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Evolution of AI Services in the 5G Era

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The 5th Generation mobile communications system (5G) era has begun and a digital transformation*1 using AI, cloud computing, and other advanced technologies is unfolding throughout the world based on high-speed, high capacity, and low-latency networks. According to a survey conducted by the International Data Corporation (IDC) on the worldwide AI market, total sales of AI-related software and services are forecast to grow significantly from 327.5 billion dollars (approximately 35,055.6 billion yen) in 2021 to 554.3 billion dollars (approximately 59,332.3 billion yen) in 2024 [1]. In Japan, meanwhile, a survey conducted by the Fuji Chimera Research Institute shows the AI market nearly doubling in size from 1,108.4 billion yen in FY2020 to 1,935.7 billion yen in FY2025 [2]. These figures represent a transition from a phase of studying the introduction of AI with vague expectations to a phase that combines know-how and solutions on the vendor side with trials and full-scale implementations for solving specific business problems.

At present, AI software provides machine learning, image recognition, and natural dialogue as main functions for use in a variety of applications including optimization of business processes, demand prediction, and enhanced customer experiences through recommendations and personalization.

Here, I would like to introduce two examples of how NTT DOCOMO is putting AI to work. These are the "DOCOMO Image Recognition Platform" using image recognition AI and "AI Phone Service" using natural dialogue AI.

The DOCOMO Image Recognition Platform provides image-recognition training-model creation and an Application-Programming Interface (API) as cloud services that enable developers to easily and quickly develop image-recognition engines while holding down development and operating costs. Using communication paths that directly connect the NTT DOCOMO network and the cloud, the DOCOMO Image Recognition Platform can also support solutions that require low latency and high security [3].

Next, the AI Phone Service enables conventional call-handling operations dealing, for example, with reservations, inquiries, and calls made to corporate phone numbers to be performed by AI. As a cloud-based service, it is applicable to local governments, retail stores, and eating and drinking establishments that have no call center, and it can even be used for elderly care [4].

Both of these services were created through NTT DOCOMO's TOPGUN initiative that forms cross-organizational teams between NTT DOCOMO's R&D and corporate sales divisions with the aim of developing solutions to problems affecting corporate customers. To make AI truly practical, a co-creation process is essential: team members must work together to determine what functions and level of accuracy are needed at service sites by talking with customers and conducting verification trials. Refining technology and interacting with a variety of partners are also important. For example, young personnel in NTT DOCOMO's R&D division publish technical information on "Qiita," a service managed by Increments Inc. for sharing engineering-related knowledge [5].

Going forward, I can envision that the spread of AI technologies in our society will further contribute to diverse industries such as finance, urban development, transportation, entertainment, education, sports, and energy and supporting the development of solutions to social problems. NTT DOCOMO's R&D division will drive the evolution of AI services and contribute to new value creation through the development of advanced AI technologies and co-creation with customers.

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*1 Digital transformation: The use of IT technology to revolutionize services and business models, promote business, and change the lives of people for the better in diverse ways.

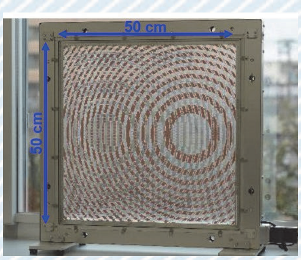
NTT DOCOMO
Technical Journal
Vol.23 No.2 Oct. 2021

[Contents]

DOCOMO Today

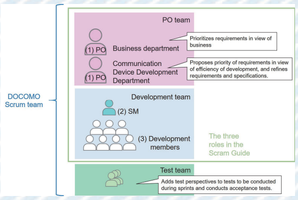
Technology Reports (Special Articles)

Special Articles on 5G evolution & 6G (1)



(P.14)

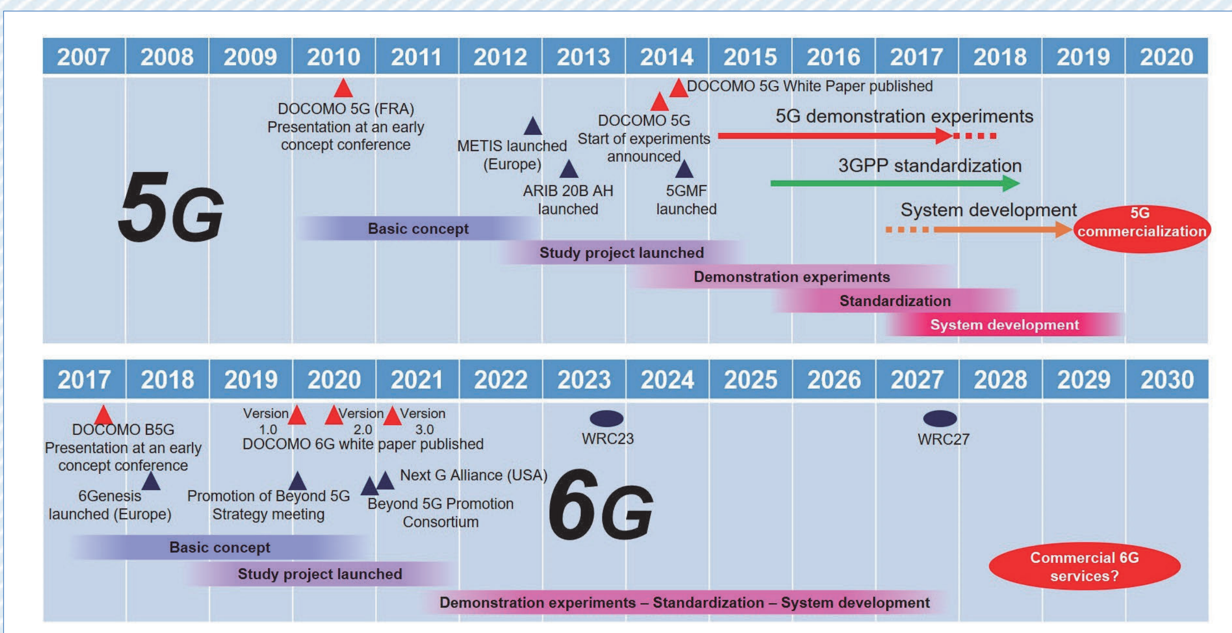
(P.24)



(P.48)

Technology Reports

News



Technology Reports (Special Articles) Trends and Target Implementations for 5G evolution & 6G (P.4)
5G development history and 6G schedule

Technology Reports (Special Articles) 5G evolution & 6G Requirements Wireless Technology

Special Articles on 5G evolution & 6G (1)

Trends and Target Implementations for 5G evolution & 6G

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In Japan, commercial 5G services first became available in March 2020. Studies of the next generation of communication services (6G) and the telecommunication technology of the 2030s are now gathering momentum. This article provides a summary of the domestic and international trends and schedule prospects for 6G research and development, and the 5G evolution & 6G concept proposed in the DOCOMO 6G White Paper.

1. Introduction

Mobile communication systems have been continuously developing and evolving, with a new generation of systems coming out roughly once every decade. In the 1980s and 1990s, the 1st and 2nd Generations mobile communication systems (1G and 2G) mostly supported voice calls, with some support for simple messaging functions. With the arrival of 3rd Generation mobile communication systems (3G) in the 2000s, it became possible for anyone to access multimedia content such as photos, music and video. And from 2010, the launch of 4th Generation mobile communication systems (4G) with Long Term Evolution (LTE) technology capable of speeds in excess of 100 Mbps supported the explosive spread of smartphones. Then in March 2020, Japan's first 5th Generation mobile communication systems (5G) services were launched, offering maximum transmission speeds of over 4 Gbps.

5G includes technical advances such as high speed/large capacity communication, low latency, and the ability to connect to multiple terminals simultaneously. It not only improves on the multimedia communication capabilities of 4G, but is also expected to create new value as an infrastructure technology for business and society in the fields of Artificial Intelligence (AI) and the Internet of Things (IoT). In particular, the combination of 5G and AI technology is expected to lead to the creation of new services and solutions in diverse industrial fields by enhancing "cyber-physical fusion*1" whereby the real world is recreated in cyberspace to facilitate future predictions and the acquisition of new knowledge. Since this trend is likely to continue until the 2030s, it is necessary to promote research and development so that 5G evolution and 6th Generation mobile communication systems (6G) can provide the fundamental technological infrastructure for industry and society in the 2030s. This article presents a summary of the domestic and international trends in 6G technology, and the expected schedules for the introduction of this technology. It also discusses the 5G evolution & 6G concept proposed in the DOCOMO 6G White Paper [1].

2. 6G Trends and Schedules

Figure 1 shows the development history of 5G and the schedule for the introduction of 6G. Following the launch of 4G LTE services in 2010, DOCOMO began studying 5G with the aim of implementing services by around 2020. In our 5G White Paper of 2014, we announced the start of 5G demonstration experiments in cooperation with major global vendors. Discussions on the international

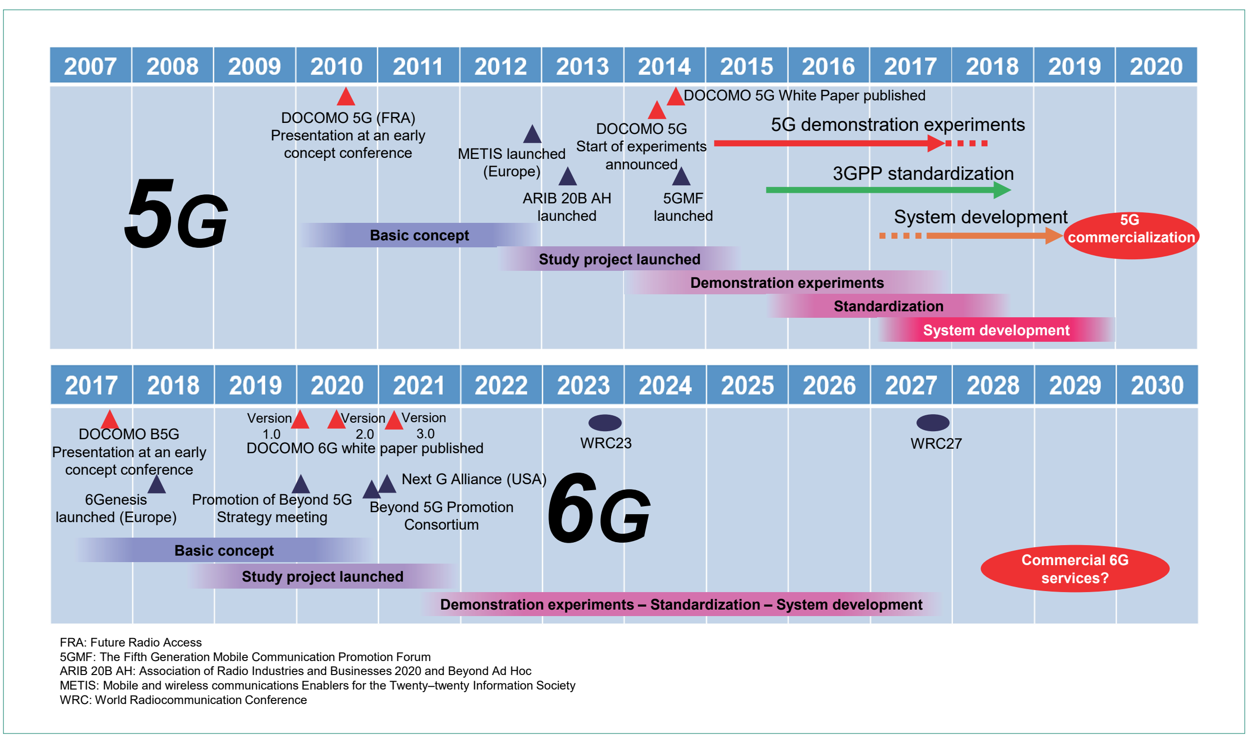

Figure 1 5G development history and 6G schedule

*1 Cyber-physical fusion: Services and systems for realizing a better and more advanced society by collecting information in real space (physical space) from various sensors, etc. and linking it to virtual space (cyberspace).

standardization of 5G began at the 3rd Generation Partnership Project (3GPP)*2 in around 2015, and the first commercial 5G services were launched overseas in 2019 based on the Release 15 specification (the first international 5G standard) [2].

