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Perspectives on 6G Wireless Communications

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Abstract

Since its first commercialization in early 2019, 5G has been making progress around the world and penetrating daily lives. Now, research interest in wireless communication is quickly shifting to the next generation mobile system, 6G. This paper envisions the 6G as a union of physical space, cyberspace, and connectivity with intelligence. Also, interactivity is a critical component to provide users with a truly immersive experience. In this paper, 6G usage scenarios and use cases which cannot be properly supported under the 5G regime are proposed. Major key performance indicators (KPIs) to support these use cases are considered. The 6G-related state-of-the-art technologies and standardization activities are discussed in terms of interactivity, intelligence and connectivity. Also, future works to be accomplished for the completion of 6G are shortly stated.

Keywords: 6G; usage scenario; tactile Internet; key performance indicator; enabling technology

1. Introduction

The International Telecommunication Union Radiocommunication Sector (ITU-R), Working Party 5D (WP5D) published its first release of the IMT-2020 (5th generation, 5G) Recommendation in Feb. 2021 [1]. While work on revisions of IMT-2020 will continue, WP5D initiated works for future technology trends (FTT) Report and Vision Recommendation for “IMT towards 2030 and beyond (6th generation, 6G),” which are expected to complete around June 2022 and June 2023, respectively. Also, the 3rd generation partnership project (3GPP) Technical Specification Group Radio Access Networks (TSG RAN) will approve its Rel-18 package for 5G-Advanced in Dec. 2021, which focuses on enhanced mobile broadband (eMBB)-driven/non-eMBB-driven functional evolutions and cross-functionalities for both eMBB and Non-eMBB. In accordance with the ITU-R Vision Recommendation, 3GPP and other proponents will prepare the technical specifications of 6G for ITU-R approval. As the name implies, the first commercial roll-out of 6G services is expected to be around 2030.

Most of the previous contributions have described 6G in terms of interactions between the physical world, digital world, and biological (human) world, especially emphasizing the real-time integration of cyber and physical spaces [2-3]. Based on those previous contributions, we conceptualize 6G as a triangle, as shown in Figure 1, where three vertex points are represented by cyberspace, physical space, and connectivity with the inner core representing intelligence.

Fully integrated cyberspace and physical space will become the new platform of Internet for providing various kinds of 6G verticals including metaverse or cyber-physical system (CPS) based applications. The connectivity, provided by future advanced communication technologies, will play a role in establishing links between cyberspace, physical space, and humans. Artificial intelligence (AI) has the potential to be the foundation of 6G such that it will be native and ubiquitous to make every component of 6G intelligent. Also, interactivity will be one of the main components of 6G. It will enrich everyday life by providing immersive and tactile experiences to human users. Unlike the previous generations of mobile terrestrial systems focusing on connectivity, 6G should be viewed as a mixture of connectivity as well as cyberspace,

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physical space, intelligence with interactivity.

Before detailed discussions on 6G usage scenarios and their applications (use cases) in section 2, major KPIs in section 3, and relevant enabling technologies in section 4, the brief descriptions of cyberspace, interactivity, intelligence, and connectivity are provided as follows:

Cyberspace: All things, including space, time, and even thoughts, can be digitalized. Through such digitalization, we can create a cyberspace residing somewhere in the network. The cyberspace might be a digital replica of a real (physical) space or a digital expression of a series of thoughts. A digital replica of a physical space is also called a digital twin. When thoughts are digitally expressed, they can be called an imaginary digital twin. Therefore, cyberspace can be a form of either a digital twin, an imaginary digital twin or a mixture of the two. Up to now, the Internet has been understood as an exemplary case of cyberspace. What differentiates the 6G-cyberspace from the 5G-Internet is having the ability to enter the space of interest to experience it, rather than typing some search words in and obtaining the necessary information.

Interactivity: Human beings can access cyberspace using highly advanced sensing devices which can allow them to feel as if they were actually present in the place of interest, directly interacting with its virtual surroundings as well as other users. The use of volumetric videos with either 6 degrees of freedom (6DoF) or hologram technology, 6DoF spatial audios, gesture/speech recognition, haptic perception, and multisensory integration can all help people enjoy realistic experiences, even in cyberspace.

Intelligence: AI will be embedded everywhere, not only in the network including the core, but also down to the air-interface design. In addition, AI will become a part of new services provided by the network. AI will lead to a more autonomous, secure, and flexible network as well as more customized and privatized applications. Also, AI may strengthen RAN capabilities by improving the physical (PHY) layer functionalities and radio resource management (RRM). The prediction capabilities of AI can enable 6G use cases with extreme requirements, by proactively reacting to changing environments in terms of channel, traffic patterns, and user behaviors. Accordingly, everything everywhere will become intelligent and inter-connected.

Connectivity: Connectivity between cyberspace and physical space is provided by communication links. Building up relationships between these two could greatly impact future industry and society by creating and developing new usage scenarios and applications. In order to provide future Internet users with truly immersive experiences, volumetric vision with haptic interaction is unavoidable. This requires an unprecedented high data rate and high precision in terms of latency, synchronicity, reliability and localization. For 6G connectivity, the requirements for data rate, latency, synchronicity, reliability, localization and connection density have to be not only more stringent, but also satisfied simultaneously.

