White Paper

5G Evolution and 6G

NTT DOCOMO, INC.

February 2021 (Version 3.0)

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1. Introduction

Nippon Telegraph and Telephone Public Corporation (NTT) launched the world's first mobile communication service using a cellular system on December 3, 1979. Since then, the radio access technology for mobile communications has evolved into a new generation system every 10 years. Along with technological development, services have also made progress. In the years from the first generation (1G) to the second generation (2G), the services were mainly voice calls, but finally advanced to simple text messaging. The third generation (3G) technology enabled anyone to use data communication services represented by "i-mode" and send multimedia information like pictures, music and video. In the fourth generation (4G), high-data rate communication over 100 Mbps was achieved by the LTE (Long Term Evolution) technology, leading to the exploding popularity of smartphones and emergence of various multimedia communication services. The 4G technology has continued to evolve in the form of LTE-Advanced and now achieved a maximum data rate of over 1 Gbps. Further technical progress has made the fifth generation (5G) a reality. DOCOMO rolled out 5G commercial service using its 5G mobile communication system [1-1] on March 25, 2020.

5G is characterized by high data rate / high capacity, low latency and massive connectivity. With these features, 5G is expected to further upgrade multimedia communication services from the level achieved by the previous generations including 4G, and to provide new value as a fundamental technology that supports future industry and society along with AI (artificial intelligence) and IoT (Internet of Things). As shown in Fig.1-1, mobile communication technology has been evolving into a new generation every 10 years while mobile communication services have undergone a major change every 20 years. If this trend continues, a "third wave" 5G is anticipated to generate will be bigger than the previous one, fueled by the technologies of an upgraded version of 5G (5G evolution) and the following sixth generation (6G) and to support industry and society in the 2030s.

This white paper describes DOCOMO' technological vision on 5G evolution and 6G. The following Chapter 2 considers future directions of technological evolution from the viewpoints of 5G evolution and 6G, respectively. Chapter 3 discusses the requirements and use cases. Chapter 4 gives an outlook on technological research areas. Note that this white paper has been updated from the first edition published in January 2020 with addition of new ideas conceived to date (February 2021). Today, discussions are actively underway regarding telecommunications expected in the 2030s [1-2, 1-3] at the "Beyond 5G Promotion Strategy Roundtable [1-4]" meetings led by the Ministry of Internal Affairs and Communications (MIC) of Japan and by others at home and abroad. We will continue to promote discussion among the parties concerned in various industries as well as between industry, academia and government, and update this white paper to reflect changes made in the future.

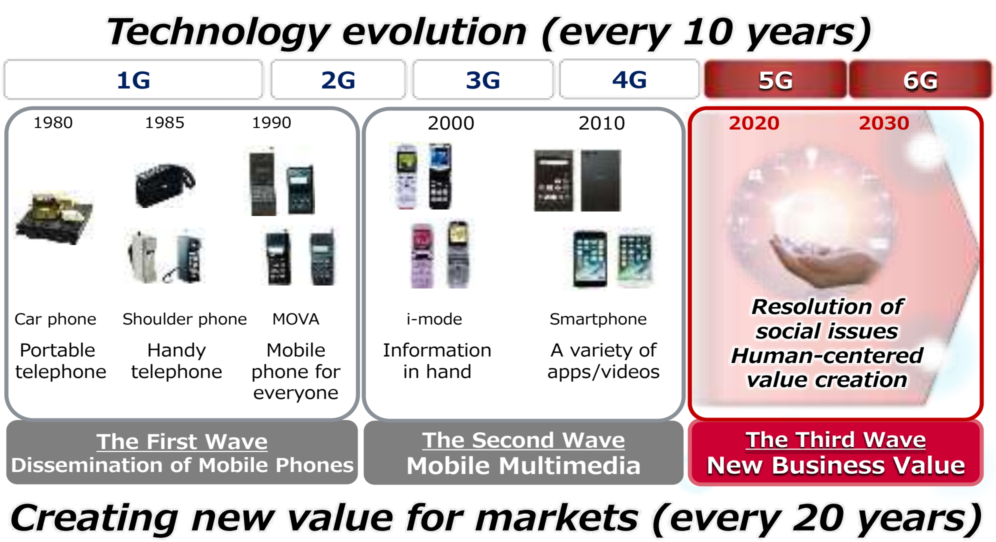


Figure 1-1. Evolution of technologies and services in mobile communications

2. Direction of Evolution “5G Evolution and 6G”

2.1. Considerations for 5G evolution

Commercial introduction of 5G has already started worldwide. DOCOMO also launched its 5G commercial service in March, 2020. Meanwhile, we have found the issues and further expectations to be fulfilled regarding 5G, and this necessitates technological development of a more enhanced version of 5G called "5G evolution" in several years within the 2020s.

Fig. 2-1 shows current technical challenges of 5G. In fact, 5G is the first generation of mobile communication systems advanced enough to support high-frequency bands above 10 GHz, such as millimeter waves, with technology that enables super-fast wireless data communication of several Gbps-class speeds using a several hundred MHz frequency bandwidths, by far wider than before. On the other hand, it is becoming clear from 5G technical trials that millimeter wave (mmW) technology in mobile communications has many aspects that need to be improved, such as coverage in a non-line-of-sight (NLOS) environment and uplink performance.

Furthermore, 5G is attracting a lot of attention as a technology that supports future industry and society, especially for industrial use cases demanding special requirements and high performance. In Japan, "Local 5G" has started, which is dedicated to such industry applications and has become of a focus of interest by industry [2-1]. It is necessary therefore to further develop 5G technology in order to flexibly deal with such a wide range of industrial requirements in the years to come.

In the initial stage of 5G standardization (New Radio (NR) Release 15), 3GPP focused on high data rate / high-capacity communication (eMBB: Enhanced Mobile Broadband) and part of Ultra-Reliable and Low Latency Communications (URLLC). It is because of this background that 5G has been developed with a focus on achieving best-effort services emphasizing faster downlink speeds, as was the case with LTE. In contrast, 5G evolution is expected to propel high-reliability communication technology, as shown in Fig. 2-2, which guarantees communication quality mainly for industrial applications, while improving uplink performance. Some industrial use cases include services with the prospect of uploading a huge quantity of video data or services requiring a guaranteed quality and constant speed. For this reason, it is more important for industry applications to improve the coverage and throughput on the uplink and provide communication technology ensuring guaranteed quality than for services geared toward general users.

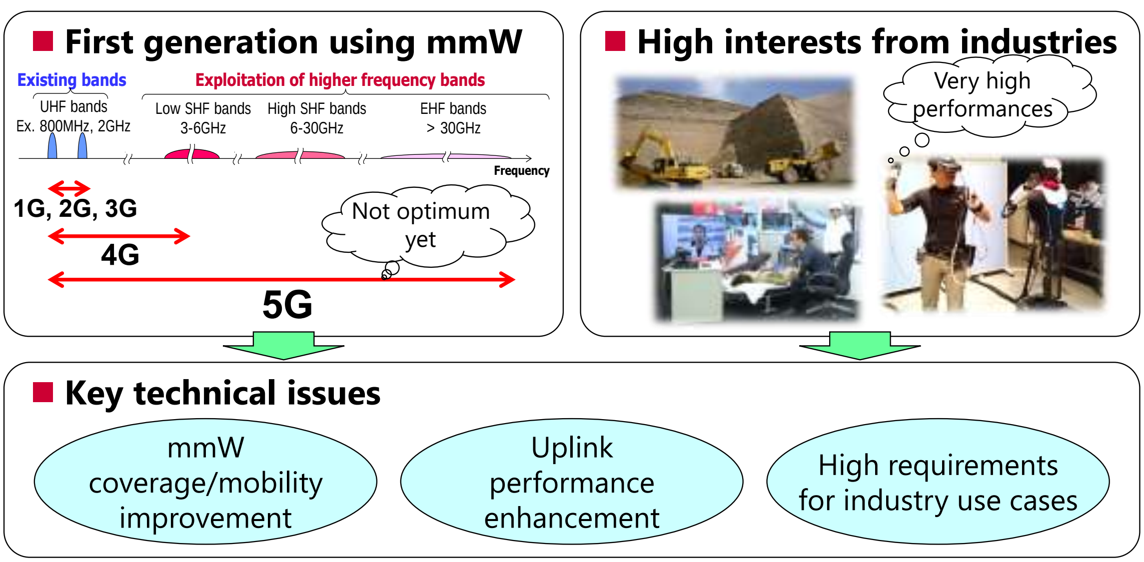


Figure 2-1. Current technical challenges of 5G

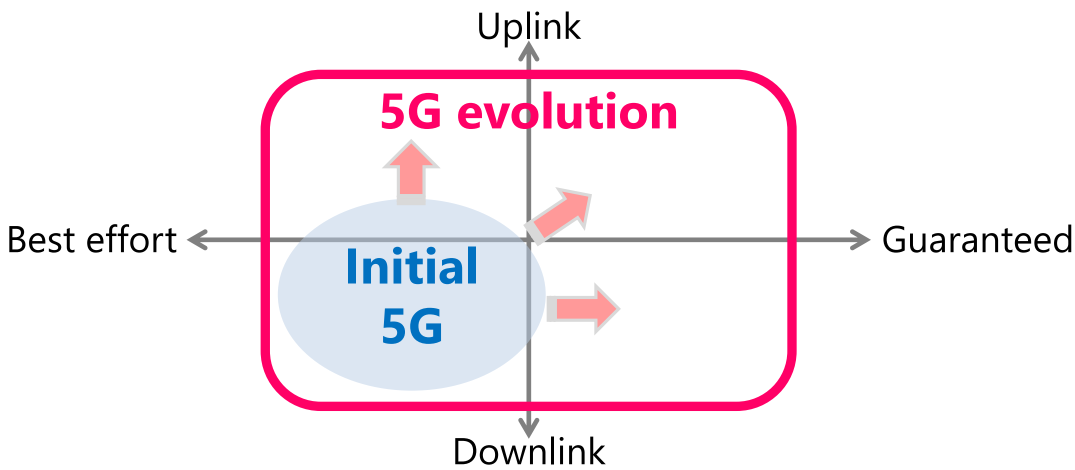


Figure 2-2. Direction of performance improvement to 5G evolution

Today, as big data and AI are widely applied, cyber-physical fusion is drawing an increasing attention [2-2]. As shown in Fig. 2-3, cyber physical fusion is a system concept where AI creates a replica of the real world on the cyberspace (Digital Twin) and emulates it beyond the constraints of the real world to “predict the future” and discover "new knowledge." By making practical use of this concept for services in the real world, we can offer various values and solutions for social problems. If we view this real world as one of many worlds reproduced on the cyberspace, we can assume that there are a large number of humans, things and events present in all worlds, not only the real ones but also their avatars and variants are present, and this recognition can potentially contribute to resolving social issues, such as labor shortage and low-birth rate and aging population [2-3]. Wireless communication is anticipated to play certain roles in this cyber physical fusion system, such as sending a huge quantity of real-world data including video and sensing information to the cyberspace, which will require high capacity, low-latency transmission, and actuating the real world, which will demand low-latency control signal transmission. This assumption is generating high expectations for high-performance communication utilizing 5G features. If we compare a cyber physical fusion system to a human body, communication in the cyber physical fusion would be the nervous system, which transmits information signals between the brain (AI) and different organs such as eyes and arms and legs (devices). We can easily imagine that an overwhelming quantity of information (Uplink) enters the brain. Therefore, the directions of performance improvement shown in Fig. 2-2 apply in this case as well.

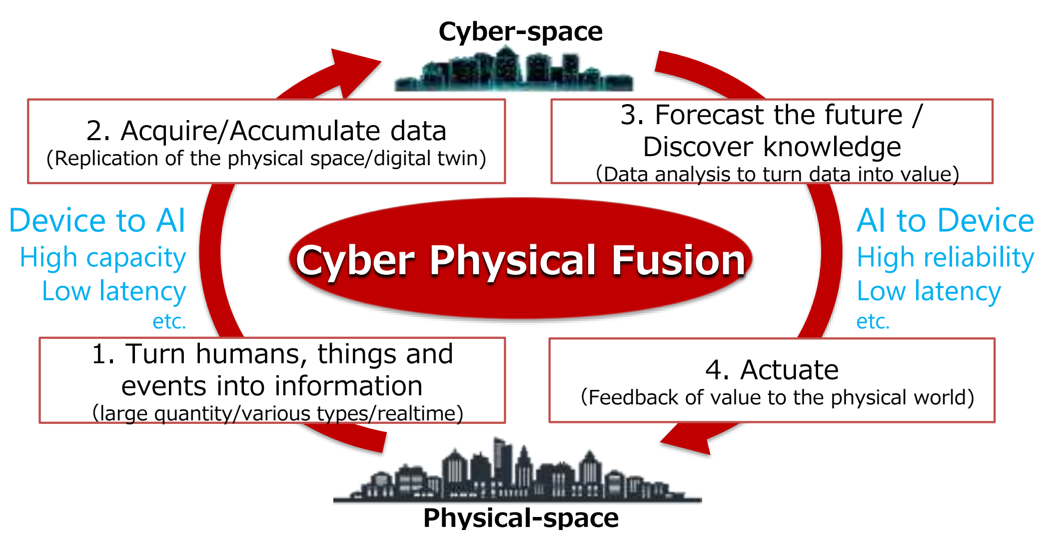


Figure 2-3. Cyber-physical fusion and wireless communications

2.2. **Considerations for 6G**

For discussing the requirements, use cases and technological developments regarding 6G, we should consider our vision of a future world in the 2030's, when 6G is anticipated to be introduced. The use cases and solutions for social issues expected to be achieved by 5G will have considerably realized and become widespread by the end of the 2020's. Even in the 2030's, we will need their wider and deeper dissemination in their evolved forms. In addition, we will witness further advanced services, the fusion of multiple use cases and the creation of needs for new use cases arising along with faster signal processing and a wider range of advanced devices. Following are some specific examples of our vision.