In contrast, worldwide discussions on the standardization of 6G for the 2030s tended to start earlier. This can be attributed to the impact of global competition in the development of 5G. Projects studying 5G in Japan and overseas gradually took shape from around 2012, which preceded the launch of 5G by about 8 years. On the other hand, discussions related to 6G started in around 2018, which precedes the expected launch by 12 years. These include the 6Genesis Project led by Oulu University in Finland, and the efforts being made in the United States following then President Trump's call for stronger efforts in the development of 6G in 2019 and the decision by the Federal Communications Commission (FCC)*3 to make terahertz waves*4 available for research purposes. These early global initiatives are summarized in **Figure 2** [3]. In Japan, the Ministry of Internal Affairs and Communications (MIC) launched the Beyond 5G Promotion Strategy Roundtable in January 2020 to formulate a comprehensive strategy for Beyond 5G*5, and published a roadmap outlining the expectations for telecommunications infrastructure in the 2030s and the direction of policies to achieve these targets [4]. Then in December 2020, the Beyond 5G Promotion Consortium was established to promote strong and proactive collaboration between

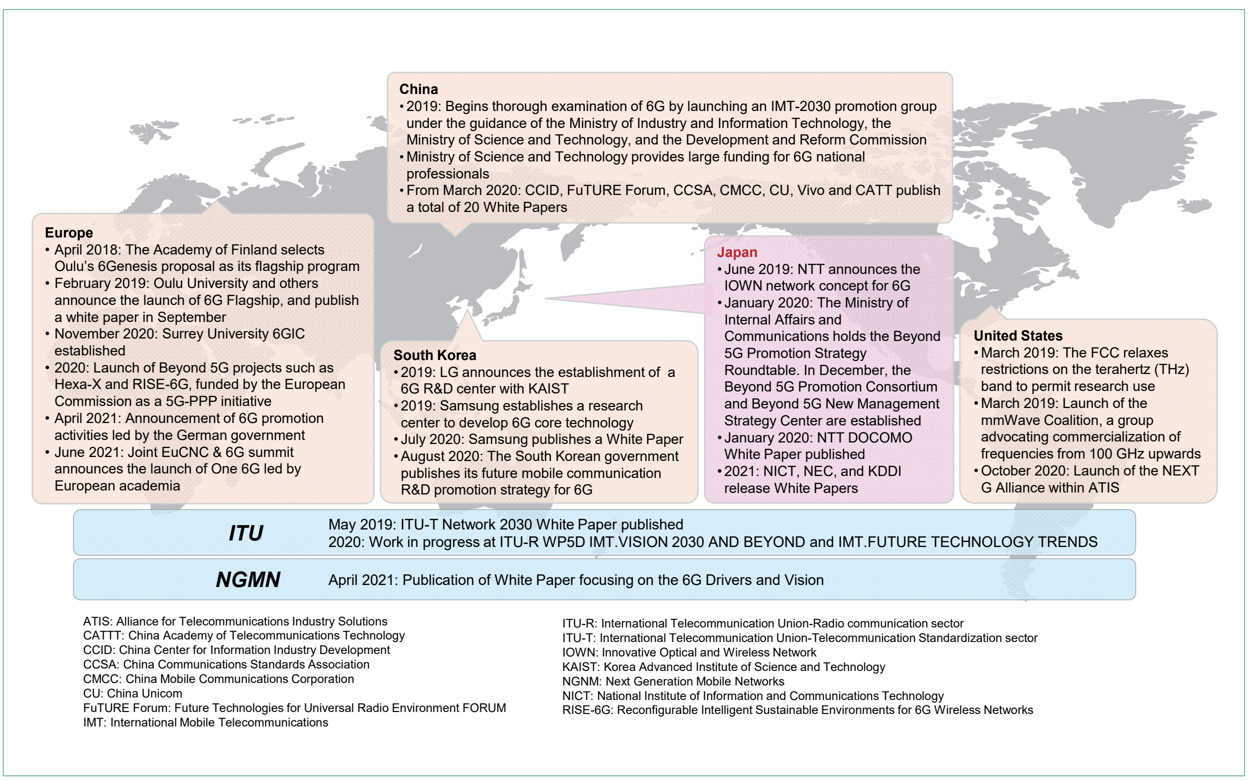

Figure 2 Global Trends for Beyond 5G & 6G

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*2 **3GPP**: An organization that creates standards for mobile communications systems.

*3 **FCC**: The Federal Communications Commission of the USA. Has the authority to approve and license industries including television, radio, telegraph and telephone.

*4 **Terahertz waves**: Electromagnetic waves with a frequency of around 1 THz. Often used to refer to frequencies ranging from 100 GHz to 10 THz.

*5 **Beyond 5G**: A term that is widely used to describe wireless communication systems that emerge after 5G. It is almost synonymous with "6G."

industry, academia, and government on 6G technology [5].

At DOCOMO, we have been studying Beyond 5G since around 2017 [6], and released the first version of the DOCOMO 6G White Paper in January 2020. This is currently being updated to version 3.0 [1]. In addition, research institutes and major vendors in Japan and other countries have also released a slew of white papers related to Beyond 5G and 6G, as shown in Fig. 2. Compared to the launch of 5G studies, it can be seen that there is a more positive trend towards 6G around the world.

In the future, it is expected that demonstration experiments and international standardization efforts will be promoted with the aim of introducing 6G commercial services by 2030. **Figure 3** shows the standardization schedule for 5G evolution & 6G that was drawn up by the 3GPP.

3. 5G evolution & 6G Target Implementations

In the following, we will describe the concept of 5G evolution & 6G as proposed in the DOCOMO 6G White Paper.

Figure 4 shows the six requirements that we aim to achieve in 6G based on 5G evolution. These include the requirement for further performance enhancements compared with 5G, and are expected to cover a wider range of features in new areas that are not supported by 5G or earlier systems. These requirements and their expected use cases are summarized below.

3.1 Extreme-high-speed and High-capacity Communication

Communication systems with higher communication speeds and larger communication capacities

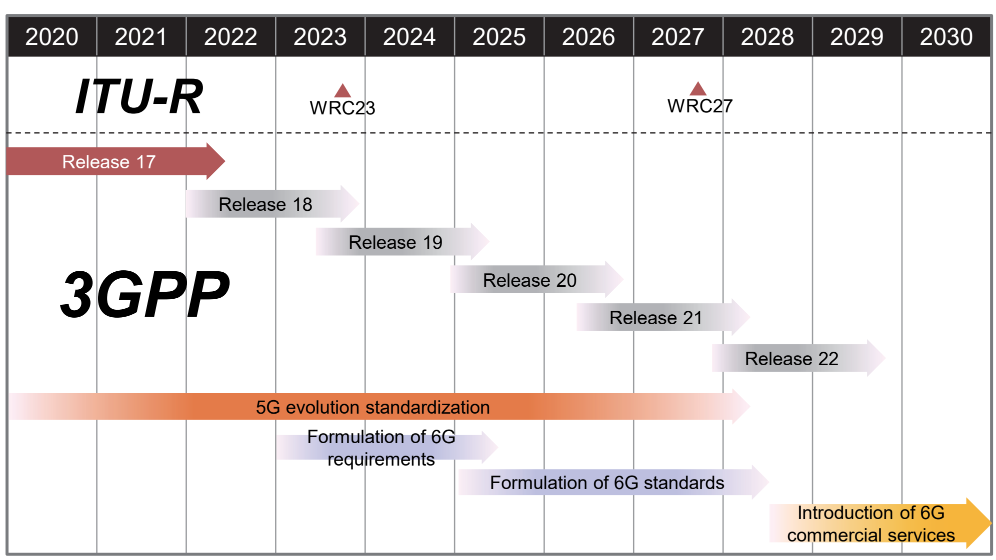

Figure 3 Expected standardization schedule for 5G evolution & 6G

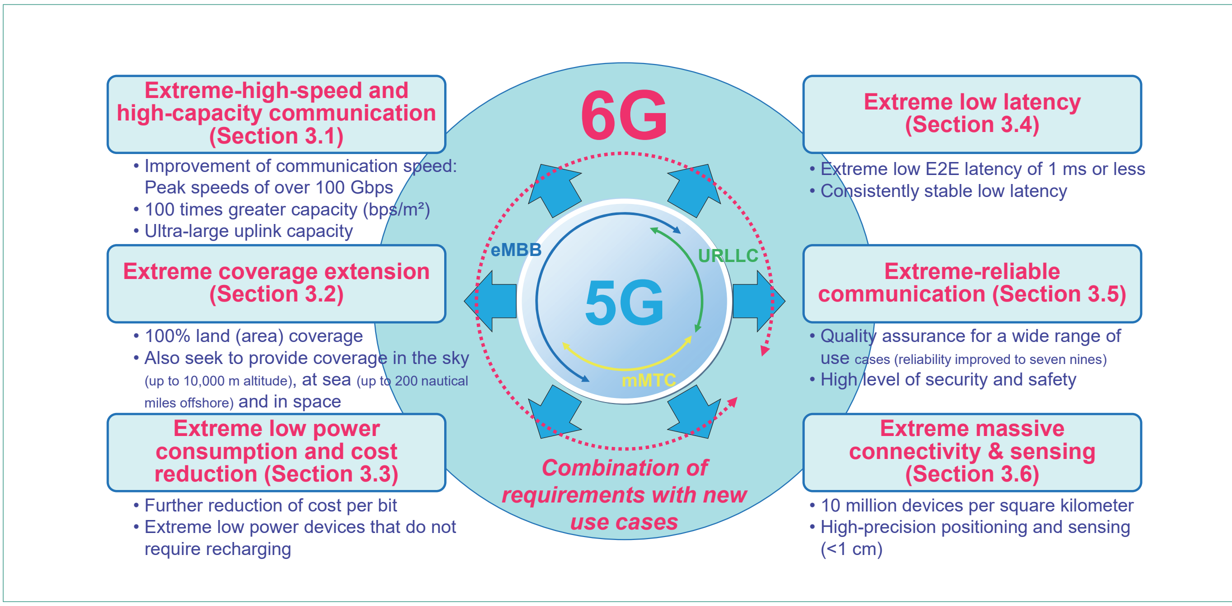

Figure 4 Requirements for 6G

are universal requirements for all generations of mobile communication systems. With 6G, it should be possible to combine extremely high speed and ultra-large capacity so that large numbers of users can enjoy services at the same time. As communication speeds approach the speed at which information is processed by the human brain, it should become possible to realize not only video (visual and auditory) transmission, but also sensory communication that conveys a sense of reality by involving the five senses, and "multi-sensory communication" that includes other sensations such as atmosphere and a sense of security. In order to implement these unprecedented extreme-high-speed and high-capacity communication services, user interfaces will have to exceed what can be implemented on a smartphone. For example, it is expected that new interface technologies will evolve to support features such as 3D holographic playback and wearable devices such as eyeglass-type terminals. It is also expected to be possible to share these new sensory-type services among multiple users in real time through the use of ultra-high capacity communication, thereby facilitating new synchronized applications such as shared experiences and cooperative work in cyberspace. Furthermore, if industrial use cases and trends such as cyber-physical fusion are taken into consideration, it is particularly important to achieve much higher speeds and capacities in the uplink*6 because it will be necessary to transmit diverse real-world information in real time to the cloud and AI processes that constitute the "brains" of the network.

3.2 Extreme Coverage Extension

In the future, communications will become as ubiquitous as the air, and will provide a lifeline of equal or even greater importance than electricity and water supplies. 6G should therefore aim to

*6 Uplink: The flow of information from terminals to the network.

provide the maximum possible service area so that mobile communications services are available everywhere. For this reason, the aim is to provide 100% coverage over all the world's lands. With the establishment of communication areas in other environments and the commercial development of space, there are also plans to extend this coverage to include air, sea and space environments where existing mobile communication systems do not operate. As a result, we can expect further expansion of the environment for activities involving people and things, and the creation of new industries. Promising examples include logistics applications such as drone home delivery, and the use of unmanned and/or more sophisticated technology in primary industries such as agriculture, forestry, and fisheries. In the 2030s, it could also be applied to more futuristic use cases such as flying cars, space travel, and underwater travel.

3.3 Extreme Low Power Consumption and Cost Reduction

Reducing the power consumption and cost of networks and terminals in mobile communication systems is an important challenge for realizing the sustainable society that the world needs in order to address global environmental issues.

Assuming that network traffic will continue to increase in the future, we aim to significantly reduce the per-bit power consumption and cost of communication. For example, if communication traffic increases a hundredfold, the per-bit capital investment and operating costs should be reduced to less than 1/100th to achieve both high performance and economy.

Furthermore, there are also expectations that the terminal devices of the future will not require charging due to the development of power supply technology using wireless signals and technology for reducing the power consumption of devices. The need for this technology will become even greater if (as expected) the number of terminals such as sensor devices grows due to the increased sophistication of cyber-physical fusion and the growth of use cases involving wearable user interfaces.

3.4 Extreme Low Latency

In cyber-physical fusion, the wireless communication that connects between AI processes and devices is equivalent to the nerves that transmit information in the human body. To implement more advanced remote services based on real-time interactive AI, a basic requirement is End-to-End (E2E) communication with low latency that is always stable. Our goal is to achieve E2E with extremely low latency of 1 ms or less. This will enable lag-free services to provide immediate feedback from cyberspace, and will allow robots and other devices that are remotely controlled by AI to approach or exceed the capabilities of humans in terms of performing agile movements and/or understanding subtle cues. For example, a robot controlled remotely by AI may be able to instantly determine a user's needs based on cues such as the user's tone of voice and facial expression, allowing it to respond with at least the same level of consideration as a human would be able to achieve. This could be particularly important in the post-coronavirus era, when extreme low-latency communication will be essential in such fields as teleworking, remote control, telemedicine, and distance learning.

3.5 Extreme-reliable Communication

When radio communication is used for industrial and lifeline applications, reliability is a key requirement. In particular, in some industrial use cases — such as the remote control of industrial equipment and factory automation — the quality and availability of communication have a significant impact on safety and productivity. Extreme-reliable communication is therefore an important prerequisite for ensuring the required levels of performance and safety, and 6G is expected to surpass 5G in terms of reliability and security. For Ultra-Reliable and Low Latency Communications (URLLC),[*7] researchers are studying how to achieve a "six nines" level of reliability (99.9999%) in 5G. For 6G, a target of "seven nines" (99.99999%) is assumed.

Attention is also being drawn to Non-Public Networks (NPNs) that are specialized for industrial use and depart from the best-effort services of public networks such as private 5G. URLLC technology is mainly being considered for limited areas such as factories. On the other hand, in the future, as robots and drones become more widespread and wireless coverage expands to the air, sea, and space, it will be necessary to provide reliable communication over a wider area.

3.6 Extreme Massive Connectivity & Sensing

With advances in cyber-physical fusion, there is expected to be a massive proliferation of communication-related devices used by people and things, and it is considered that 6G will have to support ten times the connectivity of 5G (i.e., 10 million devices per km^2). For human users, there are expected to be use cases in which cyberspace provides real-time support for people's thoughts and actions via wearable devices and micro-devices attached to the body. It is also expected that cyberspace will provide links between all manner of things, including cars and other vehicles, construction machinery, machine tools, surveillance cameras, and diverse sensors. This will make it possible to realize a world where cyberspace supports industry and transportation, provides solutions to social issues, and helps people to enjoy safe, secure, and affluent lifestyles.