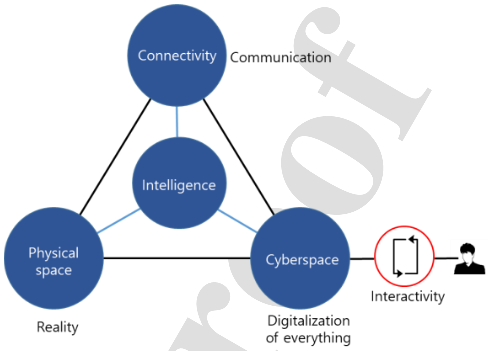

Figure 1. Concept of 6G and its components.

2. Usage Scenarios and Applications

2.1 Usage scenarios

Like the classifications in 5G, the use cases of 6G which have similar requirements can be categorized into groups, or specific usage scenarios. The followings are suggested usage scenarios for 6G.

- Ultra mobile broadband (uMBB): The use cases under this scenario require much higher data rate than the one required in 5G eMBB usage scenario.
- Ultra-massive machine-type communication (uMTC): The use cases under this scenario require much more massive number of simultaneous connections per space than the one required in 5G massive machine-type communication (mMTC) usage scenario.
- Ultra-high precision communication (uHPC): The use cases under this scenario require much lower latency, higher reliability, more precise synchronicity, or more accurate positioning than those required in 5G ultra-reliable low-latency communications (URLLC) usage scenario. These requirements are enforced either independently or in combination with each other.
- Extended 3-dimensional coverage (e3DC): The use cases under this scenario require the integration of terrestrial land mobile and non-terrestrial satellite communications including drones, air-borne, and high-altitude platform stations (HAPS) to provide connectivity to every corner on earth.
- Mixed usage scenarios
    - Combined uMBB and uHPC – In order to provide use cases under this mixed scenario, the requirements for both uMBB and uHPC have to be simultaneously supported.
    - Combined uMTC and uHPC – In order to provide use cases under this mixed scenario, the requirements for both uMTC and uHPC have to be simultaneously supported.

2.2 Use cases

The Internet has been unfolding as a universal platform for all the types of telecommunication services we are now interested in. It is reasonable to expect that new Internet services will appear in the 6G era. Future Internet services could be provided under two plausible environments.

The first one occurs in the link between cyberspace and users, via interactivity, as shown in Figure 1. In this case, cyberspace is a sort of digitalization of human acts of thinking. Users can enter the cyberspace, interact with its surroundings and even meet with other users there. Here, interactivity might deliver various types of terminals by adopting advanced video/audio and man-machine interface technologies such as holograms, 6DoF, gesture recognition and so on.

Figure 2 is a conceptual diagram of this service environment. Users will enjoy truly immersive experiences in the fields of games, education, conference, tourism as well as commerce. For example, a cyber-outlet having many stores emulating the most recognized real brands integrated with a delivery system consisting of drones, autonomous vehicles, and robots connected to the network might bring a revolution in online commerce. Consumers could enjoy a real shopping experience with a quick delivery of goods after placing an order. As cyberspace becomes a part of our lives, digital real estate businesses may emerge and thrive.

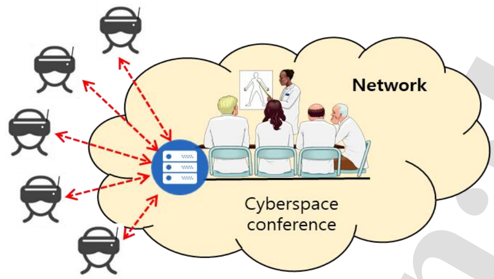

Figure 2. Cyberspace based immersive tactile Internet.

The second one employs the link between cyberspace and physical space via interactivity as shown in Figure 1. In this case, cyberspace is a kind of digitalization of a physical space, thus, a replica emulating a real object and its surroundings. In this case, through interactivity, someone's work at a digital workplace in cyberspace has the same effect on the physical workplace in a physical space in a very similar manner. This is a fundamental element of the 4th industrial revolution, known as CPS. Figure 3 is a conceptual diagram of this service environment. The major use cases in this environment will include telesurgery, the remote operation of future factories and the remote driving of heavy equipment, cars, airborne and even ships.

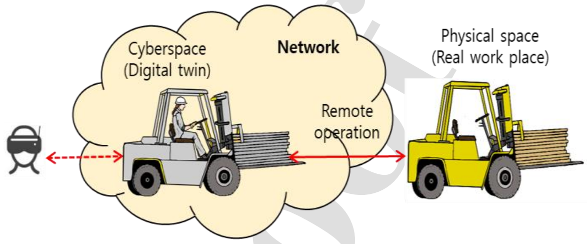

Figure 3. CPS based immersive tactile Internet.

