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NTT docomo

## White Paper

# 5G Evolution and 6G

**NTT DOCOMO, INC.**
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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, and the direction of further upgrading by combination with "Innovative Optical and Wireless Network (IOWN) Initiative [1-2]" proposed by NTT is also described. Chapter 3 discusses the requirements and use cases. Chapter 4 describes new offering value in the 6G era, and Chapter 5 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 (January 2022). Today, discussions are actively underway regarding telecommunications expected in the 2030s [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.

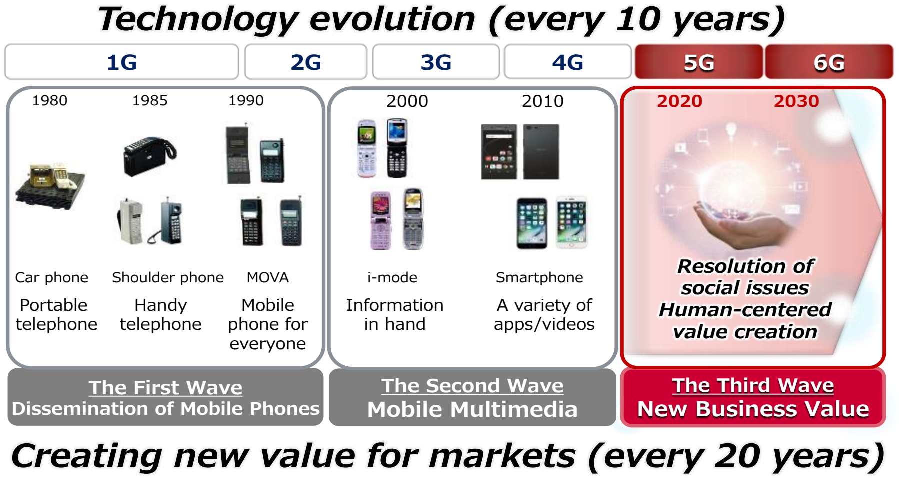


Figure 1-1. Evolution of technologies and services in mobile communications

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

## 2.1. Direction of Evolution to 5G Evolution

### 2.1.1. 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.

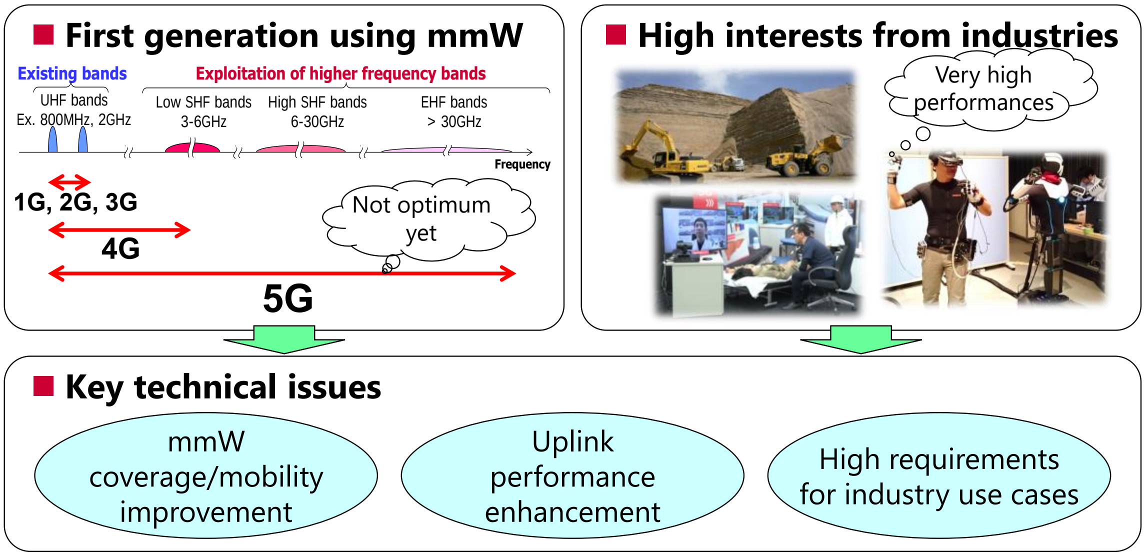


Figure 2-1. Current technical challenges of 5G

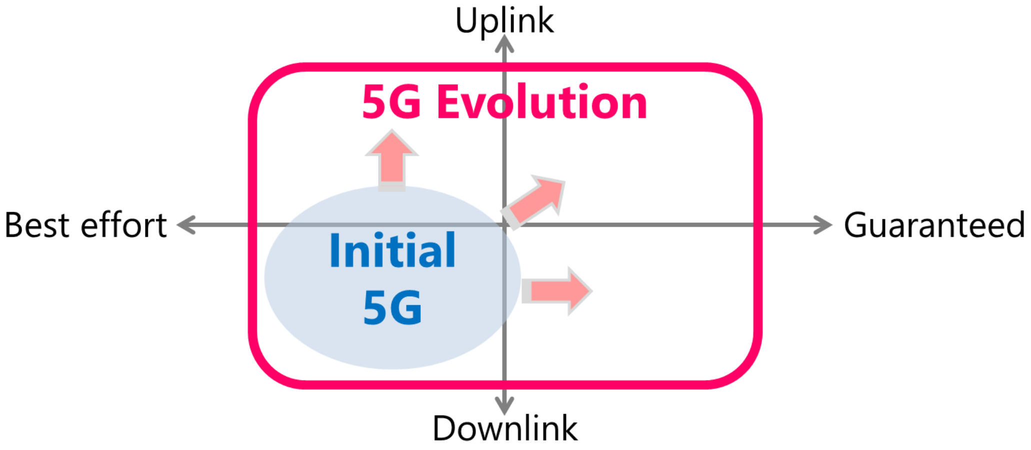


Figure 2-2. Direction of performance improvement to 5G Evolution

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.

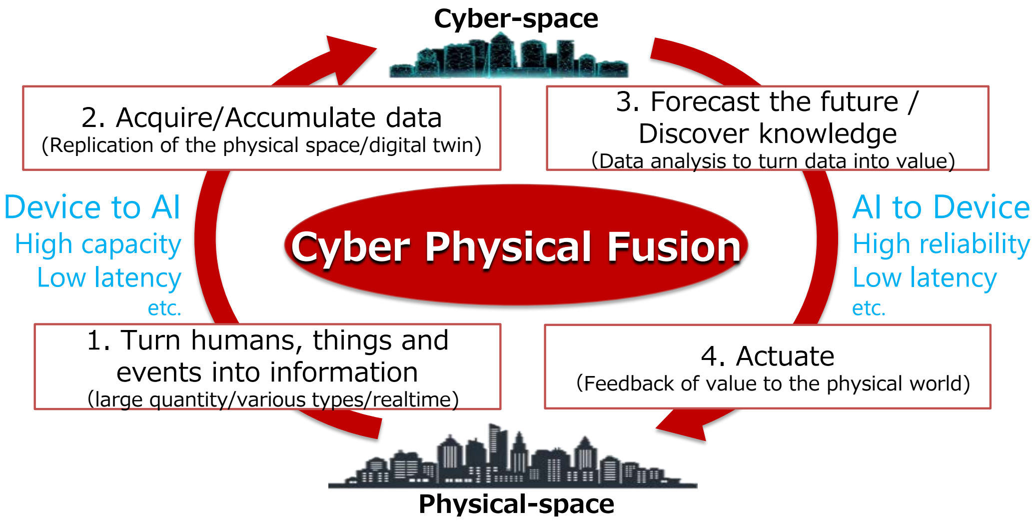


Figure 2-3. Cyber-physical fusion and wireless communications

### 2.1.2. **3GPP Release 17 and Release 18 Standardization Trends**

In 3GPP, following the specification of the first 5G standard in Release (Rel-) 15, the specification of Rel-16 was completed in June 2020 as its development, and discussions for Rel-17 specification have already started (the specification is scheduled to be completed in June 2022). In particular, Rel-17 will continue to evolve by further expanding on the functionality introduced in Rel-15/16 (MIMO, URLLC, network slicing, etc.), as well as meeting market demand by specifying new functionality (Reduced Capability (RedCap), Non-Terrestrial Networks (NTN), extending current NR operation to 71 GHz, etc.) that will explore new areas.

In 3GPP, Rel-18 and later are defined as "5G-Advanced", and discussions for the scope of specification technology started in June 2021 with a view to starting specification work in 2022. In Rel-18, the balanced evolution is aimed at 3 viewpoints of 1) eMBB evolution vs. further vertical domain expansion, 2) immediate vs. longer term commercial needs, 3) device evolution vs. network evolution. As the characteristic evolution for 5G-Advanced, both aspects of the evolution of 5G up to Rel-17, such as the improvement of uplink performance (data rate, capacity, coverage), the enhancement of functions for eXtended Reality (XR), network energy saving, artificial intelligence (AI) and machine learning (ML) for Radio Access Network (RAN), and the extension of functions aiming for 6G such as the evolution of duplex operation, AI/ML for air interface, UE aggregation, passive IoT, are discussed.

Table 2-1. 3GPP Release 18 candidate technologies (as of October 2021)

| **candidate technology** |
|---|
| MIMO Evolution for Downlink and Uplink |
| Uplink enhancements (such as coverage enhancements) |
| Additional Topology Improvements - Smart Repeater |
| Sidelink enhancements |
| RedCap Evolution |
| Expanded and Improved Positioning |
| Evolution of duplex operation |
| AI/ML for Air Interface |
| Network energy savings |
| Mobility Enhancements |
| Enhancements for XR |
| Sidelink Relay Enhancements |
| NTN evolution |
| Evolution for Broadcast/Multicast Services |
| Uncrewed Aerial Vehicle: UAV in NR |
| Multiple SIM Enhancements |
| In-Device Co-existence: IDC Enhancements |
| Additional Topology Improvements - Integrated Access and Backhaul: IAB and Vehicle Mounted Relay: VMR - |
| AI/ML for RAN |
| Self-Organized Networks: SON and Minimization of Drive Tests: MDT Enhancements |
| Quality of Experience: QoE enhancements |
| Inter-gNB coordination |
| UE aggregation |
| High-speed packetization |
| Small Data Transmission |
| Carrier Aggregation: CA and Dual-Connectivity: DC Enhancements |
| Passive IoT |

## 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.” These are discussed in detail in Chapter 4.

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.

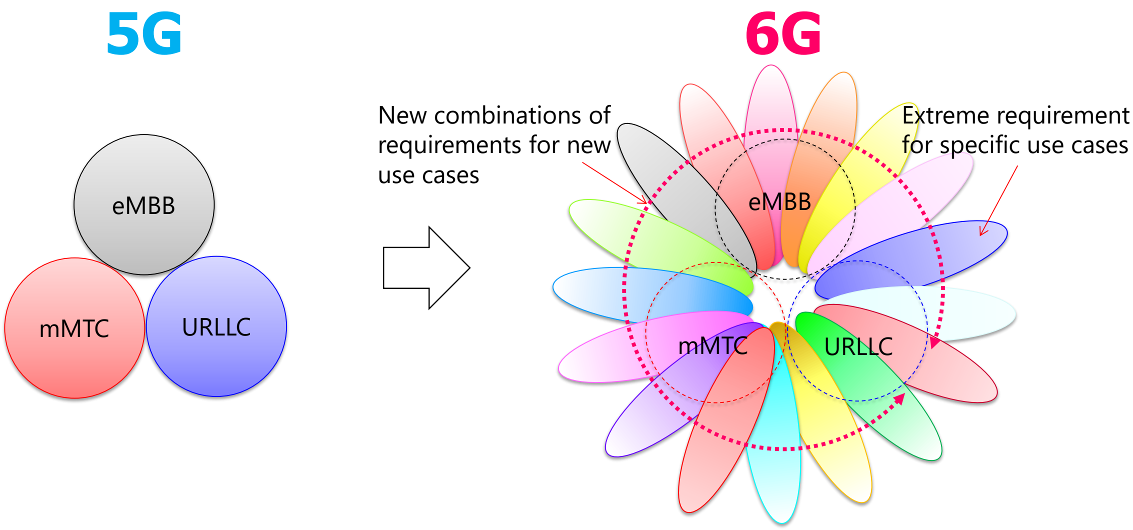


Figure 2-5. Image of wireless network technology evolution toward 6G

## 2.3. **Direction of further evolution through combination with IOWN**

NTT announced the concept of IOWN (Innovative Optical and Wireless Network) in May 2019 as an initiative for a new ICT infrastructure for the 2030's when 6G will be deployed, and has started R&D with the aim of realizing the initiative. IOWN represents an innovative network and information processing infrastructure utilizing optical and other cutting-edge technologies capable of providing extreme-high-speed communication, extreme-low latency, and extreme-low power consumption. With those features, this infrastructure will go beyond the limits of conventional infrastructures to leverage any types of information, provide services remotely for any scenarios and help build a society that embraces diversity [2-16]. IOWN consists of the following three parts: “All-Photonics Network (APN)” that uses photonics-based technologies in all of its components ranging from the network to the device, “Digital Twin Computing (DTC)” that utilizes a integration of the real physical world and digital world to predict the future and implement optimization, and “Cognitive Foundation (CF)” that realizes control optimally matching all manner of ICT resources.

APN is a network designed to provide full-mesh connections between multiple points by offering a dedicated optical path at a given wavelength for each device, user and service [2-17]. It is aimed at becoming a platform to transmit and process information high-capacity/high-quality, low latency, and low-power consumption by making the best use of optical technologies deployed on an end-to-end basis from the network to the device, such as photonics-electronics convergence technology and optical communication technology. In addition, we can make the optical access network highly reliable and responsive by making a shift in access design from a conventional star-shaped configuration to a multi-loop configuration [2-18]. If such optical transmission and access networks are applied to mobile networks or mobile fronthaul systems, there is a possibility that we can achieve end-to-end low latency communication and deploy radio base stations flexibly and quickly. Furthermore, we could utilize environment information collected in an end-to-end manner through a combination of optical fiber environment monitoring technology [2-19] and radio sensing technology. The former technology uses optical fiber sensing to utilize the optical fibers deployed nationwide in non-communication domain.

DTC is a technology that realizes the cyber-physical fusion described earlier. This technology will create a variety of virtual societies where different things and humans interact in a sophisticated manner beyond the constraints of the real world. In a virtual society, the real world will expand and transcend itself in fusion with the virtual world. Using DTC, we aim to expand human activity into the virtual society for amplifying the potential of humans and also create innovative services so far unachievable, such as social design and decision-making support services to tackle complex social issues with large-scale simulation and future prediction capabilities [2-20]. On the other hand, as a platform supporting DTC, R&D is underway on 4D digital platform. This platform is expected to enable data fusion with different industrial platforms and future prediction by integrating sensing data collected from humans, things and events into high-precision spatial information in real time. There is also a possibility that we can use this platform in combination with various types of IoT data to upgrade wireless communication control through simulation and future prediction capabilities brought by DTC in a virtual society.

CF provides service functions to optimize overall resource allocation including computing and IoT as well as wire and wireless communication. CF will create an information processing platform which enables system- and data-type-agnostic analysis and prediction by means of end-to-end distribution of virtualized ICT resources and interaction with various systems and networks [2-16].

IOWN will address societal challenges and further contribute to the same world envisioned for the 6G era. The IOWN vision encompasses technologies and architecture which will enable a wide range of new use cases and their underlying requirements, and be highly synergistic with 6G. 5G Evolution and 6G mobile networks technologies can be combined with IOWN's ultra-high capacity, ultra-low latency and ultra-low power technologies based on breakthrough photonics, to further enhance the next generation ICT infrastructure, and respond to the pressing needs of society.

# 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.

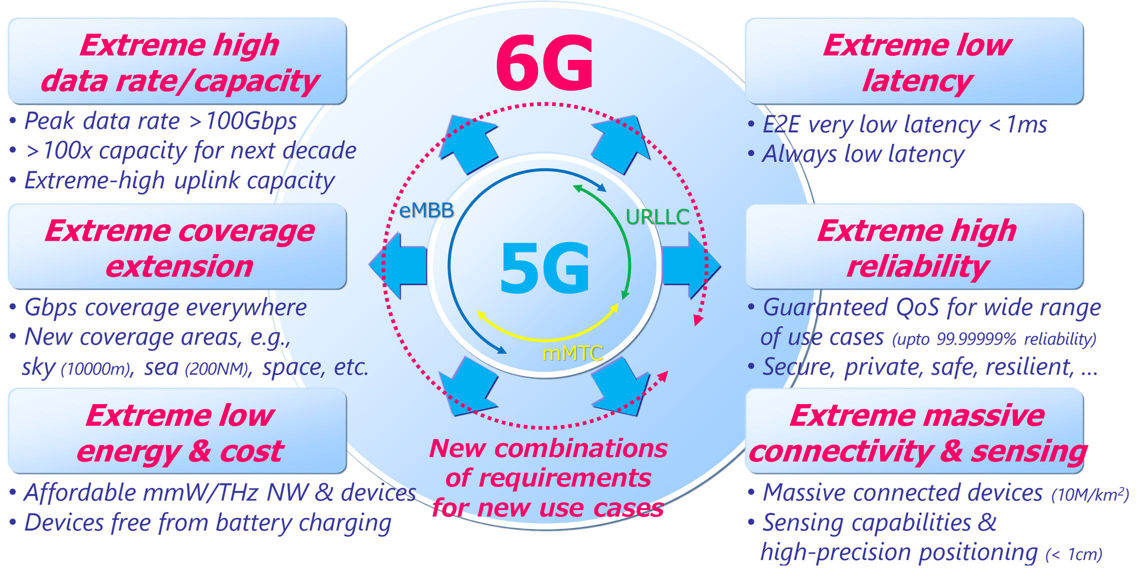


Figure 3-1. Requirements for 6G wireless technology

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

Increasing data rate and system capacity are universal requirements for all generations of mobile communication system. In the case of 6G, realization of extremely high communication speed and high capacity communication which can be enjoyed by many users simultaneously is considered, and concretely, realization of communication speed over 100 Gbps and capacity over 100 times is aimed at. As the communication speed approaches the level of information processing speed of human brain, not only mere image transmission (visual sense and auditory sense) but also information transmission of sensory quality by five real senses, and furthermore, expansion such as multisensory communication is also considered. In order to materialize such extreme-high-speed and high-capacity communication service, it is necessary that the user interface also exceeds smartphone. For example, the realization of a device which can reproduce 3D hologram and the evolution of a wearable terminal such as glasses type terminal are expected.. In addition, such new sensory service is shared even among multiple users in real time by the ultra-high capacity communication, and the realization of new synchronized application such as virtual coexperience and virtual cooperative work, etc. on the cyberspace is also expected.

And, considering trends such as use cases for industry and cyber-physical fusion, it is necessary to transmit various real world real time information to cloud and AI which are brains on the network, and drastic speedup and capacity enlargement in the uplink will become quite important.