Figure 2-4. Image of a future world in the 6G era

- Solving social problems

In 2030, the world population will reach 8.5 billion, growing from about 7.7 billion in 2019. This will be mostly attributable to the population increase in Asia and Africa, such as India, Nigeria, Pakistan and Democratic Republic of Congo [2-4]. In terms of GDP, China, U.S.A. and India will be ranked top three. We will see the economic power center of the world shifting from the existing developed countries and regions such as North America, Europe and Japan. [2 -5]. The year 2030 is the target year by which we should achieve the world's common goals known as the SDGs (Sustainable Development Goals), 17 goals and 169 targets aiming for a sustainable and better world [2-6]. For the climate change problem, the goal has been set by the Paris Agreement adopted in 2015 to limit the rise in global average temperature. Toward this goal, countries around the world are taking measures to address the global environmental problems through energy saving and renewable energy utilization.

In Japan, there are a lot of social issues that we need to address: a more aged society with a dwindling birthrate, where one out of three citizens will be estimated to be 65 or older, a declining working-age population, growing social security payments, increasing idle assets and deteriorating social infrastructure. Strategies and policies are discussed in order to realize Society 5.0, extend healthy life expectancy and improve the quality of life. Amid this situation, it seems important for each of us to envision the future we want to achieve or create and take proactive action, aiming to make Japan an advanced country committed to proactively solving social problems. [2-7, 2-8, 2-9, 2-10].

The pandemic of the novel coronavirus (COVID-19) is expanding, causing a serious impact on the economy, environment and society. Under the "Stay-Home" policy, physical flows of people have dramatically decreased as most people stay at home or specific places. On the other hand, data continues to flow at high data rates throughout the internet space, and a large quantity of goods is moving around even in the real world. A “twisted state,” as it were, is generated on a world scale. The current infection trend shows that population concentration in metropolitan areas around large cities such as Tokyo has contributed to the spread of the virus infection. This may be a warning against the "excessive" and "superfluous" state in which we have lived lives of too much concentration, too much production, too much selling, too much investment and too much travel in pursuit of economic growth [2-11, 2-12, 2-13]. What is important for our future is to think about how we should raise awareness for problems and in which direction and with what purposes we should take future actions. In the face of changing times, it is essential to take another look at social issues and determine the most serious issues for us and for the earth.

By the mid-2020s, 5G will have addressed some of the many social issues and needs as expected. For social issues such as regional revitalization, aging society with fewer children and labor shortage, a wide range of solutions will be provided, such as telework, remote control, telemedicine, distance education and autonomous operation of various equipment including cars, during the 2020s through high-data rate, low-latency communication networks. Despite such positive developments, it is debatable whether all of the social problems can be solved by the end of the 2020s. For example, if we want to “eliminate poverty” and “reduce inequality within and among countries" as advocated in the SDGs, we need to develop strategies to eliminate relative poverty and disparities that have spread not only in developing countries but also in developed countries. This necessitates a drastic review of various fundamental elements, ranging from capitalist economy, education, to society. We need to discern every step we can take, and in that process to determine what role technology can play to contribute to society in order to eradicate the problems and achieve social development toward the 2030s.

Regarding regional revitalization, due in part to the influence of COVID-19, we may see a trend toward an "open and sparse” environment in the years to come [2-14]. This trend is completely in the opposite direction of the value creation based on a closed and dense environment, which has been promoted by mankind for at least several thousand years. The new trend holds a potential to contribute to solving the problem of population concentration in metropolitan areas.

- Communication between humans and things

The importance of communication is universal and timeless although what information to communicate and how to communicate it are always changing. For example, when we talk with someone in a remote place today, we can transmit characters and symbols (verbal information) by phone or e-mail, or send body movement, facial expressions and emotions (non-verbal information) through a camera. In the future, our communication will include transmitting non-verbal information directly and efficiently in a society characterized by such concepts as IoH (Internet of Human) and IoA (Internet of Abilities), where humans, abilities, things and events are connected [2-15]. Let’s suppose we take a sports lesson by receiving information on physical movement and kinetics from an instructor in a remote place. We can potentially learn more efficiently by actually feeling the instructor’s movement and directly moving our body than only by listening to instructions (verbal information) and watching his/her movement (visual information).

In transmitting nonverbal information and linking abilities, we can utilize Human Augmentation and brain-related communication. Human Augmentation means enhancing human abilities in terms of physical strength, perception, cognition and presence. From the viewpoint of connecting the senses, we can feel a potential of “multisensory communication. Multisensory communication intends to make use of not only conventional auditory (voice) and visual (video) senses, but also tactile, gustatory and olfactory senses of the five senses, as well as impressions that we get from places and things including atmosphere, and physiological senses such as a sense of security that innately reside within humans just like other animals.

If we examine the viewpoint of connecting humans from another angle, we will notice the presence of certain inner functions, such as of visualizing the algorithms and thoughts lying inside us or in our mind and of making inward/outward approach into/from ourselves. If we think about the existing technologies developed until today, most of them seem to have been intended to affect the external environment of humans. In the future, however, the existence of "introspective technology," which directly affects our inner perceptions or thoughts, may become more important. In recent years, the word "well-being" has been used to indicate good physical, mental and social conditions, but it also holds the potential to become a technology that cares about our feelings and thoughts for our happiness and better way of life. Technology has so far existed to enrich human life. Looking toward the future, technology would rather need to evolve into “technology that can impact the existence of humans.”

As technologies used for connecting humans, we can also refer to functionally-enhanced wearable devices like XR (VR, AR, MR) devices and real and rich communication utilizing 8K or higher-definition images and holograms. We can use these technologies to provide innovative entertainment and enterprise services for gaming, sports, live watching, etc. anytime, anywhere.

From the viewpoint of connections between things, the demand for communication of things will grow dramatically, driven by the rapid dissemination and development of IoT services. Things will be processing a massive amount of data including high-definition images and controlling devices with low latency between themselves. This will raise the need for high-data rate, low latency communication with the performance by far exceeding that of humans.

- Expansion of communication environment

The importance of communication in solving social issues and sharing information between humans and things suggests that communication will become so pervasive that it will be taken for granted just like the air, being a lifeline as important as or more important than power and water utilities. Our everyday activity domains will be extended to high-rise buildings, drones, flying cars, airplanes, ships, and even space. Needs for various sensor networks, unmanned factories and unmanned construction sites will necessitate communication coverage even in environments with no human existence. As a result, all areas will need to be covered by communication services, whether it be the ground, sky, sea or space.

We can read some trends about space by looking at space-related business projects pursued more and more actively in recent years. “Space Big Data,” for example, aims to collect data of the earth from space, such as the number of cars in parking lots or flow of things and people on the ground, leading to business opportunities on earth. "Space Internet" will provide communication service coverage on earth and in space from space. These projects are expected to become active in a short period of several years. There are also other projects, but they may require a mid-and-long term of over 10 years to take off. These include "planetary exploration," which intends to extract resources or establish human settlements on the moon and Mars and other planets, and "space travel," in which even general people will enjoy trips into space just like they do on earth. All of these projects suggest that the idea of extending mobile communication coverage to space in the 2030s is not unrealistic at all. What seems to be important is to proceed on a step-by-step basis in establishing service areas and communication methods suitable for each of these multiple space business projects.

- Sophistication of cyber-physical fusion

In the 2020s, many services utilizing cyber-physical fusion will be created and put into practical use in all environments. In the 2030s, a further advanced cyber-physical fusion system will be required. Transmission and processing of a large amount of information between cyberspace and physical space without delay will enable closer collaboration of these two space domains. Ultimately, the cyberspace and physical space will be fused into one domain with no gaps. For humans, the cyberspace will be able to support human thinking and activity on a real-time basis via wearable devices or micro devices attached to the human body through the above-mentioned brain-related communication and other technologies. All things will be collaborating with the cyberspace, such as transportation equipment including cars, construction machines, machine tools, security cameras and various sensors, and will provide safety and security, solve social problems and support affluent human lives.

Fig. 2-5 illustrates how wireless network technology will evolve toward 6G in order to realize such a future world. As shown in this figure, it is anticipated that new use cases will appear, demanding a combination of requirements that cannot be covered by the 3 categories of 5G: eMBB, URLLC, and massive connectivity (mMTC: massive machine type communication) in addition to extreme high performances even 5G cannot achieve.

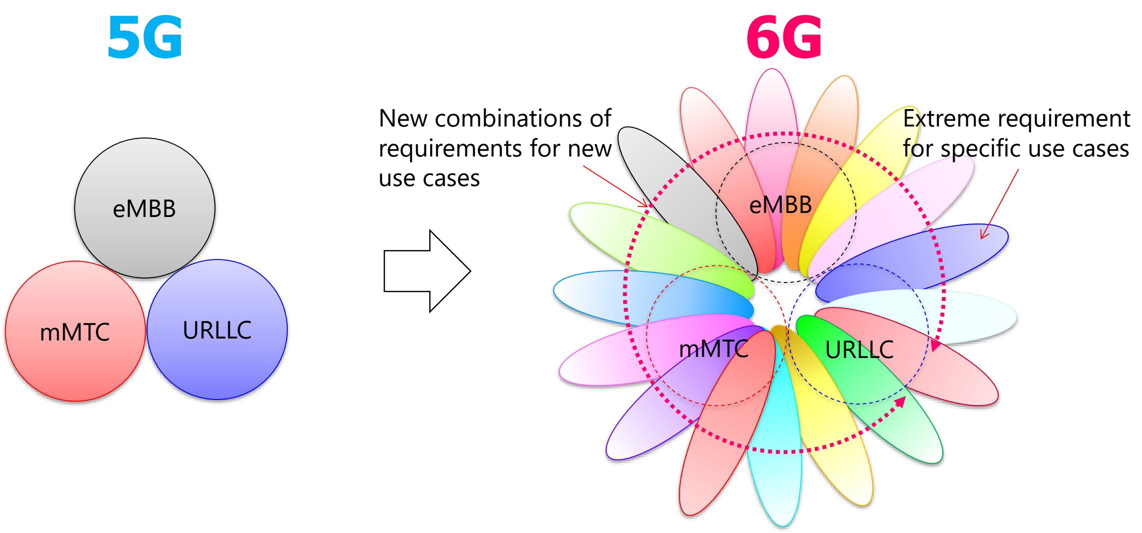


Figure 2-5. Image of wireless network technology evolution toward 6G

3. Requirements and Use Cases

Fig. 3-1 shows the requirements that we will be aiming to achieve for 6G wireless networks after going through 5G evolution [3-1]. The requirements will become wider and more diverse compared to 5G, comprising enhanced 5G requirements as well as new requirements which have not been taken into consideration for 5G. As with 5G, it will not be necessary to fulfill all the requirements simultaneously, but some new use cases will demand a combination of requirements. The requirements for 6G wireless network technology are described below with their use cases.

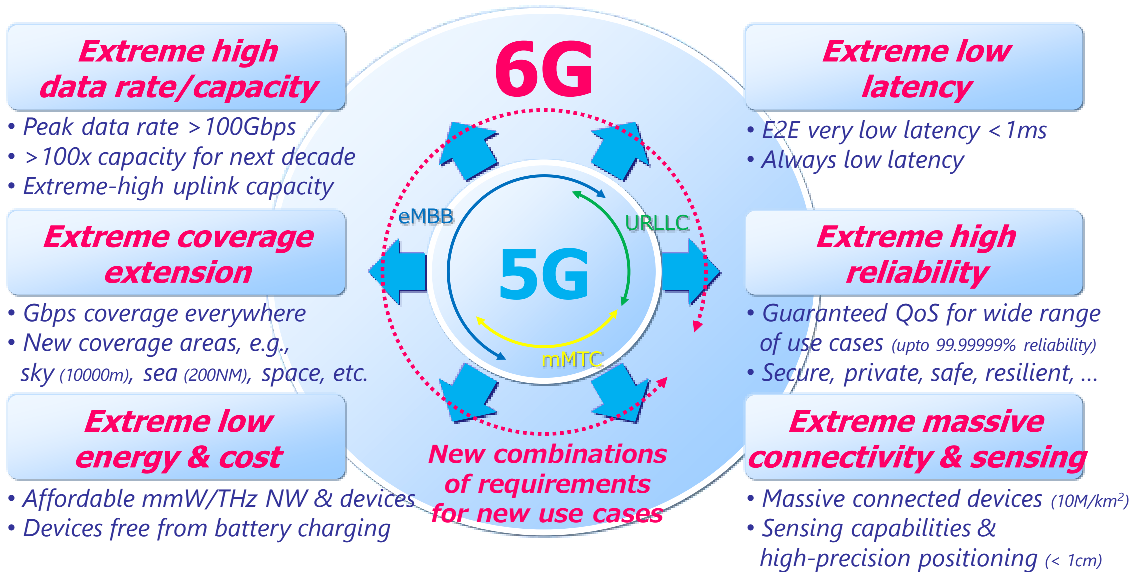


Figure 3-1. Requirements for 6G wireless technology

3.1. Extreme-high-speed and high-capacity communications

If communication speeds are further improved to enable wireless technology to deliver "extreme high-data rate and extreme high capacity communication" exceeding 100 Gbps, new sensory services will be a reality. Those services aim to provide the quality of experience equal to that actually achieved by the five senses or even superior and comparable to "multisensory communication." User interfaces for such services will gradually evolve into wearable forms such as advanced eyeglass-type terminals. Extreme high capacity wireless network communication will enable such new sensory services to be shared among users in real time. It may also be possible for users to share their virtual experience or engage in virtual collaboration in the cyberspace, using new synchronization applications. If we consider the trend toward industrial use cases and cyber-physical fusion, the key will be to improve the uplink performance as stated in the previous chapter, because various types of information should be transmitted in real time to the cloud and AI, the “brain” of the network.