Furthermore, the wireless communication network will itself be equipped with functions for sensing the real world, such as using radio waves to measure the position of terminals and detect surrounding objects. These position measurements are expected to achieve ultra-high accuracy with an error of no more than a few centimeters in some environments. In wireless sensing, it is expected that the combined use of radio waves and AI technology will be able to support object identification and behavior recognition in addition to highly accurate object detection.

4. Development of Wireless Technology in 5G evolution & 6G

Figure 5 illustrates the development of technology from previous mobile communication generations to 6G. Earlier generations had a single representative technology (RAT: Radio Access Technology)[*8] that they used for radio access, but since 4G, mobile communication has used multiple technologies based on Orthogonal Frequency Division

*7 URLLC: A generic term for communications that require low latency and high reliability.

*8 RAT: Radio access technologies such as NR, LTE, W-CDMA, and GSM.

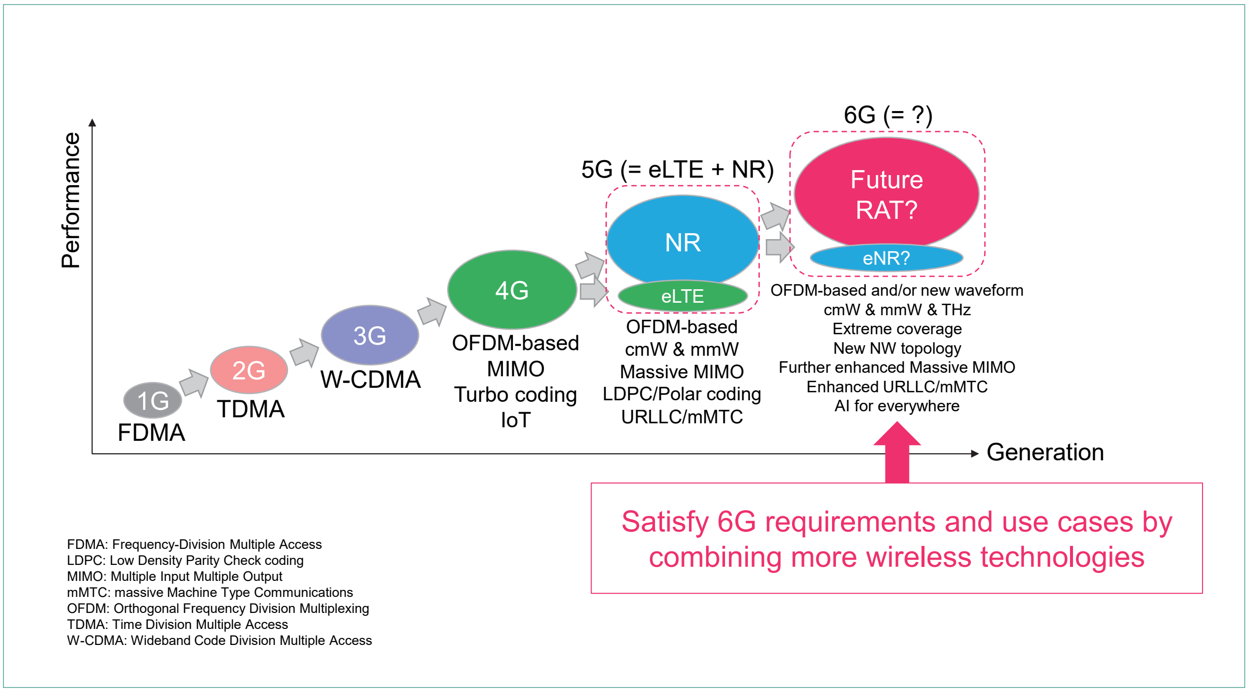

Figure 5　Technological development of mobile communication systems towards 6G

Multiplexing (OFDM).*9 As a result, RAT now comprises a mixture of wireless technologies, resulting in extended technological development. This is because OFDM-based radio technology has already achieved frequency utilization efficiency*10 close to the Shannon limit*11, while the requirements for mobile communication systems, frequency bands, and use cases are continuously being expanded.

Therefore, 6G will require the combination of even more radio technologies after 5G evolution, and it will also be necessary to consider how these combinations can be extended to include technologies other than mobile communication in order to fulfil the above requirements and various use cases. In addition, whereas 5G was defined by the combination of LTE enhancements and New Radio (NR)*12, the NR aspect of 5G is designed to be highly expandable to accommodate the future introduction of new technologies. It will therefore be necessary to discuss the definition of RAT in 6G.

The technology areas that need to be considered for 5G evolution & 6G are shown in **Figure 6** [1].

With an advanced spatially distributed network technology (New Radio Network Topology), communication will be performed via the shortest possible distance and by line of sight (the path of least loss) wherever possible. Also, as many communication paths as possible will be created to provide a broader selection of paths (greater redundancy). In this way, we will pursue wireless communication with extreme high speed, high capacity (especially in uplinks) and improved reliability. To achieve this, we need to figure out how to economically implement a distributed antenna deployment to build a distributed wireless network topology*13 in the spatial domain.

*9 OFDM: A digital modulation method where information is divided into multiple orthogonal carrier waves and sent in parallel making for high spectral efficiency in transmission.

*10 Frequency utilization efficiency: The number of bits of information that can be sent per unit time and unit bandwidth.

*11 Shannon limit: The theoretical maximum rate at which information can be transmitted through a communication channel of a given bandwidth and Signal-to-Noise (SN) ratio.

*12 NR: A radio system standard formulated for 5G. Compared with 4G, it enables faster communication by utilizing high frequency bands (e.g., 3.7 GHz and 28 GHz bands), and low latency and highly reliable communication for achieving advanced IoT.

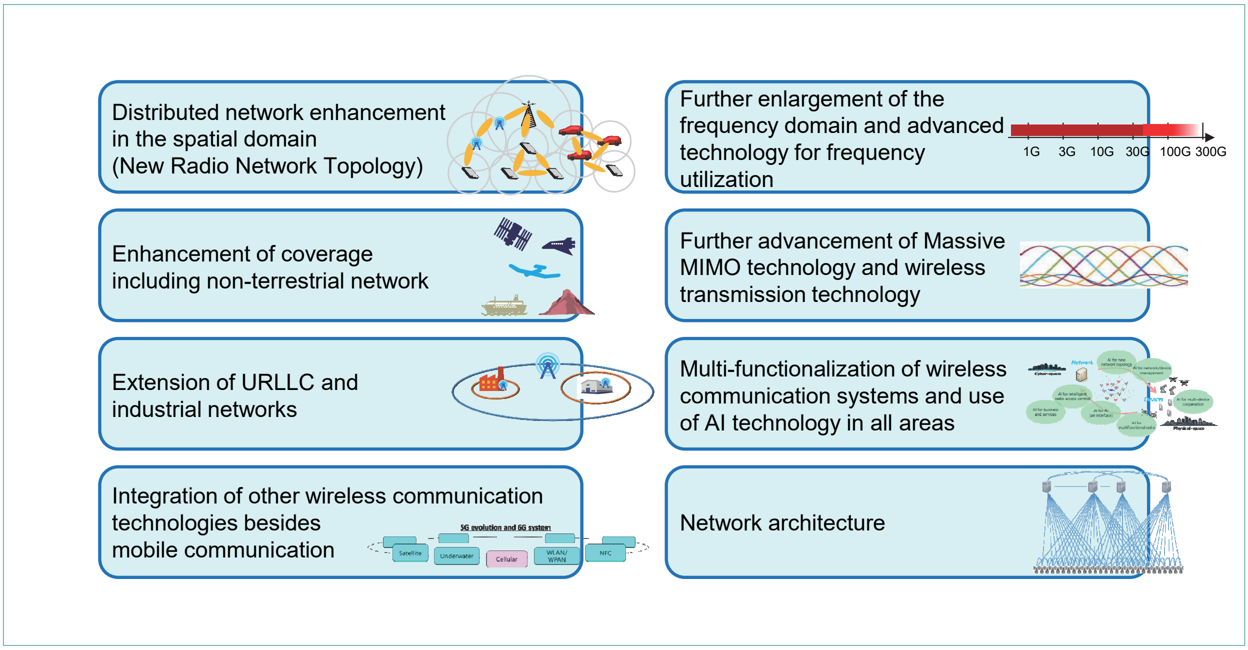

Figure 6　Technology areas that need to be considered for 5G evolution & 6G

This extended coverage technology will include Non-Terrestrial Networks (NTNs) by incorporating geostationary satellites, low-orbit satellites and High-Altitude Platform Stations (HAPSs), allowing it to provide coverage in remote mountainous areas, out at sea, and even in outer space. 3GPP has already begun studying the use of satellite and HAPS systems to expend NR to NTNs.

For further expansion in the frequency domain and technology for making more advanced use of frequency resources, we will establish wireless technology for 6G that is capable of working with millimeter waves and terahertz waves in the 100 to 300 GHz range (above the frequency bands used by 5G). To study these frequency bands, we will also need to clarify their radio wave propagation characteristics, build propagation models, and address any technical issues that arise in devices using these frequencies.

With the multifunctional use of wireless communication systems and the pervasive use of AI technology, it will be possible to analyze not only information obtained by radio waves, but also video pictures and information obtained by diverse forms of sensing, thereby facilitating various benefits including advanced control of wireless communication, high-precision measurements of positions and distances, object detection and wireless charging systems.

We will also need to carry out a fundamental review of the 6G network architecture in order to accommodate additional future requirements and keep abreast of changes in the market, while considering how to optimize the deployment of functions and the generalization of equipment across the entire network, so there are still many network design issues that need to be resolved.

Although this article has skimmed over the

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*13　Topology: The location and network configuration of devices.

details of each technical area, discussions of related R&D activities can be found elsewhere in this journal [7]–[9].

5. Conclusion

In this article, we have presented an outline of domestic and international trends and schedule prospects for 5G evolution & 6G, and the concepts proposed in the DOCOMO 6G White Paper. At present, studies are being vigorously pursued by the Beyond 5G Promotion Consortium and 6G-related projects in Japan and overseas, and we hope to continue contributing to discussions of 6G among various stakeholders from industry, academia and government.

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Technology Reports (Special Articles) 5G evolution / Millimeter Wave / Metasurface

Special Articles on 5G evolution & 6G (1)

Research of Transparent RIS Technology toward 5G evolution & 6G

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Kensuke Miyachi Yoshihisa Kishiyama

The introduction of 5G commercial services has begun throughout the world, and at present, research toward the further development of 5G (5G evolution) and the development of 6G as the next-generation mobile communications system is being actively pursued. In this article, we describe IRE, an important concept in "New Radio Network Topology" now under discussion on the road to 5G evolution & 6G. We also describe NTT DOCOMO's initiatives toward RIS, an important component of IRE, and metamaterial/metasurface technologies as elemental technologies of RIS.

1. Introduction

In Japan, NTT DOCOMO launched commercial services of the 5th Generation mobile communications system (5G) in March 2020. This launch has raised expectations for the application of 5G technology to XR*1 such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) and to a variety of fields as in industry/infrastructure enhancement though Internet of Things (IoT) devices [1]. Against this background, NTT DOCOMO has come to demonstrate through field experiments the potential of 5G for achieving high-speed/high-capacity, low-latency, and high-reliability communications using radio signals in the millimeter-wave*2 frequency band [2] [3].

However, it became clear through these field experiments that problems existed in the effective use of millimeter waves in radio communications of a cellular system. With millimeter waves, radio signals have a strong tendency to propagate in a straight line much like light, so their ability to wrap

† Currently NTT Device Technology Labs., NTT Corporation

around shielding objects (diffraction) is small. It can therefore be said that the key to using millimeter waves in radio communications of a cellular system is determining how to expand the area covered by a base-station antenna to non-line-of-sight locations.

In this article, we first present the concept of the Intelligent Radio Environment (IRE) that is now attracting attention as a useful approach to forming coverage areas in the millimeter-wave band, an important issue in achieving 5G evolution & the 6th Generation mobile communications system (6G). We then turn to NTT DOCOMO initiatives surrounding the Reconfigurable Intelligent Surface (RIS) as key to achieving IRE and describe metamaterial*3/metasurface*4 technologies, the elemental technologies of RIS.

2. IRE and RIS

2.1 IRE

Research toward IRE has been quite active in recent years with the aim of adaptively and dynamically controlling the radio environment to achieve non-line-of-sight coverage in the millimeter-wave band [4]. In a white paper [1] issued by NTT DOCOMO toward 6G, a New Radio Network Topology was proposed to increase the number of connection paths to the network including discussions on controlling the radio environment. In this regard, it is difficult to solve the problem of radio waves being blocked by shielding objects simply through the evolution of transmitter/receiver technology, so the need is felt for constructing a new radio network system.

Against this background, means of achieving a dramatic jump in radio network performance are being vigorously studied by breaking with the traditional assumption that the radio environment is uncontrollable and treating it instead as a controllable entity. This type of approach has come to be called the "Intelligent Radio Environment (IRE)" or "Smart Radio Environment (SRE)" to emphasize its conceptual difference with the conventional radio network system. A conceptual diagram of IRE is shown in **Figure 1**. Given an environment with shielding objects, IRE can secure propagation routes that make detours around shielding objects by optimally controlling not only the Transmitter (Tx) and Receiver (Rx) but the propagation channel*5 (H) as well.