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

## 3.2. Extreme coverage extension

Because future communications can be as commonplace as air, and as important a lifeline as power and water, or even more so, in the case of 6G, we aim to extremely extend coverage so that mobile services are available everywhere. The target area coverage ratio on land is 100%, and the coverage expansion is also aimed at all places including the sky, the sea, and the space which the conventional mobile communication system does not cover, in participation of construction of the communication area in the other environment and development of the space business. This is expected to widen the activity domains of humans and things and create new industries. For example, promising use cases include logistics services such as home delivery using drones, and unmanned or highly sophisticated operations in primary industries such as agriculture, forestry, and fisheries. Application to futuristic use cases in the 2030s is also likely, such as in the future flying cars, space travels, and undersea travel.

Figure 3-3. Extreme coverage extension

## 3.3. **Extreme-low power consumption and cost reduction**

Extreme low power consumption and cost reduction of mobile communication system network and terminal devices are important challenge for achieving a worldwide goal of the sustainable society making consideration of global environmental problem.

In the network, it is assumed that the communication quantity will increase in future more and more, we aim the power consumption and cost drastic reduction required per communication speed unit (bit). For example, when the communication traffic quantity increases by 100 times, it is necessary to reduce the cost per bit for CAPEX/OPEX to 1/100 or less to achieve both high performance and economic efficiency.

In addition, in the future, the development of the power supply technology using the signal of the radio and the reduction technology of the power consumption of the device can be expected that the charging of the terminal becomes unnecessary. This is considered to be more necessary when the number of terminals such as sensors increases by upgrading of cyber-physical fusion, and when the user interface evolves to wearable use cases are assumed.

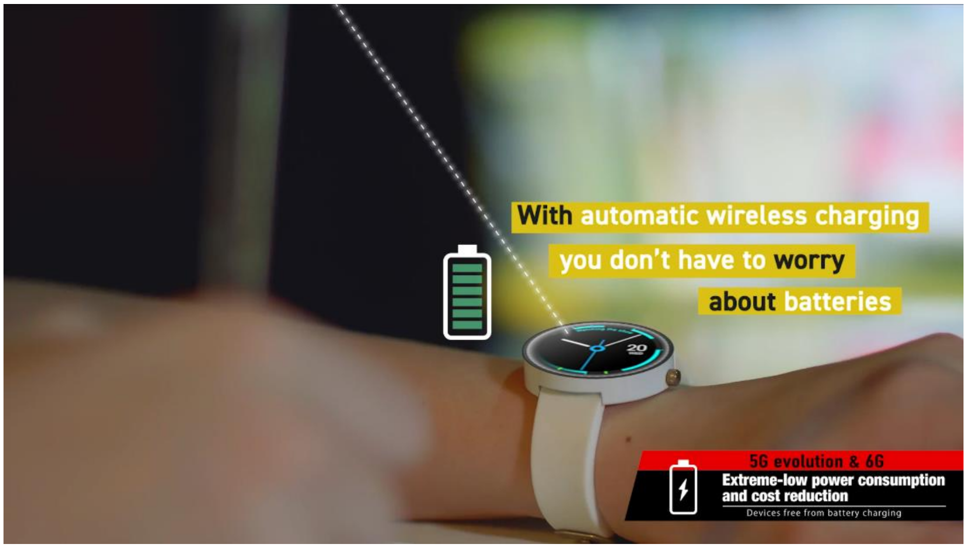


Figure 3-4. Extreme-low power consumption and cost reduction

## 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, end-to-end low latency will be a fundamental requirement. The goal is to achieve extreme-low latency of 1 ms or less at end-to-end. As a result, it is possible to realize the service without the 'sense of incongruity' by the low delay feedback from the cyberspace, and the correspondence in which equipment and robot controlled remotely by AI can read the nimble action and subtleties which are close to or exceed the human is also expected. For example, we can instantaneously judge what the user wants from information such as tone of voice and facial expression, and respond services that are as attentive as or more attentive than humans may be realized by remote control of robots by AI. Especially, in the world of after COVID-19, applications in various fields such as telework, remote control, telemedicine, and remote education by such ultra-low delay communication are expected.

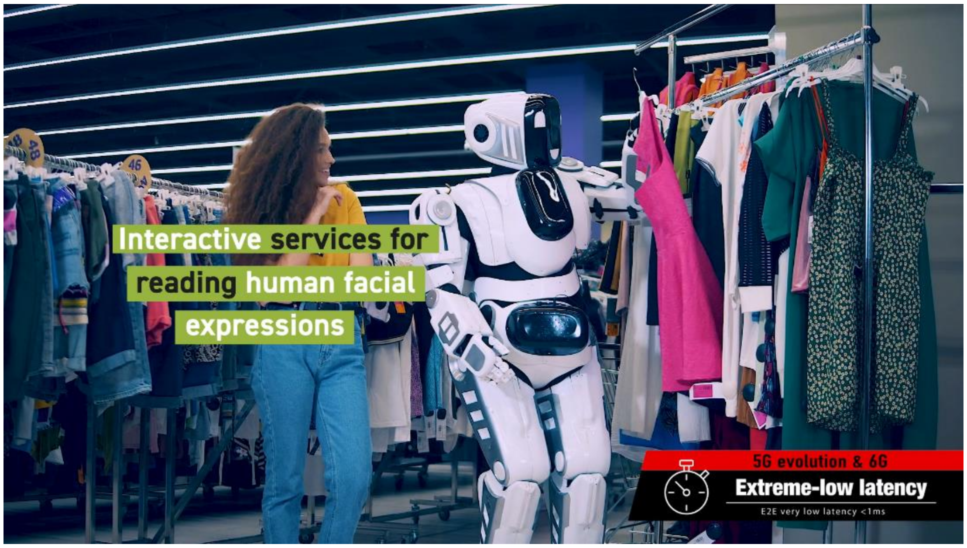


Figure 3-5. Extreme-low latency

## 3.5. **Extreme-reliable communication**

When wireless communication is used for industrial and lifeline applications, its reliability is an important requirement. Among the use cases for especially industries, there are cases in which quality and availability of communication greatly affect safety and productivity such as remote control of industrial equipment and factory automation. Therefore, necessary performance and realization of the ultra-high reliability communication in order to secure the safety are important requirements, and 6G is expected to realize higher level of reliability than 5G. In ultra-high reliability low delay communication (URLLC) in 5G, the realization to 99.9999% is examined as a reliability, and in 6G, the improvement of one digit (99.99999%) is assumed as a target value. And, the network which specialized for the industry unlike the best effort type service of the public network like "local 5G" is noticed at present, and the URLLC technology in the limited area such as the factory is mainly examined. On the other hand, in the future, with wide popularization of robots and drones and expansion of radio coverage to air, sea and space, etc., realization of wider area highly reliable communication will be required. In addition, you need to have a more holistic, end-to-end view, including application reliability information.

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.

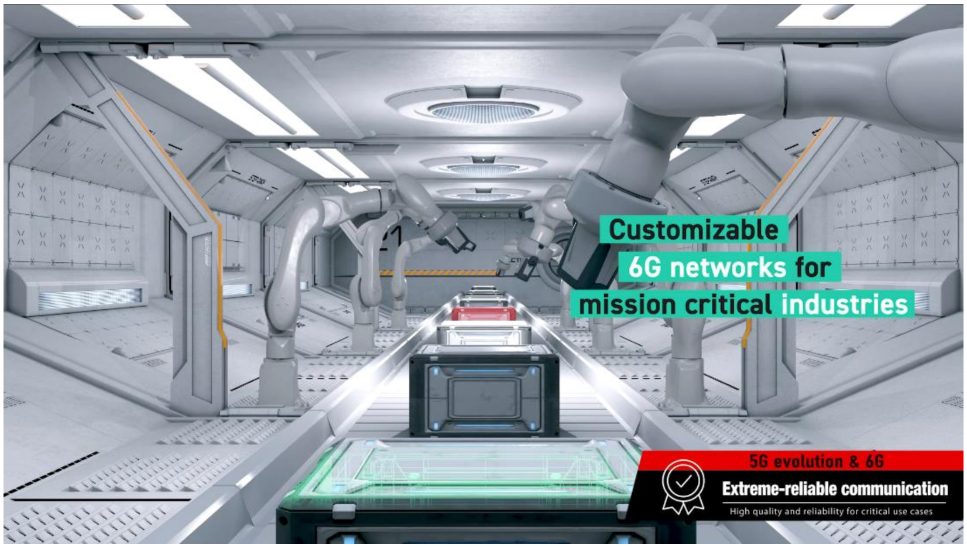


Figure 3-6. Extreme-reliable communication

## 3.6. **Extreme-massive connectivity & sensing**

It is assumed that a ultra-large number of devices related to communication of people and things will spread by upgrading of cyber-physical fusion, and ultimate multiple connection which is 10 times more (= 10 million devices per square km) than the requirement of 5G is considered to become a requirement of 6G. For the human, the use case in which the cyberspace supports the thought and action of the human in real-time by wearable device and micro device that is mounted on the human body is considered. And, the realization of the world in which all things such as transportation equipment including the car, construction equipment, machine tool, monitoring camera, various sensors are linked with the cyberspace, and industry, traffic, solution of the social problem and human safety and security and rich life are supported is expected.

In addition, wireless communication networks themselves are also anticipated to be equipped with functions for sensing the real world using radio waves, such as positioning of terminals and detection of terminal. Regarding positioning, which is expected to provide extreme high precision with errors of one centimeter or less depending on the environment. As for wireless sensing, it is expected to realize the capabilities to identify objects and recognize actions as well as highly precise object detection through the combined use of radio wave and AI technologies.

Figure 3-7. Extreme-massive connectivity & sensing

# 4. **New Value Provision in the 6G Era**

## 4.1. **Generations of mobile communication systems and changes in the values provided**

## **- From Smart to Well-being -**

"Well-being" is a concept that has become widely used in different fields. The Constitution of the World Health Organization (WHO) says: "Health is a state of complete physical, mental and social Well-being and not merely the absence of disease or infirmity [4-1]." This means that if we hope to achieve health, we need to consider physical, mental, social and environmental factors that could affect individuals and groups of individuals. Another reason why this Well-being concept has become a focus of attention is that it is incorporated into one of the SDGs (Sustainable Development Goals), which states: "Ensure healthy lives and promote Well-being for all at all ages (GOAL3) [4-2]." The term well-being seems to have taken on new meaning reflecting people's modern-day view of good health and happiness. Although happiness is perceived differently from person to person, indicators of happiness have arguably shifted from quantitative indexes driven by economic development to more qualitative and emotional measures such as "diversity" and "Well-being." In concert with the shift in the meaning of happiness, people's perception of "richness" is undergoing change. In the 1980's and 90's, a period filled with economic prosperity, economic richness was a source of happiness. In the 2000's, however, the economic growth levelled off and became stagnant in the wake of the Lehman Shock. From this period, people began to feel the need to secure their happiness in the things near at hand and find joy in social and environmental richness. Moving into the future, the 2020's and 30's will be totally different from the past, and will be referred to as the "VUCA Era" (Volatile, Uncertain, Complex and Ambiguous) where changes in people's environments will be volatile and unpredictable. People born in the VUCA Era will be surrounded by digital devices since birth, be exposed to large quantities of information, and have choice of communities they want to be part of. Growing in such an environment, they will naturally place great importance on diversity and empathy. They will not feel happiness even when they are happy unless people around them are also happy. They are expected to find happiness in the richness of emotions and ideas. Such value changes associated with happiness will undoubtedly affect how communication services ought to be provided in the future, and will need to be addressed in future services.

The important question becomes, how communication services should evolve to address these changes. As described in Chapter 1, the previous generations of mobile communication services have evolved across three major waves. The first wave came in the 1980's and 1990's when mobile phones became widely available (1G to 2G), and the services were centered on voice communications. The second wave came with mobile multimedia (3G to 4G) in the 2000's and 2010's. From this period, music distribution, video, games, payment, and the use of blockchain became commonplace, as well as services that are rooted in everyday life. The 5G and 6G generations that will follow in 2020 and beyond are the third wave. 5G will bring high-speed/high-capacity communication, enabling wider deployment of communication technologies. Services will be expanded to include XR, remote medicine, remote control and autonomous driving in addition to smartphones and smart tablets. In the 2030's onwards, 6G will become a reality, accelerating the speed of the third wave and fulfilling the promise of human augmentation, BrainTech and transmission of emotions. This will trigger a major paradigm shift in the value-add provided by communication services. In addition to making "smart" functional improvements and providing convenience, ensuring Well-being is expected to become one of the major values to be provided.

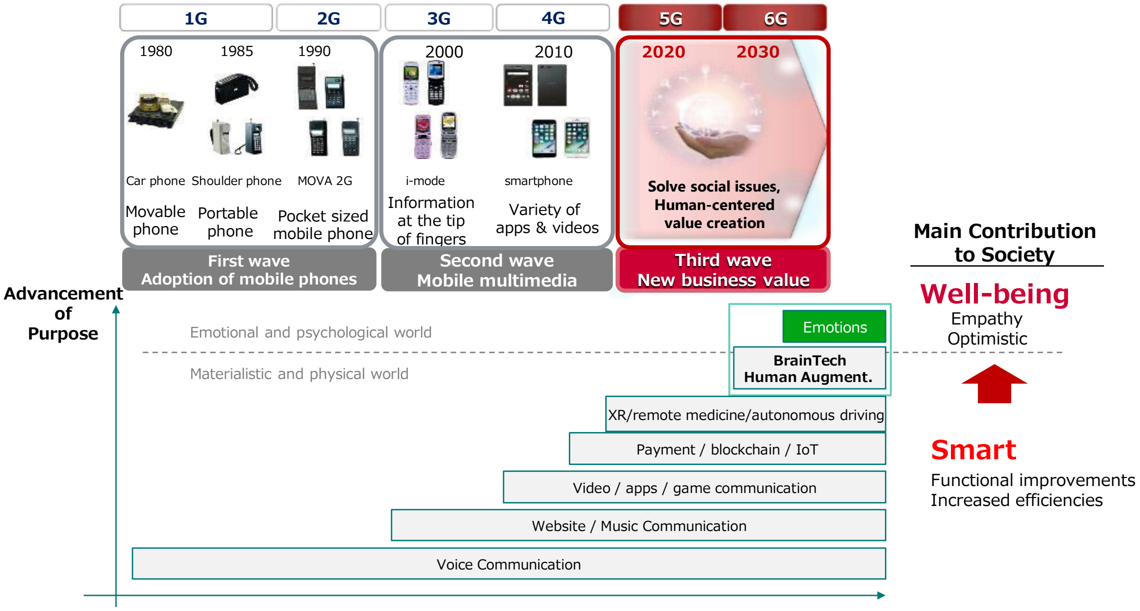


Figure 4-1. Generations of mobile communication systems and changes in the values provided

## 4.2. **Technologies worthy of attention in the 6G Era**

In considering how to achieve the aforementioned Well-being, the following sections will discuss important new technologies that extend beyond the capabilities of video and audio technologies of today.

### 4.2.1. **Human augmentation**

Human augmentation can be divided into four domains: “augmentation of the physical capabilities,” “augmentation of the presence,” “augmentation of the perception” and “augmentation of the cognitive capabilities.”

The augmentation of the physical capabilities is an approach to sensing the human body’s information mainly from the brain and muscles such as brain waves and myoelectric activity for actuating the actual muscles and exoskeleton. The aim is to aid people with certain physical disabilities by complementing lost or weakened physical functions, enhance existing abilities or even provide people with new abilities. Technologies in this area include power assist suits, artificial limbs and third arms (robotic arms).

The augmentation of the presence realizes remote (cooperative) activity, such as tele-presence and tele-existence, by eliminating the limits associated with physical presence. Some examples in this field are remote surgery robots, digital avatars and experience sharing.

The augmentation of the perception means sharing and amplifying the five senses. Technologies for visual and auditory sensory perception have achieved a certain level of maturity, while haptics technologies for tactile sensory perception are emerging with various interface techniques. For gustatory and olfactory sensory processing, studies are still at a nascent stage with research on receptors making progress. Technologies in this field include XR glasses, artificial eyeballs and artificial retina and cochlea.

Lastly, research on augmenting a person's cognitive capabilities is focused on expanding the process of understanding or learning itself, or improving the ability to acquire new motor skills in, for example, sports by artificially providing athletes an out-of-body perspective. Technologies in this area include brain information monitoring for learning and training, and memory chips.

### 4.2.2. **Brain Technologies**

BrainTech aims to complement and enhance human capabilities or acquire new abilities by sensing biological signals from the human brain, extracting relevant signals and triggering the intended physical actuation. To achieve a viable service, not only will it be important to create smaller and more accurate devices, the development of robust AI to process biological signals will be crucial. Today there are many BrainTech applications in the medical field, including the systems to control external devices only with biological signals [4-3] and to drive “smart artificial arms” [4-4] and other external skeleton-type devices and “silent speech systems” [4-5] that provide speech support for users who are unable to speak or have difficulty in speaking due to illness. It is considered important for this field to focus more on development through industry-academia collaboration.

### 4.2.3. **Perception sharing**

For sharing perception through digital devices, technologies have been developed mainly for visual and auditory information, and some of them have been already utilized. Technologies for other sensory information (gustatory, olfactory and tactile) are still emerging. On the other hand, R&D on virtual reality or value creation based on digital synesthesia is in progress at research organizations in different countries by utilizing combinations of such different types of perceptual information. One example is an “artificial skin” that can present virtual tactile information. In fact, researchers have already succeeded in transmitting tactile sensory information in real time by skillfully controlling the amplitude and frequency of transmitted signals, producing the sensation of actual human touch [4-6]. By applying these research results, it will be possible to allow people far away from each other to send and receive tactile signals alongside voice and images so that they can feel the touch of others. Such communication has the potential to enrich interpersonal communications and foster tighter bonds between people.

As for gustatory information, different research projects are in progress to quantify and evaluate smell and taste sensory information [4-7].

### 4.2.4. **Multilayered sensory information**

In the world under the COVID-19 crisis, social distancing has disrupted normal face to face communication among people. In this context, digital communication technology is becoming more important as a means to make up for the loss of communication between people. In business, for example, “online meetings” are held often and expected to be further utilized in business settings. Because the communication technology in this field has focused on visual and auditory information, the conveyed virtual reality is still missing a realistic sense of presence or atmosphere.

If newer types of sensory information become available for transmission, it will be possible to achieve digital communication which also conveys a realistic sense of presence or atmosphere. Furthermore, it is expected to create a “sixth sense” conventionally unachievable by placing different layers of information on such digital communication.

From the standpoint of achieving Well-being, it will be essential to develop technologies for achieving such sophisticated communication with realistic senses of presence and atmosphere and creating a sixth sense through multi-layered information in a virtual reality environment.

## 4.3. **Realization of Well-being using the 6G network**

As described in Chapter 3, 6G has six requirements: 1) extreme-high-speed and high-capacity communications, 2) extreme coverage extension, 3) extreme-low-power consumption and cost reduction, 4) extreme-low latency, 5) extreme-reliable communication and 6) extreme-massive connectivity and sensing. Although all of these requirements demand innovative technologies, the most significant technology for realizing Well-being is extreme-low latency. If a latency of less than 1 msec is achieved, it will be shorter than the response time of the human nervous system, which is approximately 20 msec, the time for any information conceived in the brain to be reflected in the body [4-8]. Namely, the network will be able to respond faster than the human nervous system. Given these figures, it will be possible to extend human senses in the network by connecting the information of the brain and body with the network.