Figure 3-2.　Extreme-high-speed and high-capacity communications

3.2. **Extreme coverage extension**

We will expand area coverage to make Gbps-class communication speeds available everywhere, aiming to achieve "extreme coverage extension" in all places including the sky, sea, and space, which are not covered by current mobile communication systems, with a view to providing communication service coverage in environments with no human existence and developing space business. This is expected to widen activity domains of humans and things and create new industries. Promising use cases include logistics services such as home delivery using drones and unmanned operation or highly sophisticated operation in primary industries such as agriculture, forestry, and fisheries. Application to futuristic use cases is also likely, such as flying cars and space travels.

Figure 3-3.　Extreme coverage extension

3.3. Extreme-low power consumption and cost reduction

"Extreme low power consumption and cost reduction" of networks and terminal devices is an important requirement for achieving a worldwide goal of sustainable society. This requirement is important from both the business and environment standpoints as is the case with other generations including 5G. A drastic reduction of power consumption needs to be accomplished in mobile communication networks through CAPEX/OPEX reduction per communication speed unit (bit) and the use of a combination of advanced technologies for mobile communication and non-mobile communication [1-3]. Toward the future of 6G, it may be possible that devices will no longer need any batteries in themselves with the development of a power supply technology using wireless signals.

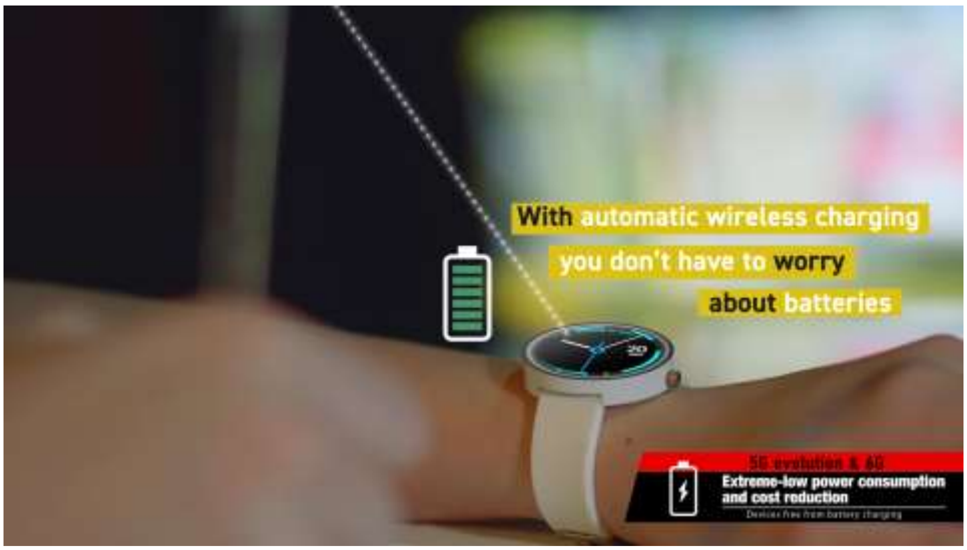


Figure 3-4. Extreme-low power consumption and cost reduction

3.4. Extreme-low latency

If we compare a cyber physical fusion system to a human body, wireless communication would be the nervous system, which transmits information. In order to realize more advanced real-time interactive AI service, E2E (End to End) low latency will be a fundamental requirement. Communication between things such as AI and devices will further develop toward 6G. In those use cases, "extreme low latency" of about 1ms or less will be required on an E2E basis. If such low latency is achieved, it may be possible to realize interactive customer service in unmanned shops, where robotics remotely controlled by AI deals with customers attentively, at a level rivaling or even outperforming human counterparts.

Figure 3-5. Extreme-low latency

3.5. Extreme-reliable communication

As described in the previous chapter, it is expected that there will be a trend of requiring communication with guaranteed quality in addition to best-effort communication in 5G evolution and 6G. In fact, there are many industrial use cases where a certain level of performance must be guaranteed, such as remote control and factory automation. Highly reliable wireless transmission of control information, therefore, is an important requirement, and 6G is expected to realize higher level of reliability than 5G. In addition, with the spread of robots and drones and the expansion of wireless coverage to the sky and sea, high-reliability communication may be required not only in limited areas such as factories but also in wider areas. In this way, highly-reliable communication is expected to be realized in various situations.

In addition, cyberattacks such as eavesdropping, spoofing, falsification, denial, and unauthorized operations can lead to theft or leakage of property/personal information, invasion of privacy, and suspension of services due to system malfunctioning. Furthermore, they could result in accidents that can threaten the lives of many people, social dysfunction and terrorism. Under increasing security threats such as more advanced cyberattacks and leakage of personal information, strong defense and secure communication service must be provided for networks serving various industries and administration offices, as well as terminals.

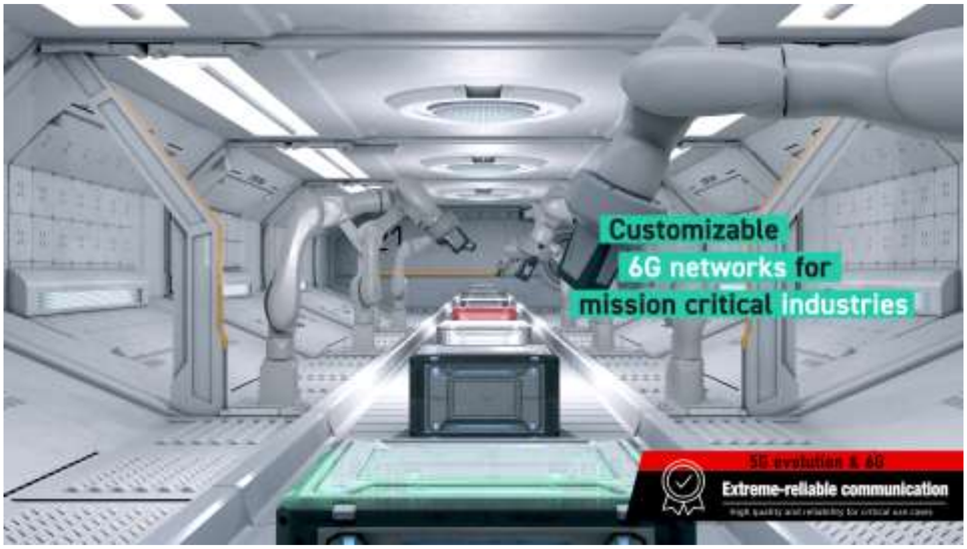


Figure 3-6. Extreme-reliable communication

3.6. Extreme-massive connectivity & sensing

In the 6G era, wearable user devices and a staggering number of IoT devices that collect images and sensing information in the real world are expected to be more widely available. There may be a requirement for extreme massive connectivity dealing with 10 times as many connections as 5G (= 10 million devices per square kilometer). In addition to the approach of connecting a large number of IoT devices to the network, wireless communication networks themselves are also anticipated be equipped with functions for sensing the real world using radio waves, such as positioning of terminals and detection of terminal users and their surrounding objects. Regarding positioning, standardization discussion is already underway toward 5G evolution, which is expected to provide extreme high precision positioning with errors of one centimeter or less depending on the environment. As for sensing, it is expected to realize the capabilities to identify objects and recognize actions as well as highly precise object detection through the fusion of AI and wireless communication technologies.

Figure 3-7. Extreme-massive connectivity & sensing

4. Technological development and research areas

Fig. 4-1 illustrates technological evolution from the past generations of mobile communications to 6G. In early generations including 3G, each had one representative technology symbolizing its wireless access technology (RAT: Radio Access Technology). In contrast, in 4G and onwards, each generation's RAT has consisted of a combination of OFDM-based multiple technologies. In 6G, its technology field will be more diversified. This is because the existing OFDM-based technologies have already achieved the communication quality close to the Shannon Limit, and the requirements and use cases have been expanding to a wider range as described in the previous chapter.

In 6G, therefore, more combinations of the radio access technologies will be required after going through 5G evolution. Use cases and requirements given in the previous chapter will be realized through integration with other technologies as described later. 5G has been specified as a combination of upgraded LTE and NR (New Radio). As 5G's NR is designed to be highly "future proof" in consideration of new technologies to be introduced in the future, it will be also necessary to consider the definition of 6G RAT. In the core network, we have promoted the modularization of 5G functions and the utilization of general-purpose technology for inter-functional interfaces. In addition to this trend, there may be an acceleration in the introduction of software-based network functions and open architecture. Hence, in designing network architecture, it will be necessary to consider functional configuration optimization and general-purpose equipment introduction. The following sections give an outline of each candidate technical areas for 5G evolution and 6G and their problems.

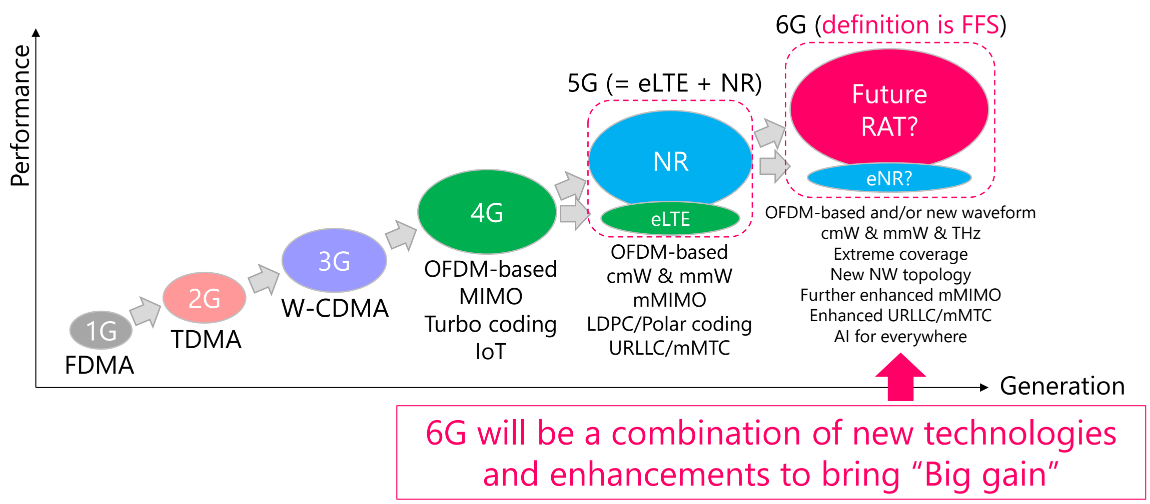


Figure 4-1. Technological evolution up to 6G in mobile communications

4.1. New Radio Network Topology

For pursuing extreme high data rate, extreme high capacity (especially uplink) wireless communication with improved reliability, it is ideal to communicate in a shorter distance with a LOS (Line of Sight) environment (in a path with a smaller loss) and increase the number of communication paths to provide more options (more redundancy) as much as possible. Satisfying these conditions will require a network topology distributed in the space domain. As shown in Fig. 4-2, early generations considered it ideal to configure a cellular network with hexagonal cells to avoid inter-cell interference. In the future, however, there will be an evolution to a New Radio Network Topology. This new form of wireless network will be a further extension of a heterogeneous network which has been studied since 4G, with overlapping multiple cell areas for creating more LOS environments and path options, and with more connection routes to/from mobile terminals nearby as well as other networks including NTNs (Non-Terrestrial Networks) described later. Such a spatially distributed network is considered to be compatible with the high frequency bands to be explored discussed later, Distributed MIMO technology, wireless sensing and wireless power supply.

On the other hand, from a common-sense viewpoint, this New Radio Network Topology may not be an ideal network configuration as it generates inter-cell interference and has many redundant antennas. This topology is not immune to interference because it does not adopt advanced beam control or path selection, or a cell configuration where each antenna forms a zone to avoid interference. Hence, a technical solution is required to help prevent interference, such as a Cell-free configuration [4-1], which configures a cell by multiple antennas. How to economically realize this New Radio Network Topology is also a fundamental problem, and we can think of various approaches to tackle this question. The standard solution would be not to use conventional base station antennas. As shown in Fig. 4-3, there are a lot of research areas that can be addressed: the use of existing objects such as street lamps, street/traffic lights, signboards, vending machines and window glass for communication antennas, integration of sensors and communication antennas and radio relay schemes such as IAB (Integrated Access and Backhaul) [4-2] and repeaters for high-frequency bands. In addition, it is also necessary to establish new optical interconnection and transmission systems which enable a distributed network topology and have a scalability to follow future evolution of wireless communications, as well as fronthaul and backhaul technologies. Furthermore, it would be necessary to consider this type of new solution in combination with existing cellular configurations. The following sections outline comparatively new technical areas related to New Radio Network Topology.