2.2 RIS

RIS is essential technology for achieving IRE described above. A RIS consists of multiple elements that scatter electromagnetic waves. Metamaterial/metasurface technologies that can design and control the distribution of these scattering characteristics are commonly used to achieve RIS. A metasurface has a thin flat shape, and depending on the base materials selected, it is even possible to manufacture one in the shape of a flexible sheet that can be installed along the side of a structure. This makes it possible to control the scattering characteristics of radio waves while maintaining the shape of existing structures. Within the Tx – propagation channel – Rx sequence, this means controlling the propagation channel. In general, RIS can be expected to adaptively control the radio environment by periodically repeating the following operations.

(1) Estimate the radio channel characteristics

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*1 XR: Generic name for technology that provides new experiences by merging virtual space and real space as in VR, AR, and MR.

*2 Millimeter waves: Radio signals in the frequency band from 30 GHz to 300 GHz as well as the 28 GHz band targeted by 5G all of which are customarily called "millimeter waves."

*3 Metamaterial: An artificial material that causes electromagnetic waves to behave in ways that they do not in natural materials.

*4 Metasurface: Artificial surface technology. As a type of artificial medium (metamaterial (see *3)), it can achieve an arbitrary dielectric constant and magnetic permeability through a two-dimensional periodic arrangement of structures each smaller than the wavelength of the propagating wave.

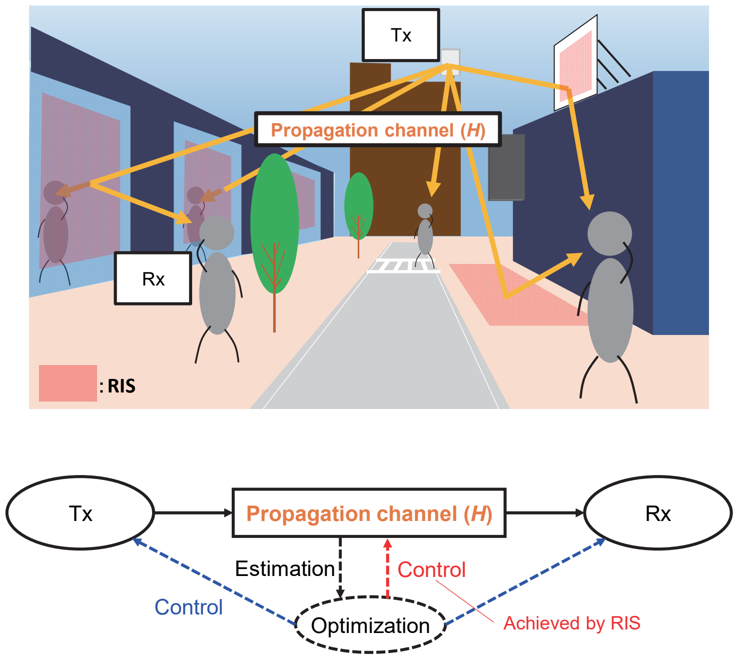


Figure 1 Conceptual diagram of IRE

required for determining RIS operation.

(2) Control the scattering intensity and phase distribution on the RIS based on the above estimated information to obtain the desired propagation channel.

Various approaches to implementing this procedure have been researched. Furthermore, as a term referring to the same technology as RIS, there is the Large Intelligent Surface (LIS), and there is also the Intelligent Reflecting Surface (IRS) that focuses only on controlling reflected waves.

1) Effect of RIS Size

Given a non-line-of-sight situation between a Base Station (BS) and Mobile Station (MS) in which a reflector or repeater*6 is used to relay radio signals (BS – reflector/repeater – MS), path loss*7 occurs two times, once in the "BS – reflector/repeater" interval and again in the "reflector/repeater – MS" interval. The drop in energy density of a wave due to propagation is larger at positions closer to the wave source. Thus, even for the same total path length, path loss is generally greater for the "BS – reflector/repeater – MS" path than the "BS – MS" path leading to a drop in received power. This tendency of path loss to increase applies to RIS as well.

Path loss via RIS is affected by surface size the same as an ordinary metal reflector, but in the case of RIS, path loss depends not only on size but also on the method of phase control. With this in mind, we first examine how RIS size affects received power and introduce the results of analyzing the relationship between path loss that occurs

*5 Propagation channel: An individual communication path in radio communications. Here, a communication path between a transmitting antenna and receiving antenna. The characteristics of a communication path are expressed in terms of its transfer function H.

*6 Repeater: Relay equipment on the physical layer that amplifies the power of a signal from a base station or mobile station and forwards the signal to a mobile station or base station.

*7 Path loss: Propagation path loss estimated from the difference between the transmitted power and received power.

twice via RIS (hereinafter referred to as "double path loss") and path loss of a direct wave for the same path length [5]. In this analysis, calculations were performed for the following two cases.

(a) Receiving a direct wave with a BS – MS of 200 m

(b) Receiving radio waves with a BS – RIS distance of 100 m and a RIS – MS distance of 100 m and no paths other than the path via RIS (total path length = 200 m)

The relationship between RIS size and path loss for each of the above paths in the 28 GHz band as determined by computer simulation is shown in **Figure 2**. In this computation, the RIS is square-shaped, reflectivity is 100%, and BS – RIS – MS is assumed to lie along a straight line. In actuality, RIS can be expected to lie at an angle with respect to BS/MS and not along a straight line, in which case its effective area decreases by the amount of that angle.

Focusing our attention on controlling only the propagation direction with no special phase control (blue line in Fig. 2) and considering the case that RIS is smaller than a certain size ((1) in the figure), double path loss via RIS is considerably greater than path loss of a direct wave for the same path length. However, as RIS size becomes larger than

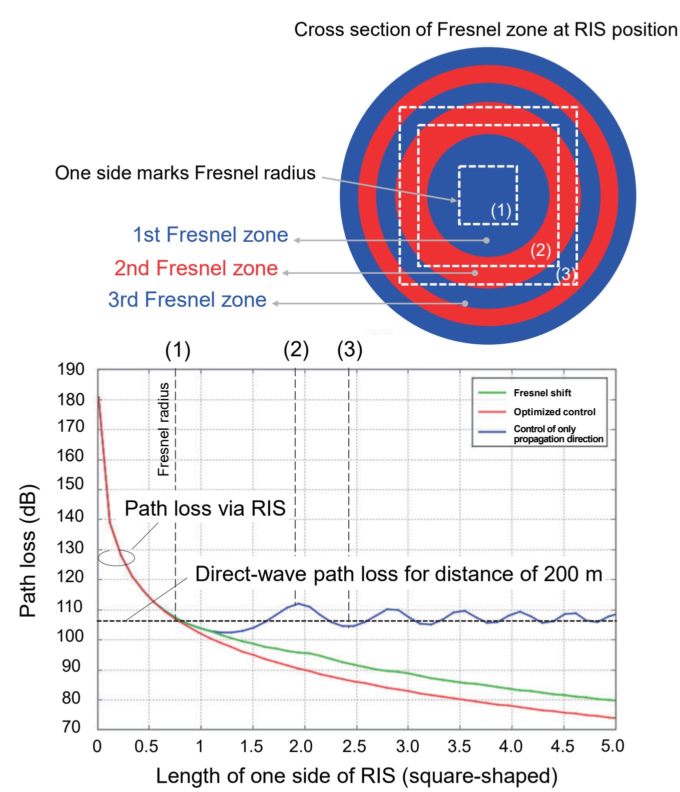


Figure 2　Relationship between RIS size and path loss

that of (1), it can be seen that double path loss asymptotically approaches path loss of a direct wave for the same path length. Furthermore, though described in more detail later, double path loss when subjecting RIS to optimized control to maximize received power at MS takes on the values shown by the red line in the figure. Now, by analytically determining the RIS size for which this optimally controlled double path loss is equal to direct-wave path loss at (1) in the figure, the length of one side of this RIS turns out to be the Fresnel radius*8. It can also be seen from the figure that, even without optimized control of RIS, the RIS size at which path loss is equal to that of the direct wave nearly agrees with the Fresnel radius, and if the RIS becomes larger than that size, an amount of power equivalent to that of the direct wave for the same path length can be received (blue line in the figure).

In addition, the reason for the alternating increase/decrease in double path loss as it asymptotically approaches path loss of the direct wave with increase in RIS size is the canceling out of signals via the odd-numbered and even-numbered Fresnel zones*9 at the receiving point.

2) Effect of Phase Control by RIS

On breaking down the BS – RIS – MS propagation path by each element making up the RIS, we consider that the received power of the BS – RIS – MS path can be maximized by performing RIS phase control so that the waves on each path have the same phase at the receiving point (red line in Fig. 2). If optimized control is performed in this way, the received power ends up having a positive correlation with RIS size instead of converging to the value of the direct wave path. Furthermore, if RIS size should be less than the Fresnel radius, practically no difference can be observed between conventional control of only the propagation direction (blue line in the figure) and optimized phase control, so direction-only control is sufficient in this interval.

When performing optimized control of a RIS from the viewpoint of received power, the amount of phase change in each element of the RIS must be set to an optimal value as described above. This, however, may complicate the control process. To simplify this process, we introduce a technique that can significantly improve received power by adding phase compensation consisting of only two values—0 and π (rad)—to direction-only control. As shown in Fig. 2 for the case of direction-only control, path loss increases and decreases repeatedly as RIS size becomes larger. Here, received power can be significantly improved by shifting the wave phase by π (rad) via the even-numbered Fresnel zones, the cause of this increase-decrease behavior (green line in the figure). This technique (hereinafter referred to as "Fresnel shift") can improve received power depending on RIS size the same as optimized control even for users positioned at any distance. Details of this technique are provided in another paper [5].

3. Study of Metasurface Technology toward Transparent RIS

As described above, metamaterial/metasurface technologies are commonly used to achieve RIS.

A metamaterial features a periodic arrangement of structures each sufficiently smaller than the wavelength of an electromagnetic wave. This artificial periodic structure can, in effect, behave

*8 Fresnel radius: Radius of the first Fresnel zone (see *9).

*9 Fresnel zone: Given the shortest distance between the transmitting/receiving points (here, the shortest distance via RIS), the range in which the difference in path lengths is less than half a wavelength, that is, in which the difference in signal phase is less than π (rad), is called the first Fresnel zone. Furthermore, the range in which the difference in path lengths is greater than $n-1$ but less than n half-wavelengths is called the nth Fresnel zone. Signals within the same Fresnel zone strengthen each other and synthesize.

as a material having a negative refractive index, so it can be used to obtain characteristics that cannot be achieved by ordinary material. As a consequence, metamaterial technology has been vigorously researched since 2000 [6]. Demonstrations of metamaterial technology were initially conducted in the microwave band (5 GHz), but studies in the millimeter-wave and terahertz-wave*10 bands have been active since 2010 [7]. This is thought to be due to various factors. For example, the elemental structures making up metamaterial are of a size on the order of mm – μm that can be easily fabricated by existing manufacturing processes. In addition, these are frequency bands for which the electrical resistance of metals can be nearly ignored, the same as for frequency bands used in conventional mobile communications.

Moreover, while a metamaterial is a three-dimensional artificial periodic structure, a two-dimensional artificial periodic structure is often called a metasurface. Controlling the reflection phase distribution on the metasurface enables the propagation of reflected waves to be controlled (**Figure 3**).

At present, metamaterial/metasurface technologies are described as important technologies in 6G-oriented white papers issued by a variety of research institutions. The following describes NTT DOCOMO initiatives surrounding metasurface technology toward the practical implementation of RIS.

3.1 Transparent Dynamic Metasurface

In 2018, researchers at NTT DOCOMO began studying static metasurface reflectors that do not provide dynamic control with an eye to expanding millimeter-wave coverage to non-line-of-sight locations [8]. However, for the metasurface reflector studied here, it was necessary to design a reflection phase distribution according to incident/reflected angles calculated from the installation location, base station position, and location targeted for reception. Another problem was that the area behind the reflector became a new non-line-of-sight location. It

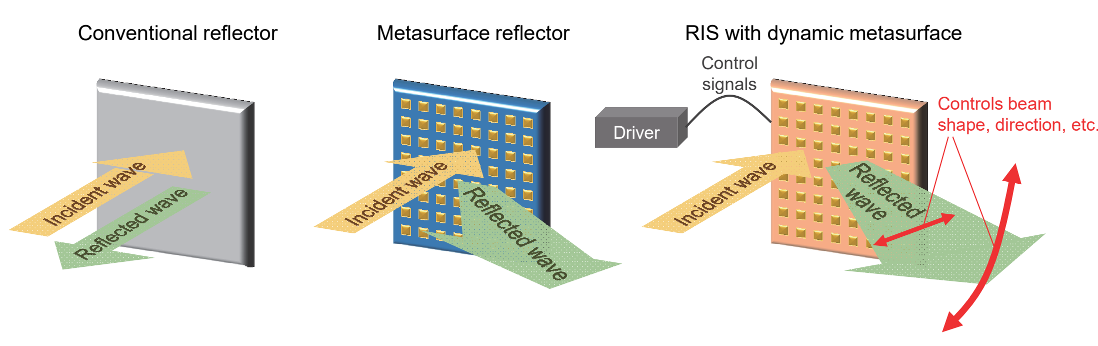


Figure 3 Conceptual diagram of RIS using metasurface technology

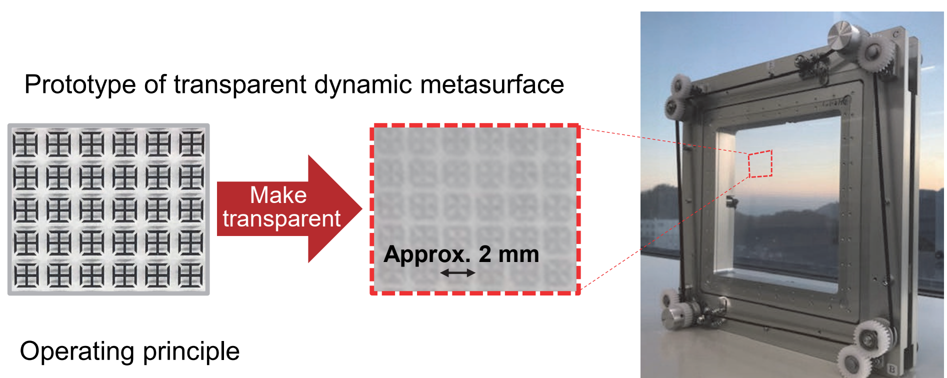
*10 **Terahertz wave:** Electromagnetic waves with a frequency of around 1 THz. Often used to refer to frequencies ranging from 100 GHz to 10 THz.

