White Paper

5G Evolution and 6G

NTT DOCOMO, INC.

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1. Introduction

Since the Nippon Telegraph and Telephone Public Corporation (NTT) initiated the world’s first cellular mobile communication service in December 1979, the technology of mobile communications has continued to develop every decade, evolving to new generation systems. With the progress of technology, services have continued to evolve. From the first generation (1G) to the second generation (2G), voice calls were the main means of communication, and simple e-mail was possible. However, from the third generation (3G), data communications such as “i-mode” and multimedia information such as photos, music, and video could be communicated using mobile devices. From the fourth generation (4G), smartphones have been explosively popularized by high-speed communication technology exceeding 100 Mbps using the Long Term Evolution (LTE), and a wide variety of multimedia communication services have appeared. 4G technology continues to evolve in the form of LTE-Advanced, and has now reached a maximum communication speed close to 1 Gbps. NTT DOCOMO plans to initiate services based on the fifth generation (5G) mobile communication system [1-1], which is a more technologically advanced system, in the spring of 2020.

5G is expected to provide new value as a basic technology supporting future industry and society, along with artificial intelligence (AI) and the Internet of Things (IoT), as well as further upgrading of the multimedia communication services with its technical features such as high speed, high capacity, low latency, and massive connectivity. As shown in Fig. 1-1, the mobile communication system has been evolving technically every decade, while the services of mobile communications have changed greatly in cycles of approximately 20 years. Therefore, the “Third Wave” initiated by 5G is expected to become a larger wave through 5G evolution and the sixth generation (6G) technology, and will support industry and society in the 2030s.

This white paper describes NTT DOCOMO’s current technical prospects for 5G evolution and 6G. Chapter 2 discusses the direction of future technological evolution from the viewpoints of 5G evolution and 6G. Chapter 3 describes the requirements and use cases, and Chapter 4 describes the prospects of technical research areas. This white paper describes the current thinking (as of January 2020). Based on this content, we will promote discussions in various industries in a joint industry-academia-government approach, and update the content.

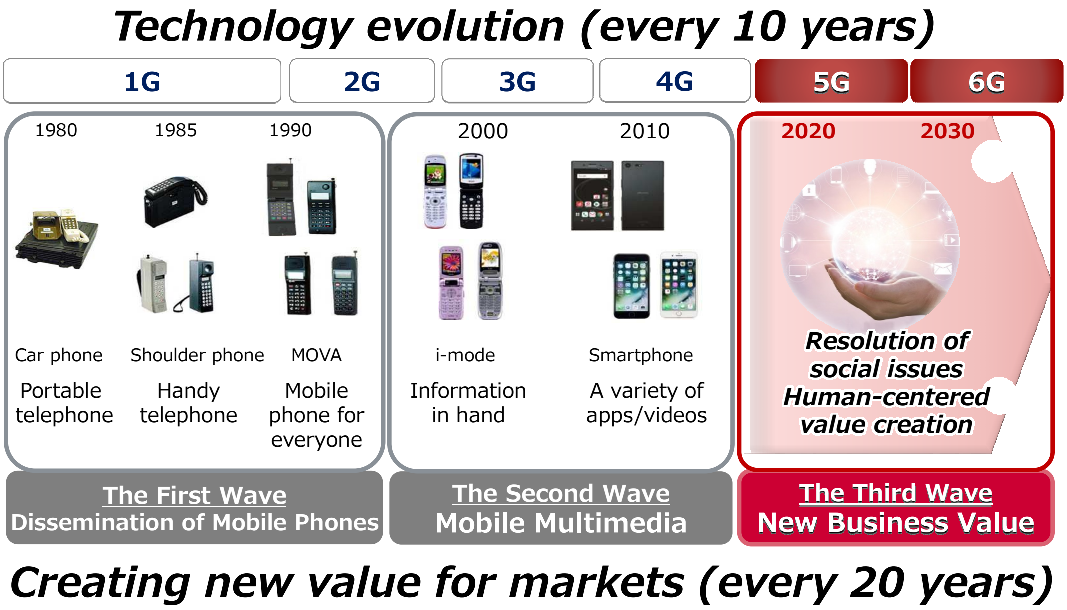

Figure 1-1. Evolution of technologies and services in mobile communications

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

2.1. Considerations for 5G evolution

The commercial introduction of 5G has already begun worldwide. NTT DOCOMO started 5G pre-service in September 2019 and is scheduled to start 5G commercial service in the spring of 2020. However, some technical issues and further expectations that need to be actualized in 5G have already been found, and further technological enhancements in the form of 5G evolution are necessary as we head into the 2020s.

Figure 2-1 shows the current technical challenges facing 5G. 5G is the first generation mobile communication system that supports high frequency bands such as the millimeter wave band that exceeds 10 GHz, and it is a technology that actualizes ultra-high speed wireless data communications of several gigabits per second using a frequency bandwidth of several-hundred megahertz, which is remarkably wider than that achieved previously. However, there is much room for future enhancement in millimeter wave technology in mobile communications. In particular, improving the coverage and uplink performance in non-line-of-sight (NLOS) environments are issues that can be discerned from 5G-related trials.

5G has attracted much attention as a technology that supports future industry and society, and special requirements and high performance in particular are often required in industrial use cases. In Japan, the discussion of “Local 5G,” which specializes in industry use cases, is on-going and it is a topic of interest in industry [2-1]. In the future, further enhancement of 5G technology will be necessary to correspond flexibly to such wide requirements in industrial use cases.

In the initial 5G, i.e., NR Release 15, 3GPP standardized radio technologies focused on enhanced mobile broadband (eMBB) and a part of ultra-reliable and low latency communications (URLLC). As with LTE, best-effort services focusing on downlink data rates were mainly actualized. In the case of 5G evolution, as shown in Fig. 2-2, a direction to promote a highly reliable radio technology for industrial applications is considered while improving the uplink performance. In particular, there are some industry cases in which the uploading of a large amount of image data is assumed and a guaranteed data rate is required in a service, and the uplink enhancements and technology to guarantee performance are more important than the communication service for general users.