When used in combination with extreme-massive connectivity and sensing, information on the five senses available across the globe will be sensed in real time, leading to realization of the ubiquitous body.

Furthermore, with extreme-reliable communication and extreme coverage extension, it will be possible to further enhance continuous connectivity to the internet and interworking with cloud technology with a high degree of accuracy. This technology can enable the archival and sharing of the human body's information and actions from the past, which in turn allows the prediction of future bodily states and even necessary actions. The aim of providing these technologies as services is to connect people across time and physical space as shown in Fig. 4-2. By reducing the perceived distance between people, whether the distance is physical space or time, it is hoped that these future services will help customers achieve Well-being.

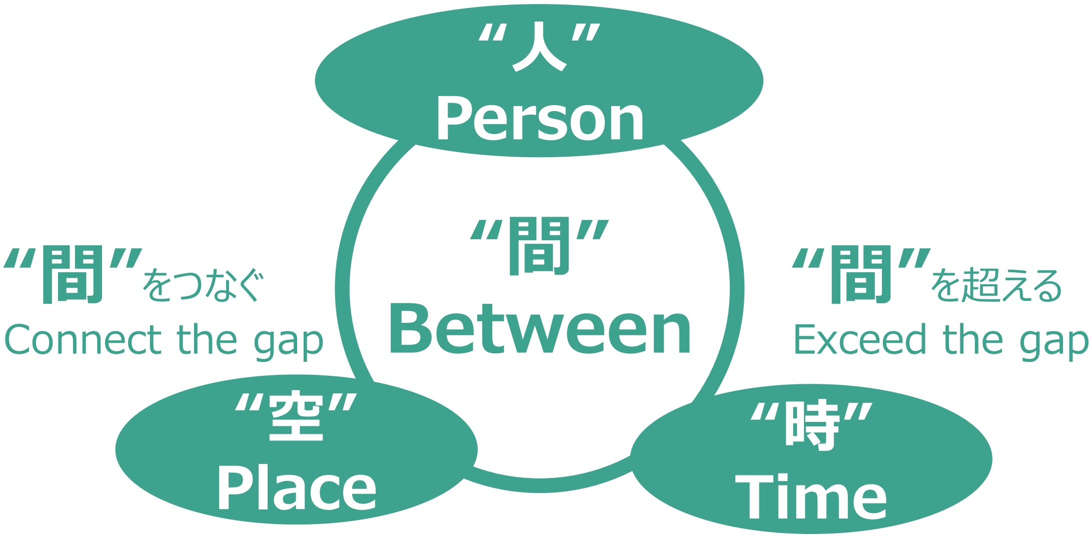


Figure 4-2. Directions for Well-being realization

The potential of sharing the body and skills via the network is summarized in Fig. 4-3. This conceptual network could enable people to share their skills and experiences easily by transcending the limits of language based communication, perform telekinetic actions remotely, and even share thoughts and emotions telepathically - an ultimate form of communication.

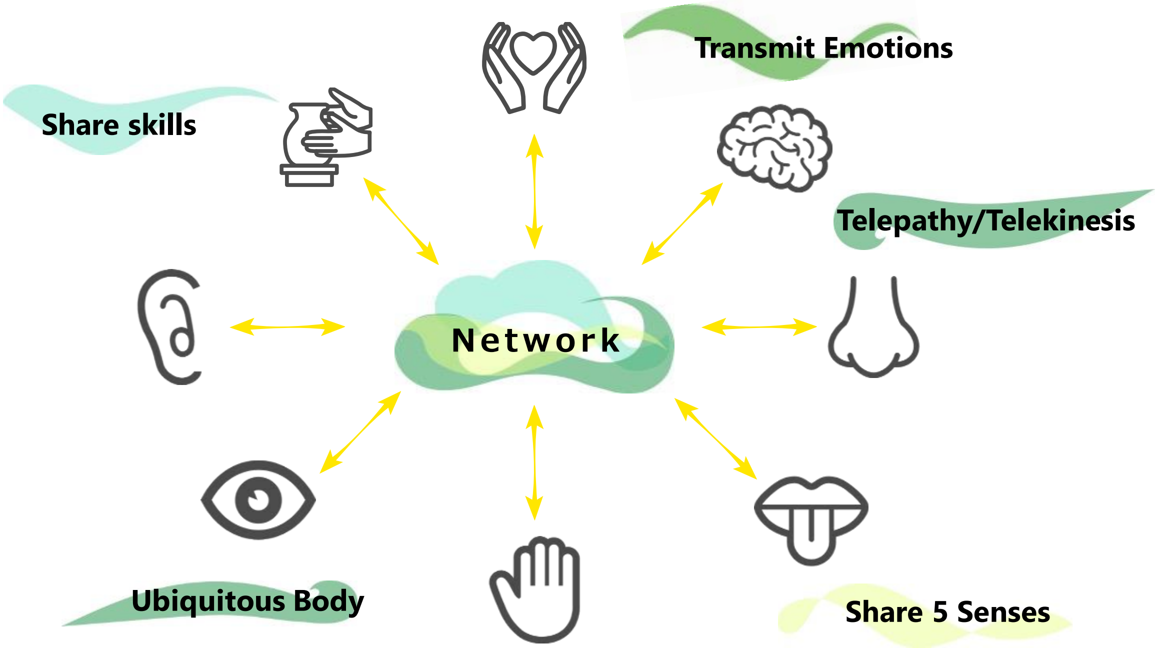


Figure 4-3. Potential of sharing the body and skills

## 4.4. Potential Use Cases in the 6G Era

### 4.4.1. Examples use cases

If we can combine the technologies such as human augmentation, BrainTech, perception sharing and multilayered sensory information described in 4.2 with the 6G network, it will be possible to provide a variety of use cases through bidirectional interaction of these technologies. Even today, there are numerous technologies available to implement those use cases, and they are expected to further develop in the 2030's. We will work together with partners who possess such technologies to realize "6G network X Technology" and shorten the perceptional distance between people, space and time to further enrich the lives of customers.

As an example using human augmentation technology, we can refer to a use case that aims to eliminate the border between the real and virtual worlds (Fig. 4-4). In this scenario, it will be possible to obtain sensation for each part of the body from a different environment or transmit our own senses via the network. Namely, without moving, we will be able to collect different information from a remote place for each of our limbs and touch things or feel things. In addition, we will be able to not only multitask activities while sitting in one place but also attend meetings from a remote location, performing functions in multiple places at one time via the network.

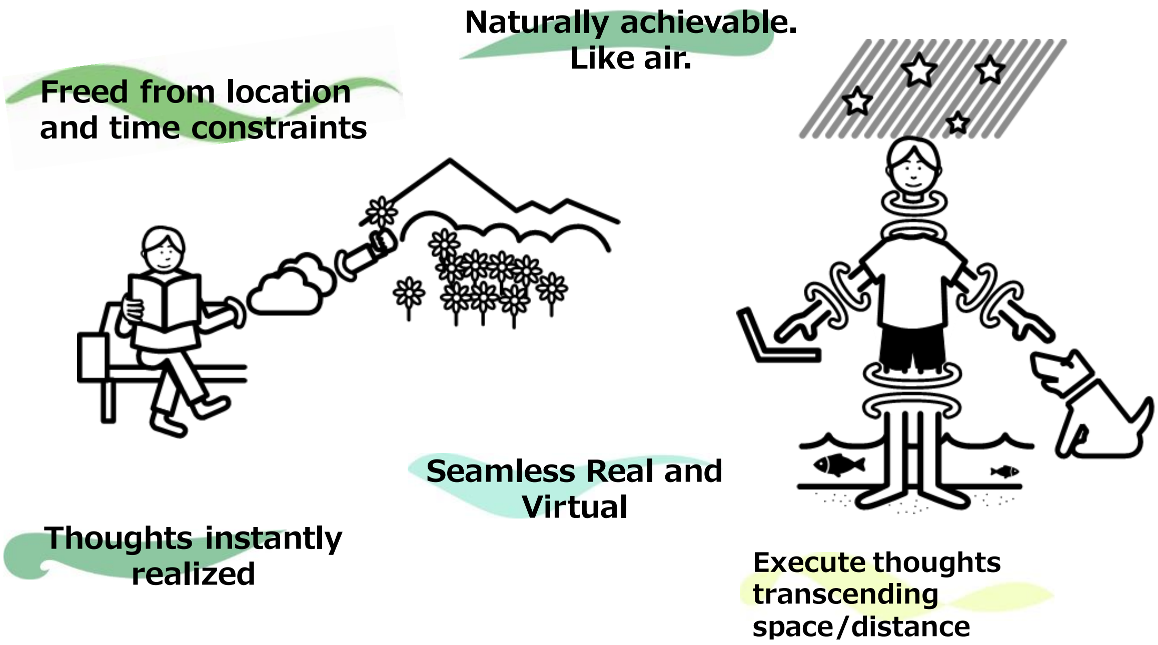


Figure 4-4. Example Use Cases

### 4.4.2. **System configuration**

Fig. 4-5 shows a system configuration in the 6G era that will realize the use cases listed in 4.4.1. It is important to achieve and maintain reciprocal interaction of sensing technology, which interacts with our body transparently whether in the real or virtual world, and actuation technology, which acts on our daily lives. To fulfill the roles mentioned above, the system consists of a cloud system, in addition to sophisticated communication technology, in order to sort out vast amounts of data collected through sensing, compare/converge the data in a manner suitable for each target of actuation and reproduce them.

With the use of this system, we will create new values such as experience, skills and entertainment for customers and enhance the values to be provided not only as a communication infrastructure but also as a network platform.

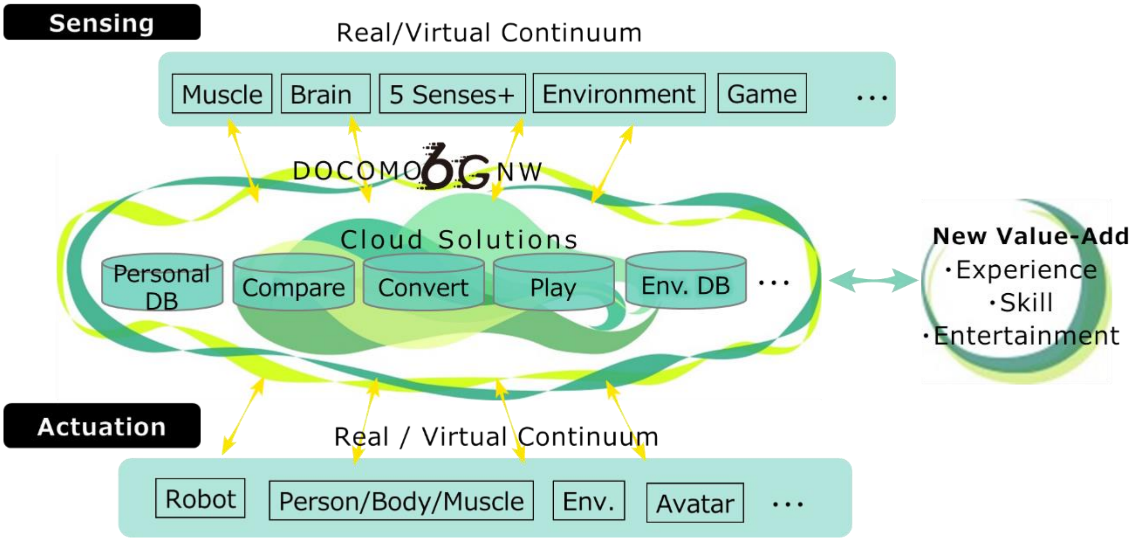


Figure 4-5. System configuration in the 6G era

# 5. **Technological development and research areas**

Fig. 5-1 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 Chapter 3.

In 6G, therefore, more combinations of the radio access technologies will be required after going through 5G Evolution, and the framework of combination will be further expanded by combination with IOWN and integration with technology other than mobile communication, and it is considered that the above-mentioned requirements and use cases, new offer value in the 6G era will be realized. 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.

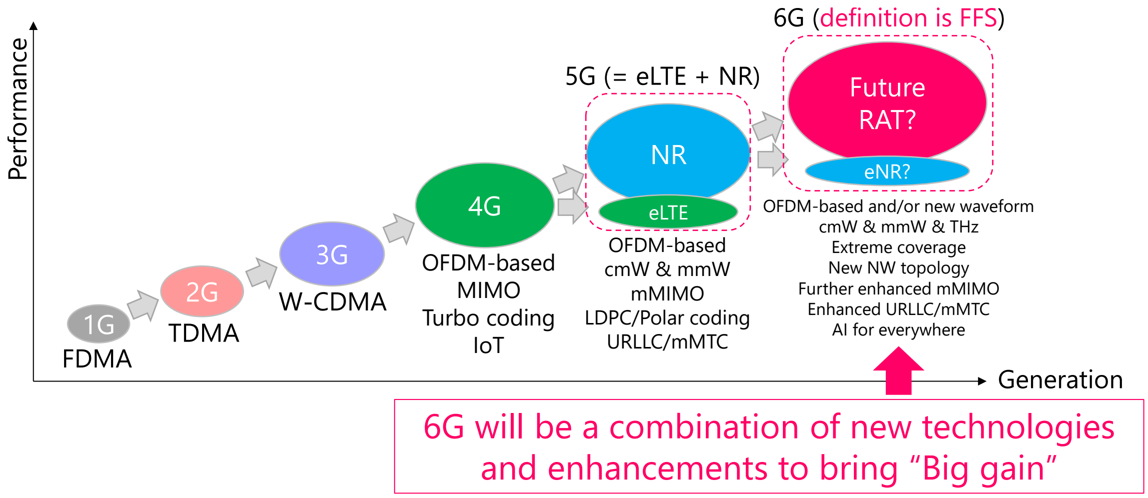


Figure 5-1. Technological evolution up to 6G in mobile communications

## 5.1. **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. 5-2, 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 [5-1], 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. 5-3, 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) [5-2] 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.

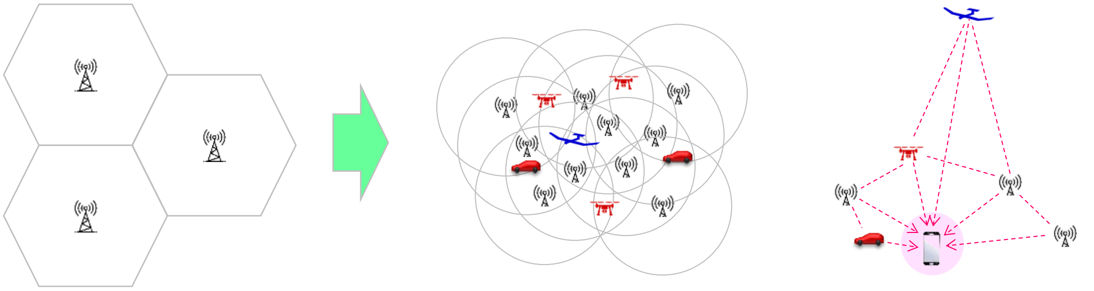

"Coordinated" "Overlapping/moving" "Multiple connection paths"

Figure 5-2. Evolution to New Radio Network Topology

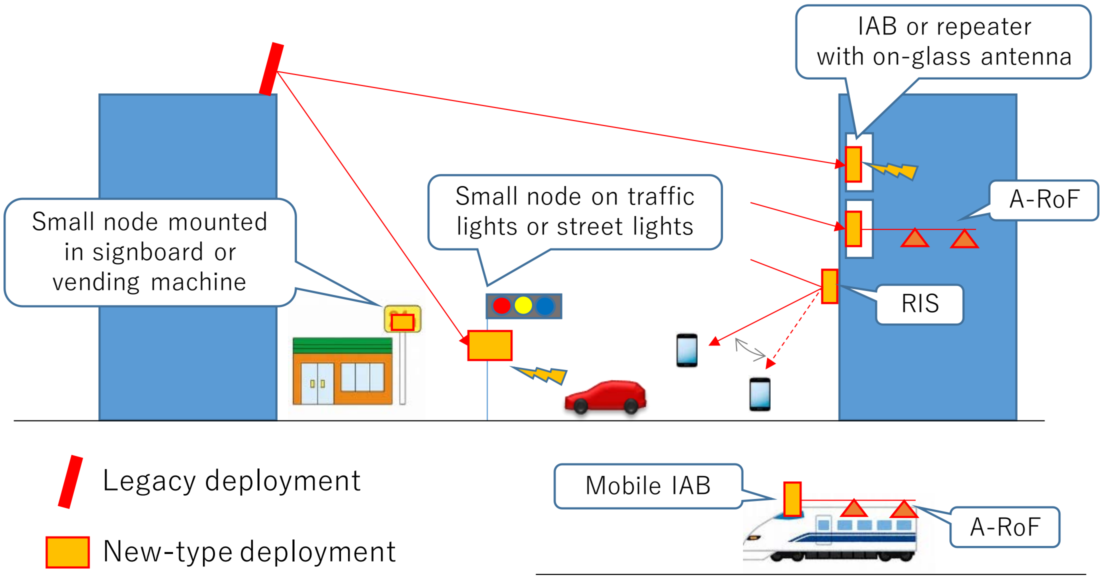
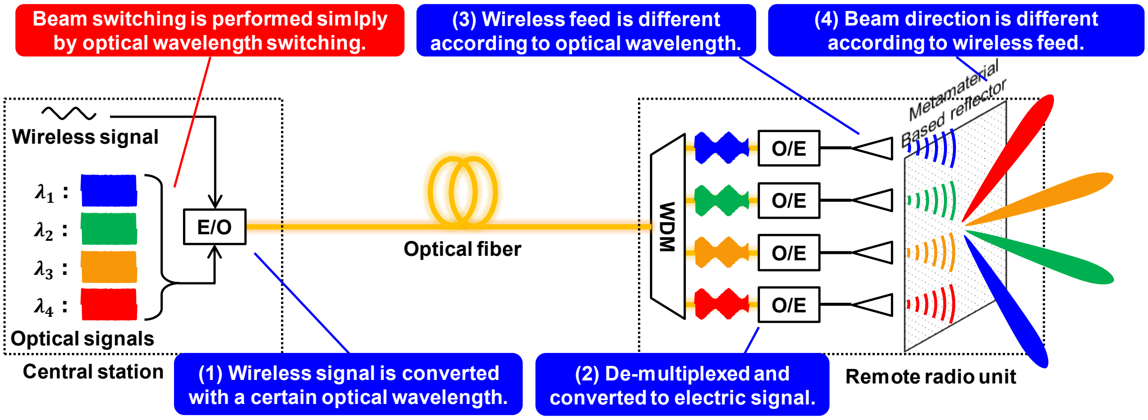


Figure 5-3. Example solution of New Radio Network Topology

### 5.1.1. **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" [5-3]. One of such implementation methods is A-RoF (Analogue-Radio over Fiber), which transmits analog radio signals to antenna systems over an optical fiber [5-4, 5-5]. 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 Analog to Digital Converter (ADC) nor Digital to Analog Converter (DAC) 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. 5-4 has also been studied [5-5]. 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 dielectric waveguide (cable) pinched with a small piece of plastic [5-6].