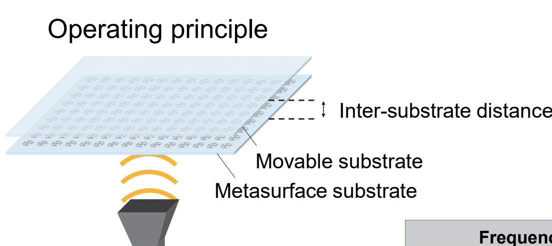
was also desirable that the reflector has a design or look that blends in with the city landscape.

In response to the above issues, we have been developing and studying a "transparent dynamic metasurface" in cooperation with AGC Inc. as a RIS prototype that can dynamically control the reflection and penetration of radio waves while maintaining high transparency (**Figure 4**) [9]. The metasurface substrate is covered with a transparent glass substrate to make it transparent, and moving the glass substrate slightly enables dynamic control of radio waves in three modes: full penetration of incident waves, partial penetration and partial reflection of radio waves, and reflection of all radio waves.

The mainstream method for achieving dynamic metamaterials and metasurfaces in the past was to use semiconductors to control the resistance and electrical-capacitance components of metallic patterns. Our new method for achieving transparent dynamic metasurfaces is superior to the conventional technique using semiconductor devices by virtue of "enabling dynamic control while maintaining transparency" and "making it easy to enlarge the substrate." Use of a transparent dynamic metasurface also minimizes impact on the surrounding environment and on existing designs on installation.

A trial performed to assess the performance of the prototype RIS showed that it could achieve transmittance of approximately –1.4 dB or greater in penetration mode and approximately –10 dB or less in reflection mode (calculated as reflectivity of –1 dB or greater) in 400 MHz or higher bands (Fig. 4).





	Inter-substrate distance
Reflection mode	＞200 μm
Penetration mode	0 μm

Trials results

Frequency		26.8 GHz	26.9 GHz	27.0 GHz	27.1 GHz	27.2 GHz	27.3 GHz
Transmittance	Penetration mode	– 0.3 dB	– 1.4 dB	– 0.8 dB	– 1.2 dB	– 1.2 dB	– 0.3 dB
	Reflection mode	– 15 dB	– 14 dB	– 10 dB	– 11 dB	– 11 dB	– 10 dB

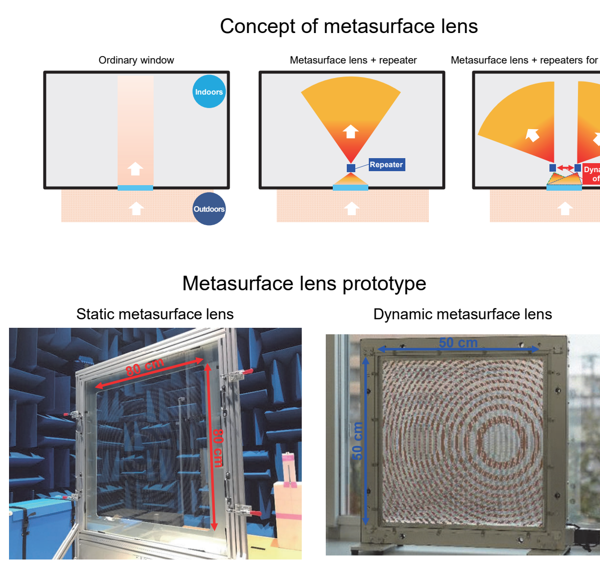
Figure 4　Transparent dynamic metasurface initiative

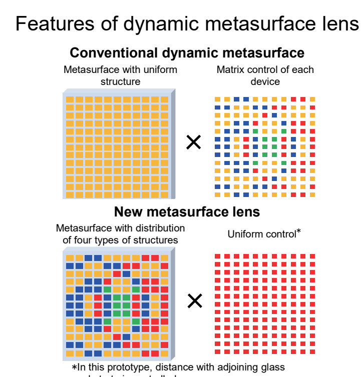
Going forward, we plan to study further functional enhancements such as functions for controlling penetration/reflection directions with the aim of achieving a practical transparent RIS.

3.2 Making Windows into Radio-wave Lenses by Transparent Metasurface Lens

Compared with radio waves in the frequency bands currently used in LTE and the Sub6*11 band, radio waves in the millimeter-wave band have high straight-line propagation properties and attenuate easily. For this reason, radio waves emitted from outdoor base station antennas attenuate before arriving at the glass window of a building, and in addition, attenuated and weak radio waves penetrate an indoor space without spreading out. It is therefore difficult to make such an indoor space into a coverage area using outdoor base station antennas.

In response to these issues, we developed in cooperation with AGC Inc. a "transparent metasurface lens" that can guide millimeter waves passing through a glass window to a specific indoor location (referred to below as a "focal point"). This is a film-like lens that can be affixed to a glass window from the indoor side [10] [11]. Focusing weak radio waves that pass through the entire surface of a glass window at a focal point in this way can increase power, so installing an area improvement tool such as a repeater, reflector*12, or RIS at the focal point position should make it possible to extend area coverage from outdoor base station antennas to the inside of a building (**Figures 5** and **6**). In a trial using this metasurface lens, we found that





Trial results

Static metasurface lens

	(1) Float glass	(2) (1) + metasurface lens
Received power at focal point	0 dB	>24 dB

*Values when using as reference the received power at focal point with only float glass

Dynamic metasurface lens

		Focal-point 1	Focal-point 2
Received power at focal point	Single focal point mode	11 dB	0 dB
	Double focal point mode	6 dB	6 dB

*Values when using as reference the received power at focal-point 2 in single focal point mode

Figure 5　Concept of making windows into radio-wave lenses by transparent metasurface lens

*11 **Sub6:** A specific range of frequencies. Radio signals having frequencies from 3.6 GHz to 6 GHz.

*12 **Reflector:** In this article, reflectors include conventional metal reflectors and metasurface reflectors.

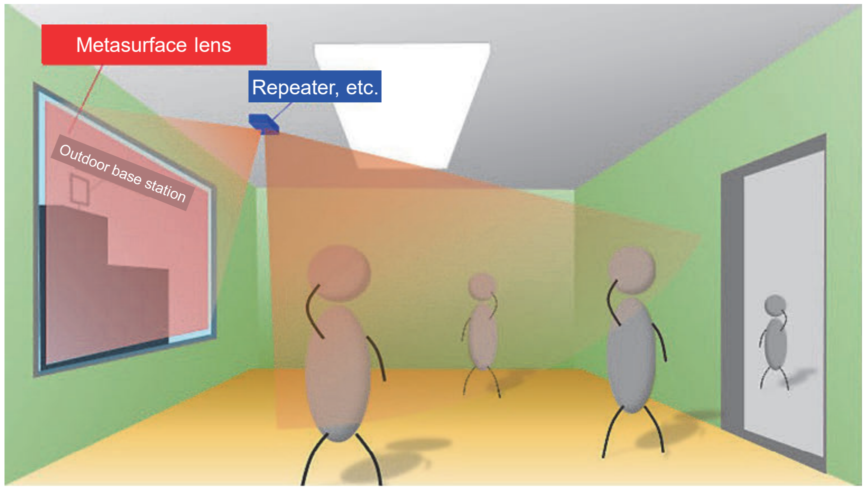


Figure 6 Example of using a transparent metasurface lens

the received power at the focal point could be improved by 24 dB or more compared with the case of an ordinary transparent glass.

We also tested a function for dynamically controlling focal points. In this regard, the conventional approach to controlling the penetration/reflection direction of radio waves was to configure a metasurface with a uniform arrangement of identical devices and to apply different control signals to each device. In contrast, our new dynamic metasurface lens appropriately arranges devices with four different types of structures so that focal point positions can be switched (presently between a single focal point and two focal points) even when applying the same control signal to all devices (Fig. 5). In single focal point mode, the received power at focal-point 1 was shown to be 11 dB higher than that at focal-point 2 indicating that only focal-point 1 was functioning as a focal point. Meanwhile, in double focal point mode, received power at both focal-point 1 and focal-point 2 was shown to be 6 dB higher than that at focal-point 2 in single focal point mode indicating the formation of two focal points. Simplifying the control process in this way raises the possibility of dynamically controlling focal points even with a large-area metasurface lens.

4. Conclusion

In this article, we presented the concept of IRE that attempts to adaptively control the radio environment, which is deemed to be a useful approach to achieving non-line-of-sight coverage in the millimeter-wave band, an important issue in achieving 5G evolution & 6G. We also described RIS as an elemental technology of IRE and metamaterial/metasurface technologies that form the foundation of RIS. When influencing the propagation environment by a reflector or RIS of limited area, controllability increases the larger is that area with respect to that wavelength, i.e., the higher is the frequency of the propagating wave. The technology described here is expected to become a base technology for constructing coverage areas not only for 5G but also for 6G and beyond radio systems whose frequencies are expected to be even higher.

Going forward, we plan to assess the effectiveness of the RIS technology described in this article in actual environments and to study the application of even higher frequencies with RIS toward 6G.

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Technology Reports (Special Articles) NTN HAPS Extreme Coverage Extension

Special Articles on 5G evolution & 6G (1)

Research on NTN Technology for 5G evolution & 6G

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In 5G evolution & 6G, extreme coverage extension is being studied for use cases in all places including air, sea, and space. NTNs using GEO satellites, LEO satellites, and HAPS are promising tools for providing high quality communication services in areas that cannot be covered by the conventional mobile communication network. In this article, we describe these technologies and the details of a 39 GHz band airborne propagation measurement experiment performed using a small airplane at an altitude of about 3 km.

1. Introduction

While the 5th Generation mobile communication system (5G) is expected to be an important technology for regional development and solving regional issues, a key issue for the 5G evolution and 6G era is expected to be expanding the communication area to any place where its benefits can be enjoyed [1]. As shown in **Figure 1**, NTT DOCOMO is conducting research and development aimed at realizing extreme coverage extension*1 whereby mobile communication can be made available in all locations, including the air, sea and space, that are not adequately covered by conventional mobile communications networks, thereby extending coverage to drones, flying cars, ships, and even space stations.

To achieve this extreme coverage extension, we are focusing on Non-Terrestrial Network (NTN)*2 technology using satellites and High-Altitude Platform Stations (HAPS)*3. This technology is able to provide communication coverage in mountainous and remote areas, at sea, and even in outer space by employing satellites and HAPS systems that are

Figure 1 Extreme coverage extension

free of geographical restrictions.

This article describes extreme coverage extension, which is one of the key issues for the realization of 5G evolution & 6G. Specifically, we describe the concept of NTN technology, which has been attracting attention as a promising approach, the use cases and technical issues of wireless system technology using HAPS, and our work on measuring the propagation of radio waves using a small aircraft.

2. Extreme Coverage Extension and NTN Technology for 5G evolution & 6G

Extreme coverage extension supports use cases in any location, including air, sea and space. This will extend coverage to users that cannot be covered by conventional mobile communication networks, including drones, flying cars, ships and space stations. To achieve extreme coverage extension, it will be necessary to develop technologies that facilitate highly efficient long-range wireless transmission over at least several tens of kilometers.

As shown in **Figure 2**, by considering the use of (1) GEOstationary (GEO) satellites, (2) Low Earth Orbit (LEO) satellites, and (3) HAPS, we will be able to cover mountainous and remote areas, the sea, the sky, and even outer space, and to provide communication services to these areas [2].

(1) A GEO satellite that orbits the Earth at an altitude of about 36,000 km. Although the one-way radio wave propagation time between a GEO satellite and a ground station antenna is relatively long (about 120 ms), just three or four GEO satellites can provide the entire planet with constant coverage. Even today, GEO satellites are used to complement terrestrial networks by providing a mobile backhaul*4. Since additional network capacity will be required in the 6G era, Very High Throughput Satellites (VHTS) are being

*1 Extreme coverage extension: Extending the area in which base stations can communicate with mobile terminals to any location, including the air, sea and space, that is not covered by the current mobile communication system.

*2 NTN: Any network in which the communication area is not limited to the ground but extended to other places such as the air, sea and space through the use of non-terrestrial equipment such as satellites and HAPS.

*3 HAPS: An airborne platform that is designed to operate in the stratosphere on board a vehicle such as a solar-powered aircraft or airship.