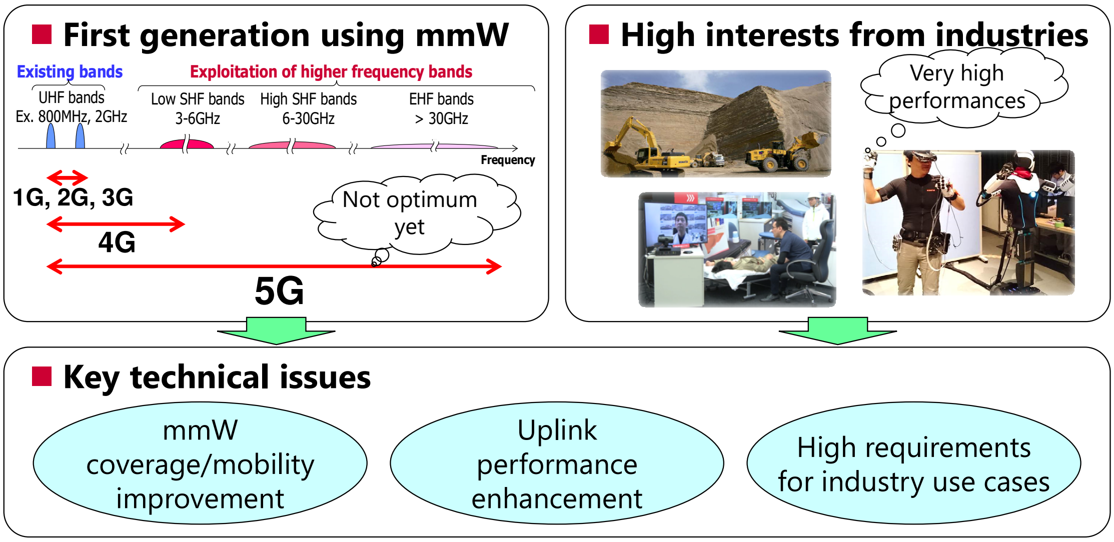

Figure 2-1. Technical challenges on 5G real issues

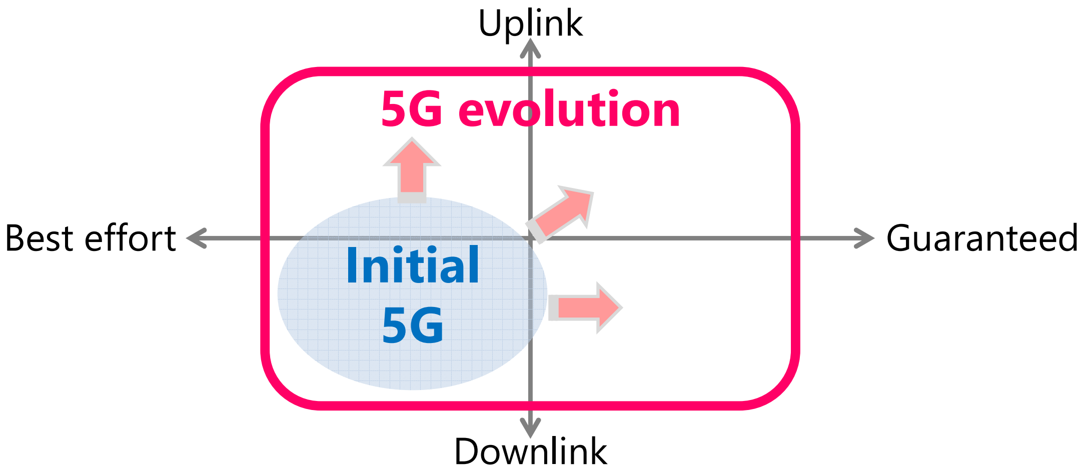

Figure 2-2. Direction of performance improvement to 5G evolution

At present, with the popularization of big data and AI, the interest in cyber-physical fusion has become heightened [2-2]. As shown in Fig. 2-3, AI reproduces the real world in cyberspace and emulates it beyond the constraints of the real world, so that “future prediction” and “new knowledge” can be discovered. Various values and solutions such as the solution to social problems can be offered by utilizing this in services in the real world. The role of wireless communications in this cyber-physical fusion is assumed to include high capacity and low latency transmission of real world images and sensing information, and feedback to the real world through high reliability and low latency control signaling. When considering a human analogy, radio communications in the cyber-physical fusion corresponds to the role of the nervous system that transmits information between the brain, i.e., AI, and each organ, i.e., device, such as the eyes and limbs. Thus, it is easy to imagine that the quantity of information entering the brain, which corresponds to the uplink, overwhelmingly increases. Therefore, the direction of performance improvement shown in Fig. 2-2 is considered to be applicable to this case.

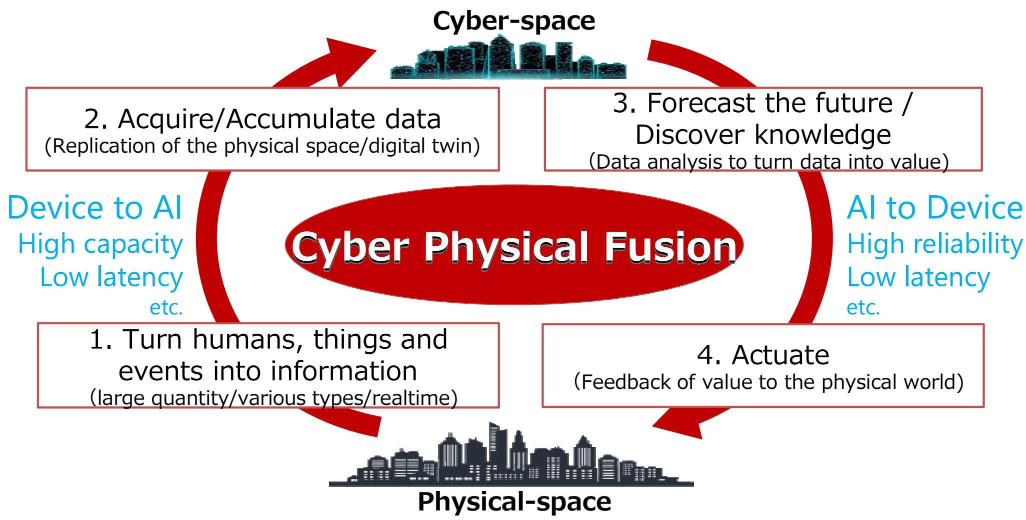

Figure 2-3. Cyber-physical fusion and wireless communications

2.2. Considerations for 6G

In order to examine requirements, we must investigate 6G use cases, technological evolution, society, and the worldview in the 2030s when 6G will be introduced. The use cases and problem solutions expected in 5G will mostly be actualized in the 2020s and expand from there. It is considered that wider and deeper diffusion will be required as a type of further development in the 2030s. In addition, there will be the need for more advanced services, integration of multiple use cases, and new use cases along with the acceleration of signal processing and the evolution of various devices. Below are some specific views of the world.