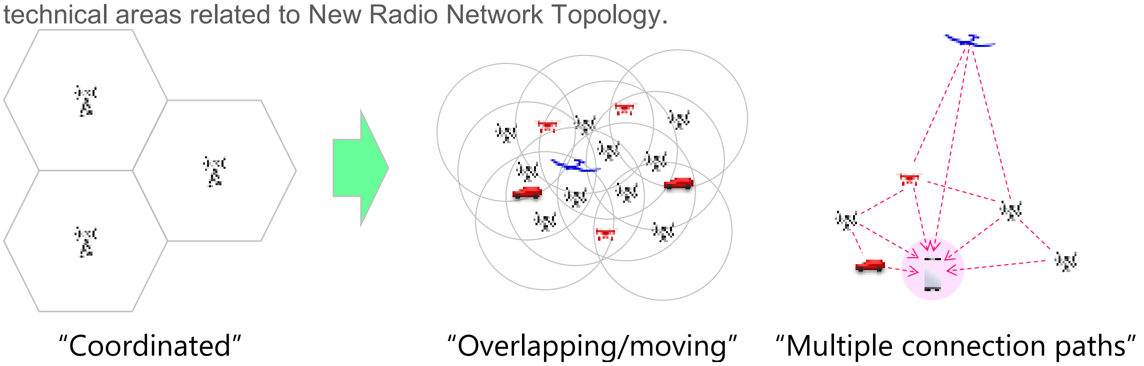


Figure 4-2. Evolution to New Radio Network Topology

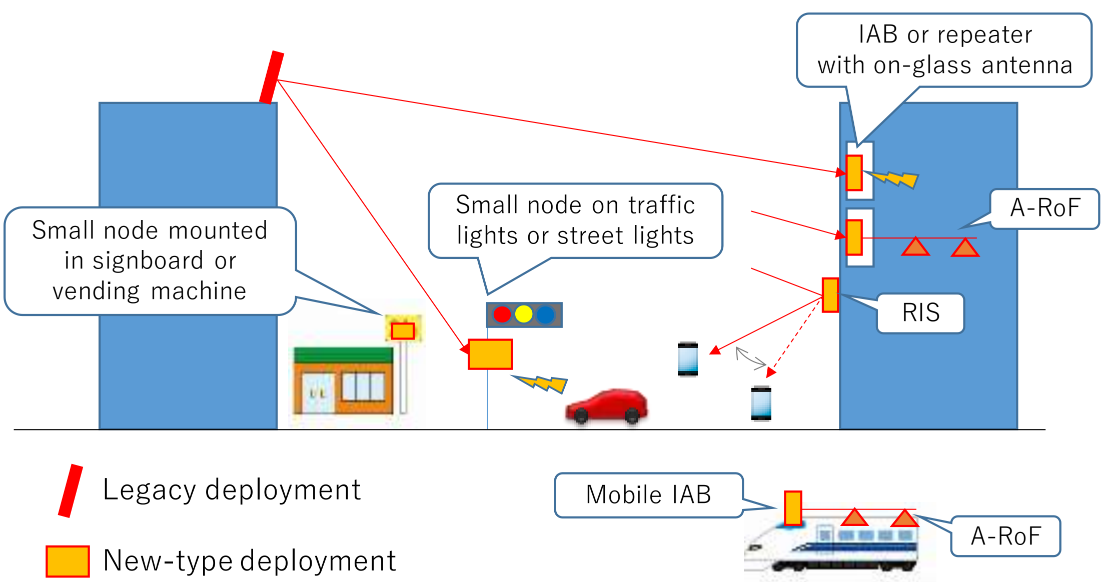


Figure 4-3. Example solution of New Radio Network Topology

4.1.1. Distributed antenna deployment with a "line"

In New Radio Network Topology, how to deploy numerous antenna systems efficiently will be a challenge. In order to deal with this, an approach that offers promise is to connect a large number of miniaturized and economical antenna systems with a "line" [4-3]. One of such implementation methods is A-RoF (Analogue-Radio over Fiber), which transmits analog radio signals to antenna systems over an optical fiber [4-4, 4-5]. A-RoF has more difficulty in maintaining its signal quality during optical transmission compared with D-RoF (Digital-Radio over Fiber), which transmits radio signals after converting them into digital information. On the other hand, by adopting A-RoF, neither A/D (Analog/Digital) nor D/A converters are needed on antenna systems and that prevents from the transmission bandwidth expansion, i.e., the optical transmission bandwidth can be reduced. Thus A-RoF can be an effective means of miniaturizing and economizing a large number of antenna systems. With A-RoF, by connecting antenna systems in a cascading configuration, it is possible to realize a distributed antenna deployment like a "line." In addition, a technique to control the beam of an antenna system at a remote location by assigning a wavelength to each beam in A-RoF as shown in Fig. 4-4 has also been studied [4-5]. Traditionally, D-RoF has been used in wide areas, while A-RoF has been applied mainly in limited areas such as indoor facilities. Such technologies will make it possible to use A-RoF in wider areas by means of optical fiber transmission of 10 kilometers or more.

Another technology being studied is to cause radio waves radiated from any part of a "line"-shaped antenna. Applying this technology, DOCOMO has developed a tool to create a communication area around a cable (transmission path) carrying high-frequency radio signals by having radio waves propagated through a part of the dialectic waveguide (cable) pinched with a small piece of plastic [4-6].

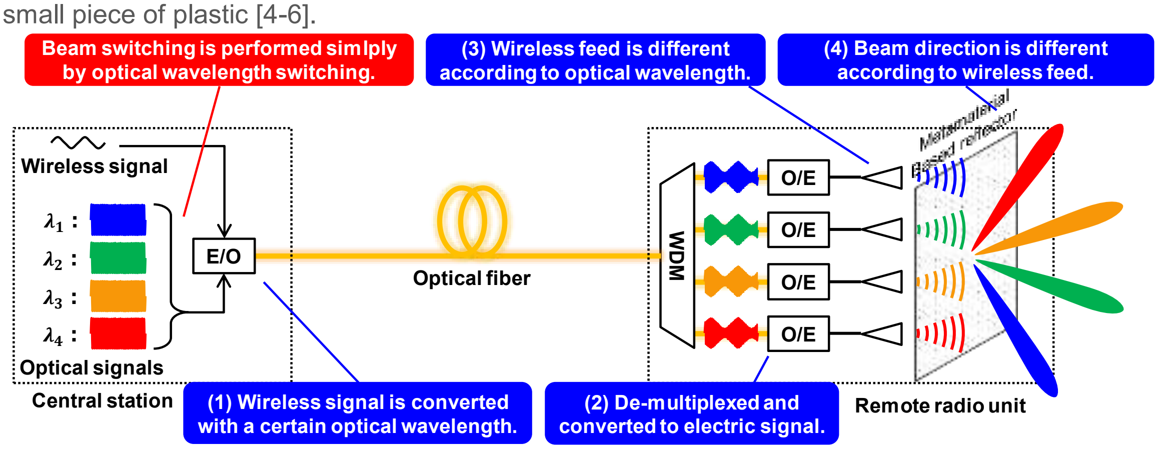


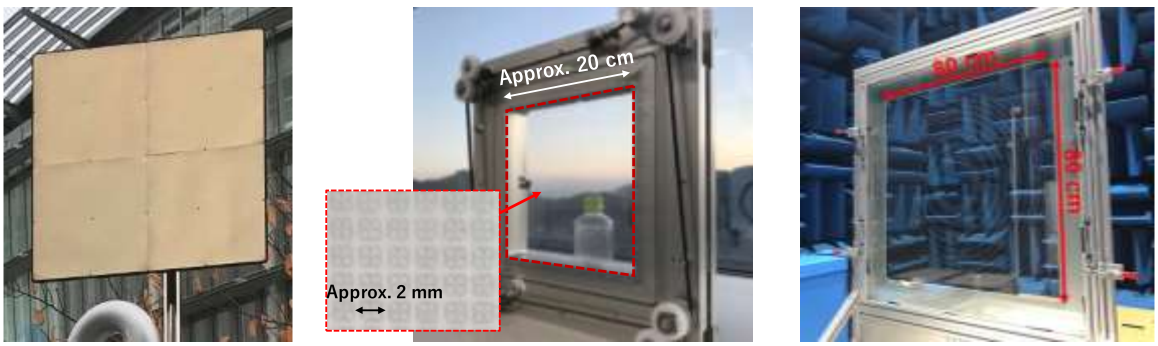
Figure 4-4. Technology using A-RoF to control beams of remote antenna systems

4.1.2. Reflector (RIS) technology

How to use multipath propagation of reflected waves has been one of the research areas pursued for a long time in mobile communications. Recently, advanced reflector (RIS: Reconfigurable Intelligent Surface) technology and its control technology are attracting attention for improving various radio performances in high frequency bands over millimeter waves. It is possible to use a RIS to provide a coverage area by attaching it on the wall or window glass and by controlling the radio waves reflecting on and pass through the RIS [4-7, 4-8].

DOCOMO is conducting R&D on a technology to use a transparent glass as an antenna [4-9, 4-10] in combination with the RIS technology. In an experiment using the metamaterial reflector shown in Fig. 4-5 (a), we verified a technology to reflect millimeter radio waves in arbitrary directions and expand the communication area [4-11]. In an experiment using the transparent dynamic metasurface shown in Fig. 4-5 (b), we successfully demonstrated a technology to allow millimeter radio waves to reflect on and pass through the transparent glass substrate [4-12]. Furthermore, in an experiment using the metasurface lens shown in Fig. 4-5 (c), we verified a technology to direct millimeter radio signals arriving from outdoors to specific points indoors by using a window glass quipped with this technology [4-13].

For practical application of RIS, we need technological examination to clarify its use cases, size design and application effects. In addition, if the RIS and repeater can remotely control beam directions, etc., it will be effective for communication area extension especially in high frequency bands, and therefore, we also need to consider a method to implement that capability.



(a) Metamaterial reflector (b) Transparent dynamic metasurface (c) Metasurface lens

Figure 4-5. Demonstration trials of reflector (RIS) technology

4.1.3. Inter-terminal coordinated transmission and reception technology

As a technique to realize a New Radio Network Topology, it may be possible to use a technology to enable coordinated transmission and reception between terminals [4 -14]. In 5G, the requirement for massive connectivity (mMTC) is 1 million connections per 1 square kilometer. But for 6G, “extreme massive connectivity” with approximately 10 times the density of 5G is anticipated, driven by increasingly advanced wearable terminals and cyber physical fusion. This is equivalent to the density of 10 terminals per 1 square meter, and in such an environment where many terminals exist densely, it may be possible to create many communication paths through coordinated communication among terminals without increasing antenna systems on the network side. Use cases of "extreme massive connectivity" should support a variety of terminals that are expected to appear, ranging from high-function sophisticated terminals to energy-saving communication terminals. It is necessary therefore to consider a technical scheme that factors in a wide range of terminal capabilities (UE Capability).

4.1.4. Win-Win distributed antenna deployment with sensing and energy-saving communications

As described later, sensing technology using communication signals for location estimation and object detection has been studied toward 5G evolution and 6G [4 -15]. In recent years, energy saving communication technology has also attracted interest, such as backscatter communication for realizing battery-less terminals [4-16]. Networks that realize these technologies are considered to have common features in their configurations. In wireless sensing and backscatter communication, a source signal needs to be emitted from a base station, mobile station or device emitting some radio waves (the signal transmitter in the figure) in the communication area as shown in Fig. 4-6. In addition, some receiving points must be provided in the communication area for observation purposes. This figure illustrates an example of multiple receiving points deployed using distributed antennas connected with a "line" as mentioned above. In radio sensing, radio waves reflected from objects are received by distributed antennas and analyzed in the network for location estimation and object detection. In backscatter communication, battery-less devices can transmit information to the network with low power by externally modulating the source signal while receiving power using the source signal.

It is also necessary to incorporate the network configurations used for such sensing and energy saving communication into radio communication systems in a natural way as part of the New Radio Network Topology concept.

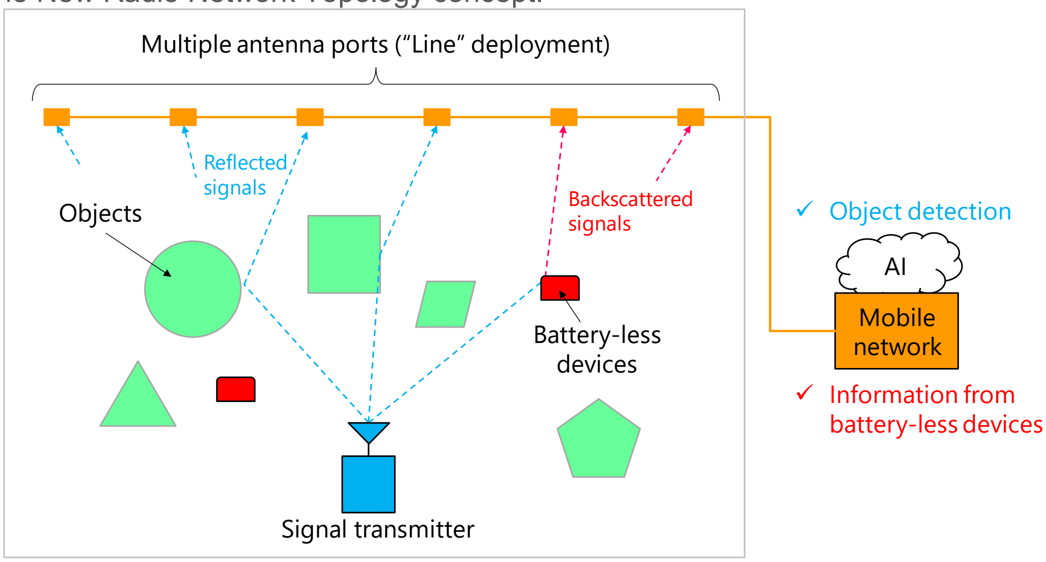


Figure 4-6. Example of network configuration assuming sensing and Backscatter communication

4.2. Coverage extension technology including Non-Terrestrial Networks

"Extreme-coverage extension" assumes use cases that will cover all locations including the sky, sea and space. This will require extension of area coverage to provide mobile communication services to areas with drones, flying cars, ships, space stations, and so on that conventional networks have not sufficiently been able to cover. Therefore, it is necessary to examine the above-mentioned New Radio Network Topology in three dimensions including the vertical direction. In addition, 5G evolution and 6G will require a technology that enables long-distance radio transmission at least over a distance of dozen kilometers in a highly efficient manner.

If we can use a geostationary satellite (GEO), low-earth orbit satellites (LEO) and high-altitude platform station (HAPS) systems as shown in Fig. 4-7, it will be possible to cover mountainous and remote areas, over the sea and space and provide communication services to these areas [4-17]. The GEO satellite is placed on a geostationary orbit at an altitude of 36,000 kilometers. For the GEO satellite, one-way signal propagation between the satellite and the ground station antenna takes a relatively long time of about 120 ms. On the other hand, 3 or 4 GEO satellites can cover the whole earth surface while communicating constantly with ground stations, and thus they have complemented the networks on the ground as a mobile backhaul. As further capacity increase will be required in the 6G era, the use of a VHTS (Very High Throughput Satellite) is considered to be a method to increase system capacity by optimizing the power and frequency of multiple beams [4-18]. The LEO satellite is an orbiting satellite that operates at an altitude of several hundred to about 2,000 kilometers. By comparison with GEO satellites, LEO satellites are in orbit at a lower altitude, therefore they are used for satellite mobile phones and satellite sensing, taking advantage of its low latency communication with a one-way signal propagation time of approximately 3 ms. LEO satellites can be also used as a large-capacity, low-latency backhaul if we can reduce satellites' manufacturing costs, extend the expansion of communication capacity by MIMO technology, etc. and achieve satellite constellation in which multiple satellites cooperate to form a network in the future [4-19].