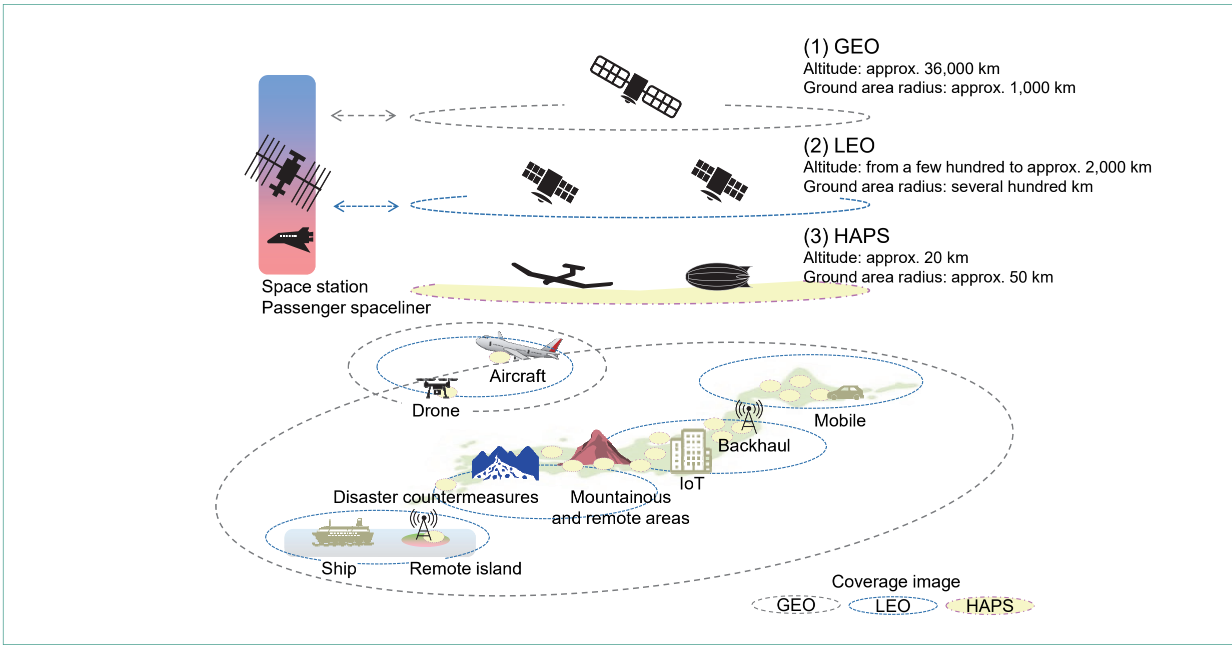

Figure 2　Illustration of how satellites and HAPS can be used to extend coverage to the sky, sea, and space

studied with the aim of improving system capacity by optimizing the allocation of power and frequency across multiple beams [3].

(2) An LEO satellite orbits the Earth at an altitude ranging from a few hundred km to about 2,000 km. Unlike a GEO satellite, it has a much lower orbit and a much smaller propagation delay (just a few ms for a one-way trip). LEO satellites are currently used for satellite mobile phone systems and satellite sensing*5. They are also expected to be used for the expansion of communication capacity through the reduction of satellite fabrication costs and the use of Multiple Input, Multiple Output (MIMO)*6 technology, and for high-capacity, low-latency backhauls in satellite constellations that form networks through cooperation between multiple satellites [4].

(3) HAPS have recently attracted renewed attention due to their ability to parked at an altitude of about 20 km in fixed locations, allowing them to provide services across terrestrial cells*7 with a radius of approximately 50 km or more [5]. Since their altitude is lower than that of LEO satellites, it is possible to achieve a one-way radio wave propagation time of about 0.1 ms, depending on the cell radius. As a result, they are considered to be an effective way of deploying services not only in regions that have been hit by natural disasters but also in many of the industrial use cases envisioned for 5G evolution & 6G.

The 3rd Generation Partnership Project (3GPP) has begun studying how satellites and HAPS can be used to extend New Radio (NR)*8 to NTNs [6].

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*4　Backhaul: In a mobile communication network, a backhaul is a fixed line that supports high-speed, high-capacity transmission of information between a large number of wireless base stations and the core network.

*5　Satellite sensing: Observing the state of the atmosphere and earth's surface from space by means of instruments carried on board satellites.

*6　MIMO: A signaling technique whereby multiple transmit and receive antennas are used to transmit signals simultaneously and at the same frequency to improve communication quality and the efficiency of frequency utilization.

3. HAPS Use Cases and Network Configuration/control Techniques

NTT DOCOMO is working on the research and development of communication methods and network architectures that can flexibly link 5G networks and other terrestrial networks with stratospheric HAPS networks [7] [8]. In addition to providing flexible support for a wide range of future use cases as envisioned in 5G evolution & 6G, this project is conducting studies aimed at the implementation of communication systems that use realistic HAPS in terms of development and operation costs.

3.1 HAPS Use Cases

As shown in **Figure 3**, for the 5G evolution & 6G era, it is expected that various use cases will involve using HAPS to relay radio waves or emit radio waves as a base station. These use cases include fixed systems that provide services for backhaul applications, and mobile systems that provide services to terminals either directly or by via repeaters and relays. In particular, the use of broadband millimeter wave*9 radio signals is expected to enable the timely provision of high-speed, large-capacity, low-latency lines required for various applications including industry and public events, regardless of whether or not optical fibers or other wired networks are available, and in any location, including at sea, in the air, or in remote areas.

The requirements of HAPS systems can vary widely from one use case to the next. As shown in **Figure 4**, different use cases require different communication speeds and different bandwidths. There is a need for flexible communication methods and systems that can support all use cases of fixed and

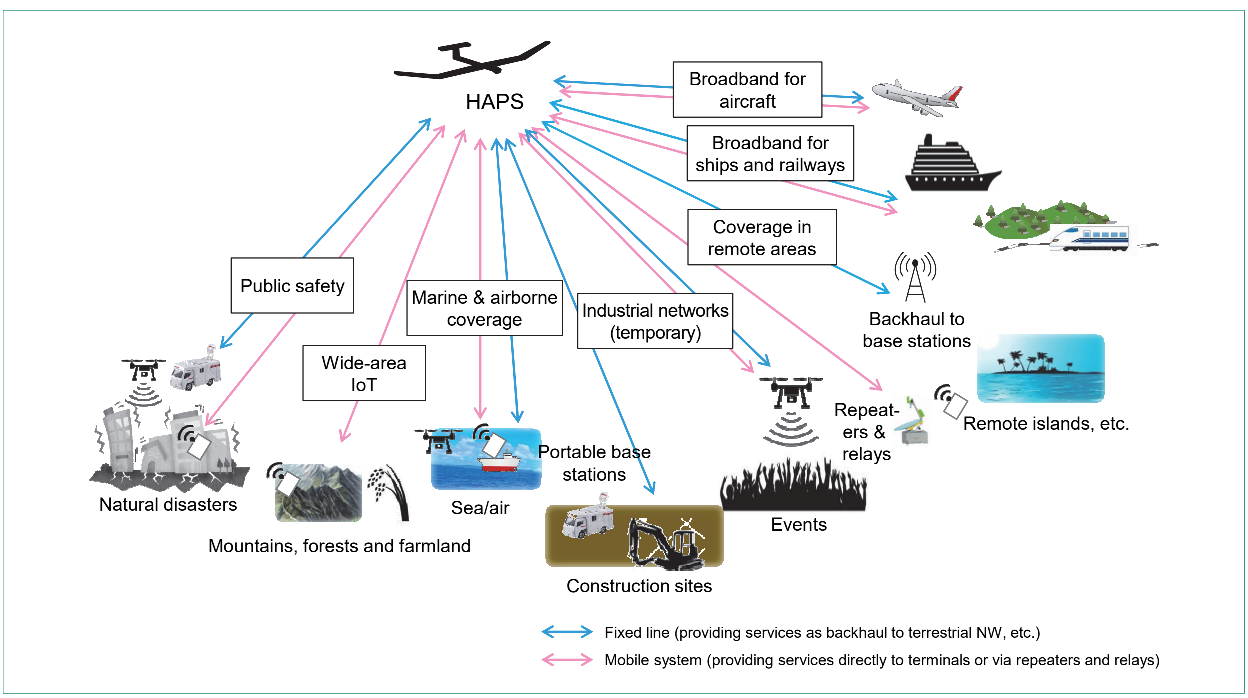

Figure 3 Various use cases expected for HAPS

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*7 **Cell**: The unit of area division that makes up the service area of a mobile communications network.

*8 **NR**: A radio system standard formulated for 5G. Compared with 4G, it enables faster communication by utilizing high frequency bands (e.g., 3.7 GHz and 28 GHz bands), and low latency and highly reliable communication for achieving advanced IoT.

*9 **Millimeter waves**: Radio signals in the frequency band from 30 GHz to 300 GHz as well as the 28 GHz band targeted by 5G all of which are customarily called "millimeter waves."

mobile systems.

For example, it is considered that the communication speed for backhaul applications to 5G base stations will have to be at least 1 Gbps per service link*10. Furthermore, to provide multiple simultaneous service links, the feeder link*11 will have to be capable of even faster communications speeds (several Gbps to several tens of Gbps) and must operate as stably as possible regardless of weather-related effects.

It is also necessary to flexibly control lines so that they can be adapted from normal business applications to public safety*12 applications in the event of a disaster. Current disaster countermeasures are geared towards providing basic communication services such as voice calls and SMS, but in the future, it may also be necessary to consider use cases that require faster communication speeds, such as remote control of equipment at disaster sites, video transmission, and communication via drones. For disaster countermeasures, it will also be necessary to study network configurations and control techniques that assume the ability of a system to operate even if some devices become unavailable.

3.2 Technology for Network Configuration and Control in Conjunction with 5G Networks

1) Classification of HAPS - mounted Stations

In the network configuration and control technology used when implementing backhauls to 5G base stations via HAPS, we are focusing on the categorization of HAPS-mounted stations. They can be roughly divided into two types: (1) relay stations, which receive signals from ground stations and relay them back to other ground stations after performing necessary processes such as frequency conversion, and (2) base stations, which are made by installing 5G network base station equipment

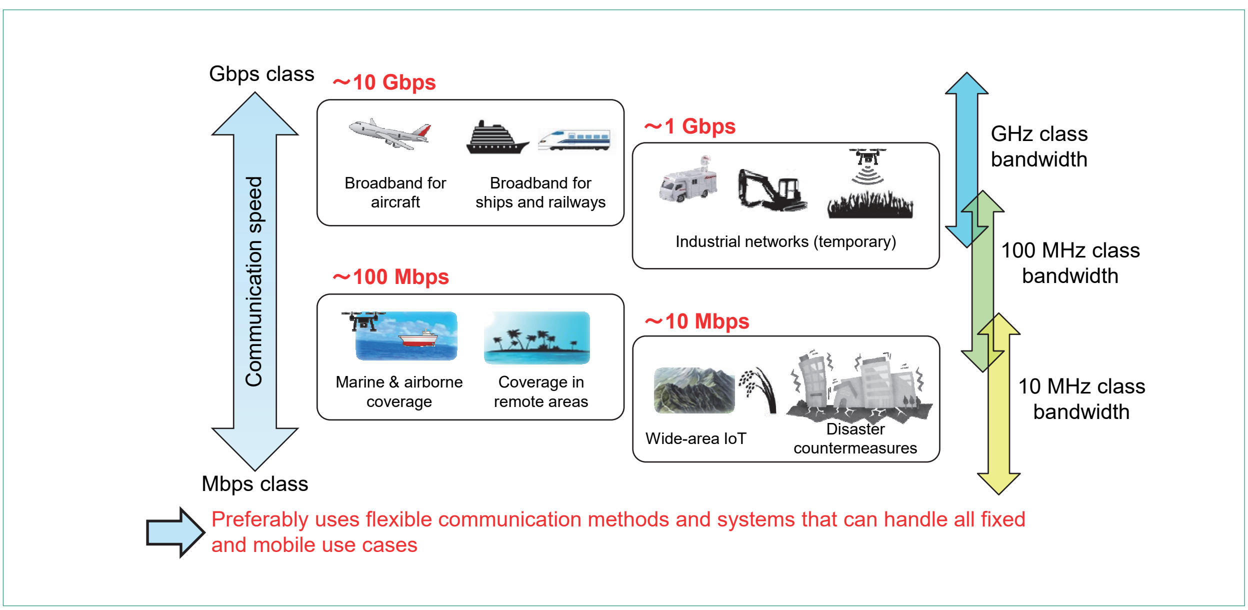


Figure 4 Requirements for each HAPS use case

*10 Service link: A communication path between a satellite or HAPS and a terminal in an NTN communication system.

*11 Feeder Link: A communication path between a satellite or HAPS and a terrestrial base station (gateway) in an NTN communication system.

*12 Public safety: A generic term for services that ensure the safety of the public, including disaster prevention, police, fire, and first-aid services.

(or at least part of it) in a HAPS.

(1) The relay type is effective when the number of on-board devices is relatively small and the size, weight, and power consumption of the HAPS-mounted station are strictly limited.

(2) The base station type is formed by equipping a HAPS with an antenna device, together with many base station functions. The more of these functions it includes, the greater the amount of control that can be performed within the HAPS, making it possible to reduce the amount of feeder link information. On the other hand, installing more functions results in a station that is larger, heavier, and consumes more power.