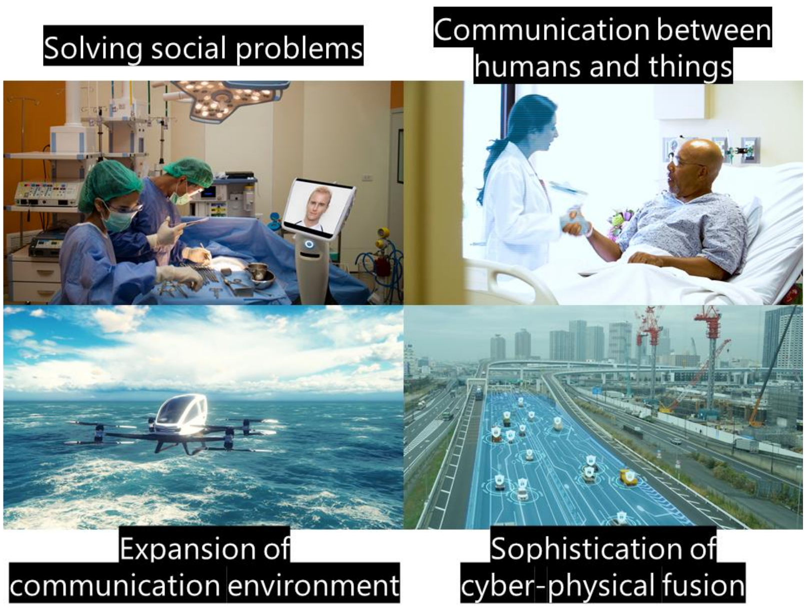

Figure 2-4. Image of the worldview in 6G era

- Solving social problems

Many social issues and needs expected in 5G will be resolved in the 2020s. It is expected that various solutions such as telework, remote control, telemedicine, distance education, and autonomous operation of various equipment including cars will be provided by high-speed and low-latency communication networks for social problems such as regional creation, low birth rate, aging, and labor shortage in the 2020s. Further popularization of solutions and more advanced correspondence in the 2030s will require complete problem solving and development. The world is expected to become a place in which all people, information, and goods can be accessed anywhere in an ultra-real experience, and the constraints of working place and time are completely eliminated. This will dramatically eliminate social and cultural disparities between rural and urban areas, avoid urban concentration of people, and promote local development. It can also make people's lives more stress-free.

- Communication between humans and things

Advanced functions of wearable devices including XR (VR, AR, MR) devices, high definition images and holograms exceeding 8K, and new five sense communications including tactile sense will proliferate, and communications between humans and between humans and things will become ultra-real and rich. As a result, innovative entertainment services and enterprise services for games, watching sports, etc. will be provided without time and place restrictions.
Through rapid popularization and development of IoT services, the demand for the communications of things will become very large. High speed and low latency performance that far exceed the human ability will be required for communications because large data processing including high-definition images and control of equipment with ultra-low latency will be carried out by machines.

- Expansion of communication environment

Communications are now as ubiquitous as the air around us and as vital as electricity and water. Therefore, users do not need to be aware of communication settings and the communication service area. A communication environment will be required in all places with the expansion of the activity area of people and things. High-rise buildings, drones, flying cars, airplanes, and even space will be natural activity areas, and not only the ground but also the sky and space will be indispensable communication areas. The need is increasing for communication areas at sea and under the sea. Due to the needs of various sensor networks, unmanned factories, and unmanned construction sites, it is also necessary to construct a communication area in an environment without human beings. As a result, every place on the ground, sky, and sea will become a communication area.

- Sophistication of cyber-physical fusion

Many services utilizing cyber-physical fusion will be created in the 2020s and will be used practically in all environments, but more advanced cyber-physical fusion will be required in the 2030s. By transmitting and processing a large amount of information between cyberspace and physical space without delay, tighter cooperation between both spaces will be achieved, and ultimately, fusion without a gap between the spaces will be actualized. For humans, it will become possible for cyberspace to support human thought and action in real time through wearable devices and micro- devices mounted on the human body. All kinds of things such as transportation equipment including cars, construction machinery, machine tools, monitoring cameras, and various sensors will be linked in cyberspace. They will support safety and security, solutions to social problems, and a rich life for people.

Figure 2-5 shows an image of the technological development toward 6G to actualize the above concept. In the future, there will be use cases that require extreme performance that even 5G cannot achieve, as well as new combinations of requirements that do not fall into the three categories of 5G: eMBB, URLLC, and massive machine type communication (mMTC).

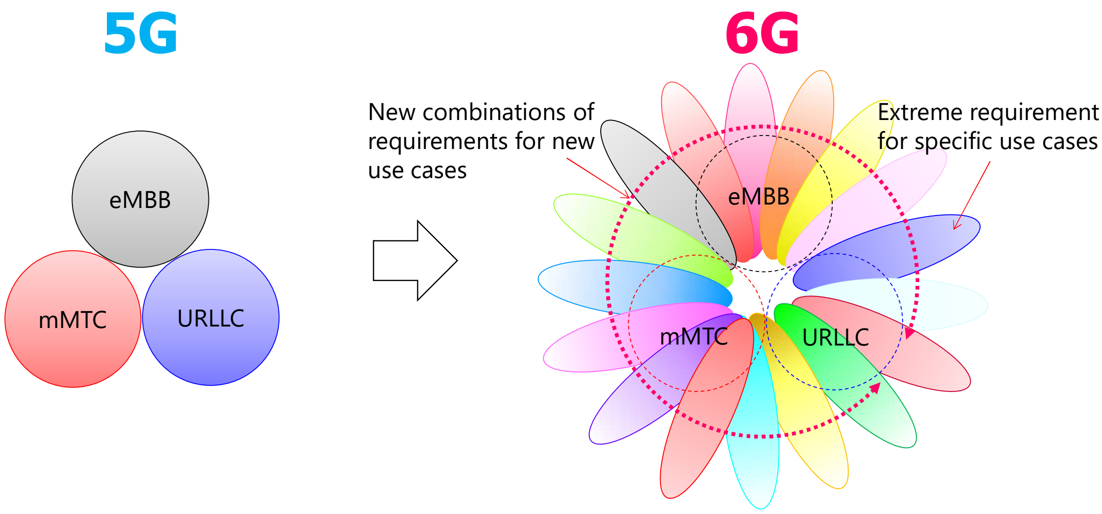

Figure 2-5. Image of technological development toward 6G

3. Requirements and Use Cases

Figure 3-1 shows the requirements for wireless technology to be actualized by 6G through 5G evolution [3-1]. In addition to the higher requirements of 5G, new requirements that were not considered in 5G have been added, and they have been expanded more widely. Moreover, as with 5G, not all requirements need to be met at the same time, but new combinations of requirements will be required for the future new use cases. The requirements are outlined below with use cases.