Recently HAPS has attracted a renewed attention because of its capability to stay at a fixed location at an altitude of about 20 kilometers, forming a coverage area with a cell radius of more than 50 kilometers on the ground [4-20]. As HAPS systems stay at a lower altitude than LEO satellites, they can achieve even a lower latency with a one-way propagation time of about 0.1 ms, depending on the cell radius. It would be effective therefore to use HAPS not only for disaster countermeasures but also for many industrial use cases anticipated in 5G evolution and 6G. As shown in Fig. 4-8, HAPS can be used for backhaul applications (fixed system) for high-data rate, large-capacity terrestrial networks (fixed systems), which are even faster than satellites, for directly supporting mobile terminals using radio access standards such as LTE and NR, or for use cases that support terminals via relays (IAB) and repeaters (mobile systems). HAPS is thus expected to be used for a wide range of applications including those mentioned above. On the other hand, from the radio technology perspective, there are some areas that require further study, such as extending the radio interface to so as to be suited to long distance communication, finding a method for achieving higher spectrum efficiency with ground networks, realizing network design for highly efficient cooperation between HAPS systems and ground networks.

3GPP has started its study on the extension of NR to non-land network (NTN) using these satellites and HAPS [4-21].

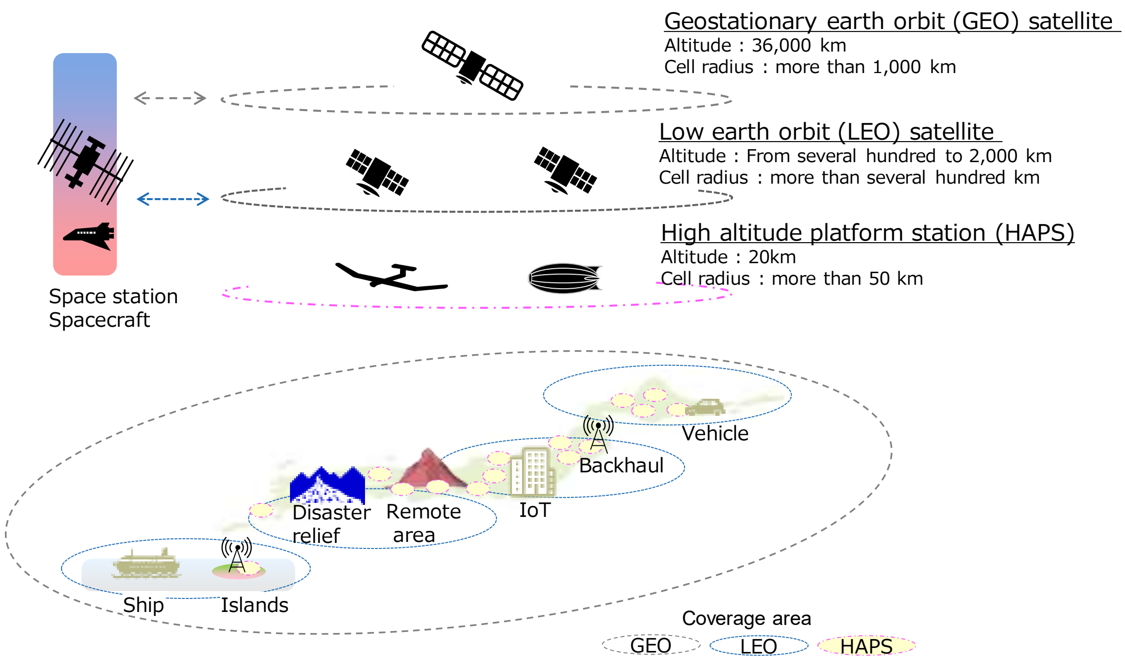


Figure 4-7. Coverage extension to the sky, sea and space using satellites and HAPS

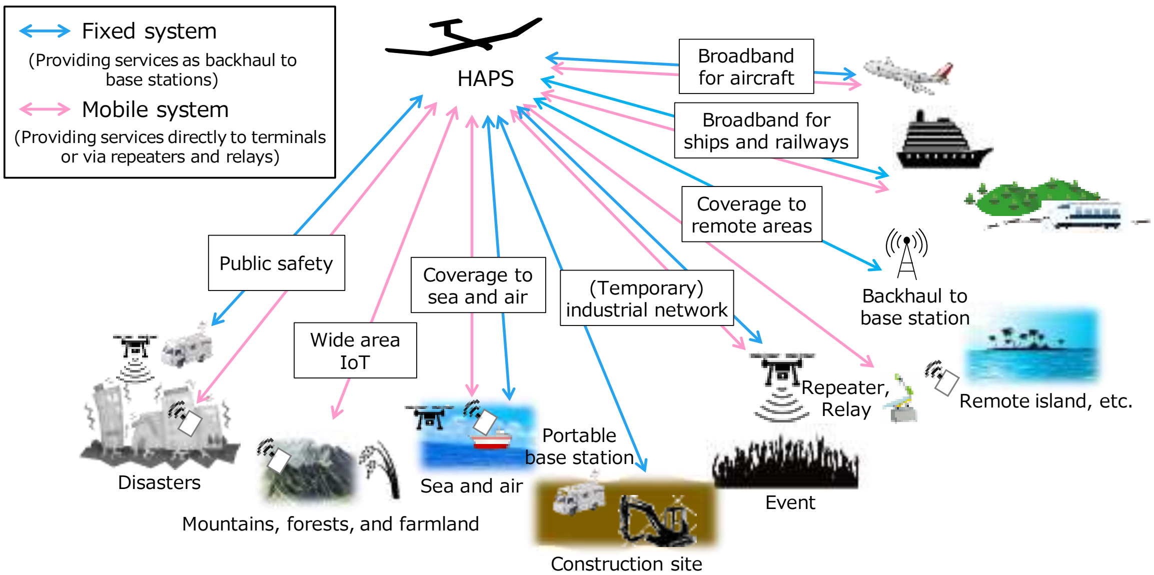


Figure 4-8. Various use case expected in HAPS

4.3. Technology for further broader frequency domain and advancement of frequency utilization

As shown in Fig. 4-9, 5G NR supports the frequency bands up to 52.6 GHz, and the possibility of extending its support to about 90 GHz is being studied for future releases. In addition, the Federal Communications Commission (FCC) recommends that higher frequency bands than those used in 5G, such as 95 GHz to 3 THz, be studied for 6G [4-22]. In the higher frequency spectrum from the "millimeter waves" to "terahertz waves," it is possible to use a drastically wider bandwidth compared to 5G. For this reason, studies have started on the possibility of achieving “extreme high data rate and high capacity" communication exceeding 100 Gbps [4 -23, 4 -24]. At present, as shown in Fig. 4-9, "radio waves" up to about 300 GHz are considered to be within the scope of 6G. However, "terahertz waves" have a stronger tendency to travel through a straight path than "millimeter waves" and cannot propagate for a long distance. In order to address this problem, it is necessary to carry out technical examination on terahertz waves to clarify their radio propagation characteristics and establish their propagation model and high-precision propagation simulation technique, as well as to study how to utilize terahertz waves based on the New Network Topology mentioned above.

For example, as for device technology, it is necessary to realize a digital signal processing circuit able to support further wider bandwidths, DAC (Digital to Analog Converter) and ADC (Analog to Digital Converter) at low cost and low power consumption. In addition, antennas, filters, amplifiers, mixers and local oscillators that operate in high frequency bands must be developed so as to be compatible with Massive MIMO’s multiple antenna elements described later. RF (Radio Frequency) circuits must be enhanced for higher performance and higher integration in high frequency bands exceeding 100 GHz. As semiconductor devices, they must be manufactured with a level of precision and cost applicable to actual commercial services. As the wiring loss will be larger in those high frequency bands, the composition of chips and circuits, and implementation method for connecting antennas are also major challenges. A research theme would be how to achieve optimization of both the pursuit of performance of the device itself and the improvement of performance of the device by digital signal processing, factoring in the evolution of future semiconductor manufacturing technology. Deciding whether to adopt chemical compound-based or silicon-based semiconductor will still be an issue in 5G evolution and 6G. When it comes to utilizing those semiconductor devices for terminals, how to achieve minitualization, low power consumption and high heat dissipation also needs to be addressed.

Figure 4-10 illustrates a concept of radio access technology in consideration of such high frequency bands and the above-mentioned "extreme-coverage extension" to the sky, sea, and space. These are different directions of development, but have common technical problems in the sense that this is the area where the coverage and power efficiency will become more important than the spectrum efficiency. In this area, single-carrier signal waveform becomes more dominant over OFDM as a radio technology. As we apply radio technologies including IAB to a wider range of areas, the importance of power-efficient radio technology such as single carrier may increase [4-25, 4-26].

In addition, as we add new frequency bands such as millimeter and terahertz waves in addition to the existing frequency bands, we will have to utilize more very wide frequency bands than in the past. This may necessitate consideration in a lot of related technological fields to achieve optimized selection of bands for different applications, reexamine inter-cell frequency reuse methods, upgrade uplink/downlink duplexing methods and review spectrum utilization methods in low frequency bands. In 5G, not only millimeter wave bands but also Sub 6GHz (3.7/4.5 GHz) bands are important, and this will be also the case toward 6G. It will be important to explore new frequency bands and improve performance in millimeter-wave and lower frequency bands as shown in Figure 4-9, because such efforts will lead to improved user experience everywhere and also to stronger motivation for introducing 6G for mobile carriers. It is also necessary to reexamine the possibility of newly introducing technologies that have not been achieved prior to or for 5G, because they may also contribute to improving the spectrum efficiency in the existing frequency bands and expanding the scope of new use cases. Such technologies include the above-mentioned New Radio Network Topology, AI technology described later in Section 4.6, optimization technology using cyber-physical fusion and high-precision sensing technology linked to high frequency bands, as described in, Section 4.6, it is possible to improve the frequency utilization efficiency of existing frequency bands and expand the scope of application to new use cases. In addition, the advanced radio transmission technology described in Section 4.4 can be widely applied to lower frequency bands below millimeter wave frequencies. Furthermore, for the existing frequency bands, designing new radio technology which can coexist with existing technologies such as 5G NR will also be become also an important requirement.

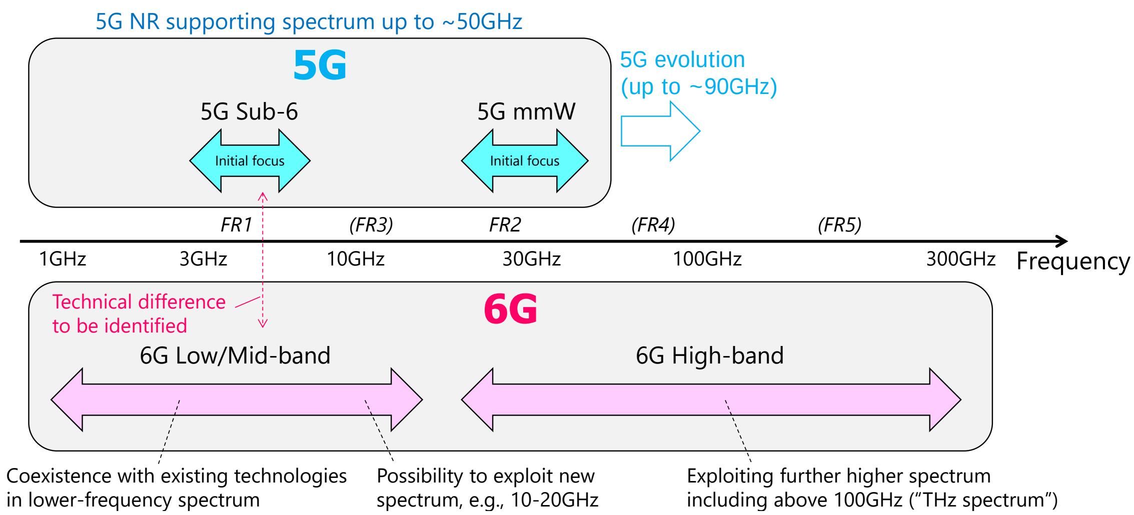


Figure 4-9. Exploration of frequency bands for 6G

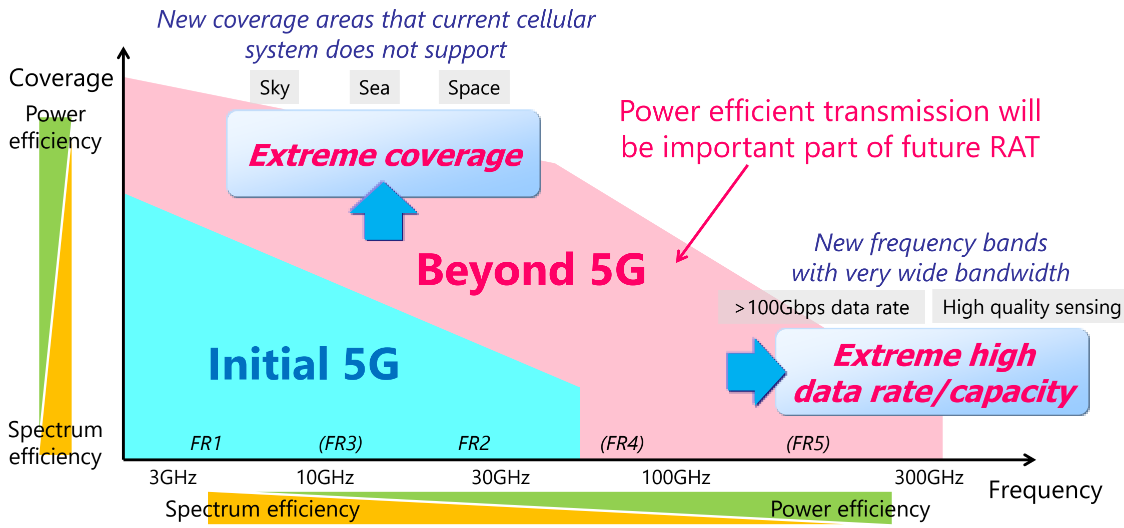


Figure 4 -10. Expansion of radio access technology for higher frequency band exploration and coverage expansion

4.4. Further advancement of Massive MIMO and wireless transmission technologies

In 5G, Massive MIMO (mMIMO) technology using a massive number of antenna elements has been a key, especially as a technology to make effective use of millimeter waves [1-1]. In 5G evolution and 6G, further advanced forms of mMIMO are expected, such as multi-element/multi-layer mMIMO [4-27, 4-28] and Distributed mMIMO for a distributed antenna configuration combined with New Radio Network Topology. Distributed MIMO combined with New Radio Network Topology is particularly promising in high-frequency bands such as millimeter-and terahertz waves. As shown in Fig. 4-11, it will be necessary to examine how to achieve the following technologies: (i) the technology to deploy distributed antennas to ensure LOS (line-of-sight) propagation paths for mobile terminals with a high-probability, (ii) the technology to control distributed propagation paths to switch the communication paths and track very narrow beams following the movement of user terminals and (iii) the technology to achieve distributed cooperative MIMO that realizes multi-user transmission for a large number of user terminals by using several cooperation methods such as inter-terminal communications [4 -5].

