RF spectrum is used.

ITU-R manages global mobile telecommunication standards and provides guidance and roadmap for next generation communication R&D by defining the vision for next generation mobile telecommunication, including 6G. ITU-R Working Party 5D (WP5D) is responsible for the overall radio system aspects of International Mobile Telecommunications (IMT) systems, comprising IMT-2000, IMT-Advanced, IMT-2020 and IMT for 2030 and beyond.

In February 2021, ITU-R WP5D produced the report "Future Technology Trends towards 2030 and beyond" [4] soliciting inputs from related organizations. WP5D also launched the 6G Vision Group in early 2021 to take charge of establishing the 6G Vision, including defining the key capabilities, working on technology development, and creating timelines on standardization and commercialization of 6G. Starting with completing the 6G Vision by

2023, ITU-R plans to develop technical requirements and recommendations for 6G through industry standards organizations such as 3GPP. Out of those candidate technologies for 6G, the technologies that pass ITU-R's evaluation will be approved as the global standards for 6G around 2030.

The key objectives of the Vision towards IMT for 2030 and beyond are:

- Focus on continued need for increased coverage, increased capacity and extremely high user data rates;
- Focus on continued need for lower latency and both high and low speed of movement of the mobile terminals;
- Fully support the development of a Ubiquitous Intelligent Mobile Society;
- Focus on tackling societal challenges identified in UN SDGs, in particular to meet the needs of Industry, Innovation and Infrastructure;
- Consider what the future heterogeneous mobile broadband networks can offer to the society and the economy through the applications and services they support;
- Target the changing global scenario on how people work and how people stay safe during the societal challenges such COVID-19 pandemic and global climate changes;
- Focus on delivering on digital inclusion and connecting the rural and remote communities.

There are four key pillars for the vision:

1. Any future technology should help in the development of a Ubiquitous Intelligent Mobile Connected Society.

2. Any future technology should support technologies that can help bridge the digital divide.

3. Any future technology should support technologies that can Personalize / localize services.

4. Any future technology should support the connectivity / compute technologies that can address issues of real-world data ownership sensitivities.

It is important to note that the WP5D does not create the actual technical specifications for IMT, but defines IMT in cooperation with the regional standardization bodies and maintain a set of recommendations and reports for IMT, including a set of Radio Interface Specifications (RSPCs). These recommendations contain "families" of Radio Interface Technologies (RITs) for each IMT generation, all included on an equal basis. For each radio interface, the RSPC contains an overview of that radio interface, followed by a list of references to the detailed specifications. The actual specifications are maintained by the individual SDO and the RSPC provides references to the specifications transposed and maintained by each SDO.

- *ITU-R World Radiocommunication Conferences (WRC):*

A key part of the RF spectrum allocation and coordination in ITU-R is done through the WRC, held every three to four years. At WRC, the Radio Regulations are revised and updated, resulting in revised and updated use of the RF spectrum across the world.

The most recent WRC was held in 2019 (WRC-19), and the next one is to be held in 2023 (WRC-23). The Radio Regulations from the WRCs define frequency allocations, technical and regulatory conditions for use of spectrum by a given service. This is important to ensure compatibility, prevent and resolve cases of harmful interference. The Radio Regulations are international treaties that are binding to ITU member states. In addition to the radio spectrum regulation, WRC also governs the use of the geostationary- and non-geostationary satellite orbits.

ITU-R organizes six study groups to guide the work done in the preparatory process and make ready the technical bases for decisions at the WRCs. The six study groups are:

- Study Group 1 (SG1): Spectrum management
- Study Group 3 (SG3): Radiowave propagation
- Study Group 4 (SG4): Satellite services
- Study Group 5 (SG5): Terrestrial services
- Study Group 6 (SG6): Broadcasting services
- Study Group 7 (SG7): Science services

5.4.4 Industry Forums

Industry forums are industry-led groups to promote specific technologies or interests. Some examples of industry forums in mobile communications are introduced, including the GSM Association (GSMA) [36], Next Generation Mobile Networks (NGMN) Alliance [125], Next G Alliance [128], and Open Radio Access Network (O-RAN) Alliance [99]. Linux Foundation has been supporting the Open Network Automation Platform (ONAP) [125]. The 6G Smart Networks and Services Industry Association (6G-IA) [127] has also been gaining momentum and attention.