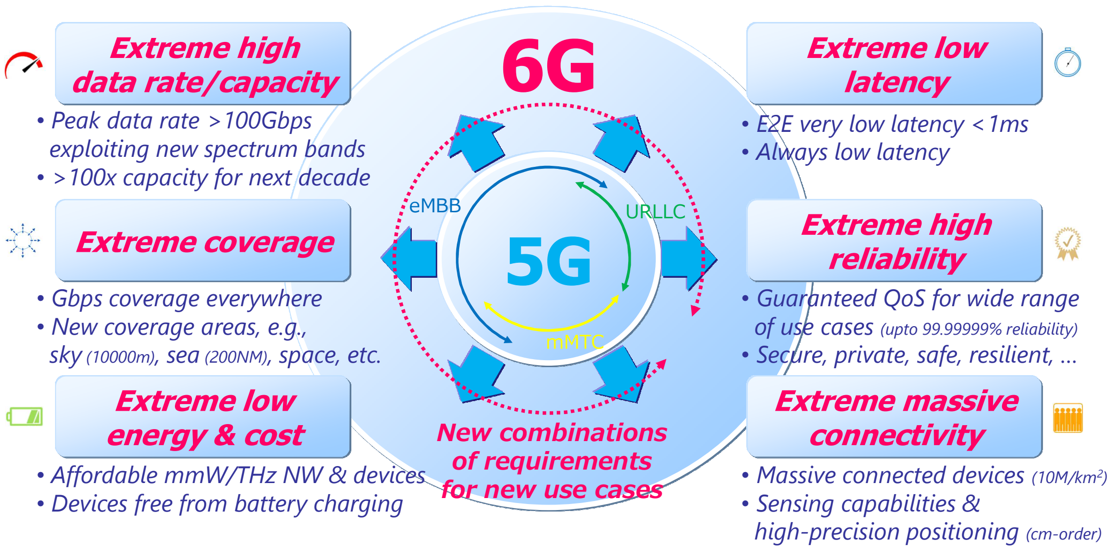

Figure 3-1. Requirements for 6G wireless technology

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

Through further improvements in communication speed, for example, by wireless technology with extremely high speeds exceeding 100 Gbps, it is considered that new sensory services equal to or exceeding actual sensory quality can be actualized. It is anticipated that the user interface that actualizes such a service will evolve as a wearable device through the evolution of glasses-type terminals. Such new experience services will be shared among multiple users in real time, and new synchronized applications such as virtual experience and virtual collaboration in cyberspace can be expected. In addition, considering trends such as use cases for industry and cyber-physical fusion, various types of real-time information will be required to be transmitted to the cloud and AI, which are "brains," so improvement in the uplink performance becomes more important.

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

3.2. Extreme coverage extension

In the future, we will aim to develop "extreme coverage extension" that can be used in all kinds of places, including the sky, sea, and space, which are not covered by current mobile communication systems. Through this, further expansion of activity environments for humans and machines and the creation of new industries are expected. This expansion is also expected to be applied to future use cases such as flying cars and space travel.

Figure 3-3.　Extreme coverage extension

3.3. Extreme-low power consumption and cost reduction

As with 5G, low power consumption and cost reduction for network and terminal devices will be important requirements in 6G from both business and environmental viewpoints. In the future including 6G, a world in which devices do not need to be charged by, for example, the development of power supply technology using radio signals is also expected.

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

3.4. **Extreme-low latency**

In cyber-physical fusion, wireless communications that connect AI and devices is analogous to the human nervous system which transmits information. In order to actualize services in real-time and be highly interactive, an always stable end-to-end (E2E) low latency seems to be a basic requirement. For 6G, concretely, an approximately 1 ms or less E2E latency is considered as the target value. With this, for example, in a shop automated by robotics, interactive services that respond attentively similar to a human by watching the facial expression of a customer may be actualized.

Figure 3-5. Extreme-low latency

3.5. **Extreme-reliable communication**

As described in the previous chapter, 5G evolution and 6G are expected to trend toward requiring not only best-effort communication but also quality assurance communication. Wirelessly communicating highly reliable control information is an important requirement for many industrial use cases such as remote control and factory automation, and 6G is expected to achieve higher levels of reliability and security than 5G. With the popularization of robots and drones and the expansion of radio coverage to the sky, etc., there is a possibility that highly-reliable communications in not only limited areas such as factories but also wider areas will be required, and actualization of highly-reliable communications in various scenes is also expected.

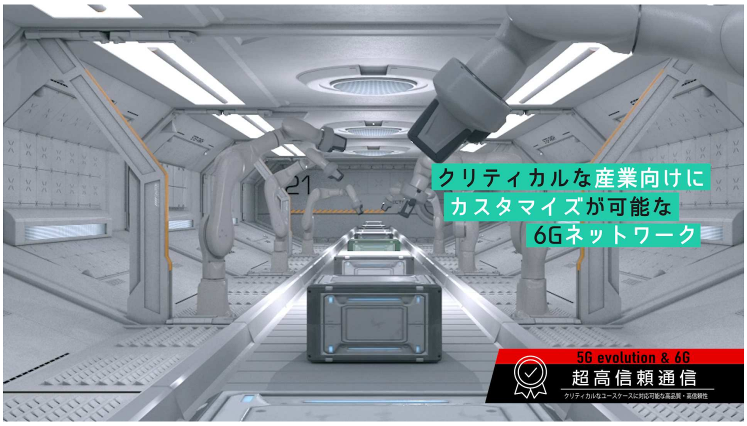

Figure 3-6.　Extreme-reliable communication

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

Wearable user devices and an extremely large number of IoT devices that collect images and sensing information of the real world are expected to spread further in the 6G era, and an extremely large number of connections that are approximately 10 fold (= 10 million devices per square km) more than the 5G requirements are expected. In addition to the approach of connecting a large number of IoT devices to a network, the wireless communication network itself is expected to evolve to have functions for sensing the real world such as positioning and object detection using radio waves. In particular, the study of positioning has already advanced for 5G evolution, and it is expected that ultra-high-precise positioning with the error of several centimeters or less can be achieved in some environments.