Regarding radio access technologies, ones based on the OFDM signaling approach the Shannon limit. Faster-than-Nyquist (FTN) signaling has been recently studied, which packs data non-orthogonally at a sampling rate faster than bandwidth [4-29]. Even if the system employ the FTN signaling, it would be difficult to exceed the Shannon limit. However, the FTN signaling may yield another gain, e.g. peak-to-average power ratio (PAPR) [4-30]. Furthermore, as shown in Fig. 4-12, Virtual Massive MIMO (VM-MIMO) technology has been proposed as a technique for realizing spatial multiplexing antenna gain comparable to mMIMO with a single antenna [4-31]. VM-MIMO technology can create a super-massive number of virtual antennas and increase the number of space division multiplexing channels by using a reception sampling rate greater than the frequency bandwidth as is the case for FTN, and by changing the antenna characteristics at ultra-high data rates and periodically. In contrast to FTN, VM-MIMO can bring about the effect of extend the bandwidth relative to the Shannon Limit by causing the propagation path to fluctuate at high data rate, and has the potential of obtaining large gain theoretically, despite certain remaining challenges such as its application conditions and feasibility under real environments.

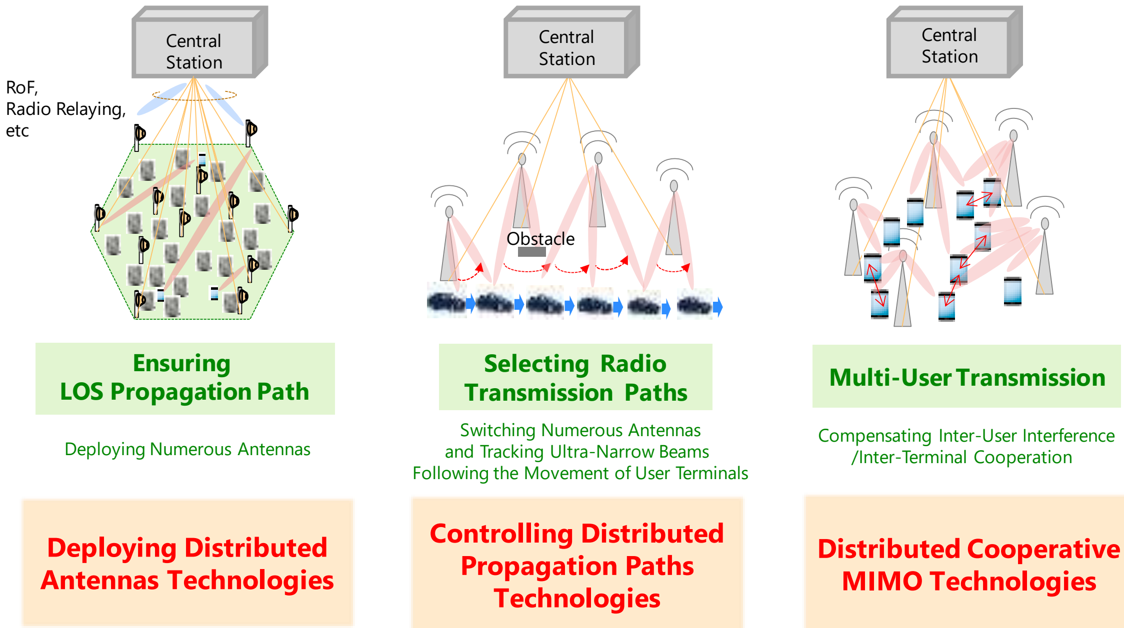


Figure 4-11. Current issues for Distributed MIMO

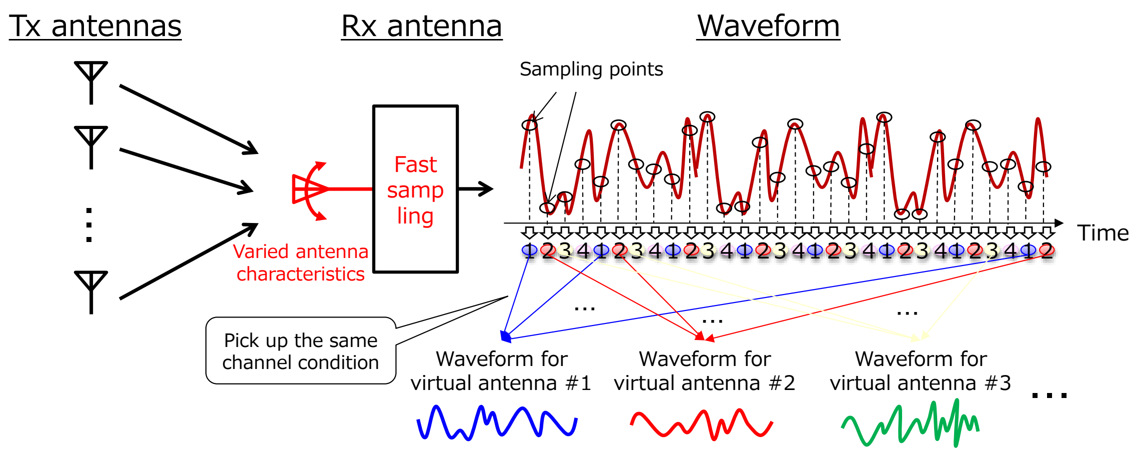


Figure 4-12. Example of non-orthogonal transmission technology using a sampling rate greater than the frequency bandwidth (VM-MIMO)

4.5. Extension of Ultra-Reliable and Low Latency Communications (URLLC) and industrial networks

Many industrial use cases such as remote control and factory automation require guarantee of necessary performance. A recent focus of attention is Non-Public Networks (NPNs), which are specialized for industry applications and differentiated from Public Networks characterize by best-effort services, leading to various discussions on how to implement it efficiently. In addition to "Local 5G" in Japan, current global research projects such 5G-ACIA are joined by many companies [4-32]. Industrial use cases are characterized by their wide range of requirements, which vary among industries and applications. Low latency is not always required; however, it is necessary to anticipate use cases that would require very demanding conditions and not be simply satisfied with an average low latency but demand stable low latency that will never fluctuate.

Automation systems in factories are expected to use different applications to make their automated operation more effective. As shown in Fig. 4-13, it is anticipated that factory automation will need to support "Mixed Traffic," in which different systems with different communication requirements coexist. In this example, a data transmission system that requires high-capacity communication and a control system that requires low-latency and high-reliable communication are simultaneously operated. It is necessary therefore to realize a system that can respond to a wide range of requirements, such as achieving high-capacity communication while maintaining low latency and high reliability [4-33]. 6G is also expected to provide higher levels of reliability and security than 5G.

As shown in Fig. 4-14, there are a lot of options being studied in terms of performance, cost and speed of deployment regarding the mobility between Public Networks used by general users and NPNs for industry applications and network configurations, which are now discussed at 5G-ACIA and other groups.

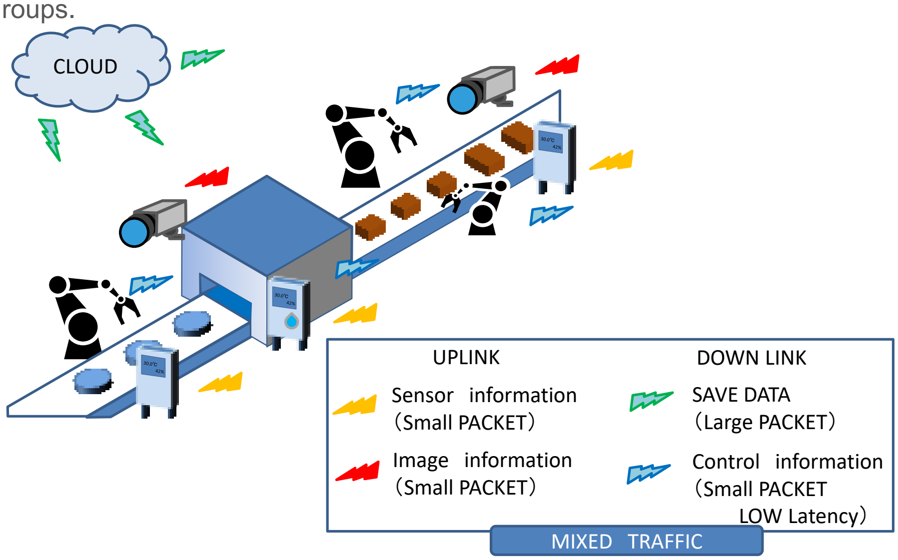


Figure 4-13. Support of various types of traffic in industrial networks

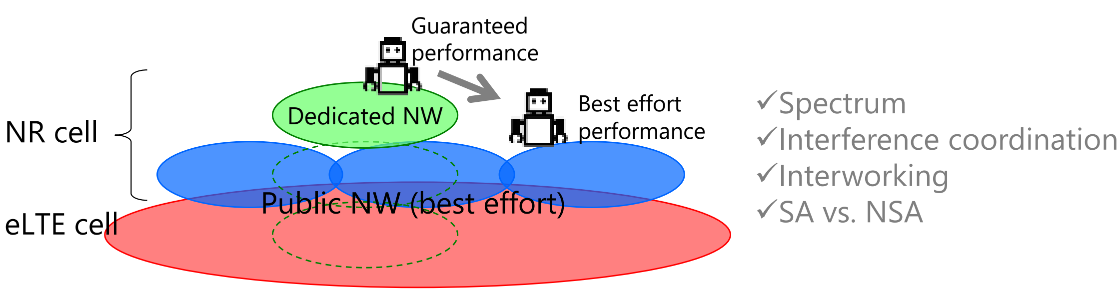


Figure 4-14. Overlay of Public Network and industrial network (NPN)

4.6. Multifunctional wireless communication systems and utilization of AI technology in all areas

In cyber-physical fusion, images and a variety of sensing information are transmitted to the network through IoT devices. There should be certain technological areas for analyzing transmitted information as well as information measured by radio communication signals by AI technology and utilizing them to upgrade radio communication control functions such as propagation path prediction and beam control. In addition, there is a potential for an evolution in which radio communication waves will be used not only for information transmission but also for various applications, including sensing such as positioning and object detection [4-34, 4-35] and wireless power supply technology (energy harvesting [4-36], etc.). High frequency band such as millimeter and terahertz waves will worth attention from the aspect of realizing high-precise positioning and sensing as well as for the purposes of high-data rate, high-capacity communication. Also utilizing AI technology is a key. AI analysis of various kinds of information in addition to information from radio communication signals can greatly improve the accuracy of positioning and object.

In addition, technological areas have been expanded to include object and behavior recognition beyond object detection such as human detection as a result of recent computational capability improvement and AI technology advancement. Specifically, the following technologies are widely examined: Intrusion detection (one or multiple persons), congestion rate calculation in a certain area, human action recognition (walking, sitting, cooking, watching TV, etc.), gesture recognition by fingers and arms, vital sign monitoring and user identification. From the technical point of view, the conventional object detection technology has mainly taken an approach of detecting objects based on the changes in the received power. On the other hand, the recent wide use of OFDM and MIMO has made it possible to obtain more detailed propagation channel information (CSI: channel state information) in frequency and space domains. This has brought about an explosively increase in the quantity of information available for analysis. Since most of information that can be obtained from wireless networks still remain untapped, this area is expected to grow continuously.

As shown in Fig. 4-15, the use of AI technology has been considered in all areas of wireless communication systems, including different types of control and algorithms, network and device management and automatic optimization functions for use cases and environments. AI application is considered in different technologies such as those to improve latency and reliability in non-orthogonal multiple access (NOMA) [4-37, 4-38], to predict a propagation environment and communication quality with environmental changes [4-39, 4-40], to perform intelligent route switching with other integrated and coopering radio technologies based on a predicted propagation environment and communication quality [4-41] and to autonomously and continuously install mobile base stations in optimum locations [4-42]. For efficient and effective use of the above-mentioned New Radio Network Topology, topology management and control technology utilizing AI will also be an important factor. The sensing information acquired by utilizing AI is considered to be effective for network control and parameter optimization in 5G evolution and 6G as well as for provision of additional value for users. Thus, AI is also expected to contribute to stable network operation.

It is necessary to discuss what kind of wireless network standards will suit the needs of such AI technology utilization. But in the future, we may be able to let AI technology do all the work of wireless network interface design.