Figure 4 explains why mixed usage scenarios are so important in 6G. Many future critical use cases outside of the triangle in Figure 4 cannot be provided by the 5G usage scenarios, namely eMBB, URLLC, and mMTC. Most of the use cases spun off from the above two environments, and applications based on tactile IoT are closely related to the mixed scenarios of 6G, already mentioned in section 1. In addition, holographic telephone and many other use cases that belong to future intelligent transport system (ITS), Internet of things (IoT), smart cities, or factory automation can be provided under uMBB, uMTC, or uHPC usage scenarios.

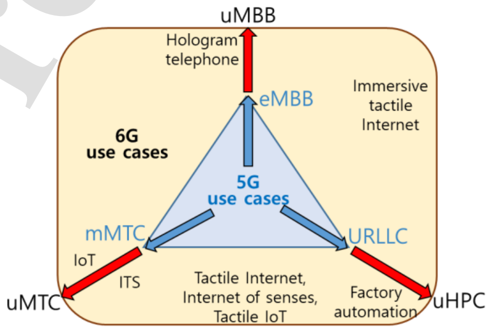

Figure 4. 6G use case examples based on mixed usage scenarios.

3. Considerations on major KPIs

The chosen eight KPIs for 5G were as follows; peak data rate, user experienced data rate, latency, mobility, connection density, energy efficiency, spectrum efficiency, and area traffic capacity. On the other hand, it is unclear for now how many and what kind of parameters will be chosen for the KPIs of 6G. In section 2.2, we anticipated immersive tactile Internet as the future game-changing service-platform. Most of the use cases spun off from this immersive tactile Internet are related to the mixed usage scenario, i.e., the combination of uMBB and uHPC. Therefore, the following capabilities relating to the uMBB and uHPC could be considered as major KPIs of 6G.

3.1 Data rate

Most data-consuming future use cases are related to reproducing a volumetric 3-dimensional (3D) vision based on a light field (LF), a conceptual representation of light emanating from an object in a space. LF can be described using the mathematical plenoptic function with 7 parameters (3 for spatial position coordinates, 2 for angular direction coordinates, 1 for color, 1 for time). A perfect volumetric 3D display is achievable if the LF is completely reproduced by either omnidirectional 6DoF or holography. Just as the Moving Picture Expert Group–4 (MPEG-4) accomplished H.264, the most advanced compression format for 2D video signals, MPEG-Immersive (MPEG-I) is trying to accomplish the same thing for an immersive video format based on 6DoF.

Stereoscopic high dynamic range (HDR) 360-degree 8K video at 90 frames per second requires a data rate higher than 200 Mbps, and further omnidirectional 6DoF video requiring 0.2–1 Gbps will be feasible in the near future [4]. The compressed data rate for the holography of a life-sized man is expected to be well above 1 Tbps. Also, there is an assessment that the compressed data rate for ultimate VR with a full view 24K video is up to 95.55 Gbps [5].

3.2 Latency

There are many different definitions of latency in a communication link. In ITU-R, the user plane air-latency is defined by the one-way time (either downlink or uplink) it takes to successfully deliver an application layer packet from the protocol layer 2/3 service data unit (SDU) ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface in the network for a given service in unloaded conditions (a single user), assuming the mobile station is in the active state [6].

On the other hand, 3GPP defines end-to-end (E2E) latency as the time measured from the point when a piece of data received at the communication service interface (CSIF) in the source communication device, until the same piece of data is passed to the CSIF in the target communication device [7]. Because the 3GPP network does not cover the complete International Standardization Organization – Open System Interconnection (ISO-OSI) communication stack, the protocol layers that are part of the 3GPP network are called lower communication layers (LCL) and the OSI layers related to providing data to the application are known as higher communication layers (HCL). The interface between LCL and HCL is referred to as CSIF [7]. In addition, from an application point of view, 3GPP defines "transmission time" as the time measured from the point when a piece of data is handed from the application layer interface of the source application device, until the same piece of data is received at the application layer interface of the target application device [7].

In the tactile Internet, a system which has tactile input and an auditory/visual feedback, services should be provided within the required E2E round trip time (RTT). A tactile sensor perceives the gestures of a user and a reaction from the connected system is heard or seen by the same user without cybersickness. The Motion-to-Photon (MTP) latency has a meaning similar to the E2E RTT. Also, in a factory automation setting, latency refers to the cycle time, transfer interval, or update time of cyclic data communication services, including the round trip. Remote driving and free-viewpoint videos are good examples of applications which require E2E RTT. In remote driving, the user's tactile steering of a wheel is carried out, while reactions are being presented simultaneously through auditory/visual feedback. In free-viewpoint videos, the user's viewpoint is manipulatively rendered to another space of interest according to the user's head motion or the change in eyesight direction.

Among the various types of latency definitions, the most appropriate to user experience is the "transmission time" or E2E RTT. In order for tactile Internet use cases to be provided in a fully synchronized manner without cybersickness, 1-20 ms latency in terms of E2E, transmission time, or E2E RTT should be supported [7-10].