Beam switching is performed simlply by optical wavelength switching.

(3) Wireless feed is different according to optical wavelength.

(4) Beam direction is different according to wireless feed.

(1) Wireless signal is converted with a certain optical wavelength.

(2) De-multiplexed and converted to electric signal.

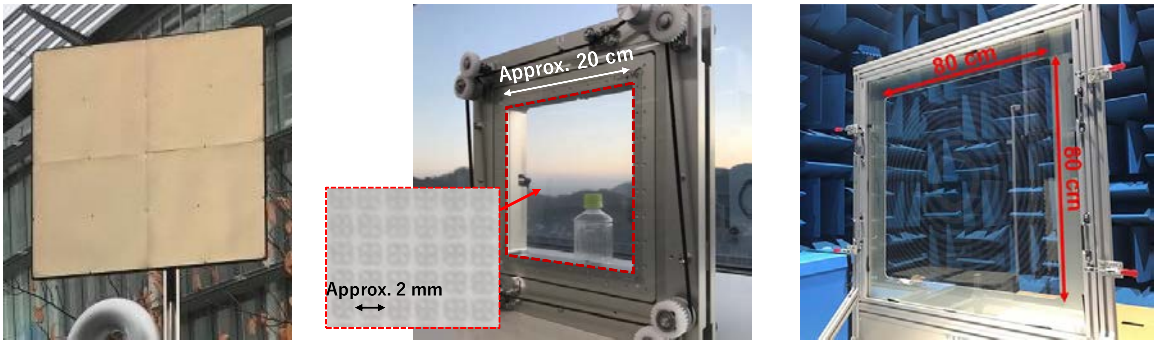
Figure 5-4. Technology using A-RoF to control beams of remote antenna systems

### 5.1.2. **Radio propagation path control by RIS**

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 passing through the RIS [5-7, 5-8].

DOCOMO is conducting R&D on a technology to use a transparent glass as an antenna [5-9, 5-10] in combination with the RIS technology. In an experiment using the metamaterial reflector shown in Fig. 5-5 (a), we verified a technology to reflect millimeter radio waves in arbitrary directions and expand the communication area [5-11]. In an experiment using the transparent dynamic metasurface shown in Fig. 5-5 (b), we successfully demonstrated a technology to allow millimeter radio waves to reflect on and pass through the transparent glass substrate [5-12]. Furthermore, in an experiment using the metasurface lens shown in Fig. 5-5 (c), we verified a technology to direct millimeter radio signals arriving from outdoors to specific points indoors by using a window glass equipped with this technology [5-13, 5-14]. We are also demonstrating the usefulness of building an actual indoor area in combination with area improvement techniques such as relay devices.

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. We are also conducting the verification of the actual area expansion effect in the 28 GHz repeater system, and the clarification of the effective area expansion technique.



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

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

### 5.1.3. 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 [5-15]. 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).

### 5.1.4. 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 [5-16]. In recent years, energy saving communication technology has also attracted interest, such as backscatter communication for realizing battery-less terminals [5-17]. 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. 5-6. 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.

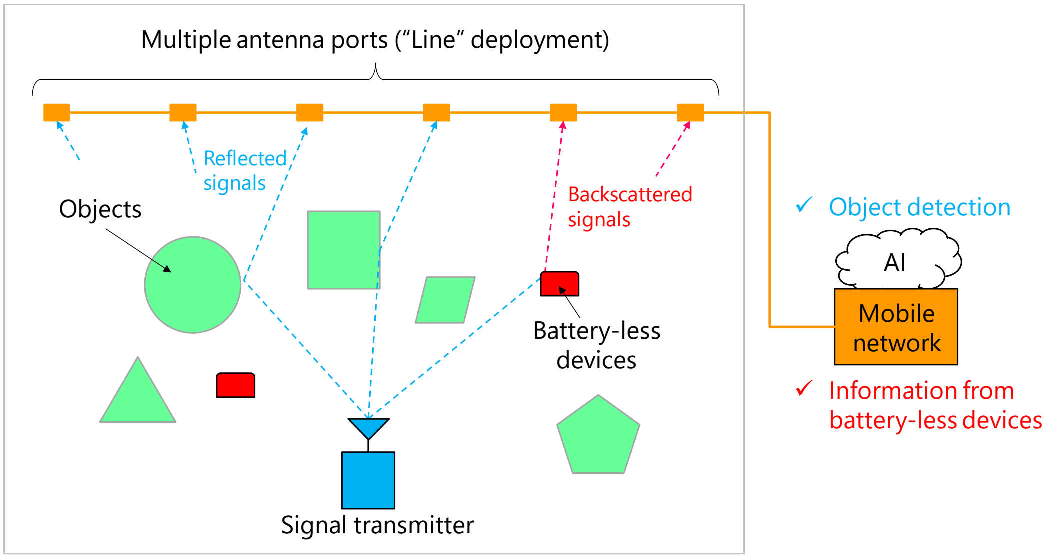


Figure 5-6. Example of network configuration assuming sensing and backscatter communication

## 5.2. 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 an 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, communication in air, sea, and space will require a technology that enables long-distance radio transmission at least over a distance of dozen kilometers in a highly efficient manner.

Until now, communications and technological studies using geostationary orbit satellite (GEO), low-earth orbit satellites (LEO) and high-altitude platform station (HAPS) have been advanced not only on land but also in the air and sea. By enhancing the functionality of these communication technologies and cooperating with terrestrial 5G networks, we can expand the coverage of cellular networks to all areas including the air, sea, and space as shown in Fig. 5-7, aiming at a world providing advanced wireless communication technologies [5-18]. 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 [5-19]. 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 [5-20].

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 [5-21]. 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. 5-8, 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.

3GPP has started its study on the extension of NR to non-terrestrial network (NTN) using these satellites and HAPS [5-22]. As shown in Fig. 5-9, the multi-layered NTN system, in which satellites and HAPS are connected to the terrestrial 5G (or future 6G) core network, is a larger scale and three-dimensional heterogeneity network than before. It is expected that the ground network, satellite, and HAPS cooperate and provide seamless communication according to the place (including air, sea, and space) to offer the service and the required communication speed and delay. And, 2 systems of the relay system which accesses the mobile terminal from satellite and HAPS through the relay station and direct access (DA) system which accesses directly from satellite and HAPS are examined for the access system to the mobile terminal in NTN, and the mobile terminal can be accessed by various methods according to the optimization of use case and whole network.

For the realization of NTN, the following are problems: Expansion of radio interface suitable for long-distance communication, efficient frequency effective utilization method with the ground network, and network design to realize high efficiency cooperation with the ground network. In addition, there is room for investigation in wireless technologies such as handover, carrier aggregation (CA), and dual connectivity (DC) between NTN and terrestrial networks. On the other hand, since each NTN platform has different features such as capacity and propagation delay, it is necessary to consider routing and network construction considering the features of each platform. NTN is also promising as a means to cost-effectively advance the future expansion of coverage of 5G networks already introduced, and it is possible to consider the optimization of network development from the beginning in the 6G era. Maybe 6G starts from the sky.

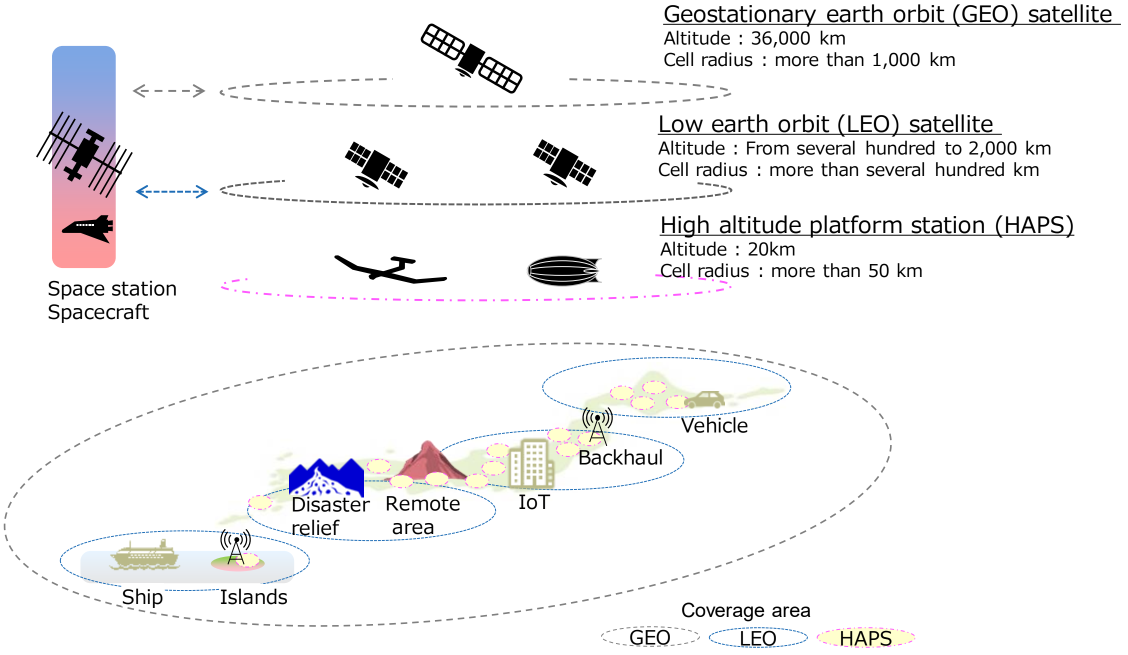


Figure 5-7. Coverage extension to the sky, sea and space using satellites and HAPS

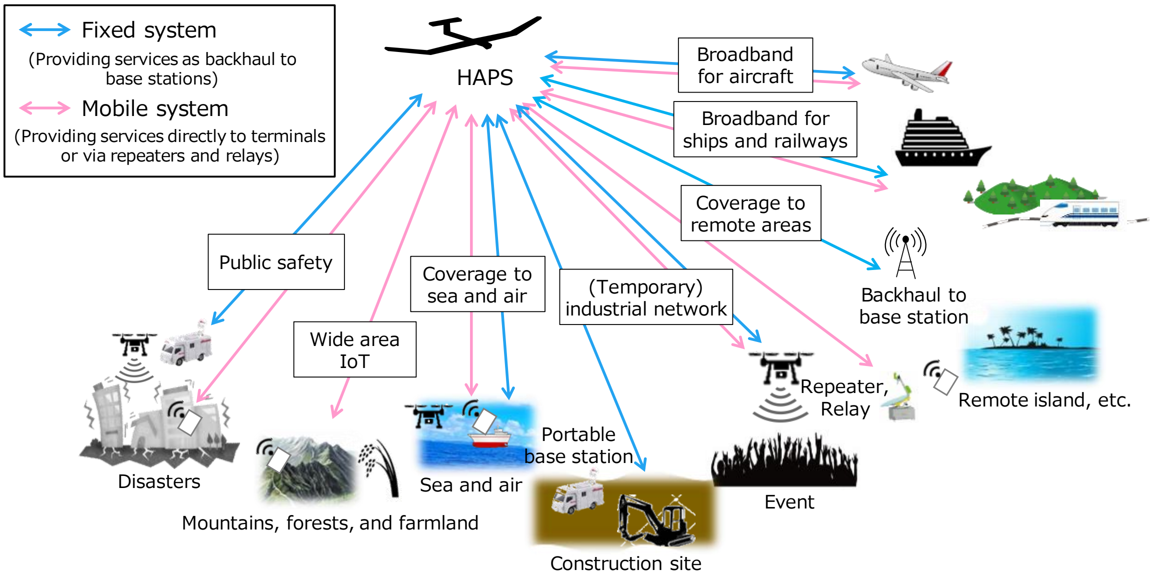


Figure 5-8. Various use case expected in HAPS

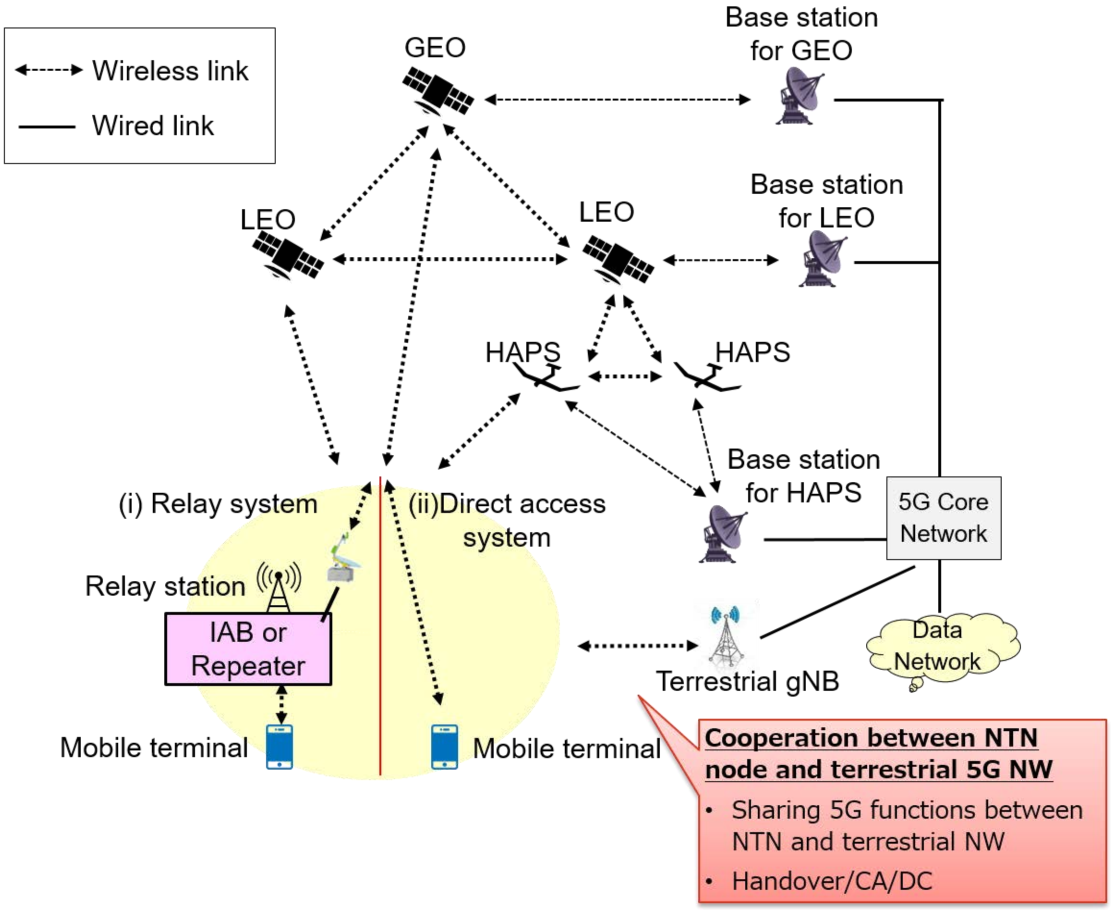


Figure 5-9. Multilayer network system using satellite and HAPS and cooperation with terrestrial 5G network

## 5.3. Technology for further broader frequency domain and advancement of frequency utilization

As shown in Fig. 5-10, 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 [5-23]. 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 [5-24, 5-25]. At present, as shown in Fig. 5-10, "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. Regarding radio propagation characteristics of terahertz waves, in addition to basic characteristics such as reflection, scattering, and transmission, measurement reports of indoor environments [5-26, 5-27, 5-28, 5-29] have been carried out. And measurement examples in outdoor environments have begun to be reported [5-30, 5-31]. However, it is a problem that the amount of measurement data necessary for the construction of the propagation model is still insufficient for more than 100 GHz bands. In addition, technology examination such as progress of the device technology and utilization on the premise of the above-mentioned New Radio Network Topology is also required.

Regarding device technologies, it is necessary to develop digital signal processing circuits which support further wider bandwidths, DAC and ADC 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 using the compensation technology by digital signal processing to be described later, 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. In addition, miniaturization, low power consumption, and high heat radiation are also necessary, when those semiconductor devices are utilized for the terminal, and realization of the RF circuit corresponding to the multiband and the miniaturization are also large problems on the premise of CA in millimeter wave and terahertz wave. Research and development for the above-mentioned technical problems in the high frequency band exceeding 100 GHz has become an international competition, and examination has been started in Japan by the research and development project of the Ministry of Internal Affairs and Communications [5-32]. For example, research and development will be carried out on radio system configuration technology to realize 100 Gbps at a distance of 100 meters within sight in high frequency band, antenna integrated front-end IC technology to realize Massive MIMO, compound semiconductor technology to enable high power transmission, and terahertz band RF technology to operate in 350-600 GHz band considering application to mobile backhaul and fronthaul. The results of research and development on these device technologies will be important for utilizing terahertz waves in 6G.

Compensation technologies of the device by digital signal processing for RF imperfection are also important. For example, in order to improve power consumption, DAC and ADC with the low resolution and technologies which mitigate degradation from them are also examined [5-33]. And, for RF device in the terahertz bands, phase noise with high carrier frequency and frequency selectivity for wide bandwidth get more severe than millimeter wave band, and these compensation techniques in digital signal processing have started to be widely examined [5-34].

Fig. 5-11 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 there 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 preferable to OFDM waveform 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 [5-35, 5-36]. However, because extremely high performance and manufacturing accuracy are required for wireless devices depending on imperfections in frequency characteristics of terahertz wave devices and the relationship between signal bandwidth and frequency utilization efficiency to realize 100 Gbps, CC (Component Carrier) may be introduced in the same way as 5G in order to mitigate these requirements. In order to utilize ultra-wideband signal bandwidth in terahertz waves, it is important to design wireless parameters such as bandwidth of CC, number of CCs, and signal waveforms to be introduced while taking power consumption of baseband signal processing systems into consideration. In order to further improve the power efficiency of DFT-s (spread) - OFDM adopted in the uplink of 5G NR, FDSS (frequency-domain spectral shaping) that performs spectrum shaping in the frequency domain, is investigated [5-37].

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 Fig. 5-11, 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 5.6, optimization technology using cyber-physical fusion and high-precision sensing technology linked to high frequency bands. As described in Section 5.6, 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 5.4 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 become also an important requirement.