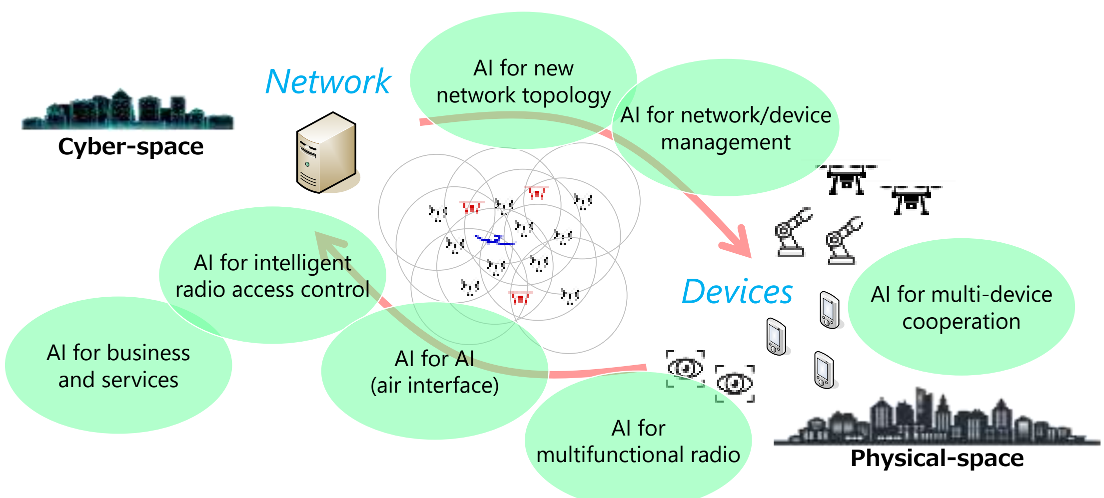


Figure 4-15. Utilization of AI technology in all areas of mobile communications systems

4.7. **Integration of various wireless technologies**

As we continue to expand the 5G evolution and 6G technology areas in order to support all use cases, it will become necessary to consider how to coordinate or integrate mobile communication technologies with other current and future wireless technologies dedicated to specific applications as shown in Figure 4-16. As with 5G, it will be important to complementary use or cooperate with unlicensed-band wireless communications, such as wireless LAN and Bluetooth, and short-range wireless communications. In addition, we should consider how to achieve new forms of cooperation with wireless communications using waves other than radio waves, such as optical wireless communications [4-43, 4-44] and underwater acoustic communications [4-45]. Further integration of fixed and mobile communications is also a possibility. As mentioned above, cooperation with satellite communication systems is also important in order to realize the coverage extension to the sky, sea and space.

On the other hand, we can also refer to other examples such as the expansion of mobile communication technology to unlicensed bands (LAA: License Assisted Access) [4-46], integration of access and backhaul links by mobile communication technology (IAB) and examination of NTN in 5G. In view of these wireless technologies, we can potentially take an approach to supporting their use cases comprehensively by extending mobile communication technologies, instead of applying other communication standards or frequency bands as we have done so far.

In order to realize all requirements and use cases of 5G evolution and 6G, it will be mandatory to integrate such multiple types of wireless network technologies through their cooperation and integration and will be necessary to find out implementation methods to achieve these. This may also be related to how to "define" 6G. The ideal is to establish an ecosystem that can support a wider range of use cases in a user transparent manner, in other words, without making users aware of which wireless network technology they are using.

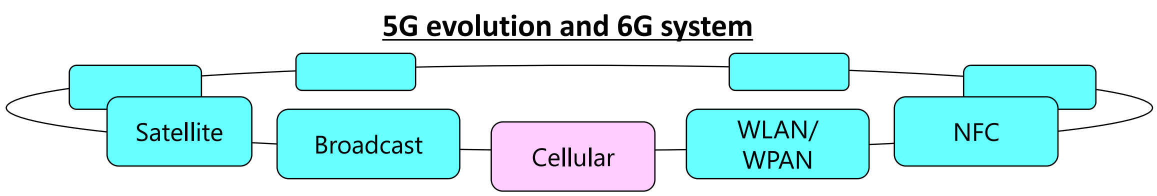


Figure 4-16. Integration of wireless communications technologies.

4.8. **Network architecture**

5G's network architecture needs to satisfy the requirements for high-data rate, high capacity, low-latency and high-reliability communication and massive connectivity and support a wide range of services and applications in the market. To achieve this, new technologies and concepts have been introduced to 5G, such as virtualization technology, network slicing and Service Based Architecture (SBA) in the core network as well as in the wireless access network. It is still necessary however to examine the network architecture including its drastic review in order to follow the market trend in the latter half of 2020s and 2030s, further demanding requirements, and the speed of market changes.

The following requirements should be taken into consideration in examining the network architecture.

1. Practical application of even more diverse use cases from a wide range of industries

2. Responding to a dramatic increase in traffic, mainly data from vehicles, cameras and sensors reflecting the age of advanced cyber-physical integration

3. Use of communication networks as a lifeline, increasing demand for important communications in various industries, and ensuring the robustness of communication systems against frequent disasters

4. Diversification and increase of devices used by humans such as wearable devices, and responding to the sharing economy also expanding to the telecommunications industry

5. Responding to the efforts for sustainable global environment such as global warming gas emission control, decarbonization and reusability

6. Rapid implementation of new services in response to rapid market changes

7. Strong defense against advanced cyberattacks, increasing security threats such as personal information leakage and provision of secure communication services

8. COVID-19's rapid transformation into a remote society due to the spread of infection

The following sections discuss issues regarding the network architecture to be examined.

4.8.1. Flat network topology

In mobile communications, the use of tree and star network topologies is anticipated to continue even in the future in public networks. In consideration of various new use cases created in the future and the robustness required for systems, however, it should be necessary to consider diverse options to provide the capability to select a most appropriate topology for each location or application including new topology options. Use cases geared toward private networks represented by local 5G are expected to spread further in the future, as well as small network configurations with built-in network functions. For the coverage extension, we should also consider the possibility of introducing and disseminating technologies for distributed antenna deployment, relay node utilization and inter-terminal hopping. In addition, we need to consider network topologies factoring in the possibility of integrating technologies of mobile communications with those of Non-Terrestrial Network (NTN) communications utilizing HAPS and satellites, and with those of other wireless communications for the purposes of disaster response, rapid service area expansion and low-cost and efficient network operation.

4.8.2. Flexible deployment of network functions

In order to support various use cases expected in the future, it is necessary to allow flexible network function deployment as well as the diverse network topologies mentioned above. Regarding the deployment of RAN (Radio Access Network) and CN (Core Network) functions, there are usually concentrated in large-scale facilities in public networks. In the future, however, it is anticipated that more functions will be distributed locally in use cases of private networks or their equivalents for improved safety and low latency transmission. In addition, we need to consider the fact that if mobile device functions are deployed on the network side, it will reduce the cost, size, and power consumption of the mobile devices.

The direction shown above has been promoted by the recent trends of virtualizing and implementing network functions as software components including their containerization. In fact, considerably flexible functional development is possible even in the current stage. The core network functions are now being virtualized, as well as MEC/cloud services being offered by communication service providers, and RAN's functional virtualization has also started. More flexible distribution and unified stable operation of those diverse network functions and cloud services require further improved robustness, operability, and maintainability. In addition, it is required to ensure the scaling of network services in response to performance requirements from small to large scale communications, to reduce power consumption by software technology, and to achieve power consumption reduction, space saving and cost reduction for hardware itself.

4.8.3. Simple network

The 5G system as a whole is becoming more complex as more functions and options are implemented in order to support a variety of use cases flexibly. For multiple parameters that supports one function, a wide range of values and many combinations of values are specified. This leads to an increasing number of test cases for functional tests, and interoperability tests between systems and vendors, requiring a large amount of human resources and cost. To cope with this, it will be necessary to take measures to suppress complexity, while maintaining system flexibility. The following measures can be considered.

1. Careful selection of functions and options required in the market
2. Redundancy elimination between RAN and CN
3. Reduction of layers in the protocol stack
4. Grouping of use cases and selection of parameter values and combinations for each group
5. Unification of lifecycle management methods such as RAN and CN installation and configuration changes in virtualized environments.

4.8.4. Advanced OAM (Operation and Maintenance)

For reducing workloads and costs and quickly introducing new features to systems, zero touch operation is attracting worldwide attention, prompting its standardization and active system development. Zero touch operation means automating systems to enable them to autonomously and directly operate networks and services by utilizing AI technology without human intervention. In the current stage, the range of autonomous operation is limited, and in many cases, it requires the intervention of maintenance personnel. It is therefore necessary to gradually expand the range of autonomous operation and reduce the areas that require such human intervention.

4.8.5. Technology for integrated operation of multiple access technologies

The 3GPP has already standardized the functions to accommodate multiple access technologies, including wireless LAN and fixed communications, as functions in CN. In the future, it will be necessary to develop an advanced integrated operation technology that can select various access technologies such as fixed and satellite/HAPS communications and broadcasting, deploy them in the right places and select an optimum access technology in a user transparent manner. The following methods should be considered toward future networks.

1. How to distribute sites (Global/Local, Central/Edge, etc.) for common services
2. How to enable one terminal to use different access technologies, addresses and slices depending on the situation
3. How to operate one user’s multiple devices supporting different access technologies

4.8.6. Core network transmission/switching control technologies supporting extreme low latency

One of 5G’s achievements is the realization of low latency. 5G allows terminals to connect to multiple U plane nodes and to switch nodes at opportunities triggered by the terminals’ mobility or applications in such nodes. 5G can also monitor E2E latency. Specifications are being prepared for the nearest application server selection and cooperative switching of U plane nodes and application servers. However, in 5G, the realization of E2E low latency has only relied on the U plane’s route selections within the range visible from the communication control function. In other words, 5G has never attempted to reduce the latency in consideration of any (i) transmission paths actually installed, (ii) actual switching equipment or (iii) interfaces between the wireless and wired sections. In order to realize E2E extreme low latency in the future, we should also give consideration to the areas that 5G has not included in its study scope 5G for latency reduction. In other words, for example, it is conceivable to adopt a system in which (i) its communication control function is extensive enough to cover the control of actual physical media in the transmission path, so that the function can also control scheduling as well as path selection/configuration, (ii) no media conversion (e.g., Light - > Electricity - > Light) should performed in the switching facilities, and this is kept to the minimum even in the transmission section [4-47] and (iii) slot allocation for data transmission/reception is aligned between the wireless and wired sections to eliminate the latency. As a secondary effect, this system can also improve efficiency and reduce power consumption of deterministic communication.

4.8.7. Wide-area time synchronization and wide-area deterministic communication supporting CPS

Another achievement of 5G is the realization of time synchronization and deterministic communication required for industrial closed networks (deterministic communication, in which communication arrives at a specified time, has limited latency variations. Mainly used for periodic communications). IEEE's TSN specification which supports factory production technology has been supported since 5G. IP-based time synchronization necessary for audiovisual production is also being specified. Studies on time synchronization, time maintenance and deterministic communication necessary for the security of power distribution grids have also begun. However, 5G currently does not support (i) time synchronization among widely scattered devices with no distance limitation comparable to that of an industrial closed network, (ii) wide-range deterministic communication with no distance limitation, (iii) IP-based deterministic communication or (iv) scheduling on wired transmission paths. In the future, time synchronization and deterministic communication over a wide area will be considered to support actuation of CPS. This will also contribute to the creation of new services full of reality that use tactile senses and multiple senses (i.e., multimodal) as new communication quality. In considering how to proceed regarding (i) (ii) and (iii), it is assumed to be inefficient to control a mixture of normal traffic and traffic with distinctive characteristics. Therefore, as shown in Fig. 4-17, we should start by enhancing a mechanism for selectively using multiple advanced transmission paths specialized for data transmission with specific traffic characteristics for each call. This transmission path should be able to control the communication quality finely on an off-path basis. Regarding (4), it is conceivable that information on the user data generation time/interval generated by the control node of deterministic communication can be leveraged for the scheduling on the above-mentioned transmission path on the wired section.

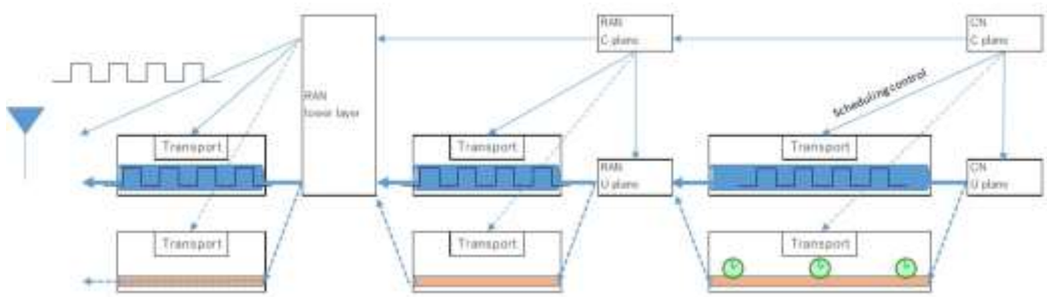


Figure 4-17. Example of architecture for wide-area deterministic communication

4.8.8. Location-based mobility control supporting extreme-coverage

In 5G, mobility control has remained largely unchanged since EPC. In other words, 5G's current mobility control (and services such as emergency calls subject to the regulations of the country where the terminal is served) does not work properly when (i) cells or base stations move relative to the ground, (ii) a combination of cells and base stations change or (iii) cells are large enough to cover part of another country across the border. In the future, the above-mentioned situations will occur normally, service coverage areas will be on the ground, in the sky and in space, and terminals and base stations will move around in a three-dimensional space. Thus, there should be a review of mobility control. For example, location-based mobility control may be employed for the idle mode. This mobility control consists of the following three parts. As shown in Fig. 4-18, (a) each area is defined as a cube which is separated with other cubes in three dimensions by the coordinates of latitude, longitude and altitude, b) each cell determines whether a terminal with a location acquisition function is inside or outside itself and (c) information of the area covered by each cell is continually updated through enhanced link connection establishment between the cell, base station and core network. As a side effect, this scheme will make it possible to directly store the terminal's location registration information as part of a digital twin of the network in the cyberspace of the CPS that manages data in terms of location (and time). This digital twin can be easily overlaid on other digital twins (e.g., urban information, traffic information and disaster information). With additional use of AI, it will be possible to utilize such information updated every second for network operation and maintenance.