3.3 Reliability

In 5G, the minimum requirement for reliability is five nines (99.999%). Minimum reliability is defined by the success probability of transmitting a layer 2/3 packet within a required maximum time (1 ms) at a certain channel quality (Urban Macro), assuming small application data (e.g., 20 bytes of application data + protocol overhead) [6]. According to the self-evaluation report from 3GPP, new radio (NR) fulfills this reliability requirement in a wide range of configurations in terms of carrier frequencies, bandwidth, antenna configurations, subcarrier spacings, and channel conditions. In some configurations, it has been reported that even ten nines (99.99999999%) of reliability is obtained [11]. Future use cases such as control/automation in vertical domains and remote robotics/surgery will require more stringent E2E latency, lower than 0.5 ms, and reliability higher than nine nines [12].

3.4 Clock Synchronicity

This is the maximum allowed time offset within a synchronization domain between the sync master and any sync device, and is also known as synchronization precision [7]. For clock synchronization services, independent user-specific UE clocks are to be aligned. The synchronicity budget for the 5G system should not exceed 900 ns. Motion control and control-to-control communication in factory automation require the most stringent clock synchronicity, of less than 900 ns [7]. It is not yet clear how much additional precise clock synchronicity is required to support 6G use cases, e.g., a multi-party cooperating remote factory based on CPS.

3.5 Positioning

Compared to 3GPP Rel-15/16, the new Rel-17 use cases require more accurate positioning. The required horizontal accuracy for inbound logistics for the storage of goods is < 0.2 m with < 1 s latency for position estimation of UE. Some other inbound logistics for the manufacturing of goods require a relatively looser accuracy of < 0.3 m, but with a tighter estimation latency of 10 ms [13]. In order to support future use cases requiring very stringent accuracy with tactile interactions such as telesurgery, cm-order accuracy in both the horizontal and vertical domains and an E2E estimation latency of less than 1 ms will be required. There is some speculation suggesting the necessity of sub-cm-order accuracy for 6G [3].

Relationships between KPIs: There always be a trade-off between the data rate and the mobility, especially in the early mobile systems like 2G and 3G. Passing through the 4G, users can enjoy a high data rate while onboarding a high speed train. However, even in the 5G era, there still exists a trade-off between them. Also, 5G defined three usage scenarios, eMBB, URLLC, and mMTC, to expand and support diverse applications on top of the typical communication services. But the maximum performance of each could be achieved at the sacrifices of the performances of the rest two. For example, in 5G, latency is measured under the assumption of unloaded conditions (i.e. a single user) for small packets (e.g., 0-byte payload plus Internet packet header). It means URLLC related KPI (latency) could be achieved by giving of mMTC and eMBB related KPIs which are connection density and user experienced data rate, respectively. In contrast to this, mixed usage scenarios of 6G require simultaneous satisfaction of multiple different KPIs. For example, immersive tactile Internet applications require both extremely high data rate and extremely low latency simultaneously. But unfortunately, there is no such technology to guarantee those two extreme KPIs simultaneously as of today. Thus, this is one of the biggest technical challenges ahead of 6G.

4. Enabling technologies

This section describes 6G-enabling technologies in terms of interactivity, intelligence, and connectivity. Interactivity will provide people with a real immersive haptic experience. Intelligence will allow autonomous operation such that 6G network can be aware of changing environments and adapt to it in real time manner without human intervention. Connectivity is the future communication infrastructure which will enable 6G usage scenarios. In this sense, 6G-related state of the are technologies and standardization activities are discussed. Also, issues requiring for further study are shortly stated.

4.1 Interactivity

We are witnessing remarkable technological enhancements of the five human senses, particularly in the fields of hearing, sight, and touch. This will lead the industry to develop various types of new terminals, providing momentum towards 6G. From the users' point of view, generation changes in mobile systems will be led by terminal technologies.

4.1.1 Hearing

Two of the key technologies needed to provide users with truly immersive experiences are spatial audio and volumetric video. The ultimate goal of MPEG-I, consisting of 12 Parts, is the standardization of compression, synthesis, and related system technologies to achieve 6DoF audio and video. MPEG-I Part 4 works to support the playback of an immersive audio bitstream with 3DoF, 3DoF+ and 6DoF. It is known that Phase 1 (3DoF, 3DoF+) immersive audio can be reproduced using the current standard MPEG-H 3D Audio. MPEG announced Call for Proposals (CfP) for 6DoF audio (spatial audio) in April 2021. Responses to this CfP should be submitted by Nov. 2021 and the completion of standardization is expected around the end of 2023. 6DoF audio will provide users with different surround sounds from all directions with respect to their positions and orientations.

4.1.2 Sight

MPEG-I Part 12 works to support the playback of an immersive volumetric scene with 3DoF, 3DoF+ and 6DoF. MPEG immersive video (MIV) is the coding standard for 3DoF+ video. A draft international standard (DIS) for 3DoF+ video is being circulated for final approval [14]. It is expected that MIV version 2 for 6DoF video will begin in 2022 and be further enhanced to achieve a much higher resolution and frame rate.