Figure 3-7.　Extreme-massive connectivity & sensing

4. Technological Study Areas

Figure 4-1 shows an image of technological evolution from the past mobile communication generations to 6G. In the previous generations, there was one representative technology in each generation. However, since 4G, radio access technology (RAT) has comprised a combination of multiple new technologies based on orthogonal frequency-division multiplexing (OFDM), and in 6G, technical fields are thought to become more diversified. This is because the communications quality close to the Shannon limit has already been achieved by technology based on OFDM, and at the same time, requirements and use cases will be further expanded as described in the previous chapter.

Therefore, in 6G, high-level requirements as described in the preceding chapter will be satisfied through a combination of many technologies. Additionally, the definition of 6G RAT also needs to be clarified. The technical fields considered as candidates for 5G evolution and 6G are outlined below.

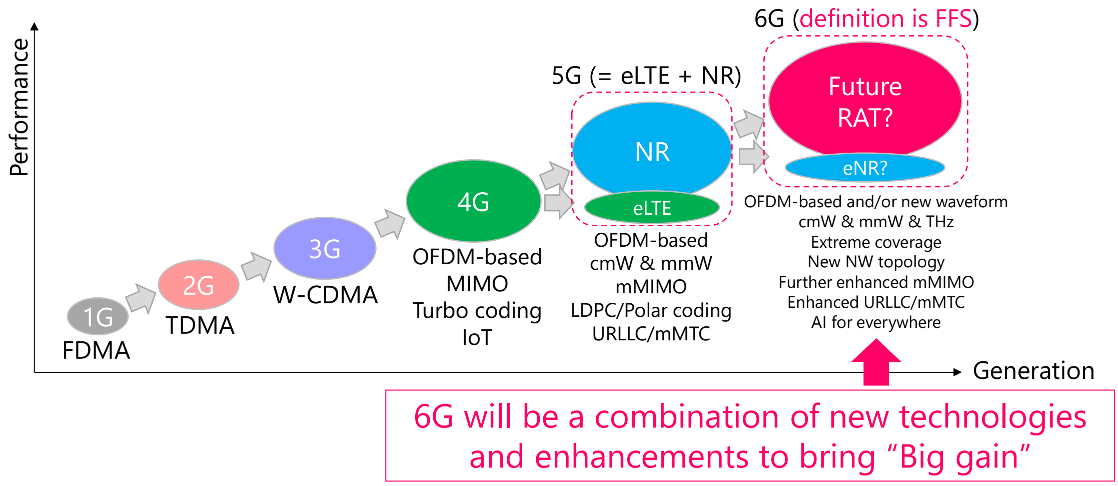

Figure 4-1. Technological evolution up to 6G in mobile communications

4.1. New network topology

When ultra-high speed, high capacity (especially uplink), and improvement in the reliability of wireless communications are pursued, it is ideal to communicate at as close a distance and in an unobstructed environment (low-loss path) as possible, and to generate as many communication paths as possible to increase path selection candidates (increase redundancy). To achieve this, a network topology that is distributed in the space domain is required. In the previous generation, it was considered ideal to construct a cellular network with hexagonal cells so that the cells do not interfere with each other; however, in order to increase the path selection, a topology of spatially non-orthogonal distributed networks will be pursued by abandoning the concept of cells as shown in Fig. 4-2. The topology of such a distributed network is considered to be familiar with the development of high frequency bands, wireless sensing, and wireless power supply.

On the other hand, according to conventional common sense, this new network topology is not a good network configuration because inter-cell interference occurs and many redundant antennas are installed. It seems that interference can be technically avoided by beam control and path selection, but the fundamental problem of how to achieve this at low cost remains. Various approaches are considered, but the solution will be one that does not use conventional base station antennas.

There are various investigations such as using glass antennas [4-1, 4-2], reflectors [4-3], integration of sensors and communication antennas, cooperation between terminals [4-4], terminal-like base stations, a new optical fiber distribution and optical transmission technology that enables the distributed network topology, extension of front-haul and back-haul technology including integrated access and backhaul (IAB) [4-5], and an uplink-only-receiving node. In order to make the new network topology function more efficiently and effectively, topology management and control technology using AI, etc. will be an important element. Furthermore, considering a network topology that utilizes these in combination with a conventional cellular composition seems to be necessary.

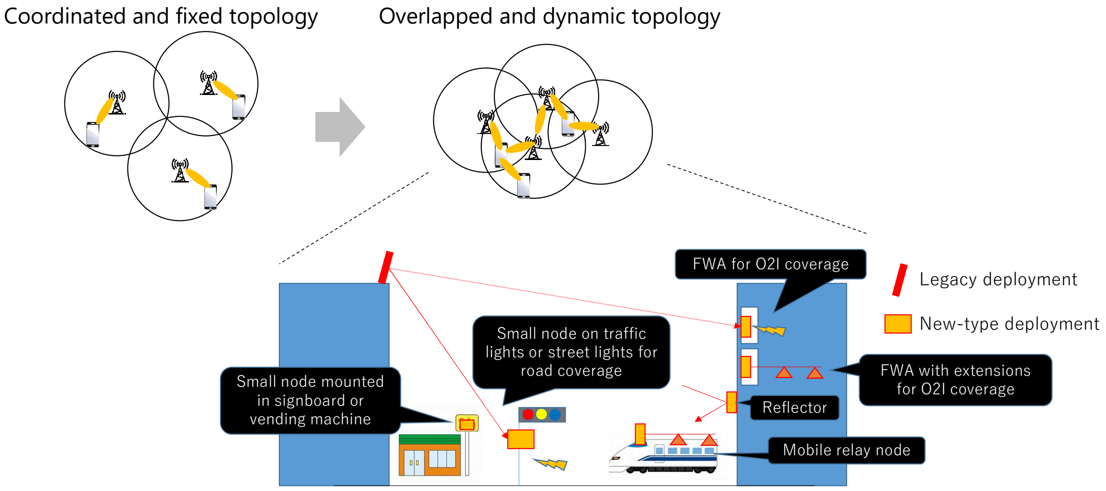

Figure 4-2. Concept of new network topology

4.2. Coverage extension including non-terrestrial network

Coverage extension technology is required in order to provide services for drones, flying cars, ships, and space stations, since their service areas such as the sky, sea, and space are not fully covered by conventional cellular networks. Therefore, new network topologies should be examined three-dimensionally including the vertical direction. In addition, a technology that achieves long distance wireless transmission over several tens of kilometers is considered to be necessary mainly on the assumption of the wireless backhaul and IAB application.