Table 1 shows a comparison of possible HAPS-

Table 1 Comparison of HAPS-mounted stations

	On-board station type	Wireless standard (FL/SL)	Applications of HAPS communication	Features (advantages)	Issues
#1	Repeater	Fixed/ fixed*1	Fixed	Reduced weight and energy requirements of on-board stations*2	Support for simultaneous connections with multiple beams
#2	Repeater	Mobile/ mobile*1	Fixed & mobile	Reduced weight and energy requirements of on-board stations*2	Support for simultaneous connections with multiple beams Increased PAPR due to use of OFDM signals*3
#3	Base station type (Full BBU)	Fixed/ fixed	Fixed	Flexible support for both FL and SL standards with a single communication system	Increased power consumption and weight of on-board stations due to higher performance (increased communication speed and number of simultaneous connections)
#4	Base station type (Full BBU)	Mobile/ mobile	Fixed & mobile	Flexible support for both FL and SL standards with a single communication system	Increased power consumption and weight of on-board stations due to higher performance (increased communication speed and number of simultaneous connections) Increased PAPR due to use of OFDM signals*3
#5	Base station type (DU/RU only)	Fixed/ mobile	Fixed & mobile	May be possible to reduce power consumption and weight of on-board stations while providing the same performance as #6	Two communication systems need to be installed, resulting in increased station power consumption and weight Increased PAPR due to use of OFDM signals (SL only)*3
#6	Base station type (Full BBU)	Fixed/ mobile	Fixed & mobile	Achieving ultra-high capacity services by independently optimizing for FL/SL frequencies and radio standards	Two communication systems need to be installed, resulting in increased station power consumption and weight Increased PAPR due to use of OFDM signals (SL only)*3

BBU: Base Band Unit PAPR: Peak to Average Power Ratio
FL: Feeder Link SL: Service Link

*1 Repeater types (#1, #2) may be able to operate regardless of the wireless standard (with multiple wireless standards).
*2 It is expected that the higher the required communication speed, the greater the relative merits of the relay type compared with the base station type.
*3 Single-carrier waveforms may be adopted by NTNs in the future, such as for 6G.

mounted station configurations. In general, implementing more of the base station functions on the ground network side has the advantages of lower development costs and ease of operation, but implementing these functions on the HAPS results in greater resilience to natural disasters. In terms of performance, a HAPS-mounted station should at least implement some functions, such as beam control when using millimeter waves. It is also necessary to comprehensively study a wide range of requirements to be considered when incorporating HAPS systems into a 5G network. These include the size, weight, and power consumption of HAPS-equipped stations, their development and operation costs, the ability of these HAPS platforms can be shared by fixed-line and mobile communications systems, and their ability to cooperate with GEO/LEO satellites.

2) Examples of Network Configuration in Conjunction with the 5G Network

An example of a HAPS base station in a network configuration linked to the 5G network is shown in **Figure 5**. Here, the Distributed Unit (DU)*13 and Radio Unit (RU)*14 of the 5G base station are mounted on the HAPS in accordance with Open RAN (O-RAN)*15 Alliance specifications [9]. In this configuration, availability is ensured by installing a Centralized Unit (CU)*16 at a disaster-resistant point on the ground. Information received by the HAPS from the CU in the feeder link is transmitted via 5G radio to a small terrestrial base station device (relay station) in the service link, thereby enabling the use of portable 5G base stations without having to use a wired backhaul. In this configuration, it is also possible to provide direct communication from the HAPS to 5G terminals

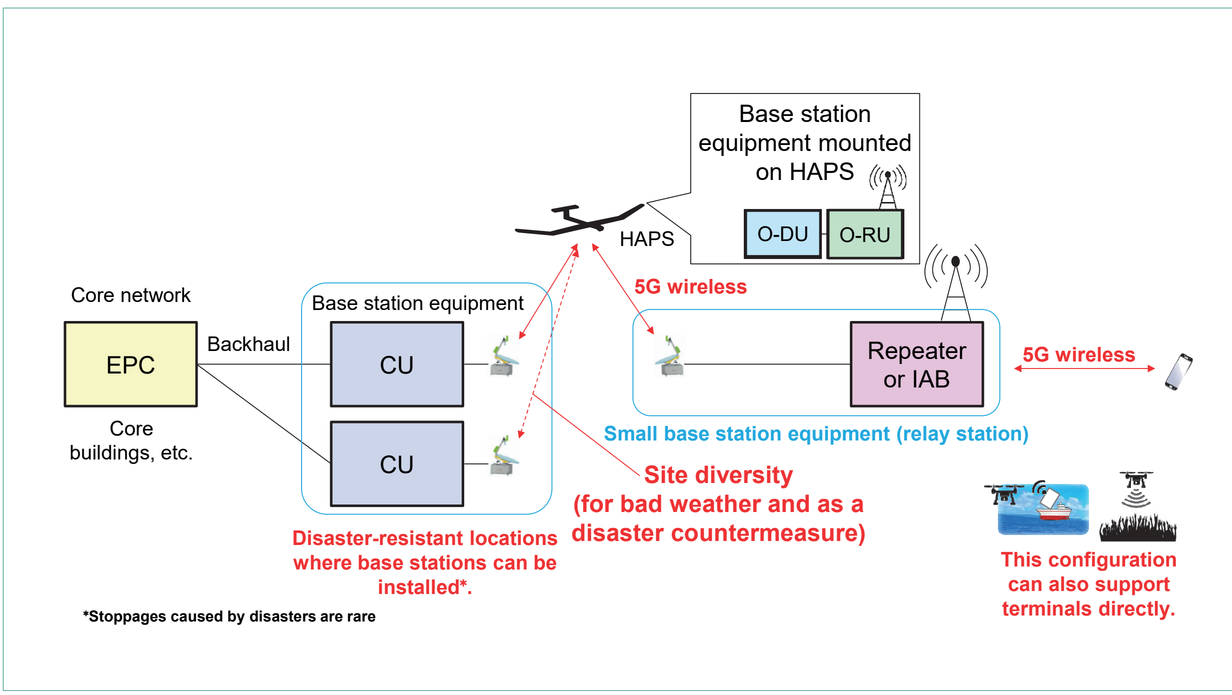


Figure 5 Example of cooperative configuration when HAPS is used for backhaul

*13 DU: A functional unit of a wireless base station that performs real-time data link layer control and other functions.

*14 RU: The radio unit of a wireless base station.

*15 O-RAN: An open, intelligent radio access network aimed at efficiently providing a variety of services in the 5G era.

*16 CU: An aggregating node that implements functions such as non-real-time L2 (Layer 2) functions and RRC (radio resource control) functions in a radio base station.

without the need for intervening relay stations. As a further extension, site diversity*17 can be implemented by using multiple CUs on the ground side to reduce the impact of bad weather and natural disasters, and mobility support*18 can be implemented by switching the communication target to a different HAPS when the terminal moves from one communication area to another.

In addition to the configuration shown in Fig. 5, we are also considering other promising configurations: one in which a HAPS is used to carry a standalone*19 5G base station, and another with a relay-type configuration where a 5G radio repeater is installed in a HAPS. For each configuration, it is necessary to conduct a comprehensive study that takes account of various attributes such as mobility support, site diversity technology and frequency sharing technology*20, as well as HAPS installation requirements such as links with GEO/LEO satellites, the equipment weight and power consumption.

4. Experimental 39 GHz Band Propagation Measurements Using a Small Aircraft

To implement a communication area from an airborne station in 5G evolution & 6G, we conducted an experimental demonstration of radio wave propagation measurements in an urban area (Odawara City, Kanagawa Prefecture), a mountain forest (Tanzawa), and a remote island (Izu Oshima) using a small aircraft (February 15–26, 2021) [10]. Before using the actual HAPS system, we performed an initial experiment to compare the propagation of millimeter wave (39 GHz band) radio signals, which are suitable for 5G high-speed communication, and signals at a lower frequency (2 GHz band), which propagate more easily than millimeter wave signals. These signals were sent from the ground to a receiver mounted on a small aircraft about 3 km above ground level. In the urban environment, we measured the effects of obstacles such as buildings and reflected waves. In the forest, we measured the effects of terrain and trees. And in the remote island, we measured the effects of clouds and low elevation angles above the sea. Our results show that radio wave propagation in the 39 GHz and 2 GHz bands depends on various environmental factors, and changes when the airplane turns.

4.1 Measurement Environment and Measured Items

Figure 6 shows an illustration of the airborne propagation measurement test. The radio wave transmission points were located in an urban area (Odawara City in Kanagawa Prefecture), a forest (Tanzawa), and a remote island (Izu Oshima), and the reception point was a small aircraft circling with a radius of 1 to 2 km. The elevation angle of the small aircraft (receiving point) from the transmitting point was determined to be equivalent to the use case of a HAPS circling at an altitude of 20 km. Specifically, we assumed a coverage radius of 50 km for an altitude of 20 km in the urban and forest use cases (elevation angle: 21.8°), and a coverage radius of 200 km for an altitude of 20 km in the remote island use case (elevation angle: 5.7–11.5°). In addition to the line-of-sight environment, we also measured the received power with intervening obstacles such as buildings and trees in each use case, as shown in **Figure 7**.

*17 **Site diversity:** A technique for improving communication quality by switching between multiple ground stations when radio waves are highly attenuated due to rain or obstacles.

*18 **Mobility support:** Technology that allows communication to continue when a terminal moves across a communication area by switching it to a different base station before communication is interrupted.

*19 **Standalone:** A deployment scenario using only NR, in contrast with non-standalone operation which uses LTE-NR DC to coordinate existing LTE/LTE-Advanced and NR.

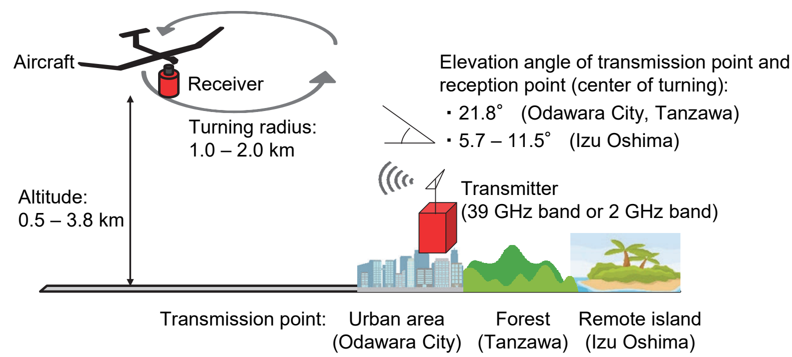
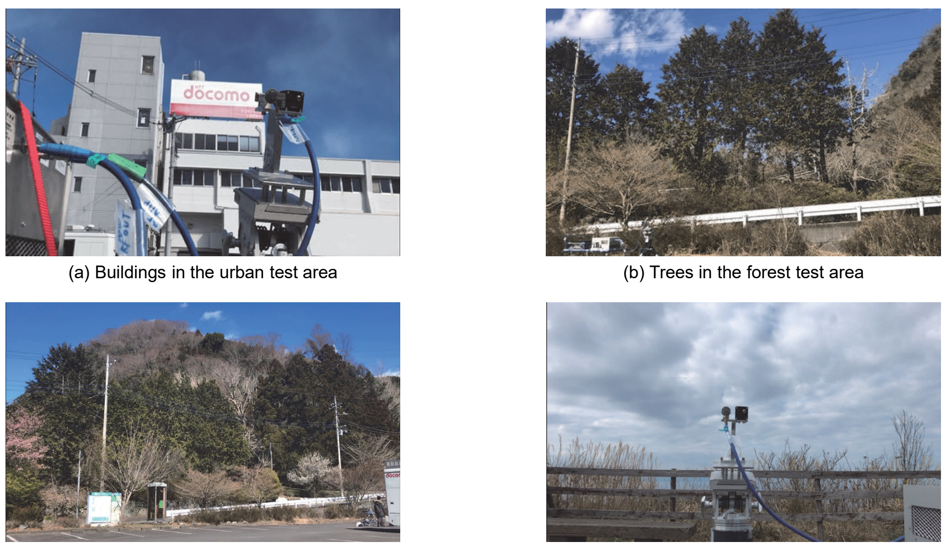


Figure 6 Illustration of the airborne propagation measurement test



(a) Buildings in the urban test area

(b) Trees in the forest test area

(c) Mountains in the forest test area

(d) Clouds in the remote island test area

Figure 7 Test environments with various obstacles

Table 2 lists the main specifications of the experimental equipment. For the transmitting antenna, we selected a product that was able to cover the turning range of the aircraft within the beam width*21, and we fixed the direction of this antenna toward the aircraft's turning center. The receiving antenna was housed in a mounting frame, and a 3-mm-thick polycarbonate radome*22 designed to cause almost no propagation loss*23 was secured to its base. We also performed an initial experiment in which neither of the transmitting or receiving antennas were provided with tracking functions, and the receiving antenna was fixed directly to the underside of the aircraft.

4.2 Evaluation

1) Overview

Table 3 shows the results of measuring the

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*20 **Frequency sharing technology:** Technology that makes it possible to share frequencies by suppressing the interference effects that occur when two systems use the same frequency at the same location. In this article, we are mostly concerned with frequency sharing between HAPS systems and terrestrial mobile communication systems.

*21 **Beam width:** The antenna radiation angle at which the beam is radiated with gain of –3dB or less from the maximum antenna gain.

*22 **Radome:** An enclosure to protect an antenna. These are made of materials that are transparent to radio waves.

Table 2 Main specifications of the airborne propagation test apparatus

	Frequency band	Main specifications of the test apparatus and equipment
Transmitter	39.75 GHz band	· Maximum transmitter output: 37 dBm · Transmitted wave type: unmodulated · Antenna type: horn · Maximum transmitting antenna gain: 14.6 dBi · Radio wave emission direction: towards the aircraft's turning center · Polarization: vertical
	2.2001 GHz band	· Maximum transmitter output: 42 dBm · Transmitted wave type: unmodulated · Antenna type: sleeve · Maximum transmitting antenna gain: 2.2 dBi · Radio wave emission direction: horizontal · Polarization: vertical
Receiver	39.75 GHz band	· Antenna type: omni · Maximum receiving antenna gain: 3.0 dBi
	2.2001 GHz band	· Antenna type: omni · Maximum receiving antenna gain: 0.0 dBi

Table 3 Summary of the airborne radio wave propagation measurement results

39 GHz band measurement environment	39 GHz band measurement results
Everywhere	· The maximum line-of-sight reception sensitivity roughly matches the results of desktop calculations in all environments (within 5 dB of error). · The predicted average/median was about 14–24 dB less than the maximum. ➢Fluctuations in the directivity pattern of the transmitting and receiving antennas due to turning, polarization losses, and occlusion by the aircraft itself have a large effect. ➢For the practical application of HAPS, it will be important to develop control technology that can suppress this sort of turning-related effect and maintain a constant received power. · The difference between the mean and median was within 2.5 dB except for Tanzawa (mountain), where there was a lot of data buried in the noise floor, and the difference was about 3.8 dB. · In the 2 GHz band, which was tested by way of comparison, the signals also tended to be attenuated due to obstacles and the effects of turning.
Odawara (buildings)	· Compared with the forecast, the average value was approximately 17 dB lower, and the median value was approximately 19 dB lower.
Tanzawa (trees)	· Compared with the forecast, the average value was approximately 18 dB lower, and the median value was approximately 19 dB lower.
Tanzawa (mountains)	· Compared with the forecast, the average value was approximately 30 dB lower, and the median value was approximately 36 dB lower.
Izu Oshima (white clouds)	· Compared with the forecast, the average value was approximately 2 dB higher, and the median value was approximately 4 dB higher. ➢Hardly any cloud attenuation was observed, and it is inferred that flight trajectory errors have a dominant effect.

airborne propagation of radio waves. From this experiment, we found that the maximum reception sensitivity in the unobstructed line-of-sight environments was almost identical to the value obtained by desktop calculations, while the loss of received power in the 39 GHz band was relatively

*23 Propagation loss: The amount of attenuation in the power of a signal emitted from a transmitting station until it arrives at a reception point.

large when there were intervening buildings and trees. To reduce the influence of obstacles of this sort, it will be necessary to consider adopting measures such as site diversity. We also confirmed that the influence of clouds was relatively small in the absence of rainfall.