Holographic videos have not yet reached the required quality in terms of size, resolution, and brightness. Also, because of the randomness of the 3D image data, the ratio of uncompressed to compressed data size is still low. For these reasons, the prototypes of holographic videos are usually demonstrated in indoor environments using apple-size objects with HD level resolution. However, they still require a few Gbps. Even though the future of holographic video is not yet clear, it will have its own use cases largely because it can be seen with the naked eye from multiple user viewpoints, unlike other volumetric projections with head-mounted displays (HMDs).

4.1.3 Touch and recognition

Along with volumetric media, human interactivity with tactile will play a key role in providing users with immersive experiences, and unleashing new verticals. As replacements for current interface devices such as the keyboard, mouse, joystick, and touch-screen, new man-machine interaction technologies such as gesture/speech recognition, haptics, and brain sensors will appear. In order to overcome the limitations of vision-based and contact-based gesture recognition, terahertz (THz) radar can be developed in the future to recognize hand gestures by detecting distance and speed. Touchable volumetric vision or remote tele-touching may open a new paradigm of tactile Internet applications.

4.1.4 Diversification of terminal types

Up until now humans have been the primary data consumer, but in the future the main data consumer will be gradually shifted from humans to smart machines equipped with AI such as cars, unmanned aerial vehicles (UAVs), ships, and robots. Along with this trend, wearables such as smart watches, smart glasses, skin-patches, bio-implants, and exoskeletons integrated with advanced man-machine interfaces may become the norm, while smartphones will still be around us. This diversification of terminal types will unleash emerging and promising new verticals. However, since devices with extreme capacity will necessarily have large power consumption, much attention needs to be paid to energy harvesting, from over-the-air transmissions or the surrounding environments. At the same time, for some mobile devices, it may be necessary to utilize available computing resources in the network to overcome their limited computing power.

4.2 Intelligence

The application of AI involves gathering various types of data from a huge number of devices, processing and analyzing the massive amounts of collected data to discover knowledge or patterns using machine learning (ML), and choosing the most appropriate action for control, management or services. So far, AI/ML has demonstrated outstanding performance in a wide range of areas, especially in the fields of computer vision, speech recognition, and natural language processing. But recently, it has emerged as a viable means of improving the performance of communication systems.

Up to now, AI/ML has been mostly used to provide consumers with personalized and customized communication services based on the history of their behaviors, such as previous purchases, searches, views, and requests. Some of the AI/ML technologies have already been standardized in 3GPP and the Open-RAN (O-RAN) Alliance. In 3GPP Rel-16, the network data analytics function (NWDAF) was specified for data collection and data analytics in a centralized manner. The standard only specifies the input/output interfaces of the NWDAF block. The service consumer of this block may be a network function (NF), application function (AF), or operations administration and maintenance (OAM). At the request of a service consumer, NWDAF collects specific data from NF, AF, OAM, and other data repositories, and provides certain data analytics to NF and AF based on the AI/ML decisions using the collected data [15]. In Rel-17, enhancements to NWDAF are being considered from the architecture point of view. A decentralized edge NWDAF is expected to appear sooner or later for real-time applications. While 3GPP tried to incorporate intelligence into the 5G core network (CN) through NWDAF, the O-RAN Alliance has introduced a new set of functions that are performed by a RAN intelligent controller (RIC), which could enable automated RAN optimization, more open and virtualized RAN, and the quick launch of new service deployment using AI/ML [16].

Regarding air-interface, even though there have been no standardization activities until recently, AI/ML is providing meaningful results to satisfy the more stringent requirements of beyond 5G wireless communication systems, such as high data rate, low latency, high reliability, and a massive number of device connections. Also, AI/ML may solve not only the hard-to-model problems with traditional approaches but also the hard-to-implement problems due to the complexity issues. The major research areas of the AI/ML-driven PHY layer are channel coding/decoding, channel estimation/prediction, link prediction, auto-encoder, MIMO symbol detection, reference signal (RS) reduction, beam management, interference management, positioning, etc.

One of the main approaches for the PHY layer is to use deep learning as a function approximator, which relieves computational load and processing delay in the wireless communication system. The decoder is one of the typical blocks that introduce complexity and severe delay, due to its inherent iteration process. A decoding scheme using deep learning has demonstrated improved performance compared to plain belief propagation, without increasing computational complexity [17].

Another approach to apply deep learning to the PHY layer is to enhance performance. While most functional blocks at the PHY layer are based on mathematical models, some blocks do not allow analytic forms to be derived mathematically. For example, the performance of conventional channel estimators relies on a channel model and it is almost impossible to represent the real channel in an analytic form. As an alternative, a deep learning-based channel estimator can be a good solution, offering better performance through the training procedure, even in a time-varying complicated wireless channel environment [18]. One of the issues in making use of ML for channel estimation is that the characteristics of the training data used for offline learning tend to mismatch the real channel data, which may cause performance loss. Online training that reflects the real channel environment might be a promising path toward future wireless technologies.