In super coverage extension, by considering the utilization of geostationary satellites (GEO), low earth orbit satellites (LEO), and high altitude pseudo satellites (HAPS), it becomes possible to cover mountainous and remote areas, sea, and space, and to provide communication services to new areas [4-6]. In particular, HAPS has attracted attention again recently because it can be stationed at a fixed location at an altitude of approximately 20 km, and can form a wide coverage area with a cell radius of greater than 50 km on land. As shown in Fig. 4-3, in addition to the broad coverage mentioned above, HAPS has the advantages of providing a backhaul to portable base stations in a timely and simple manner, and of securing independence from land-based communication networks (public networks). HAPS is considered to be effective not only as a disaster countermeasure but also for many industry use cases expected in 5G evolution and 6G.

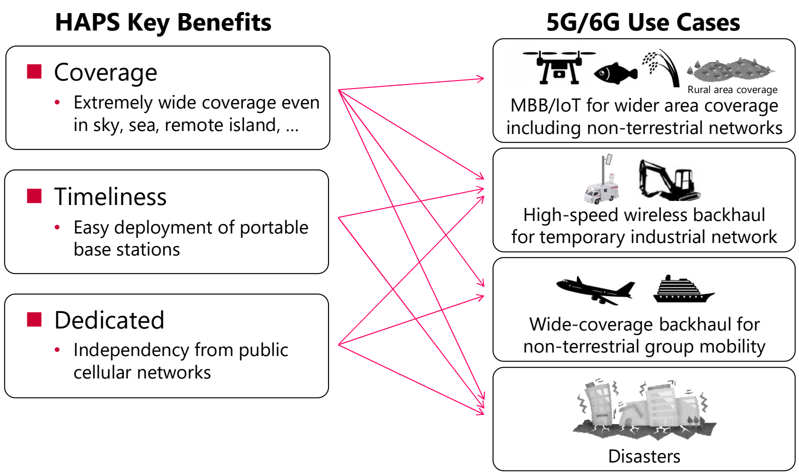

Figure 4-3. HAPS benefits and use cases

4.3. **Frequency extension and improved spectrum utilization**

In 5G NR, frequency bands up to 52.6 GHz are supported, and extension to approximately 100 GHz is examined for future release. In addition, the U.S. FCC recommends that frequencies higher than 5G, such as 95 GHz to 3 THz, be considered for 6G [4-7]. In such high frequency bands from the upper part of the millimeter wave band to the "terahertz wave" band, a remarkably wide frequency bandwidth can be utilized even in comparison to 5G, and is under investigation to achieve extreme high data rates exceeding 100 Gbps [4-8, 4-9]. At present, as shown in Fig. 4-4, we assume that radio waves up to approximately 300 GHz are considered in the examination range for 6G. However, "terahertz waves" have the problem in that the radio wave rectilinear property is higher than that for the millimeter wave and do not propagate far. Technological examination such as advance in Radio Frequency (RF) device technology and utilization based on the above-mentioned new network topology is necessary.

Fig. 4-4 shows the concept of wireless access technology that takes into account the development of such high-frequency bands and the aforementioned coverage extension including the sky, sea, and space. Although these are different directions of development, there are common technical problems in the sense that coverage and power efficiency become more important than the spectrum efficiency. As for radio technology, the signal waveform of a single carrier becomes dominant compared with OFDM, and as the application area for radio technology is expanded including IAB in the future, the importance of radio technology such as in terms of a power efficient single carrier may increase [4-10, 4-11].

In addition, when new frequency bands such as the millimeter wave and terahertz wave bands are added to the existing frequency band, very wide frequency bands will be utilized in comparison to the past. Therefore, there seem to be many related study fields such as optimizing the selected application of multiple bands according to the application, reexamining the frequency reuse method between cells, upgrading the duplexing method in the uplink and downlink, and reexamining the utilization method of the low frequency band.

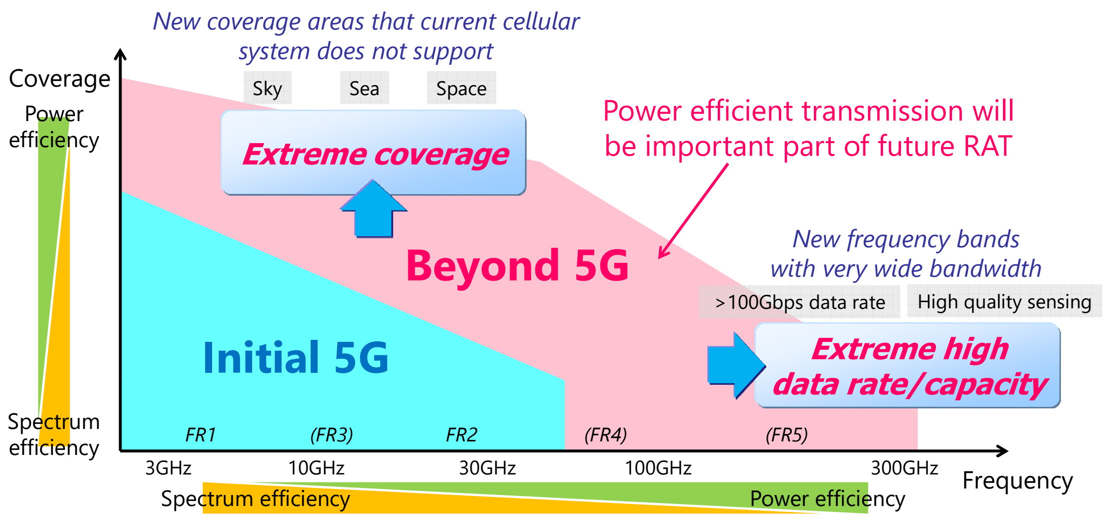

Figure 4-4. Expansion of radio access technology for exploiting new frequency and coverage

4.4. **Further advancement of wireless transmission technologies**

In 5G, massive MIMO (mMIMO) technology using multiple antenna elements was one of the keys, especially as a technology to utilize millimeter waves effectively [1-1]. In 5G evolution and 6G, further advancement is expected such as mMIMO with more antenna elements, more layers for spatial multiplexing [4-12], and distributed antenna arrangement combined with new network topology.