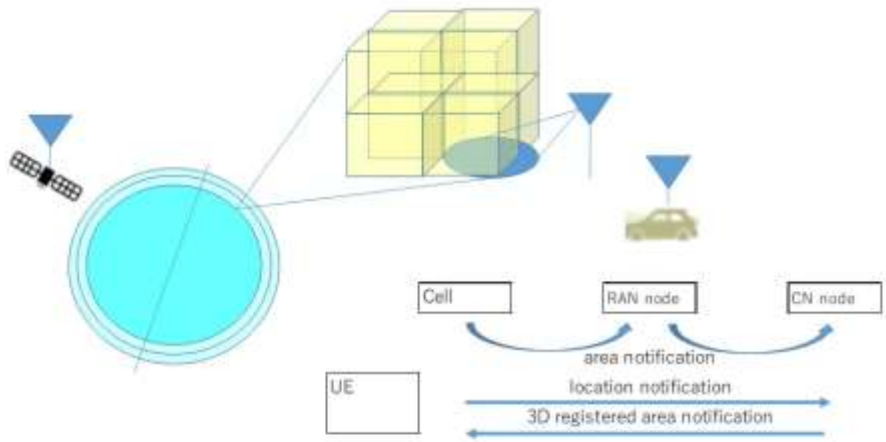


Figure 4 -18. Location-based mobility control

4.8.9. Advanced security

Cyber-attacks are becoming increasingly sophisticated, everyday examples include ransomware and phishing, but at the same time even more complex targeted attacks are also taking place. These attacks are possible due to increased softwarization and digitalization paired with connectivity and mobility that in turn increases the threat surface.

We envision enhancements in 6G will lead to extreme-massive connectivity and sensing, digital twin becoming common, increased cooperation with third parties including cloud service providers and increased interworking with wireless communication technologies other than mobile communications. At the same time we will also see increased usage of very low power consuming devices with limited resources, which will also be in use by critical infrastructure. Together with these enhancements towards 6G, we should also expect technology enhancements in the dark web. Threat actors in the form of Artificial Intelligence (AI) should be expected to increasingly appear. All these aspects of 6G era will lead to increase in threat surface leading to potentially far more security attacks than seen today. Exposed low power limited resource devices without adequate security could lead to attacks on the network as well as sensitive data, while exposure of network and services to third party could lead to numerous attacks as well.

Thus holistic security considerations from the very beginning becomes ever essential for 6G in order to provide safe and secure services so as to realize trusted cooperation across industries. Enhanced security for 6G should protect systems and data from these ever increasing threats while ensuring their confidentiality, integrity and availability.

So as to protect services and networks from cyber-attacks, it is necessary to build solutions that eliminate vulnerabilities from the very beginning and continuously, solutions that are flexible and adaptable based on service or usage and that can, preferably, quickly and autonomously detect cyber-attack as well as take remedial measures while localizing the attack. Work is already underway towards secure technologies using AI and network (NW) digital twin, advancement of vulnerability and attack detection technologies, automation of cyber-attack detection and remediation, and prediction based cyber-attack prevention techniques. The introduction of these state-of-the-art secure technologies will provide a robust security protection that will ensure confidentiality, integrity and availability. Together these will help towards the vision of zero touch and zero trust security.

Higher data-rate requirements, associated to devices with sufficient resources (memory, CPU etc.), as well as very low resource limited resources devices with requirement of ensuring adequate security will also lead to simplification of protocols, lightweight cryptography and security functions. Such enhancements will enable even low-power consumption devices to execute advanced security functions with side-effect of reduced security risks due to lower protocol complexity. In addition enhancements in encrypted traffic analysis and secure computation technology [4-48] will help prevent potential cyber-attacks and distributed ledger technology (DLT) or enhancements thereof can be beneficial for securing transactions for the expected open nature of 6G.

Moving towards 6G, we should expect quantum computing to be available. The universal quantum computer, which can execute the algorithm of Shor could crack mainstream cryptographic algorithms (RSA, Elliptic curve cryptography, etc.). Thus in 6G era, the quantum-computer-resistant cryptographic algorithm [4-49] is essential. All these aspects of security also requires associated considerations of network architecture.

The image of advanced security in 6G network is shown Fig. 4-19.

Finally, even with all the security enhancements, basic security concepts must not be forgotten such as: hardening, password management, identity and access management, monitoring, patching etc. Also, while enhancing security for 6G it is essential to understand that security is often a trade-off with business and architecture thus appropriate balance must be found that still reduces the overall security risk..

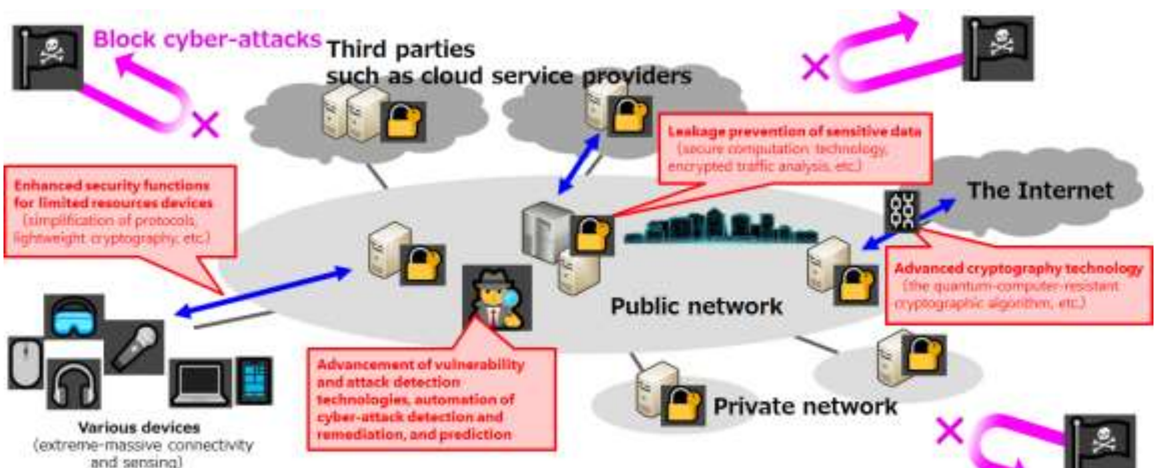


Figure 4 -19. Advanced security in 6G network

4.8.10. Distributed computing resources

To realize cyber physical fusion and digital twins, it is necessary to collect information from the physical environment for the cyber environment. Constant transmission of high-definition images, which are part of physical information, requires a huge amount of communication resources throughout the path from a large number of camera devices to digital twins. In order to reduce such communication resource consumption, some preprocessing may be necessary, such as removing redundant parts by image compression or aggregation or creating high-definition images by redundancy, using computing resources distributed in devices or in edge environments close to devices.

Use cases like an AR tourist guide will require a level of latency so low that any lag with the real world cannot be felt for improving user satisfaction. It would be preferable to perform AR and other similar processing within the device, but that will be a trade-off with the need to reduce device's weight and power consumption. Therefore, such services are anticipated to use distributed edge computing resources.

Another use case would be services that does what you currently do with your smartphone, using input/output devices around you, such as displays in your home or publicly installed cameras outdoors. Some of these services are anticipated to use edge distributed computing resources for control purposes, ensuring computing resources as well as input/output devices will always be available close to humans as they move around in order to maintain QoE.

DOCOMO currently offers DOCOMO Open Innovation Cloud (dOIC) and Cloud Direct service as edge computing resources for public use. We will distribute computing resources to more locations in addition to the 4 locations nationwide deployed at service launch. In addition, companies and local governments are installing their private systems such as local 5G, and many of them may eventually deploy computing resources as well.

In the 6G era, where digital twins and AR will become available anytime, anywhere, how much computing resources should be distributed? Suppose resources are only deployed in one location in each prefectural government or government-designated city, it would not be sufficient to meet the latency requirements. Resources should be distributed to degree that each of the special facilities such as stadiums and local tourist spots will have some. In view of the trend in which more RAN functions are deployed as software-based, virtualized components rather than in the form of physical equipment, computing resources could be deployed in all buildings accommodating RAN equipment in the way such resources are shared between end users and the RAN equipment. Furthermore, as technology makes anything smaller, computing resources could be made available in all antenna installations. As shown in Fig. 4-20, medium and small quantities of computing resources will be distributed everywhere, not just in the form of large data centers. By leveraging all of these resources, we'll be able to meet the processing demands of the 6G era.

To ensure users can easily and safely use such resources in various places, it will be more important to develop technologies for automating orchestration to handle distributed resources uniformly and for protecting and enciphering data and logic to enable various players to provide services by combining data and logic on those resources.

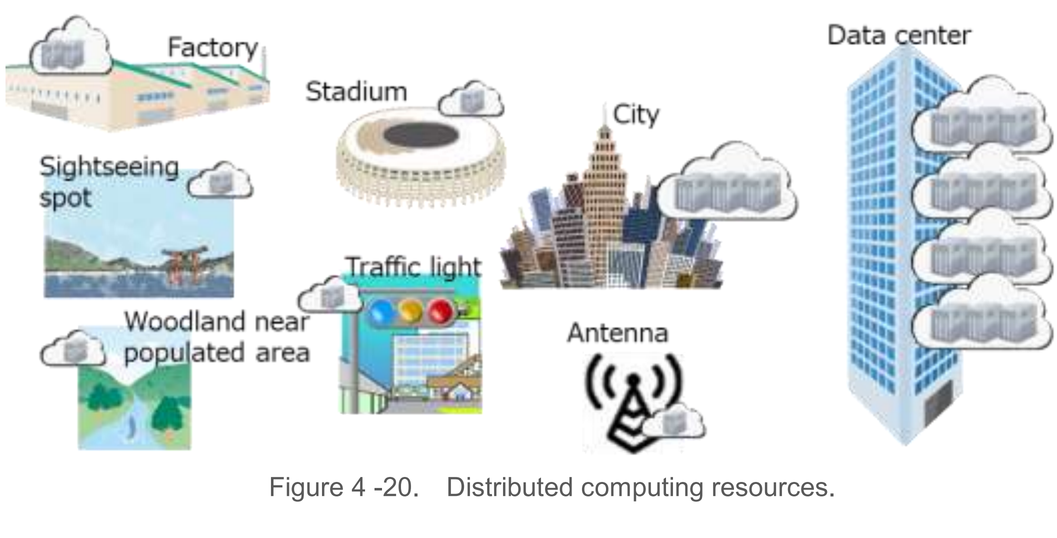


Figure 4 -20.　Distributed computing resources.

5. Conclusion

In this white paper, we have discussed the direction of evolution of mobile communication technology for 5G evolution, which is an enhancement of 5G, and toward 6G, which represents a vision of the world in the 2030's. We have provided the concepts for the requirements, use cases and technological development and research areas. Table 5-1 below summarizes the challenges that need to be addressed in each of the technological areas discussed in Chapter 4.

As 5G is expected to be utilized across various industrial fields, it is desired that research and development be conducted, foreseeing future market trends, needs, social problems and technological evolution and looking beyond the horizon of 5G. By further upgrading wireless technologies and exploring high frequency bands, DOCOMO will enhance the 5G performance in each of its features: "high data rate / high capacity," "low latency" and "massive connectivity." At the same time, we will embark on a challenging journey to new technical areas for mobile communications, such as "extending communication areas to the sky, sea and space," where it has been difficult to provide sufficient coverage; "realizing extreme low power consumption and cost communications" for achieving a sustainable society; "providing ultra-reliable communication" for wider industrial applications; and "realizing multifunctional radio communication systems." With these objectives, DOCOMO will continue our R&D efforts for the future of wireless technologies and use cases toward 5G evolution and 6G.

Table 5 -1. Challenges in 5G evolution and 6G Technologies

Technological area	Challenges
New Radio Network Topology	・Low-cost distributed antenna deployment method and fronthaul/backhaul technology ・Interference control technology in high-density distributed antenna deployment ・Win-Win distributed antenna deployment with sensing and energy-saving communications
Coverage extension technology including Non-Terrestrial Networks (NTNs)	・Radio interface extension for NTNs ・Method for highly efficient frequency utilization with ground networks ・Method for realizing coordinated operation between HAPS systems and ground networks ・Coverage extension to space
Technology for further broader frequency domain and advancement of frequency utilization	・Clarification of THz-band radio wave propagation characteristics and establishment of propagation models ・Challenges in THz-band device technology (Miniaturization, low power consumption, high heat dissipation, etc.) ・Establishment of signal waveforms and wireless technologies suitable for the THz band ・Optimization of selective use of multiple bands including existing frequency bands
Further advancement of mMIMO and wireless transmission technologies	・Study of multi-element / multi-layer mMIMO technology ・Transmission path control technology in distributed MIMO ・Development of new wireless technologies for existing frequency bands
Extension of Ultra-Reliable and	・Support of a wide range of requirements including

Low Latency Communications (URLLC) and industrial networks	very demanding requirements and "Mixed Traffic" ・Realization of further high-reliability and secure communications ・Coordinated operation between public and private networks and network configuration
Multifunctional wireless communication systems and utilization of AI technology in all areas	・Simultaneous realization of wireless communications, sensing technology and wireless power supply technology ・Study of radio standards suitable for deployment of AI technology
Integration of wireless communications technologies	・Method of cooperation or integration with other technologies ・Control of wireless technology selection transparent to users
Network architecture	・Flat network topology ・Flexible deployment of network features ・Simple network ・Advanced OAM ・Support for multiple access technologies ・Core network transmission / switching control supporting extreme low latency ・Wide-area time synchronization and wide-area deterministic communication supporting CPS ・Location-based mobility control supporting extreme coverage ・Advanced security ・Distributed computing resources

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