5.4.4.1 GSMA

The GSMA is a global industry organization, representing the interests of mobile operators of more than 750 operators as full members and nearly 400 companies in the broader mobile ecosystem as associate members, including handset and device makers, software companies, equipment providers and internet companies, as well as organisations in adjacent industry sectors. The GSMA also produces the industry-leading MWC events held annually in Barcelona, Los Angeles and Shanghai, as well as the Mobile 360 Series of regional conferences [36]. In July 2021, GSMA publishes its submission to ITU-R titled "*Vision 2030 – Insights for Mid-band Spectrum Needs*" [25].

5.4.4.2 NGMN

The NGMN Alliance is a mobile telecommunications association of mobile operators, vendors, manufacturers and research institutes. It was founded by major mobile operators in 2006 as an open forum to evaluate candidate technologies to develop a common view of solutions for the next evolution of wireless networks, and ensure the successful commercial launch of future mobile broadband networks through a roadmap for technology and friendly user trials.

In its published its 6G Vision paper [26], NGMN outlined three drivers for 6G evolution, namely, societal goals at large as well as that expressed in the UN SDGs [31], market expectations of new services and capabilities in a cost-effective manner, and operational necessities of increasingly more efficient planning, deployment, operations, management, and performance of the mobile operator's networks. For 6G standard development, NGMN advocates to broaden, align, and rationalize the scope of standards and technology development process to support a healthier and more vibrant ecosystem, moving from the current approach of piecemeal-based on proposals on only specific aspects of the system and ensuring that technologies are developed holistically across different standards organizations.

5.4.4.3 Next G Alliance

Next G Alliance is an ATIS-lead initiative in North America region to discuss and promote solutions for 6G era with industry representatives. The U.S. announced an initiative, called the Next G Alliance, a year ago with the goal of advancing U.S. leadership in 6G. Members of the Next G Alliance include AT&T, Verizon, T-Mobile, Facebook, Qualcomm, Charter Communications, Nokia, Ericsson, Google and Samsung, plus many others.

5.4.4.4 O-RAN Alliance

Open-RAN (O-RAN) Alliance [99] was established in 2018 by an initiation of group of MNOs, including AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO and Orange. Its mission is to re-shape the RAN industry towards more intelligent, open, virtualised and fully interoperable mobile networks. The O-RAN developed standards provide a more competitive RAN supplier ecosystem, i.e. supply diversification instead of using the whole solution from one OEM, with faster innovation to improve user experience. O-RAN based mobile networks also improve the efficiency of RAN deployments as well as operations by the mobile operators. Currently, the alliance has been expanded progressively with the variety of new members from different sectors, including hardware and computation unit producers such as NVIDIA, Intel, and AMD, and universities and research institutions.

It is observed that the standard development in O-RAN alliance is in fact aligned with 3GPP timeline and technology. While 3GPP focuses on development of new working and study items, O-RAN focuses on system-level realization under its open architecture and enabling open interfaces for various equipment. Further details of O-RAN standard and architecture developments are available in its white paper [100], while its working groups(WGs) are listed below:

- WG1: Use Cases and Overall Architecture Workgroup
- WG2: The Non-real-time RAN Intelligent Controller (RIC) and A1 Interface Workgroup
- WG3: The Near-real-time RIC and E2 Interface Workgroup
- WG4: The Open Fronthaul Interfaces Workgroup
- WG5: The Open F1/W1/E1/X2/Xn Interface Workgroup
- WG6: The Cloudification and Orchestration Workgroup
- WG7: The White-box Hardware Workgroup
- WG8: Stack Reference Design Workgroup
- WG9: Open X-haul Transport Workgroup
- WG10: Operations, Administration and Maintenance (OAM) Workgroup

5.4.5 6G Standard Timeline

With the evolution roadmap for the first five generations, 6G is anticipated in the 2030's. While the SDOs and regulators have yet to release the 6G standard development timeline, a few papers have provided a rather aligned roadmap while focusing on different perspectives.

In 2019, the authors of [101] have provided a 6G roadmap which was derived from the strategic plans of various standards bodies. It include the projected timelines for 6G vision, 6G requirement, and 6G evaluation, up to the year 2030, as re-produced in Figure 5-9. A similar 6G timeline has been presented in [102], as re-produced in Figure 5-10.