In regard to the radio access technology almost reaching the Shannon limit in the OFDM-based technology, faster-than-Nyquist (FTN) signaling, which compresses and transmits signals non-orthogonally using a sampling rate faster than the frequency bandwidth in the time domain, is studied. It is difficult to exceed the Shannon limit even by using FTN when considering a certain propagation path within a given bandwidth, but when considering other factors such as the peak-to-average power ratio (PAPR), FTN may provide benefits [4-13]. Furthermore, as shown in Fig. 4-5, virtual massive (VM)-MIMO technology has been proposed as a technology for achieving a spatial multiplexing gain equivalent to mMIMO with a single antenna [4-14]. In the VM-MIMO technique, as in FTN, the received sampling rate is faster than the frequency bandwidth. The antenna characteristics are varied at a very high speed and periodically to generate a large number of virtual antennas and to increase the number of layers for spatial multiplexing. Since it is not bound by Shannon limit conditions, it is considered to have the theoretical potential to obtain a large gain, although problems such as applicable conditions and feasibility in a real environment remain.

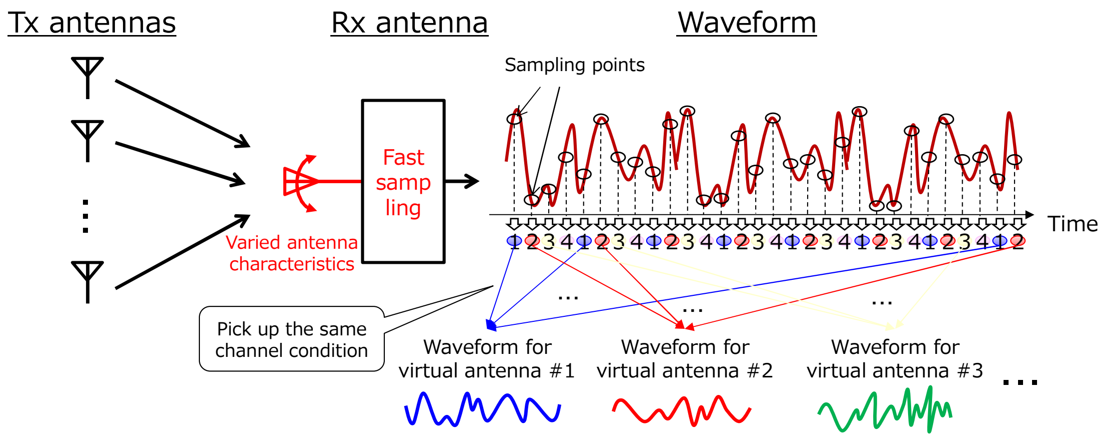

Figure 4-5. Non-orthogonal transmission using sampling rate faster than frequency bandwidth (e.g. VM-MIMO)

4.5. Enhancement for URLLC and industrial IoT networks

In many industrial use cases, guaranteeing the required performance level is necessary such as in remote control and factory automation, and a highly efficient actualization method of a network (individual network) specialized for the industry that is different from the best effort type service of a public network has been a topic of interest recently. In addition to the “Local 5G” discussed in Japan, many companies have participated in global study projects such as 5G-ACIA [4-15]. There is a wide variation in the requirements based on each industry and application, and while there are some cases that do not always require a low delay, very severe cases in which not only the average delay must be low but also a stable low delay without fluctuation is required are assumed.

As shown in Fig. 4-6, various options are considered for network configuration and mobility between public networks and industrial networks, and are discussed in 5G-ACIA, etc.

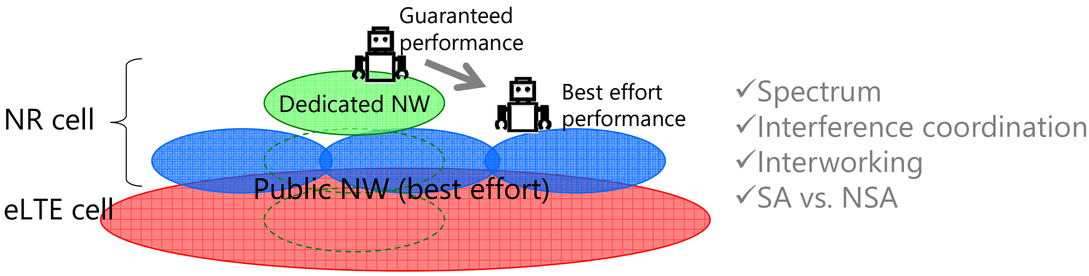

Figure 4-6. Overlays of public and industrial networks

4.6. **Expanded integration of variable wireless technologies**

When the technical domain of mobile communications is expanded to support broader use cases, cooperation and integration with wireless technologies other than mobile communications specialized for various existing applications must be considered. As with 5G, cooperation must continue with unlicensed band wireless communications such as wireless LAN. In addition, cooperation with wireless communications using waves other than radio waves, such as underwater acoustic communications [4-16], is also considered. Furthermore, license assisted access (LAA) [4-17] and integrated use of access links and backhaul links, i.e., IAB, are one example, but an approach to integrate wireless technologies using different specifications and frequencies into the mobile communication system is also conceivable. These will aid in establishing an ecosystem that can support a wider range of use cases.