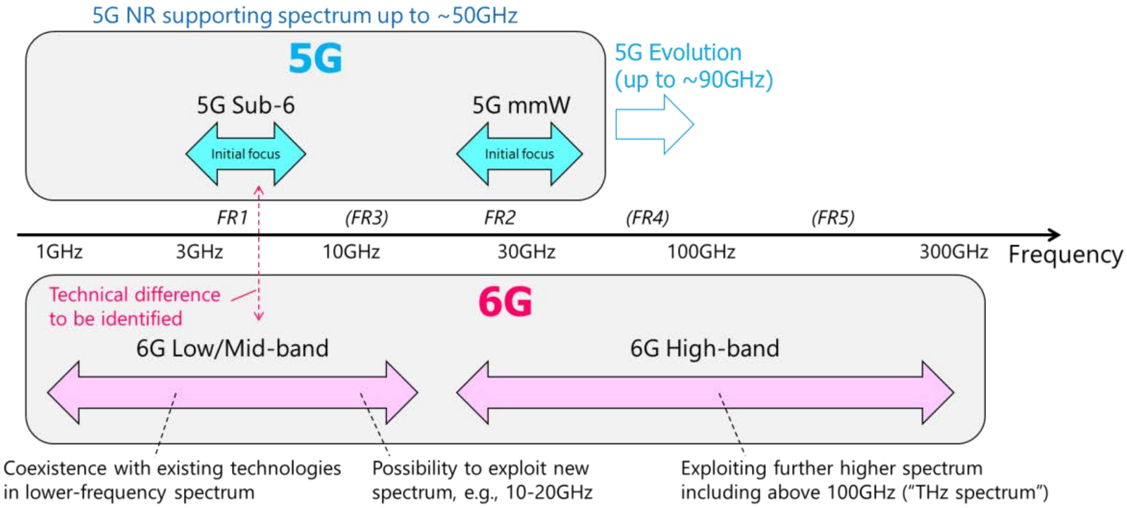


Figure 5-10. Exploration of frequency bands for 6G

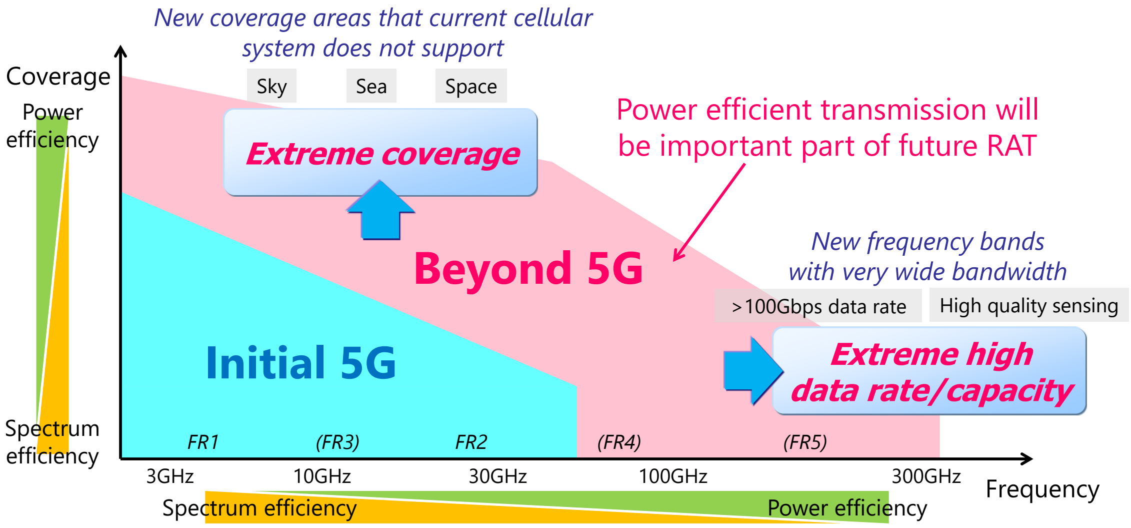


Figure 5-11. Expansion of radio access technology for higher frequency band exploration and coverage expansion

## 5.4. 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 [5-38, 5-39] and Distributed mMIMO for a distributed antenna configuration combined with New Radio Network Topology. Distributed MIMO combined with New Radio Network Topology is one of promising method for wireless access system using high-frequency bands such as millimeter- and terahertz waves. As shown in Fig. 5-12, 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 [5-5]. In the distributed antenna deployment technology, it is expected that many antenna deployment using A-RoF with beamforming technology will be utilized [5-40], because it is highly compatible with the wideband, which is a characteristic of the high frequency band. Regarding distributed propagation path control technology, antenna beam narrowing is necessary on both base station and terminal sides in order to secure system margin against propagation loss and signal broadening in the high frequency band. From this point and subarray configuration, a technology for fast detection of optimal combination between multiple beams is necessary [5-41, 5-42, 5-43, 5-44, 5-45]. And, beam search and antenna search method based on the position information are also promising on the high frequency band, because the correlation between position and radio quality is strong in the use case of line-of-sight environment such as train and car [5-46, 5-47]. In addition, the combination of the high frequency band and the distributed antenna has the potential to detect the position of user terminal by the communication radio wave itself. Beam search and antenna search methods using this position detection have been studied [5-48, 5-49]. And, regarding the distributed cooperative MIMO technology, the following have been studied: Transmission power control technology [5-50] for multi-beam of each distributed antenna considering both reduction of interference among users and low power consumption, and clustering technology [5-51], that is a method to select which distributed antenna to connect to which central station, and which distributed antennas to use for cooperative MIMO transmission from distributed antennas connected to the same central station, from the viewpoint of both distributed Multi-User MIMO transmission suitable for spatial correlation between user terminals distribution and computational complexity reduction.

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 [5-52]. Even if the system employs 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) [5-53]. Furthermore, as shown in Fig. 5-13, 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 [5-54]. 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.

In addition, as upgrading of radio transmission technology, upgrading of duplex method of up and down link is also considered, and FD (full duplex) which carries out up and down link communication at the same time and frequency is discussed in 5G Evolution [5-55]. The FD technology has the merit that by carrying out the uplink communication simultaneously, the frequency utilization efficiency can theoretically be doubled, while the overhead of guard interval and guard band, etc. which were necessary for dividing the uplink until now is reduced, and in addition, the delay and coverage improvement can be realized by increasing the transmission opportunity of the uplink. However, in the introduction of FD technology, it is technically a big problem that interference between terminals and base stations occurs between uplink and downlink. Therefore, it is necessary to consider the combination with the mMIMO technology which can reduce the interference by the beam and the careful selection of frequency band and application scenario. XDD (cross division duplex) [5-56], that follows FD concepts partially and realizes low latency and coverage improvement as well as interference suppression, is also investigated.

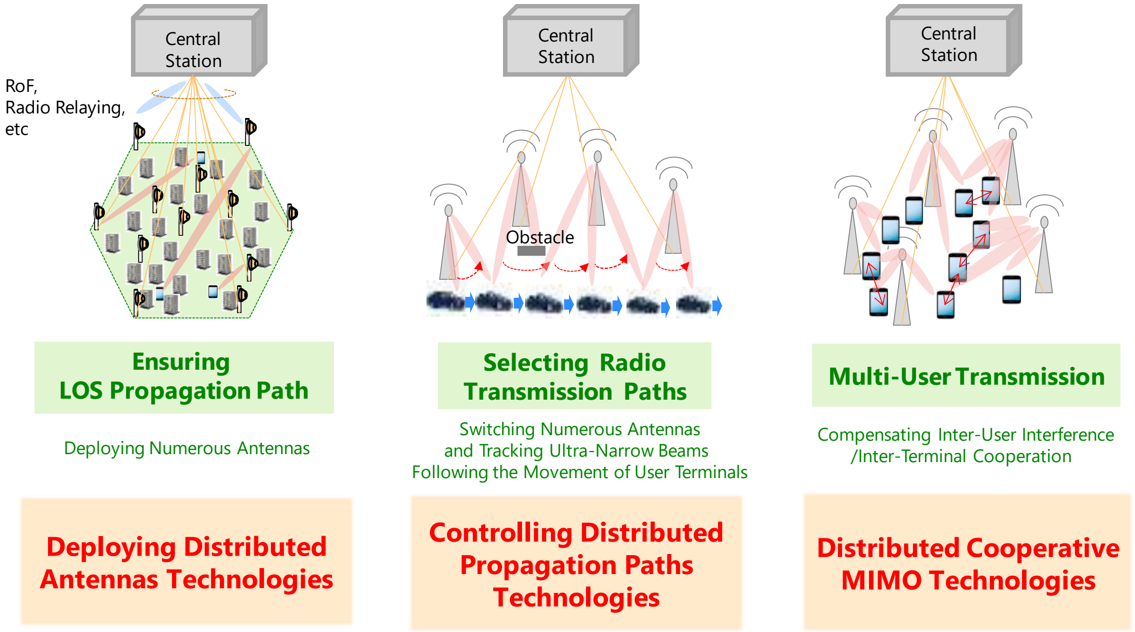


Figure 5-12. Current issues for Distributed MIMO

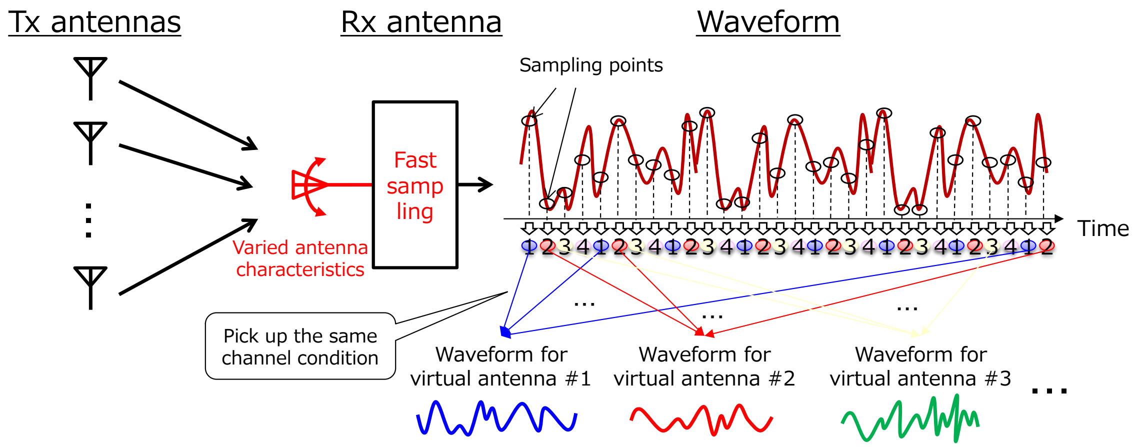


Figure 5-13. Example of non-orthogonal transmission technology using a sampling rate greater than the frequency bandwidth (VM-MIMO)

## 5.5. 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 characterized 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 [5-57]. 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. 5-14, 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 [5-58]. 6G is also expected to provide higher levels of reliability and security than 5G.

As shown in Fig. 5-15, 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.

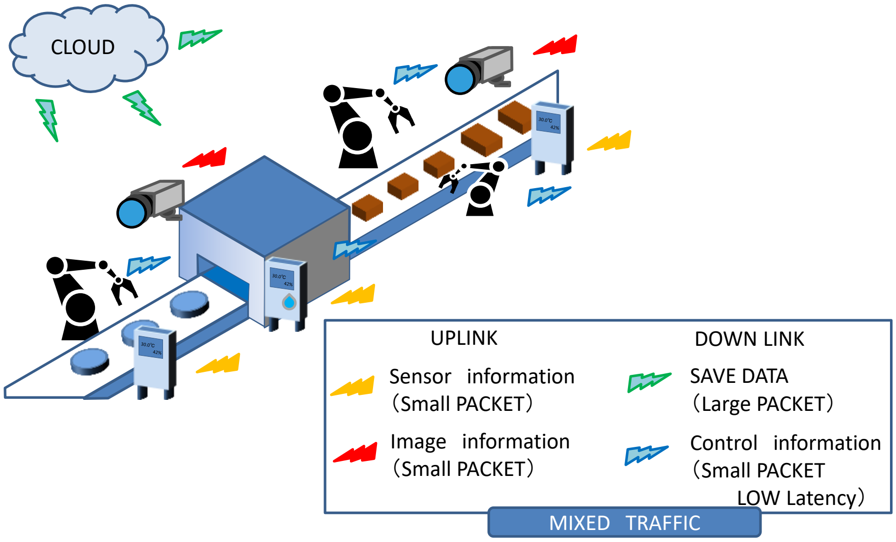


Figure 5-14. Support of various types of traffic in industrial networks

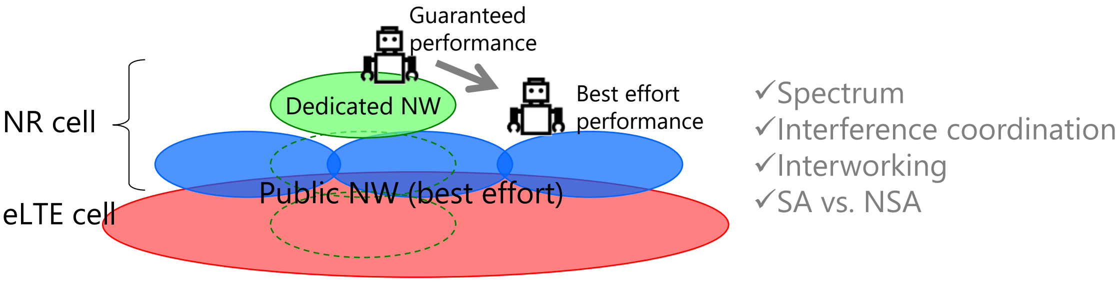


Figure 5-15. Overlay of Public Network and industrial network (NPN)

## 5.6. **Multifunctional wireless communication systems and utilization of AI technology in all areas**

In 5G Evolution and 6G, it is considered that enormous and various information such as images, voices and videos are transmitted from all terminals, and efficient analysis and utilization of vast and diverse information using AI technology is being considered for advanced radio communication control and utilization for cyber-physical fusion.

In cyber-physical fusion, images and a variety of sensing information are transmitted to the network through IoT devices. Therefore, in addition to the information measured by radio waves of radio communication, it is conceivable that such various information will be analyzed by AI technology and incorporated into the sophistication of radio communication control 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 [5-59, 5-60] and wireless power supply technology (energy harvesting [5-61], etc.). In particular, high frequency bands such as millimeter waves and terahertz waves are suitable not only for high-speed, large-capacity communication, but also for the realization of highly accurate positioning and sensing. Also about this, utilization of AI technology is the key, and it is expected that the accuracy of positioning and object detection will be greatly improved by analyzing various information in addition to the information measured by radio waves of wireless communication by AI technology.

As shown in Fig. 5-16, the use of AI technology is expected in all areas of radio communication systems, such as various controls and algorithms in radio communication, network and device management, and functions that automatically optimize for use cases and environments. And, in cyber-physical fusion, it is possible to utilize AI technology in a communication system that spans real space and virtual space, such as "communication using AI avatar as an endpoint" described later. Furthermore, various technologies can be mentioned as the sophistication of communication technology using AI. Technology to improve delay and reliability in non-orthogonal multiple access (NOMA) [5-62, 5-63],Technology that anticipates the changing environment and predicts the propagation environment and communication quality [5-64, 5-65],Technology that intelligently switches routes with other wireless technologies that integrate and cooperate based on the predicted propagation environment and communication quality [5-66],Technology to autonomously place mobile base stations in the optimal installation location [5-67], etc. In order for the above-mentioned New Radio Network Topology to function efficiently and effectively, topology management and control technology utilizing AI etc. will be an important factor. The sensing information acquired by utilizing AI is considered to be effective not only for providing to users as added value, but also for network control and parameter optimization in 5G Evolution and 6G, and stable network operation is also possible. Thus, AI is also expected to contribute to stable network operation.

The challenge is to study a radio network standard suitable for utilizing such AI technology. However, in the future, the design of the radio network interface itself may be done by AI technology.

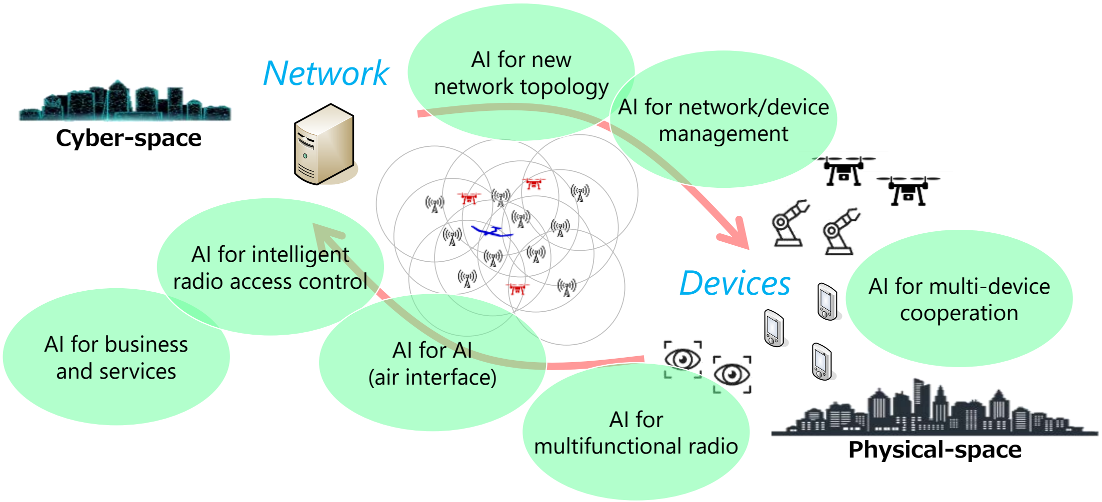


Figure 5-16. Utilization of AI technology in all areas of mobile communications systems

### 5.6.1. **Wireless sensing technology in cellular network**

Heading towards creation of added value of cellular network, wireless sensing technology which utilizes radio wave for communication is attracting a lot of attention. Fig. 5-17 shows a general view of the classification of wireless sensing technologies in the world. By utilizing wireless sensing technologies in cellular networks, it is expected that not only performance improvement of existing and future facilities but also new services will be created by utilizing sensing information such as radio wave propagation characteristics. Especially, it is considered that the cellular networks have affinity, because it can utilize radio wave propagation characteristics of many frequency bands from low frequency to high frequency. Concretely, since it is resistant to environmental changes such as solar light in such a frequency bands, it can be used even at night and in non-line-of-sights (NLOS) environments. Also since the reflectance ratio changes according to the dielectric constant of the material, there is also the feasibility of the sensing of objects with high reflectance such as human, metal or much water/moisture. Furthermore, it is also possible to detect minute vibrations which cannot be discriminated by human eyes. Information collection with careful consideration of privacy becomes possible. Thus, wireless sensing technology utilizing radio waves has high utility value from various viewpoints. On the other hand, as a mobile communication operator that owns cellular network equipment, it will be possible to collect information over a wide area and store information directly on the cloud by utilizing base stations and network infrastructure located all over the country.

Therefore, wireless sensing technology in cellular networks can contribute to the advancement of cyber-physical fusion in all aspects of informatization of people, things, and events.

On the technical side, in the field of positioning and sensing technology so far, many approaches to analyze the received power that can be easily obtained from radio communication systems such as cellular networks have been studied. 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. It is expected that the accuracy of positioning and sensing will be improved by utilizing such detailed information. In addition, due to the dramatic improvement in the capabilities of computers and the rapid evolution of AI technology, the technological domain for object identification and behavior recognition is expanding beyond capability of detection by humans. Specifically, the following technologies are widely examined: Intrusion detection (one or multiple persons), congestion rate estimation 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, and more.