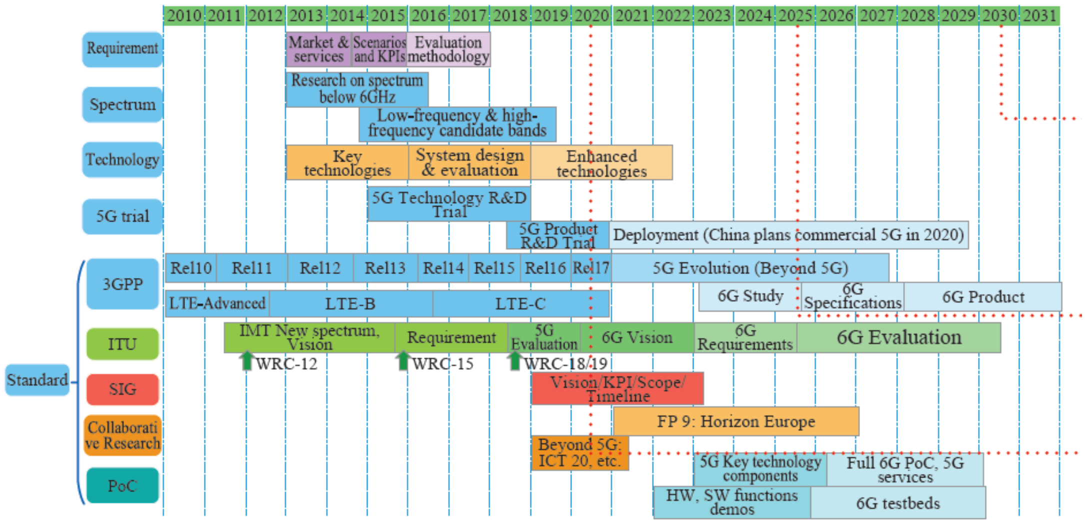

Figure 5-9 Timeline of 6G Wireless Networks [101].

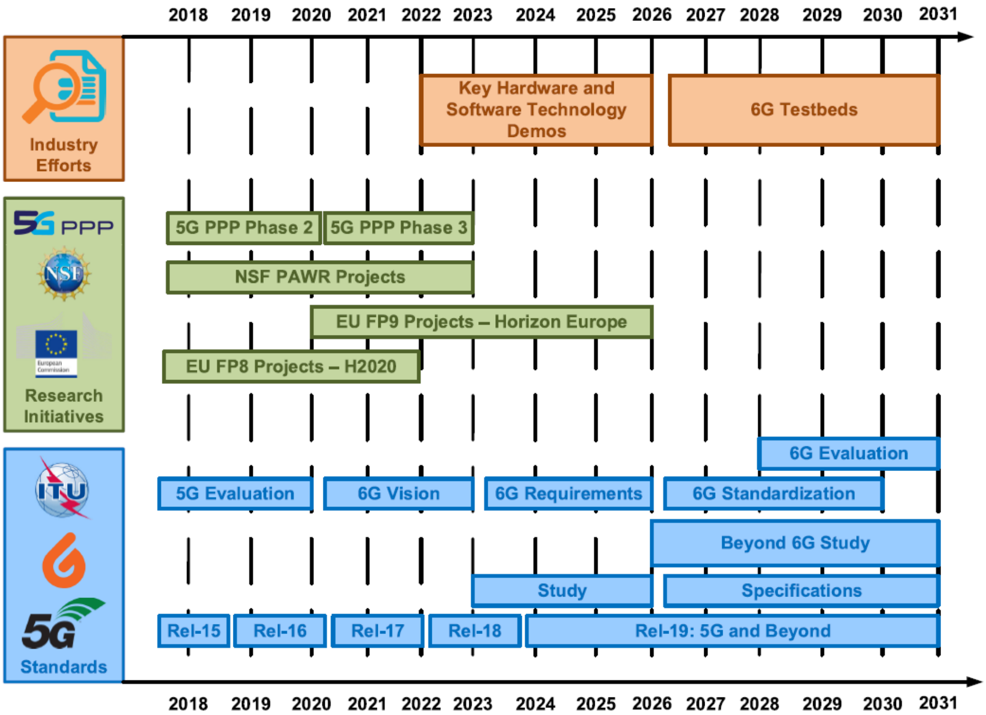

Figure 5-10 Projected Timeline of 6G and Beyond Systems [102].

5.5 Summary and Conclusions

This chapter has summarized the 6G vision, and discussed briefly the enabling technologies, and vertical use cases. The stakeholders in the 6G standardization are then introduced, which include the regulatory organizations, the standard development organizations, and industry forums. The standardization processes are shared, and timelines provided.

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