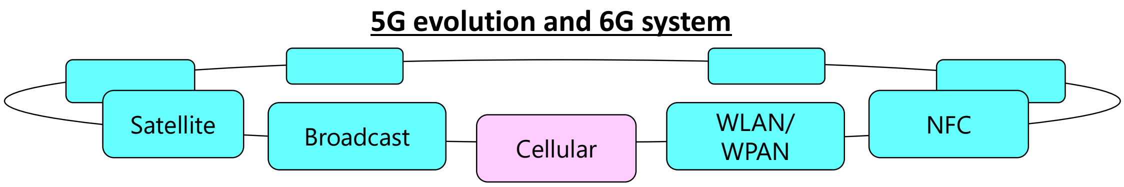

Figure 4-7. Expanded integration of variable wireless technologies

4.7. **Multi-functionalization and AI for everywhere in mobile network**

In cyber-physical fusion, images and various sensing information are transmitted to networks through IoT devices. Therefore, some technical fields are considered to analyze such information by AI and to apply it to the upgrading of radio communication control such as beam control and propagation path estimation. For instance, the use of AI is considered to enhance the latency and reliability of non-orthogonal multiple access (NOMA) [4-18], or to anticipate the changing environment and autonomously arrange transportable base stations in the optimum location at all times [4-19].

The evolution to utilize radio waves of wireless communications for various applications other than information transmission is also promising, and the application to sensing such as positioning and object detection [4-20, 4-21], and wireless power supply technology (e.g., energy harvesting [4-22]) are considered. In particular, high frequency bands such as the millimeter wave and terahertz wave bands are suitable not only for high speed and high capacity communications but also for achieving high precision positioning and sensing. The study of positioning in particular is advanced even in 5G evolution, and it is expected that ultra-high-precise positioning with the error of several centimeters can be achieved in some environments. Here, the utilization of AI technology is key. It may be used in all areas of the radio communication system, and in the future, potentially in the design of the radio interface itself.

5. Conclusion

In this white paper, 5G evolution, which is the enhancement of 5G, and the direction of the evolution of mobile communication technologies for 6G assuming the society and the worldview in the 2030s are examined, and requirements, use cases, and concepts pertaining to technical examination are described.

In the future, while 5G is expected to be utilized in various industrial fields, conducting research and development aiming at the further future of 5G is desirable by looking at future market trends, needs, social problems, and technological evolution. NTT DOCOMO will continue to enhance the ultra-high-speed, high-capacity, ultra-reliable, low-latency and massive device-connectivity capabilities of 5G technology. It will continue its research into and development of 5G evolution and 6G technology, aiming to actualize technological advances including the following.

- ✓ The simultaneous achievement of several requirements such as ultra-high-speed, high-capacity, and low-latency connectivity
- ✓ The pioneering of new frequency bands including terahertz frequencies
- ✓ The expansion of communication coverage in the sky, at sea, and in space
- ✓ The provisioning of extremely low energy and low-cost communications
- ✓ The ensuring of extremely reliable communications
- ✓ The developing of capabilities for extremely massive connectivity and sensing

References

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

[2-1] Newsletter of the MIC, Japan, “Announcement of the Local 5G implementation guidelines - Institutional development for Local 5G implementation,” Dec. 2019.

[2-2] Government of Japan, “The 5th Science and Technology Basic Plan,” Jan. 2016.

[3-1] Y. Kishiyama and T. Nakamura, “Real and future for 5G evolution and 6G,” MWE2018 Workshop FR2A-1, Nov. 2018.

[4-1] DOCOMO Press Release, “DOCOMO, AGC and Ericsson achieve world’s first 5G communication using glass antenna for 28 GHz,” May 2019.

[4-2] DOCOMO Press Release, “DOCOMO conducts world’s first successful trial of transparent dynamic metasurface,” Jan. 2020.

[4-3] DOCOMO Press Release (in Japanese), “DOCOMO conducts world’s first successful trial of expanding 5G coverage using meta-material reflector for 28 GHz,” Dec. 2018.

[4-4] 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.

[4-5] O. Teyeb, A. Muhammad, G. Mildh, E. Dahlman, F. Barac, and B. Makki, “Integrated access backhauled networks,” IEEE VTC2019-Fall, Sept. 2019.

[4-6] T. Onizawa, T. Tatsuda, N. Kita, and F. Yamashita, “Recent research and developments focusing on fixed wireless and satellite communication systems,” IEICE Tech. Rep., RCS2019-32, pp. 53-58, May 2019.

[4-7] FCC News Release, “FCC takes steps to open spectrum horizons for new services and technologies,” Mar. 2019.

[4-8] DOCOMO Press Release, “DOCOMO and Rohde & Schwarz cooperate in pioneering beyond 5G with frequency bands up to 150 GHz,” Nov. 2018.

[4-9] T. S. Rappaport, “Wireless beyond 100 GHz: opportunities and challenges for 6G and beyond,” IEEE COMCAS Keynote, Nov. 2019.

[4-10] M. Sawahashi, “Views on technical challenges of physical layer for integrated wireless access and backhaul,” IEICE Society Conference 2018, BS4-1, Sept. 2018.

[4-11] M. Taromaru, “A view of digital modulation technologies beyond 5G – Are we still to use IFFT/FFT-based modulations for the new radio?,” IEICE Society Conference 2018, BS4-3, Sept. 2018.

[4-12] 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.

[4-13] 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.

[4-14] T. Murakami, R. Ohmiya, T. Nakahira, K. Ishihara, and T. Hayashi, “Proposal of virtual massive MIMO (VM-MIMO),” IEICE General Conference 2019, B-1-123, Mar. 2019.

[4-15] https://www.5g-acia.org/

[4-16] Y. Fujino, H. Fukumoto, M. Nakano, T. Tsubaki, and K. Sakamoto, “Challenge to Mbps-class high-speed acoustic communication for wireless remote operation of underwater vehicles,” IEICE Tech. Rep., RCS2019-232, pp. 163-168, Nov. 2019.

[4-17] H. Harada, D. Murayama, and S. Nagata, “3GPP study on 5G NR based access to unlicensed spectrum,” IEICE Tech. Rep., SRW2018-70, pp. 61-65, Mar. 2019.

[4-18] 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. on Industrial Informatics, vol. 15, no. 5, pp. 2995-3005, 2019.

[4-19] T. Arai, D. Goto, M. Iwabuchi, T. Iwakuni, and K. Maruta, “AMAP: adaptive movable access point system for offloading efficiency enhancement,” IEICE Tech. Rep., RCS2016-43, pp. 107-112, May 2016.

[4-20] 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.

[4-21] 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.

[4-22] 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.