On the other hand, there are many expected use cases from the use of wireless sensing technology. From the viewpoint of terminal positioning, improvement of communication environment, cooperation with the Intelligent Transport Systems (ITS) and robotics industry, and more, can be considered. From the perspective of sensing, it is expected that data can be used for various use cases such as crime prevention measures, disaster measures, collection of statistical information, environmental protection, collaboration with the ITS/robotics industries and more. Fig. 5-18 shows an example of a use case and its procedure. (Step1) Obtaining CSI for various conditions is performed. For example, detection or non-detection of humans, state of doors such as open or closed. (Step2) Labeling is performed according to each state, and building a learning model. (Step3) Judgement a detection or non-detection of humans and the state of doors (open or closed) using a learning model prepared in Step 2.

Also, in the age of 5G Evolution and 6G, the use of higher frequency and wider band signals including terahertz waves, and the realization of fine-tuned control of the antenna beam direction using a large number of antennas are expected. Furthermore, it is expected to be fused with radar using reflected radio waves. This is also a great merit so that it leads to positioning and sensing with higher accuracy and resolution.

Information that can be obtained from a cellular network, including radio propagation information, has a lot of potential value. This field is expected to grow continuously. The acquired information is not only provided to users as added value, but also considered to be effective for 5G Evolution and 6G parameter optimization of communication systems by analyzing real-time sensing data in the communication area. It is expected that this will lead to stable network operation.

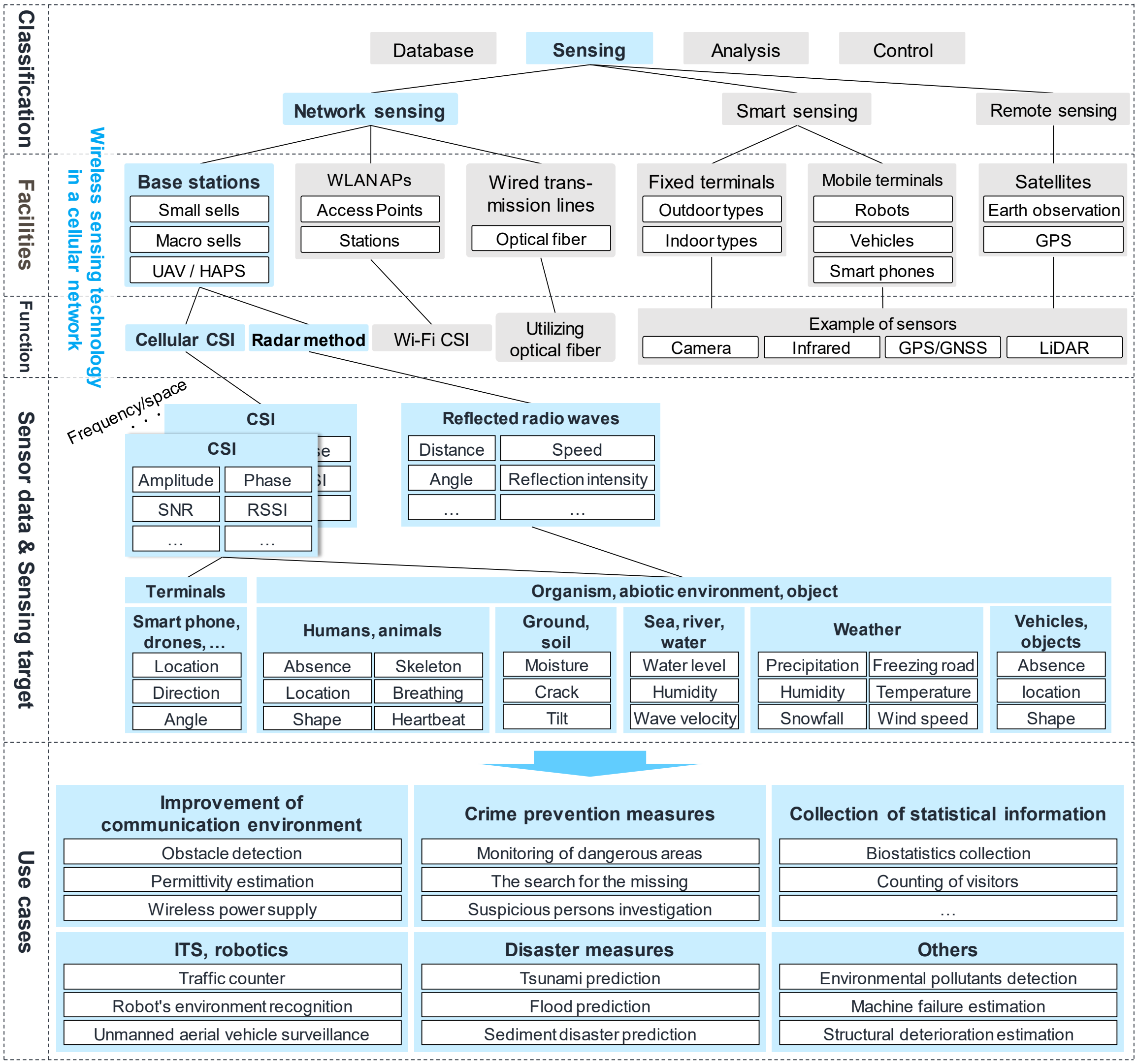


Figure 5-17. Wireless sensing technology in cellular networks

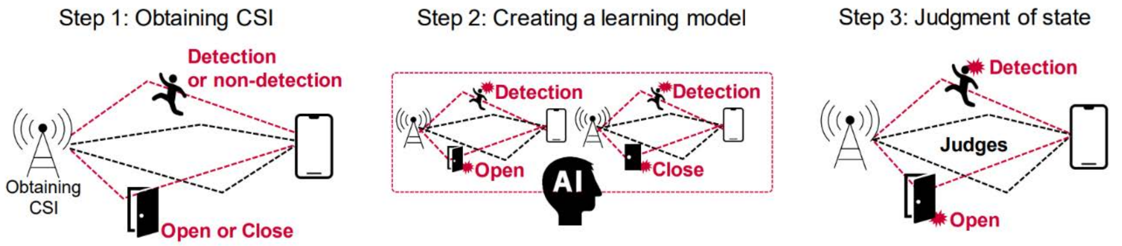


Figure 5-18. Method of positioning and sensing using channel state information

### 5.6.2. **Communication using AI avatars as endpoints**

In recent years, a wide variety of services have been born due to the spread of smart devices and the development of communication infrastructure. Based on this trend, humans face the increase of information data that should be processed. However, there are limits to the amount of services that humans can experience and to the amount of work that humans can do in physical space.

Thus, an AI avatar which can be active 24 hours a day, 365 days a year may substitute the experience and work instead of the human. Here, it can process huge amounts of data at high speed in cyberspace and make autonomous decisions on behalf of the human. The AI avatar is supposed to be a communication endpoint which communicates with humans and/or other AI avatars. There are two forms of AI avatars: digital clones, which are the alter egos of specific individuals, and avatars with artificially created imaginary personalities and intentions. The former has the knowledge and will of the person, and makes decisions and acts autonomously on behalf of the person. AI avatars in cyberspace and the original humans in physical space can act independently and share experiences. This increases opportunities for humans. The latter can be applied to various applications to streamline and optimize existing services and to develop and provision new services. There are various requirements for these AI avatars to be communication endpoints, and key requirements are as follows:

1. Deterministic communication considering low delay and low jitter for natural and smooth communication between physical space and cyber space
2. In-network computing for efficient processing of large amounts of data
3. New authentication feature to authenticate AI as a specific person
4. Policy control infrastructure for controlling permissions granted to AI
5. Learning infrastructure for continuous AI model updates

## 5.7. **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 Fig. 5-19. 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. And, in APN of IOWN Initiative, the combination of optical radio communication [5-68, 5-69] and communication using conventional radio wave is also important in order to introduce the optical technology from the network to the end of the terminal, as much as possible. Although optical wireless communication is easily affected by environment such as weather, it can be used for wireless transmission at higher speed and longer distance than radio wave, for example, as a means to connect backhaul/fronthaul and network equipment wirelessly, and for inter-node communication in NTN.

And, as a place where radio waves from the sky do not reach, for example, in "undersea", it seems to be necessary to use wireless communication using waves other than radio waves such as visible light communication and acoustic communication. At present, since the high-speed underwater wireless communication technology has not been established, the underwater work is controlled by diver and wire, but in the future, realization of wireless remote control and monitoring in each undersea market as shown in Fig. 5-20 is expected by high-speed visible light communication and acoustic communication of Mbps class. For the speedup of the visible light communication, the utilization of blue laser and photomultiplier tube for overcoming the attenuation in the sea water is examined, and the successful example of the transmission experiment of 20 Mbps at the distance of 120 meters in the deep sea area is reported [5-70]. Visible light communication has problems which are easily affected by interference of solar light and turbidity of sea water, and speedup of acoustic communication which can be used even in shallow sea area is also examined. For the speedup of acoustic communication, a new waveform equalization technology [5-71] which positively utilizes the space region is examined in order to overcome the order of magnitude inferior waveform distortion which is a problem peculiar to acoustic communication, and a successful example of transmission experiment of 1.2 Mbps at a distance of 60 meters in a shallow sea area is reported [5-72].

As mentioned above, cooperation with satellite communication system is also important in order to realize coverage expansion to air, sea and space. There are two directions of development for the integration of wireless communication technologies:

(1) Expanding the scope of integration: Integration of the diversification technologies, including ultra-coverage expansion technology (Satellite communications, undersea communications, HAPS, etc.) and integration with new wireless communication systems.
(2) Enhancing quality through integration: Integration that takes into account the unique characteristics of heterogeneous wireless access networks enables high quality and low cost (+ flexible, fast, and low power consumption) in response to time-varying application requirements and environmental changes.

In (1), it seems to be important not only to examine how to integrate the super coverage expansion under examination and to smoothly carry out connection management and connection switching, but also to examine interfaces and architectures which will be effective in integrating and controlling new wireless communication systems in the future. In (2), when integrating cellular systems and wireless LANs, etc., it is important to consider technologies that not only perform smoother connection switching and transversal and efficient accommodation control than ever before, but also flexibly and quickly follow time-varying application requirements and environmental changes, or absorb fluctuations, taking into consideration the characteristics of individual communication systems and achievable communication quality, and to consider integrated networks that maintain high quality while reducing equipment costs through the integrated use of heterogeneous networks.

On the other hand, in addition to this, we can also refer to other examples such as the expansion of mobile communication technology to unlicensed bands (LAA: License Assisted Access) [5-73], 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.

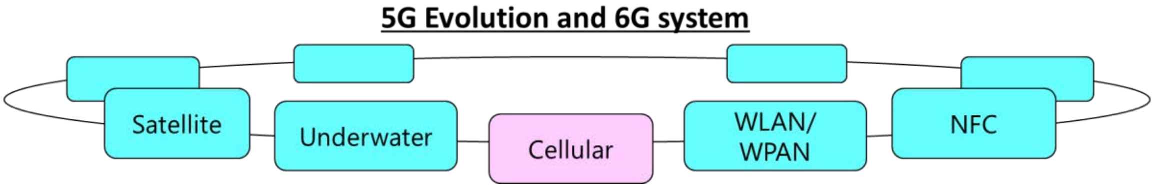


Figure 5-19. Integration of wireless communications technologies.

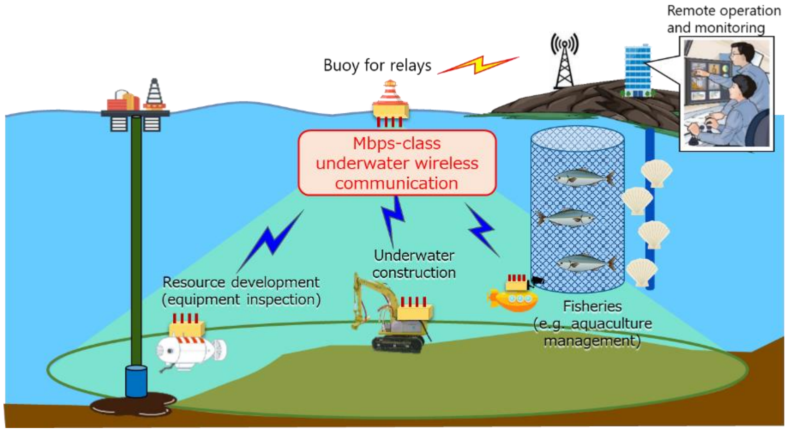


Figure 5-20. Underwater Wireless Communications

## 5.8. **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 fusion
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.

### 5.8.1. **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.

### 5.8.2. **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. It can be said that the degree of freedom of network functions placement will geographically and logically increase. For the candidates on the location of network functions, not only network operator facilities are to be considered. Regarding the deployment of RAN (Radio Access Network) and CN (Core Network) functions, they are usually concentrated in large-scale and distributed facilities in public operator networks, e.g. a radio base station and a central office. In the future, however, it is anticipated that more functions will be finely distributed locally on-premises of business users' private networks or their equivalents, for instance to address use cases for improved safety and low latency transmission. Furthermore, 3rd party public cloud providers are also starting to provide distributed infrastructure in addition to their centralized infrastructure [5-74, 5-75], which increases the freedom for such network function placement arrangement. 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. As one of the elemental technologies for this, the technology [5-76] which provides seamless communication service without depending on access/terminal and application linkage function via API by providing virtual endpoint in the network is examined.

The direction shown above has been promoted by the recent trends of virtualizing and implementing network functions as software components including their containerization and cloudification. These techniques, but in particular containerization and cloudification, can improve application portability [5-77]. In fact, considerably flexible functional development is possible even in the current stage applying virtualization technologies. But with cloudification a bigger step forward can be achieved by extending a more flexible network function design, not only at the network architecture level, but even also at the application architecture level [5-77, 5-78]. The core network functions are now being virtualized, as well as MEC/cloud services being offered by communication service providers [5-79], and RAN's functional virtualization has also started. As a result, the virtualization and cloudification momentum has expanded to the whole mobile network end-to-end. More flexible distribution and unified stable operation of those diverse network functions and cloud services require further improved robustness, operability, and maintainability.

In addition to the operation of the network functions and services, the design of the platform infrastructure is of great interest. The platform infrastructure consists of physical resources, which in turn underpins a platform enabling softwarized network functions to be deployed. In the past, operators carefully determined the border of network domains and responsibilities, and related departments have individually managed each platform infrastructure within their responsibilities, respectively. As a result, network operators have been able to build and operate huge, massive systems for telecommunication. Furthermore, up to now, since the demarcation between RAN and CN is well determined the platform infrastructures are also split between RAN and CN; generally, MEC/cloud services are handled as applications isolated from network functions and dedicated platform infrastructure is also provisioned. However, in order to realize flexible arrangement and unified stable operations of network functions and cloud services, there might be a need for network operators to consider making flexible the border between the platform infrastructures used for the different network domains, or even building no border at all. This enables the network operator to deploy and operate a homogeneous platform infrastructure, and optimize the provisioning and assets. In that sense, breaking away from statically designing the border for the infrastructures is a big challenge for network operators and one of the difficulties regarding the introduction of end-to-end cloudification and virtualization. Finally, in such flexibly distributed network, 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.

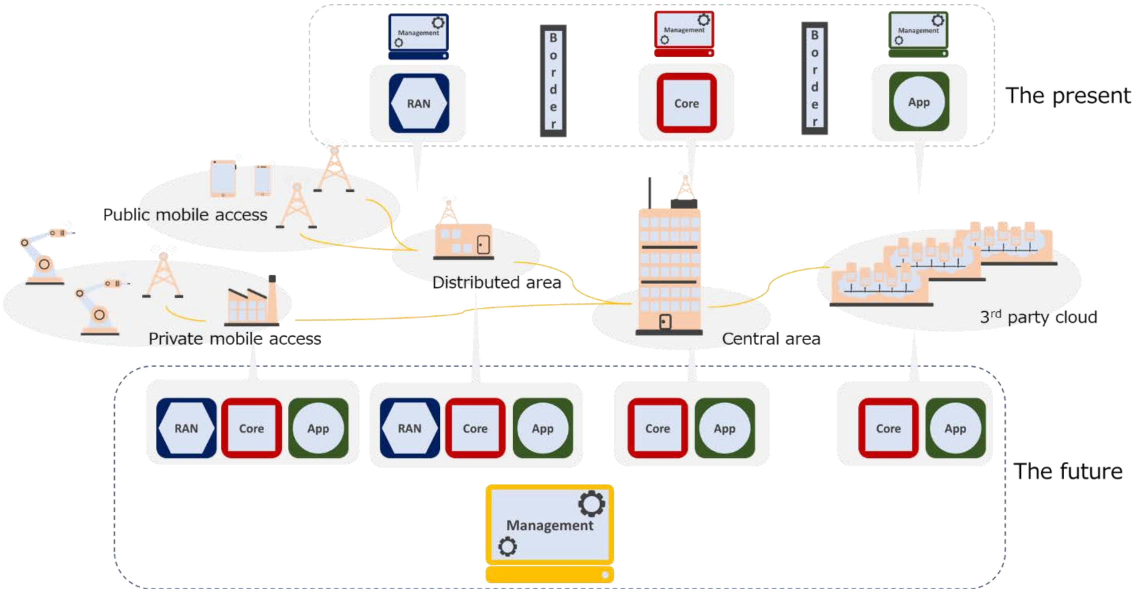


Figure 5-21. Overview of flexible deployment of network functions

### 5.8.3. **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.

Furthermore, for certain application types, some functionalities may not be needed. For example, many video applications will be based on the “best effort” requirements and work well with changing of IP. Also, majority of traffic generated by the video applications come from a nomadic behaviour of mobile subscribers.

To cope with these, it will be necessary to take measures to suppress complexity, while increase cost efficiency, and maintaining system flexibility and security in the network. 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. Reduction of network functionalities or network functions
5. Grouping of use cases and selection of parameter values and combinations for each group
6. Unification of lifecycle management methods such as RAN and CN installation and configuration changes in virtualized environments.

### 5.8.4. **RAN-Core convergence**

Some of objectives identified in section 5.8.3 to simplify the network architecture, and in particular the measures related to avoiding overlapping functions in RAN and Core network elements (measure 2), simplifying the protocol stacks (measure 3) and unifying the lifecycle management of RAN and Core functions (measure 6), could be addressed by investigating on the convergence RAN and CN functions.

The 3GPP mobile network generations until 5G are characterized by a hard architectural separation between Radio Access Network (RAN) domain and Core Network (CN) domain. For instance, in the 5G system, the adoption since Rel-15 of the service-based architecture [5-80] is limited to the CN Control Plane functions. The service-based approach is recognized as an enabler of cloud-native deployments, which bring several advantages in terms of flexibility (faster deployment of new services, shorter lifecycle management process) and sustainability (lower total cost of ownership of the network infrastructure). The progressive expansion of the adoption of virtualization technologies (e.g. ETSI NFV [5-81]) for the mobile network deployment as well as the Open RAN [5-82] standardization initiative to enable virtualized and interoperable RAN deployment options may bring to re-thinking the architectural separation between RAN and CN functions.