AI/ML application for one specific functional block will gradually evolve to apply for a number of contiguous blocks or whole processing chains in an E2E manner. As an example, the E2E receiver for channel estimation and symbol detection based on deep neural networking (DNN) has demonstrated that deep learning is beneficial when wireless channels are complicated by serious distortion and interference. This advantage is because of its ability to remember and analyze the complicated characteristics of the wireless channels [19].

Present deep learning-driven PHY layer studies are still in their earliest stages, and more comprehensive research is left for future work. However, based on the successful applications reported recently, it will play a pivotal role in solving many problems with harsh requirements in the wireless domains of 6G. Also, in the near future, federated learning, where multiple decentralized edge devices cooperate to build a common learning model without sharing data but exchanging parameters, will contribute to improving user experience and breaking the bottlenecks of wireless technologies.

4.3 Connectivity

4.3.1 Ultra mobile broadband (uMBB)

The most related KPI for uMBB is data rate. Future extended reality (XR) utilizing 6DoF or hologram will require immense amounts of bandwidth to support data rates of up to several Tbps. Also, as machines equipped with AI become the new principal data consumers, and some of them need much higher resolution and wide-angle vision than human sight, the required data rate could be unprecedentedly high. The fundamental strategies for satisfying the increases in required data rates are securing bandwidth, improving spectrum efficiency, and network densification [20].

Bandwidth: Currently, spectrum resources under 100 GHz are highly congested. To secure sufficient bandwidth, we need to explore sub-THz and/or THz frequency ranges and ensure their usability for communication [21-23].

Spectrum efficiency: Due to the short wavelength of mmWave and THz, it is possible to construct a much denser antenna array leading to ultra-massive MIMO at the network side and also massive MIMO at the terminal side. This may provide not only coverage extension by boosting beamforming gain but also improved spectral efficiency by exploiting higher spatial resolution. Extreme MU-MIMO with higher spatial resolution will enable much more efficient spectrum reuse. Smart surfaces of metamaterials or glass windows printed with transparent conductors or metallic meshes can steer radio waves impinging upon them to the desired direction, thereby eliminating shadowed areas or reducing penetration loss. These reconfigurable intelligent surfaces (RIS) have the potential to improve coverage, capacity, and energy efficiency by intelligently controlling propagation characteristics: reflection, refraction, scattering, and absorption. RIS can render random channels friendly environments [24].

Network densification: In the 3GPP RAN architecture, the gNB can be decomposed into three functional modules, the central unit (CU), distributed unit (DU), and radio unit (RU), connected by fiber optics. In this architecture, an ultra-dense network (UDN) is usually implemented by increasing the densification of RUs. In UDN, there can be more RUs than active users. For the future RAN architecture, integrated access and backhaul (IAB) should also be considered as an important axis of UDN. Replacing fiber optics with wireless can significantly reduce capital expenditures (CAPEX) and operating expenses (OPEX) of backhaul links. Also, the IAB can provide multi-hop capability, which is especially useful to enhance coverage in mmWave or future THz deployment. In addition to the use of radio communications, other applications of THz, sensing, imaging, and localization might have an impact on industry verticals. Due to the high directivity by ultra-massive MIMO and wide bandwidth of THz spectrum, the accuracy of detection and ranging will be greatly improved. Such attributes as velocity, size, distance, and posture derived from the measurements using THz will play an important role to enable 6G use cases. Therefore, taking these facts and poor propagation characteristics of mmWave and THz into account, the concept of ultra-dense integrated access and everything (UD-IAX) network should be studied to ensure the efficient use of high band spectrum [25].

4.3.2 Ultra-massive machine-type communication (uMTC)

The related KPI for uMTC is the connection density. The Narrowband-Internet of Things (NB-IoT) of LTE outperforms 5G NR from the perspective of connection density, because it was customized to the IoT traffic characteristics of long transmission time and small packet size. However, the surge in demand for industrial IoT (IIoT) applications and future tactile Internet will lead to different traffic characteristics, requiring short transmission time and high reliability. Thus, the technological challenge is to satisfy those KPIs related to uHPC and uMTC simultaneously [26-27].

Non-orthogonal multiple access (NOMA) or compressed-sensing based random access without grant is one of the promising technologies for improving connection density, but it does so by sacrificing reliability. Since there is a tradeoff between the KPIs related to uMTC and uHPC, the joint optimization of different KPIs for delivering use cases of mixed usage scenarios will be a challenging task [27].

4.3.3 Ultra-high precision communication (uHPC)

The most related KPIs for uHPC are latency, reliability, and clock synchronicity.

Latency, reliability, and clock synchronicity: In 5G NR, the basic unit of scheduling is a slot, in which a control channel containing a downlink assignment or uplink grant is transmitted from the gNB to a certain UEs. Due to the introduction of scalable orthogonal frequency division multiplexing (OFDM) numerology, the slot length of 5G NR can be shortened down to 1, 0.5, 0.25, 0.125 or 0.0625 ms. Also, thanks to the highly reduced processing time and advanced channel coding, the self-contained slot structure was introduced in NR, where scheduling, data transmission and hybrid automatic repeat request (HARQ) feedback can be located in the same slot without dependency on other slots [28].