In this context of RAN-Core convergence, there are several areas that require thorough investigation:

- Extending the adoption of the service-based paradigm to the RAN Control Plane functions and, possibly, the user plane functions. In 5G, the reference points between RAN and CN functions, as well as between different RAN functions, are still based on point-to-point interfaces that require preconfigured persistent associations between node-pairs.
- Re-distributing/combining overlapping functionalities currently implemented by 5G CN and RAN functions to simplify the system architecture.
- Re-considering the need for 3GPP specific legacy protocol (e.g. SCTP, GTP, NG-AP) not commonly supported by all IT equipment and therefore not virtualization friendly.
- With specific reference to mobility management and session management functions, separating the functionalities that specifically depend on the access technology from access-agnostic functionalities that enable the integration of multiple access technologies (E-UTRAN, 5G-NR, non-3GPP access, fixed network residential gateways, satellite, 6G RAN, …) in a common core network.
- Co-locating RAN and CN Control Plane functions to improve the control plane latency and reduce the signalling between distributed functions and centralized functions. Co-locating RAN and CN User Plane functions to further improve the user plane latency by enhancing the local offload capabilities supported by the 5G system.

The investigation on these topics and identification of suitable and commonly agreeable solutions will determine the design of the next generation network architecture.

### 5.8.5. **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.

Finally, it aims at the operation without the intervention by the maintenance person, and even in that case, it is necessary to present what was detected, result of analyzing the detection content and content and purpose of the measure to the maintenance person.

And, in order to utilize AI technology, a large amount of data of physical space such as state and situation of network, hardware, virtualization platform, and application are necessary. The means and framework to deliver the data to the cyberspace are required for AI to learn from the large data and to analyze, to decide what to do. By the decision of AI, the measures for the network and others of the physical space are carried out, and then the autonomous operation by the cyber-physical fusion is realized.

### 5.8.6. **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

In order to solve these problems, it is expected to apply technology that realizes seamless communication independent of access/terminals by providing virtual endpoints in the network described in 5.8.2.

### 5.8.7. **Core network transmission/switching control technologies supporting extreme low latency and high reliability**

One of 5G's achievements is the realization of low latency and high reliability. 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 end-to-end 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 end-to-end 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 end-to-end 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 [5-83] and (iii) slot allocation for data transmission/reception is aligned between the wireless and wired sections to eliminate the latency [5-84]. As a secondary effect, this system can also improve efficiency and reduce power consumption of deterministic communication.

Furthermore, 5G allows terminals to establish redundant paths to the server via different RAN and U plane nodes. However, in 5G, the realization of ultra-reliability was only based on the multiple path selection within the communication network. In other words, the 5G relies on redundant paths as possible with Multi-path TCP or IEEE Frame Replication and Elimination, but the communication session is dropped if the application server fails, e.g., due to power outages. Therefore, a robust reliability mechanism is required to handle the end-to-end reliability with much more coordination between the network and the application.

### 5.8.8. **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 and (v) ultra-reliability and deterministic performance concurrently as part of an integrated solution [5-85, 5-86]. 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. 5-22, 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 (iv), 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. To cope with issue (v), integration of IEEE TSN (L2) with IETF Detnet (L3) is expected to improve the relevant control and data plane processes. However, still many technical challenges are to be met towards 6G, due to highly complex multilayer (L1-L4) operations and difficulty to support paradigms like end-to-end network slicing. In addition, further research is needed on the areas of flow scheduling, queuing management and resource allocation, to realize end-to-end ultra-reliable deterministic networks.

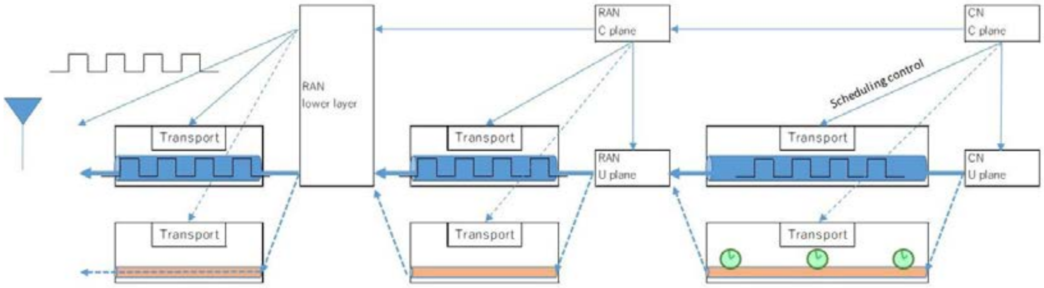


Figure 5-22. Example of architecture for wide-area deterministic communication

### 5.8.9. **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. 5-23, (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.

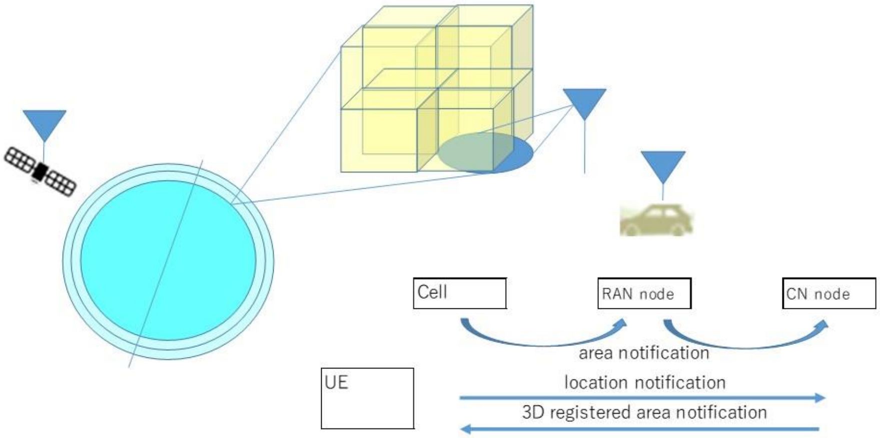


Figure 5-23.  Location-based mobility control

### 5.8.10. **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, digital contracts using various trust models, 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. Furthermore, with the rise of the Internet of Everything (IoE) paradigm, the 6G network will have to cope with the personal IoT networks such as connected wearable devices, and IoT device reside in the office or factory. As the number connected devices per person is continuously increasing, the identity management becomes a major challenge, and it will also be a cumbersome and cost-prohibitive process to provide a pre-configured cryptographic chip.

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.

On the other hand, it is assumed that the security technology itself becomes an enabler in 6G. For example, a digital twin becomes an environment where a new digital business is born and grown, and a security technology creates a new business mechanism there. Security technology is also offered as a service to customers who are not familiar enough with using it.

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 trustful cooperation across industries. Enhanced security for 6G should protect systems and data from these ever increasing threats while ensuring their confidentiality, integrity and availability. We will continue to work diligently to protect the privacy of our customers. For privacy protection, epsilon differential privacy, private information retrieval, and privacy protection database are also utilized. For various cooperation, secure value transfer system and smart contract are also required. Furthermore, we envision moving from a traditional cryptographic chip (either from plastic or embedded SIM) model to an advanced cryptographic enclave on the System-on-a-Chip (SoC) with its own security engine. In fact, secure enclaves on the SoC allow devices to store key data securely [5-87]. So the telco industry [5-88] and SDO’s [5-89] began looking into how to run cryptographic chip functionalities (such as USIM) on the SoC without requiring additional cryptographic hardware.

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 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 and low power consumption 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 [5-90] 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 [5-91] 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. 5-24.

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.

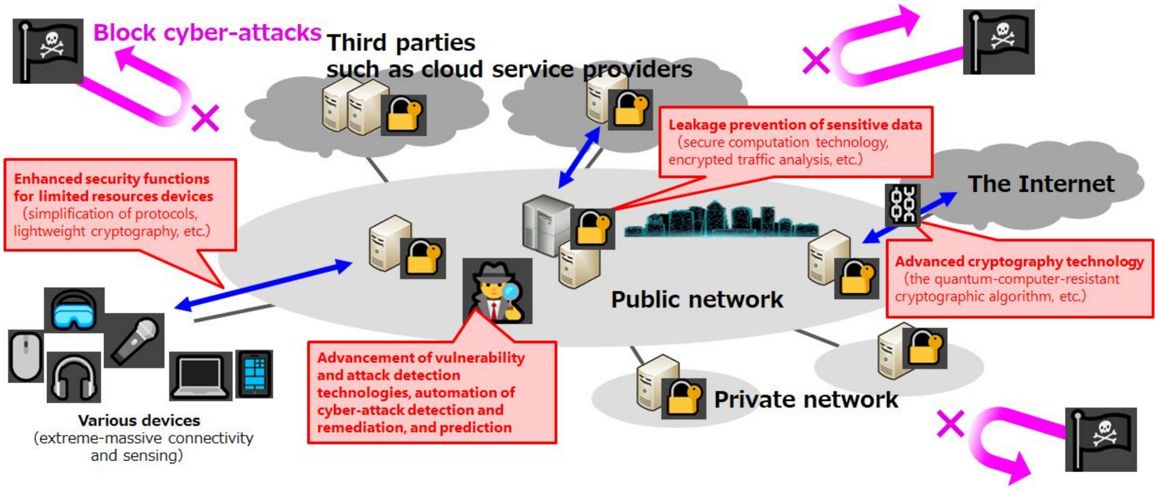


Figure 5-24. Advanced security in 6G network

### 5.8.11. **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. This matches perfectly with the vision of flexibly deploying network functions on top of a unified platform infrastructure, as introduced in previous sections. Furthermore, as technology makes anything smaller, computing resources could be made available in all antenna installations. As shown in Fig. 5-25, 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. It is considered that the distributed computing resources are effectively available even when the case of traffic demand increase locally over the assumption due to events and disasters. Furthermore, it is expected that allocation of the distributed computing resources can be optimized automatically and dynamically by the introduction of AI and ML, based on their traffic volume prediction.

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.

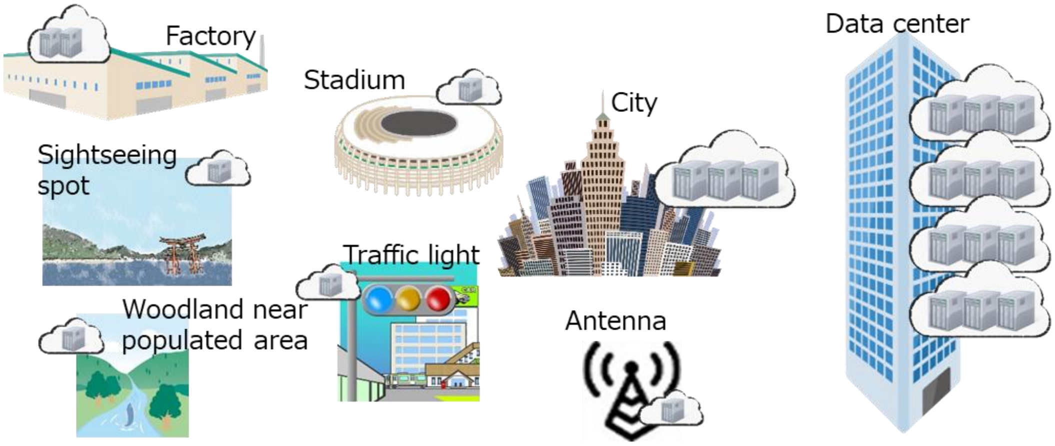


Figure 5-25.　Distributed computing resources.

# 6. **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 6-1 below summarizes the challenges that need to be addressed in each of the technological areas discussed in Chapter 5.

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 6 -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<br>・Interference control technology in high-density distributed antenna deployment<br>・Win-Win distributed antenna deployment with sensing and energy-saving communications |
| Coverage extension technology including Non-Terrestrial Networks | ・Radio interface extension for NTNs<br>・Method for highly efficient frequency utilization with ground networks<br>・Method for realizing coordinated operation between HAPS systems and ground networks<br>・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<br>・Challenges in THz-band device technology (Miniaturization, low power consumption, high heat dissipation, etc.)<br>・Establishment of signal waveforms and wireless technologies suitable for the THz band<br>・Optimization of selective use of multiple bands including existing frequency bands |
| Further advancement of Massive MIMO and wireless transmission technologies | ・Study of multi-element / multi-layer mMIMO technology<br>・Transmission path control technology in distributed MIMO<br>・Development of new wireless technologies for existing frequency bands |
| Extension of Ultra-Reliable and Low Latency Communications | ・Support of a wide range of requirements including very demanding requirements and "Mixed Traffic" |

| | |
|---|---|
| (URLLC) and industrial networks | • Realization of further high-reliability and secure communications<br>• 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<br>• Study of radio standards suitable for deployment of AI technology |
| Integration of various wireless technologies | • Method of cooperation or integration with other technologies<br>• Control of wireless technology selection transparent to users |
| Network architecture | • Flat network topology<br>• Flexible deployment of network functions<br>• Simple network<br>• RAN-Core convergence<br>• Advanced OAM (Operation and Maintenance)<br>• Technology for integrated operation of multiple access technologies<br>• Core network transmission/switching control technologies supporting extreme low latency and high reliability<br>• Wide-area time synchronization and wide-area deterministic communication supporting CPS<br>• Location-based mobility control supporting extreme -coverage<br>• Advanced security<br>• Distributed computing resources |

# References

[1-1] H. Holma, A. Toskala, and T. Nakamura, “5G technology: 3GPP new radio,” Wiley, Dec. 2019.

[1-2] J. Sawada, M. Ii, and K. Kawazoe, “IOWN beyond the internet,” NTT Publishing Co., Ltd, ISBN-978-4-7571-8299-8, Mar. 2020.

[1-3] Beyond 5G Promotion Consortium, https://b5g.jp/en/

[1-4] Ministry of Internal Affairs and Communications, "Publication of "Beyond 5G Promotion Strategy - 6G Roadmap -," June 2020.

[2-1] Ministry of Internal Affairs and Communications, “2020 WHITE PAPER Information and Communications in Japan,” August 2020.

[2-2] Cabinet Office, "The Fifth Science and Technology Basic Plan" January 2016.

[2-3] Masahiko Inami, https://star.rcast.u-tokyo.ac.jp/en/

[2-4] United Nations, "World Population Estimates"

[2-5] PwC, "2050 in the world,"

[2-6] United Nations, "2030 Agenda,"

[2-7] Cabinet Office, "White Paper on the Aging Society"

[2-8] Cabinet Secretariat, Headquarters for Overcoming Population Decline and Vitalizing Local Economy in Japan, "Anticipated social change in the future"

[2-9] Cabinet Office, "2030 Outlook and Reform Task Force Report"

[2-10] Cabinet Office, "The Council on Economic and Fiscal Policy proposed the action plan for the growth strategy."

[2-11] Thomas Picketty, "Avoiding the worst."

[2-12] Nihon Keizai Shimbun, "the future of society and the market changed by COVID-19,"

[2-13] Taku Sekine, https://goetheweb.jp/person/article/20200414-taku_sekine

[2-14] Kazuto Ataka, “"Future" brought about by depopulation”

[2-15] Rekimoto Junichi, https://lab.rekimoto.org/about/

[2-16] NTT, “NTT Technology Report for Smart World 2021,” July 2021.

[2-17] A. Itoh, “All-Photonics Network for Enabling Innovative Optical and Wireless Network (IOWN),” NTT technical review, vol. 18, no. 5, pp. 11-13, May 2020.

[2-18] J. Sawada, “Road to IOWN,” NTT technical review, vol. 19, no. 2, pp. 13-24, February 2021.

[2-19] A. Itoh, “Innovative Network for 2030 (Beyond 2020),” NTT technical review, vol.18, no. 3, pp 18-23, March 2020.

[2-20] T. Nakamura, “Digital Twin Computing Initiative,” NTT technical review, vol. 18, no. 9, pp.13-18, September 2020.

[3-1] Kishiyama, Nakamura, "Real and Future for 5G Evolution and 6G," MWE 2018 Workshop FR2A -1, November 2018.

[4-1] World Health Organization, "WHO remains firmly committed to the principles set out in the preamble to the Constitution," Available at: https://www.who.int/about/governance/constitution (Accessed: 8 October 2021)

[4-2] United Nations, "Sustainable Development Goals Goal3: Ensure healthy lives and promote well-being for all at all ages," Available at: https://www.un.org/sustainabledevelopment/health/ (Accessed: 8 October 2021)

[4-3] Udrone: The World's First Hands-Free Drone, http://www.eegsmart.com/en/home.html

[4-4] BrainRobotics AI Prosthetic Hand, https://brainco.tech/blog/2019/11/22/a-more-lifelike-prosthetic/

[4-5] Tech@FACEBOOK, “Imagining a new interface: Hands-free communication without saying a word”, https://tech.fb.com/imagining-a-new-interface-hands-free-communication-without-saying-a-word/

[4-6] N. Savage, "Technology: The taste of things to come," Nature 486, S 18 – S 19, June 2012. https://doi.org/10.1038/486S18a (Accessed: 8 October 2021)

[4-7] G. Marsh "‘Haptic skin’ creates virtual sense of touch," Nature Video, Nov. 2019 available at https://www.nature.com/articles/d41586-019-03596-z (Accessed: 8 October 2021)

[4-8] Kanouchi, Mizusawa, "New tests and important test items required by the practicing physician, Chapter 8 Neurological and Muscular Diseases" Journal of the Japanese Society of Internal Medicine, Vol. 97, No. 12, December 2008.

https://www.jstage.jst.go.jp/article/naika/97/12/97_2998/_pdf

[5-1] H.Q. Ngo, A. Ashikhmin, H. Yang, E.G. Larsson, and T.L. Marzetta, “Cell-free massive MIMO versus small cells,” IEEE Trans. Wirel. Commun., vol. 16, no. 3, Mar. 2017.

[5-2] O. Teyeb, A. Muhammad, G. Mildh, E. Dahlman, F. Barac, and B. Makki, “Integrated access backhauled networks,” IEEE VTC2019-Fall, Sept. 2019.

[5-3] Radio Stripes: re-thinking mobile networks https://www.ericsson.com/en/blog/2019/2/radio-stripes.

[5-4] Ito, Suga, Shirato, Kita, and Onizawa, “Efficiently Accommodating High frequency-band Wireless Systems by Using Analog Radio-over-fiber,” NTT technical review, vol. 18, no. 5, pp. 19-23, May 2020.

[5-5] Uchida, Iwakuni, Kita, Onizawa, Kishiyama, Suyama, Nagata, and Asai, "Distributed Antenna Systems using High-Frequency-Band targeting 6G Wireless Networks," IEICE Technical Report, RCS 2020-148, pp. 73-78, December 2020.

[5-6] NTT DOCOMO Press Releases, "Developed the world's first antenna that can construct a communication area by simply pinching a cable." January 2021. https://www.nttdocomo.co.jp/info/news_release/2021/01/20_00.html

[5-7] M.D. Renzo, et al., “Smart radio environments empowered by reconfigurable AI meta-surfaces: an idea whose time has come,” EURASIP Journal on Wireless Commun. and Networking 2019, no. 129, May 2019.