In addition to enhancing reliability, low-density parity-check (LDPC) highly contributes to latency reduction because of its highly parallelizable decoder, which benefits from its quasi-cyclic structure. In 5G NR, one slot consists of 14 OFDM symbols. However, by allowing sub-slots consisting of 2, 4 or 7 OFDM symbols, the transmission time interval (TTI) can be further reduced. The fundamental framework of 5G NR URLLC is the self-contained sub-slot structure with scalable numerology. On this foundation, most of the further works for URLLC are being put into enhancing specific channels, such as physical uplink shared channel (PUSCH) and physical downlink shared channel (PDSCH) for data transmission, and uplink/downlink control channels for HARQ feedback transmissions [29]. All these efforts are focused on delivering packets immediately and reliably even when forced by shortages in available resources [30].

The current 5G NR allows a sub-slot with 2 OFDM symbols for both scheduling and data transmission, and subsequent sub-slots for HARQ feedback. Thus, assuming the 0,0625 ms slot, a TTI over the air-interface of less than 0.02 ms is achievable. Therefore, what should be stressed in 6G URLLC is reducing the latency at the network side including backhaul and core, rather than air-interface. For this purpose, modular designs with open architecture and the use of software network functions, which facilitate dynamic and intelligent network slicing for URLLC traffics, time-sensitive networking (TSN), and mobile edge computing (MEC), should be further developed and supported.

TSN is a set of standards specified by IEEE 802 to provide guaranteed data delivery within a guaranteed time window, in contrast to the current best-effort Internet network. In order to ensure required latency, reliability, and synchronicity for IIoT, TSN is being integrated with the 5G system using TSN translators (TTs). Further works in this field would be to identify limitations and discover solutions to provide a very aligned seamless integration of 5G system with TSN networks for satisfying the stringent E2E requirements in terms of latency, reliability, and synchronicity [31].

Two types of radio access networking can be considered, wireline (optics, cables) and wireless (mmWave, THz). If X-haul is deployed in accordance with IAB, connections between IAB-nodes constitute a complicated wireless mesh network. The purpose of the IAB backhaul adaptation protocol (BAP) over 3GPP radio link control (RLC) layer is to transport packets to a destination node with multiple hops. For time-critical and reliable delivery in the X-haul, the current BAP responsible for routing and hop-by-hop packet forwarding needs to be enhanced. Also, self-interference cancellation (SIC) for full duplex deployment and network coding for reliability in the backhaul are emerging technologies for future IAB networking [32].

Positioning: The basic framework of 5G NR positioning is derived from the 4G LTE positioning architecture, with a newly added logical module, location management function (LMF), in the 5G CN. The 4G LTE positioning protocol (LPP) handles communication between UE and location server in the CN. In 5G NR positioning, not only LPP but also NR positioning protocol annex (NRPPa) handling communication between gNB and LMF is adopted [33-34].

The traditional RAT-dependent positioning method is the DL time difference of arrival (DL-TDOA), which is based on UE's measurements of reference signal time difference (RSTD) using DL positioning reference signals (PRSs) from neighboring eNBs. In 5G NR, several new methods have been introduced to support high accuracy, based on gNB's measurements using UL sounding reference signal (SRS) and other methods besides DL-TODA based on UE's measurements [35]. The LMF plays the commander role in positioning, selecting an appropriate positioning method and setting up a configuration for the required measurements.

Table 1 is a summary of positioning technologies adopted by 3GPP 5G NR. The 3GPP standards specify only a general framework for supporting positioning. How LMF determines the exact location of UE based on the reported measurements is mostly an implementation issue.

Further improvements in positioning are required to realize such things as touchable volumetric images, which are needed to implement 6G use cases, including remote surgery. Measurements using THz will be beneficial because wide signal bandwidth will reduce the error variance in delay measurements. Also, integrating the RAN-dependent technologies explained above and various kinds of other positioning technologies, such as SLAM (simultaneous localization and mapping) algorithms using location information from different types of visual and tactile sensors and global navigation satellite system (GNSS), will produce more accurate positioning.

Table 1

Summary of 5G NR positioning methods.