[5-8] M. Iwabuchi, T. Murakami, R. Ohmiya, T. Ogawa, Y. Takatori, Y. Kishiyama, and T. Asai, “Intelligent radio-wave design: distributed intelligent reflecting surface with direction-based control for millimeter-wave communications,” 2020 international conference on emerging technologies for communications (ICETC), Dec. 2020.

[5-9] NTT DOCOMO Press Releases, "Success with 5G Communications Using "Vehicle Glass Mounted Antenna" for 5G Connected Car," July 2018.

[5-10] NTT DOCOMO Press Releases, "DOCOMO, AGC and Ericsson Achieve World's First 5G Communication Using Glass Antenna for 28 GHz," May 2019.

[5-11] NTT DOCOMO Press Releases, "The world's first demonstration of a 28 GHz band 5G area expansion using a reflector to which metamaterial technology was applied was successfully conducted." December 2018.

[5-12] NTT DOCOMO Press Releases, "DOCOMO Conducts World's First Successful Trial of Transparent Dynamic Metasurface," January 2020.

[5-13] NTT DOCOMO Press Releases, "DOCOMO and AGC Use Metasurface Lens to Enhance Radio Signal Reception Indoors," January 2021. https://www.nttdocomo.co.jp/english/info/media_center/pr/2021/0126_00.html

[5-14] D. Kitayama, Y. Hama, K. Goto, K. Miyachi, T. Motegi, and O. Kagaya. ”Transparent dynamic metasurface for a visually impaired reconfigurable intelligent surface: controlling transmission/reflection and making a window into an RF lens,” Optics Express vol. 29, no. 18 pp 29292 -29307, 30 Aug 2021.

[5-15] M. Ji, G. Caire, and A. F. Molisch, “Wireless device-to-device caching networks: basic principles and system performance,” IEEE JSAC, vol. 34, no. 1, pp. 176-189, Jan. 2016.

[5-16] J. Liu, H. Liu, Y. Chen, Y. Wang, and C. Wang, “Wireless sensing for human activity: A survey,” IEEE Communications Surveys & Tutorials, vol. 22, no. 3, pp. 1629-1645, 2019.

[5-17] W. Liu, K. Huang, X. Zhou, S. Durrani, “Next generation backscatter communication: systems, techniques and applications,” in EURASIP Journal on Wireless Communications and Networking, Mar. 2019.

[5-18] Onizawa, Tatsuta, Kita, Yamashita, "Recent Research and Developments focusing on Fixed Wireless and Satellite Communication Systems," IEICE Technical Report, RCS 2019-32, pp. 53-58, May 2019.

[5-19] J. Bejarano, C. Nieto, and F. Piñar, “MF-TDMA scheduling algorithm for multi-spot beam satellite systems based on co-channel interference evaluation,” IEEE Access, vol. 7, pp. 4391-4399, Dec. 2018.

[5-20] B. Di, H. Zhang, L. Song, Y. Li, and G.Y. Li, “Ultra-dense LEO: integrating terrestrial-satellite networks into 5G and beyond for data offloading,” IEEE Transactions on Wireless Communications, vol. 18, pp. 47-62, Dec. 2018.

[5-21] HAPS Alliance, “Introducing the HAPS Alliance,” https://hapsalliance.org/

[5-22] 3GPP, RP-193234, “Solutions for NR to support non-terrestrial networks (NTN),” December 2019.

[5-23] FCC News Release, “FCC takes steps to open spectrum horizons for new services and technologies,” Mar. 2019.

[5-24] NTT DOCOMO Press Releases, "DOCOMO and Rohde & Schwarz Cooperate in Pioneering Beyond 5G with Frequency Bands up to 150 GHz," November 2018.

[5-25] T. S. Rappaport, “Wireless beyond 100 GHz: opportunities and challenges for 6G and beyond,” IEEE COMCAS Keynote, Nov. 2019.

[5-26] R. Piesiewicz, C. Jansen, S. Wietzke, D. Mittleman, M. Koch, and T. Kurner, "Properties of building and plastic materials in the THz range," Int. J. Infrared and Millimeter Waves, vol. 28, pp. 363-371, 2007.

[5-27] C. Jansen, S. Priebe, C. Moller, M. Jacob, H. Dierke, M. Koch, and T. Kurner, "Diffuse scattering from rough surfaces in THz communication channels," IEEE Trans. Terahertz Sci. Tech., vol. 1, no. 2, pp. 462-472, 2011.

[5-28] N. A. Abbasi, A. Hariharan, A. M. Nair, and A. F. Molisch, "Channel measurements and path loss modeling for indoor THz communication," in Proc. 14 th European Conf. Ant. Prop. (EuCAP 2020), Copenhagen, Denmark, 2020, pp. 1-5.

[5-29] Y. Xing, O. Kanhere, S. Ju, and T. S. Rappaport, "Indoor wireless channel properties at millimeter wave and sub-Terahertz frequencies," in Proc. 2019 IEEE Global Commun. Conf. (GLOBECOM ’19), pp. 1-6, 2019.

[5-30] M. Inomata, W. Yamada, N. Kuno, M. Sasaki, K. Kitao, M. Nakamura, H. Ishikawa and Y. Oda, "Terahertz Propagation Characteristics for 6G Mobile Communication Systems," in Proc. 15 th European Conf. Ant. Prop. (EuCAP 2021), Dusseldorf, Germany, pp. 1-5, Mar. 2021.

[5-31] M. Inomata, W. Yamada, N. Kuno, and M. Sasaki, “Path Loss Characteristics from 2 to 100 GHz Bands in Urban Microcell Environment for 6G,” IEICE Technical Report, vol. 121, no. 141, AP2021-51, pp. 19-24, August 2021.

[5-32] Ministry of Internal Affairs and Communications Press Release, "Results of the opinion solicitation for the basic plan (draft) of research and development for the expansion of radio wave resources to be newly implemented from FY 2021, and public solicitation of proposals," March 2021.
https://www.soumu.go.jp/menu_news/s-news/01kiban09_02000408.html

[5-33] S. Jacobsson, G. Durisi, M. Coldrey, and C. Studer, “Linear precoding with low-resolution DACs for massive MU-MIMO-OFDM downlink, " IEEE Trans. Wirel. Commun., vol. 18, no. 3, pp. 1595 -1609, Mar. 2019.

[5-34] Y.R. Ramadan, H. Minn, and M. E. Abdelgelil, "Precompensation and system parameters estimation for low-cost nonlinear tera-hertz transmitters in the presence of I/Q imbalance," IEEE access, vol. 6, 2018.

[5-35] Sawahashi, "Technical Issues of Physical Layer in Integrated Wireless Access and Backhaul Networks," IEICE Society Conference, BS 4-1, September 2018.

[5-36] Taromaru, "Outlook for Beyond 5G Digital Modulation - Will FFT-based Modulation and Demodulation Continue for the foreseeable future? -," IEICE Society Conference, BS 4-3, September 2018.

[5-37] I.P. Nasarre, T. Levanen, K. Pajukoski, A. Lehti, E. Tiirola, and M. Valkama, ”Enhanced uplink coverage for 5G NR: Frequency-domain spectral shaping with spectral extension, ” IEEE open journal of the Communications Society, vol. 2, 2021.

[5-38] S. Jacobsson, G. Durisi, M. Coldrey, T. Goldstein, and C. Studer, “Quantized precoding for massive MU-MIMO,” IEEE Trans. Commun., vol. 65, no. 11, pp. 4670-4684, Nov. 2017.

[5-39] H. Sasaki, D. Lee, H. Fukumoto, Y. Yagi, T. Kaho, H. Shiba, and T. Shimizu, “Experiment on over-100-Gbps wireless transmission with OAM-MIMO multiplexing system in 28-GHz band,” IEEE GLOBECOM2018, Dec. 2018.

[5-40] K. Ito, M. Suga, Y. Shirato, N. Kita, and T. Onizawa, "Experimental Evaluation of Remote Beamforming Scheme with Fixed Wavelength Allocation for Radio-over-Fiber Systems," Proc of ECOC 2020, 2020.

[5-41] M. Giordani, M. Polese, A. Roy, D. Castor and M. Zorzi, "A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies," in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 173-196, 2019.

[5-42] J. Lin and W. An, "A New Initial Beam Search Scheme in 5G New Radio", IEEE EITCE, 18 -20 Oct. 2019.

[5-43] S. Kadambar, A. Goyal, A. Kumarr Reddy Chava, "Millimeter Wave Multi-Beam Combining Algorithm for Efficient 5G Cell Search", IEEE 17th CCNC, 2020.

[5-44] H. Kim, J. Jung, S. Han, S. Kim, S. Baek, and S. Choi, "Low Complexity Beam Searching Algorithm Using Asymptomatic Property of Massive MIMO Systems", IEEE 10th ICUFN, 2018.

[5-45] S. Noh, J. Song and Y. Sung, “Fast Beam Search and Refinement for Millimeter-Wave Massive MIMO Based on Two-level Phased Arrays, ” IEEE Trans. Wirel. Commun., vol. 19, NO. 10, pp 6737-6751, Oct. 2020.

[5-46] M. Giordani, M. Mezzavilla and M. Zorzi, "Initial Access in 5G mmWave Cellular Networks," in IEEE Communications Magazine, vol. 54, no. 11, pp. 40-47, Nov. 2016.

[5-47] I. Filippini, V. Sciancalepore, F. Devoti and A. Capone, "Fast Cell Discovery in mm - Wave 5G Networks with Context Information," in IEEE Trans. on Mobile Computing, vol. 17, no. 7, pp. 1538-1552, Julie. 2018.

[5-48] W. Juncheng, C. Yawen, L. Zhaoming, W. Xiangming, and W. Zifan, "A Low-complexity Beam Searching Method for Fast Handover in MmWave Vehicular Networks", IEEE WCNCW, 2019.

[5-49] T. Iwakuni, D. Uchida, S. Wai, and N. Kita, "Millimeter - Wave Handover Experiment in 293 km/h Mobility Environment using Position Estimated from Wireless Communication Signal", IEEE 94 th VTC, 27th Sep. -28th Oct., 2021.

[5-50] H. Q. Ngo, L. Tran, T. Q. Duong, M. Matthaiou and E. G. Larsson, "On the Total Energy Efficiency of Cell-Free Massive MIMO," IEEE Trans. on Green Communications and Networking, vol. 2, no. 1, pp. 25-39, March 2018.

[5-51] E. Björnson and L. Sanguinetti, "Scalable Cell-Free Massive MIMO Systems," in IEEE Trans. on Commun, vol. 68, no. 7, pp. 4247-4261, Julie 2020.

[5-52] M. Yuhas, Y. Feng, and J. Bajcsy, “On the capacity of faster-than-Nyquist MIMO transmission with CSI at the receiver,” IEEE Globecom Workshops, Dec. 2015.

[5-53] J. A. Lucciardi, N. Thomas, M. L. Boucheret, C. Poulliat, and G. Mesnager, “Trade-off between spectral efficiency increase and PAPR reduction when using FTN signaling: Impact of non linearities,” IEEE ICC2016, May 2016.

[5-54] Murakami, Omiya, Nakahira, Ishihara, Hayashi, "Proposal of Virtual Massive MIMO (VM-MIMO)," IEICE General Conference, B-1-123, March 2019.

[5-55] NTT DOCOMO, "Study on Full duplex for NR," 3 GPP TSG RAN Rel -18 workshop, RWS -210274, Jun. 2021.

[5-56] H. Ji, Y. Kim, K. Muhammad, C. Tarver, M. Tonnemacher, T. Kim, J. Oh, B. Yu, G. Xu, and J. Lee, "Extending 5G TDD coverage with XDD: Cross division duplex," IEEE Access, vol. 9, pp. 51380-51392, Apr. 2021.

[5-57] 5G-ACIA, https://www.5g-acia.org/

[5-58] N. Shibata, P. Zhu, K. Nishimura, Y. Yoshida, K. Hayashi, M. Hirota, R. Harada, K. Honda, S. Kaneko, J. Terada, and K. Kitayama, “First demonstration of autonomous TSN-based beyond-best-effort networking for 5G NR fronthauls and 1,000+ massive IoT traffic,” ECOC2020, Th3B.3, Dec. 2020.

[5-59] T. Murakami, M. Miyazaki, S. Ishida, and A. Fukuda, “Wireless LAN based CSI monitoring system for object detection,” MDPI Electronics, vol.7 (11), no.290, Nov. 2018.

[5-60] T. Murakami, S. Otsuki, T. Hayashi, Y. Takatori, and K Kitamura, “Wildlife detection system using wireless LAN signals,” NTT technical review, vol. 17, no. 6, pp. 45-48, Jun. 2019.

[5-61] N. Zhao, S. Zhang, F. R. Yu, Y. Chen, A. Nallanathan, and V. C. M. Leung, “Exploiting interference for energy harvesting: a survey, research issues, and challenges,” IEEE Access, vol. 5, pp. 10403-10421, May 2017.

[5-62] N. Ye, X. Li, H. Yu, L. Zhao, W. Liu, and X. Hou, “DeepNOMA: a unified framework for NOMA using deep multi-task learning,” IEEE Trans. Wirel. Commun., vol. 19, no. 4, pp. 2208-2225, April 2020.

[5-63] N. Ye, X. Li, H. Yu, A. Wang, W. Liu, and X. Hou, “Deep learning aided grant-free NOMA toward reliable low-latency access in tactile internet of things,” IEEE Trans. Industrial Informatics, vol. 15, no. 5, pp. 2995-3005, May 2019.
[5-64] T. Wang, C. K. Wen, S. Jin, and G. Y. Li, “Deep learning-based CSI feedback approach for time-varying massive MIMO channels,” IEEE Wirel. Commun. Lett., vol. 8, no. 2, pp. 416-419, 2019.
[5-65] Kitao, "Mobile Propagation Study — Evolving Propagation Models and Simulations —" The Journal of IEICE, vol. 99, no. 8, pp. 820-825, August 2016.
[5-66] Wakao, Kawamura, and Moriyama, "Quality-prediction Technology for Optimal Use of Multiple Wireless Access Networks," NTT technical review, vol. 18, no. 6, pp. 17-20, June 2020.
[5-67] Arai, Goto, Iwabuchi, Iwakuni, and Maruta "AMAP: Adaptive Movable Access Point System for Offloading Efficiency Enhancement," IEICE Technical Report, RCS 2016-43, pp. 107-112, May 2016.
[5-68] M. Khalighi and M. Uysal, “Survey on free space optical communication: A communication theory perspective,” IEEE Commun. Surveys Tuts., vol. 16, no. 4, pp. 2231–2258, 4th Quart. 2014.
[5-69] Y. Hasegawa, T. Ito, Y. Ono, and M. Arikawa, “A Throughput Model of TCP-FSO/ADFR for Free-Space Optical Satellite Communications,” IEEE GLOBECOM, pp. 1-6, 2019.
[5-70] Japan Agency for Marine-Earth Science and Technology, National Research and Development Agency, "Research on adaptive underwater optical wireless communication using a photomultiplier tube," Defense Equipment Agency Security Technology Promotion System Result Report, May 2018.
[5-71] Fujino, Fukumoto, Nakano, Tsubaki, and Sakamoto, "Challenge to Mbps-class high-speed acoustic communication for wireless remote operation of underwater vehicle," IEICE Technical Report, RCS 2019-232, pp. 163-168, November 2019.
[5-72] H. Fukumoto, Y. Fujino, M. Nakano, K. Sakamoto, and T. Tsubaki, "Field Experiments Demonstrating MB-Class Underwater Acoustic Communication with Spatio-Temporal Equalization," IEEE OCEANS 2020, Oct. 2020.
[5-73] Harada, Murayama, and Nagata, "3GPP study on 5G NR based access to unlicensed spectrum," IEICE Technical Report, SRW 2018-70, pp. 61-65, March 2019.
[5-74] A. Singla, “The birth of the distributed Cloud,” The Next Platform, online [available at: https://www.nextplatform.com/2020/02/25/the-birth-of-the-distributed-cloud/, last access: 28.10.21].
[5-75] A. Sahai, "Distributed Cloud is The Way Of The Future – What This Means For Your Business", Forbes, online [available at: https://www.forbes.com/sites/forbestechcouncil/2021/06/21/distributed-cloud-is-the-way-of-the-future--what-this-means-for-your-business/, last access: 29.10.21]
[5-76] IOWN GLOBAL FORUM, "IOWN GF System and Technology Outlook - Open All-Photonic Network (APN) and Data-Centric Infrastructure (DCI) Work Items -," 2021.
[5-77] A. Wiggins, "The Twelve-Factor App", online, [available at: https://12factor.net/, last access: 28.10.21]
[5-78] CNCF, "Cloud Native Principles", online [available at: http://cloud-native-principles.org/, last access: 28.10.21].
[5-79] GSMA, "Operator Platform Concept: Phase 1: Edge Cloud Computing", January 2020.
[5-80] A. Minokuchi, S. Isobe, “5G Core Network Standardization Trends,” in NTT DOCOMO Technical Journal Vol. 19.3. On-line: https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/rd/technical_journal/bn/vol19_3/vol19_3_006en.pdf
[5-81] https://www.etsi.org/technologies/nfv
[5-82] https://www.o-ran.org/
[5-83] Kawahara, Seki, Suda, Nakagawa, Maeda, Mochida, Tsukishima, Shirai, Yamaguchi, Ishizuka, Kaneko, Koshiji, Honda, Kanai, Hara, and Kaneko, “Optical Full-mesh Network Technologies Supporting the All-Photonics Network,” NTT technical review, vol. 18, no. 5, pp. 24-29, May 2020.

[5-84] H. Nakamura, “Optical access system technology for Beyond 5G”, Optical and electro-optical engineering contact, Vol. 57, No. 10, pp. 19-24, 2019.

[5-85] A. A. Atallah, G. B. Hamad, and O. A. Mohamed, "Fault-resilient topology planning and traffic configuration for IEEE 802.1 Qbv TSN networks," in IOLTS. IEEE, 2018, pp. 151-156.

[5-86] Gagan Nandha Kumar, "Failure Handling for Time-Sensitive Networks using SDN and Source Routing", IEEE Netsoft 2021

[5-87] Apple Platform Security, “Secure enclave”, https://support.apple.com/guide/security/secure-enclave-sec59b0b31ff/web

[5-88] Trusted Connectivity Alliance, "Integrated SIM Functionality: Drivers, Approaches to Standardization and Use Cases", white paper, May 2021.

[5-89] GSMA, "iSIM and IoT SAFE: Why they ’ re perfect partners for IoT security", https://www.gsma.com/iot/resources/isim-and-iot-safe-why-theyre-perfect-partners-for-iot-security/

[5-90] Mishina, Hamada and Ikarashi, "Realization of Practical Secure Deep Learning," Computer Security Symposium 2019, October 2019.

[5-91] Abe, Tokunaga, Mehdi, Nishimaki, and xakawa, "Cutting-edge Research on Cryptography Theory in Response to Changes in Computing Environments," NTT technical review, vol. 18, no. 4, pp. 22-26, April 2020.