Methods	Used signal	Measured by	Protocol	Measurement reports
UL-AoA	SRS	gNB	NRPPa	AoA, AoZ, SRS-RSRP
UL-TODA	SRS	gNB	NRPPa	UL-RTOA
Multi-RTT	SRS	gNB	NRPPa	UL Rx-Tx time differences, SRS-RSRP
DL-TDOA	PRS	UE	LPP	DL RSTD
Multi-RTT	PRS	UE	LPP	Rx-Tx time differences, PRS-RSRP
DL-AoD	PRS	UE	LPP	DL PRS-RSRP
E-CID	SSB, CSI-RS	UE	LPP	SS-RSRP/RSRQ, CSI-RSRP/RSRQ

Angle of Arrival (AoA), AoZ (Angle of Azimuth), Relative Time of Arrival (RTOA), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Enhanced Cell ID (E-CID), Synchronization Signal Block (SSB), Channel State Information Reference Signal (CSI-RS)

4.3.4 Extended 3D coverage (3DC)

The most related KPI for 3DC might be vertical coverage. The purpose of the e3DC usage scenario is to deliver communication services to every corner of life around the globe, including in the air, on water, and in disaster locations, as well as any places lacking network infrastructure. Even though the non-terrestrial network (NTN) utilizes satellites for communication networks, it implicitly involves HAPS and low altitude UAVs. Here, HAPS can include airplanes, airships, and balloons [36].

In the 3GPP Rel-16 study, the use of S-band and Ka-band were considered, and the use of HAPS as IMT Base Stations (HIBS) with the IMT frequency band drew much attention. In typical NTN scenarios, a UE is connected to a ground gNB through the NTN payload, which is either a transparent or a regenerative network node embarked on a satellite, and the ground NTN gateway, as shown in Figure 5. The connection between the NTN gateway and the NTN payload is established via feeder link, and between the NTN payload and the UE via service link using Uu interface. The 3GPP study concludes that handheld UEs can be served by geosynchronous earth orbiting (GEO) and low earth orbiting (LEO) satellites using S-band and appropriate satellite beam layouts. Further, UEs with high transmit and receive beamforming antenna gains can be served by GEO and LEO satellites in both the S and Ka bands [37].

The long distances between satellite nodes and the high speed of moving satellites can cause issues with timing adjustment (TA) and Doppler compensation. It is known that UEs with GNSS can measure and compensate RTT and Doppler shift related to the service link. In order to establish a secure link between the UE and gNB via satellite, further enhancements are needed on medium access control (MAC), RLC and packet data convergence protocol (PDCP) protocol stacks to solve the problems caused by the long propagation delay, as well as handover issues arising from the fast moving satellites [38]. IoT over NTN (satellite or space IoT) is also an important issue for making IoT services truly ubiquitous. Future work should include NTN-IAB for the service link, where an intermediate NTN IAB-node with high transmit and receive antenna gains can be located in the air or on high ground to offload the complexity and the power consumption at the UE side [39-40].

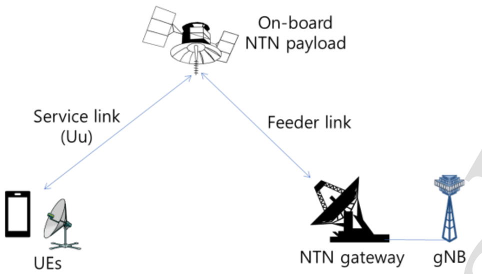

Figure 5. A Typical scenario of NTN.

5. Conclusions

The primary goal of 6G is to accomplish "intelligence and connection everywhere", to deliver a truly immersive experience and ubiquitous broadband Internet access to every person on the globe by bridging the existing digital divide. Earlier generations of mobile systems were designed as platforms to provide connectivity. In the 5G era, the definition of mobile system was changed to create an ecosystem for industry and business, emphasizing vertical domains. Nevertheless, up until now, despite the success of 5G deployment, it has not yet proven its unique strategies compared to the previous generation. In order to provide a truly immersive experience to every person on the globe, not only a number of new capabilities beyond connectivity, but also a great deal of enhancements to the connectivity itself, are required in 6G.

From this perspective, we conceptualize 6G as a triangle, whose three vertex points and inner core represent cyberspace, physical space, connectivity, and intelligence, respectively. Four usage scenarios of uMBB, uMTC, uHPC and e3DC, and two mixed usage scenarios of uHPC with relation to uMBB or uMTC are suggested to build up appropriate connections between cyberspace and physical space with emphasis on interactivity to provide upcoming 6G use cases.

As major KPIs, crucial parameters are discussed in several respects. Regarding data rate, it was noted that most data consuming future use cases are related to the reproduction of volumetric 3D vision based on LF. To provide a fully synchronized user experience without cybersickness, 1-20 ms latency in transmission time, E2E or E2E RTT is required, to support corresponding tactile Internet use cases. Future use cases such as industrial control/automation and remote robotics/surgery will require an even more stringent E2E latency, lower than 0.5 ms, and reliability higher than nine nines. Regarding positioning, there is speculation suggesting the necessity of cm-order accuracy for 6G.

As an enabling technology in the field of interactivity, the holographic video will have its own use cases, thanks to the fact that it can be seen by multiple users with the naked eyes, unlike other volumetric projections, such as head-mounted displays (HMDs). Terahertz (THz) radar can be used to recognize hand gestures by detecting distance and speed. Touchable volumetric vision and remote tele-touching could open new paradigms for tactile Internet applications. In the field of connectivity, enabling technologies will follow each scenario of uMBB, uMTC, uHPC, and e3DC.

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Conflict of interest

The authors declare that there is no conflict of interest in this paper.

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