Furthermore, since signals were transmitted and received in this experiment by means of antennas with the same directivity pattern regardless of the aircraft's position and flight attitude, it also became clear that the received power varies greatly with changes in the angle of the antenna caused by turning of the aircraft. For the practical use of HAPS in the future, these results confirm the importance of using control technology to suppress the effects of turning the aircraft and maintain a constant received power.

2) Experimental Results in Odawara

As a concrete example of the measurement results, this section describes an experiment that models an urban use case. For the line-of-sight environment in Odawara City, Kanagawa Prefecture with the aircraft circling with a turning diameter of 2 km, **Figure 8** shows the time series data of losses in the 39 GHz band, and the cumulative distribution*24 of propagation losses in the 39 GHz and 2 GHz bands are shown in **Figure 9** (a) and (b), respectively. When the maximum receiver sensitivity in the 39 GHz band is calculated from the free space loss shown in Fig. 8, the results generally match the figures obtained in desktop calculations with an error of only about 1.2 dB. On the other hand, the time-series data fluctuated greatly when the aircraft turned, with the average received power decreasing by about 17 dB from the maximum value and the median*25 decreasing by about 14 dB. It is thought that these reductions were mainly caused by fluctuations in the directive gain of the transmitting and receiving antennas, polarization losses*26, and the obstruction of radio waves by the aircraft itself when the underside of the aircraft was facing away from the transmission point.

Next, using the data obtained while flying with a turning diameter of 2 km in an environment with buildings as obstacles, Fig. 9 (c) shows the cumulative distribution of 39 GHz band propagation losses,

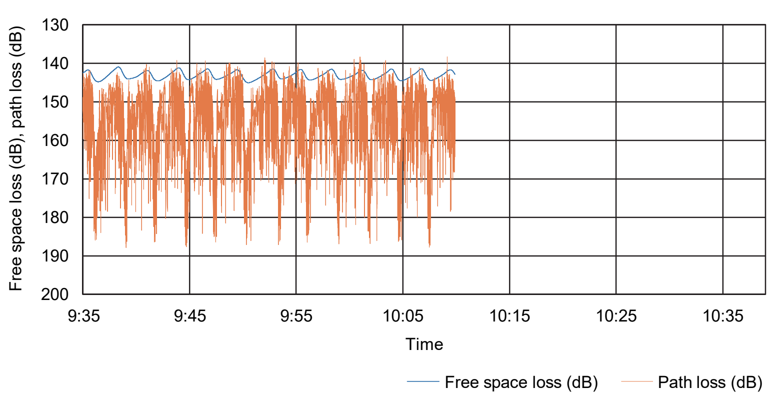

Figure 8 Propagation loss time series data in the 39 GHz band at Odawara City (line of sight)/2 km turning diameter

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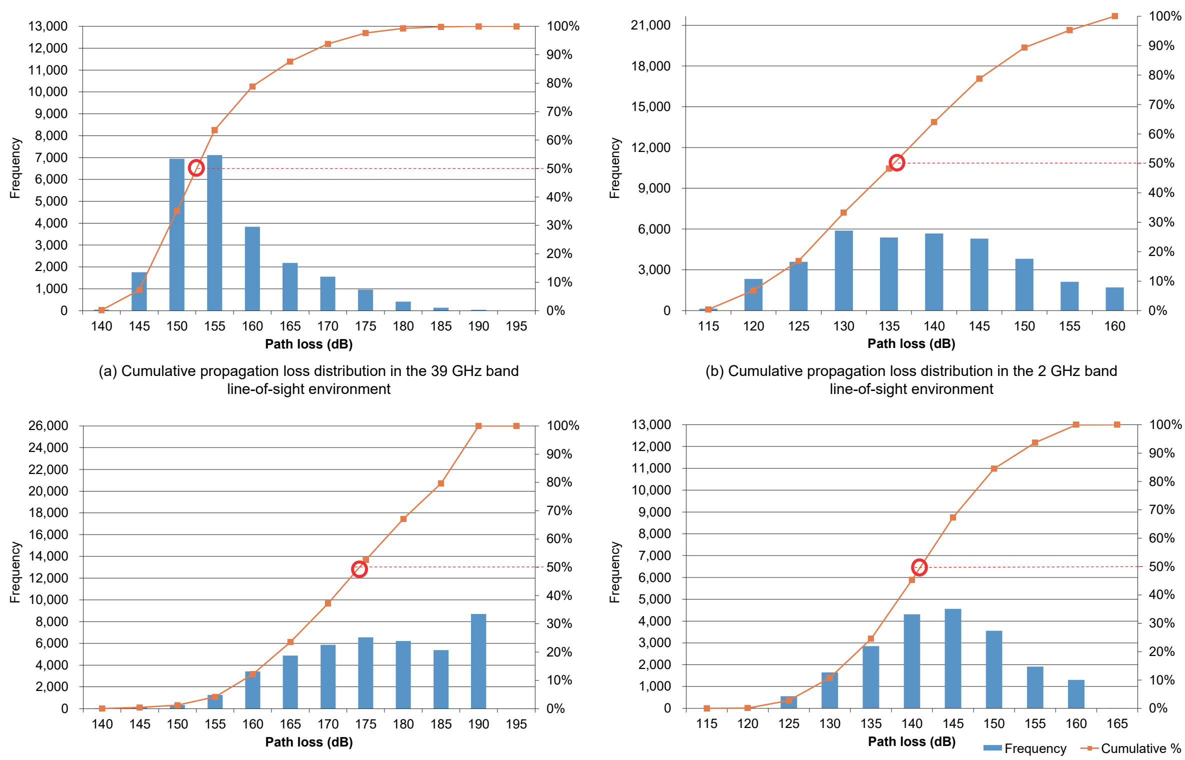
*24 Cumulative distribution: A function that represents the probability that a random variable will take on a value less than or equal to a certain value.

*25 Median: The value in the middle when countable data is ordered in increasing (or decreasing) size.

*26 Polarization loss: A loss of power received by a receiving antenna that occurs due to the vibration direction (polarization) of the electric field when radio waves propagate in space.



(a) Cumulative propagation loss distribution in the 39 GHz band line-of-sight environment

(b) Cumulative propagation loss distribution in the 2 GHz band line-of-sight environment

(c) Cumulative propagation loss distribution in the 39 GHz band building-obstructed environment

(d) Cumulative propagation loss distribution in the 2 GHz band building-obstructed environment

Figure 9　Cumulative distribution of propagation loss in Odawara City with a 2 km turning diameter

Fig. 9 (d) shows the cumulative distribution of 2 GHz band propagation losses, and **Figure 10** shows a map of propagation losses in the 39 GHz band. Comparing the mean and median values of Fig. 9 (a) and (c), the 39 GHz propagation loss has a mean value about 17 dB larger and a median value about 19 dB larger in the building-occluded environment compared with the line-of-sight environment. By comparing the average and median values of Fig. 9 (b) and (d), it can be seen that although obstruction by buildings also affects the 2 GHz band, the losses are relatively small – about 8 dB in the average value and about 9 dB in the median value – compared with the line-of-sight environment. Furthermore, from Fig. 10, it can be seen that when the underside of the aircraft is tilted towards the transmitting point, the received power is at least 40 dB greater than when the aircraft is tilted in the other direction.

5. Conclusion

In this article, as part of our efforts towards implementing extreme coverage extension, which is one of the important issues for 5G evolution & 6G, we have described NTN technology, especially

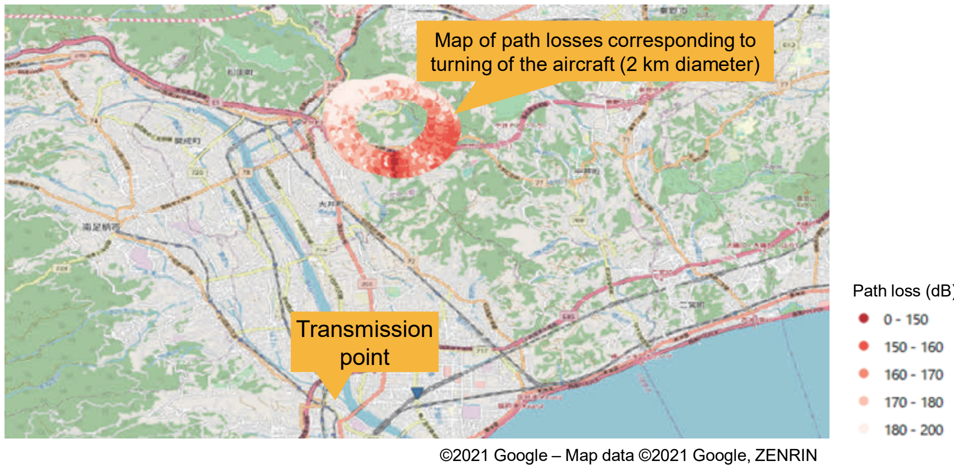


Figure 10 Map of propagation losses in the 39 GHz band at Odawara City (buildings)/2 km turning diameter

HAPS use cases and network configuration/control technology, and we have shown the results of airborne radio propagation tests performed using a small aircraft assuming HAPS use cases. NTT DOCOMO will continue developing NTN technology aimed at achieving extreme coverage extension and technology for realizing HAPS networks, and promoting demonstration experiments and standardization activities.

Finally, part of this research and development is carried out by the Ministry of Internal Affairs and Communications (Research and Development for Expansion of Radio Resources; JPJ000254).

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Technology Reports (Special Articles) Digital Beamforming Base Station Cooperation Outdoor Experimental Trials

Special Articles on 5G evolution & 6G (1)

Improving Communication Performance in High-mobility Environments by Millimeter-wave Base Station Cooperation for 5G evolution

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Nobuhide Nonaka Takahiro Asai

Although 5G commercial services are now being provided, further evolution of 5G is needed to meet a variety of future demands. As part of these studies, we consider the provision of millimeter-wave high-speed communications over a wide area to multiple mobile stations traveling at high speed. In a high-mobility environment, area construction must be performed over a wide area through the co-operation of multiple base stations. Additionally, to achieve simultaneous communications with multiple mobile stations, interference must be suppressed so that signals transmitted to each mobile station do not interfere with each other. To deal with these issues, we developed millimeter-wave base station cooperation technology to enable multiple base stations to cooperate with each other while suppressing inter-mobile-station interference by applying digital beamforming to base stations to generate and control beams by digital signal processing. We showed through outdoor experimental trials that high communication speeds could be achieved over a wide area.

1. Introduction

In the 5th Generation mobile communications system (5G), high-speed communications is being pursued using frequency bands below 6 GHz and the so-called 28 GHz millimeter-wave*1 band. Here, to compensate for the large path loss*2 of high-frequency bands such as the millimeter-wave band, BeamForming (BF)*3 technology using Massive Multiple-Input Multiple-Output (Massive MIMO)*4 has come to be researched as a 5G radio access technology.

NTT DOCOMO is rolling out 5G commercial services using the 3.7, 4.5, and 28 GHz bands. Here, the available bandwidth in the 28 GHz band is wider than that in the 3.7 and 4.5 GHz bands, so high-speed communications can be expected. On the other hand, strong straight-line propagation and large path loss of millimeter waves means that technical issues still remain in the provision of stable high-speed communications over a wide area. Nevertheless, the use of the millimeter-wave band is essential to further the evolution of 5G [1].

In this article, we show by outdoor experimental trials that high-speed communications can be provided over a wide area by (1) using multiple 28 GHz band experimental base stations equipped with digital BF to perform BF by digital signal processing and (2) having those base stations cooperate with each other while suppressing the interference generated between multiple mobile stations traveling at high speed. We present and discuss the experimental results.

2. Overview of Experimental Equipment Equipped with Millimeter-wave Base Station Cooperation Technology by Digital BF

2.1 Effects of Applying Digital BF and Base Station Cooperation to High-mobility Environments

The following problems must be solved to achieve even higher communication speeds using millimeter waves:

(1) While higher communication speeds can be expected for each base station through simultaneous communication with multiple mobile stations (by achieving multi-user MIMO), interference generated between mobile stations must be suppressed.

(2) For example, when a base station is communicating with mobile stations within vehicles traveling on an expressway at 100 km/h, cooperation among multiple base stations is necessary to provide wide-area communications.

A variety of methods have been proposed to suppress inter-mobile-station interference such as transmitting signals to mobile stations using a different beam for each. Nevertheless, interference can still occur between beams, so this method is not necessarily able to sufficiently suppress interference. Furthermore, given the large path loss of millimeter waves, the service area of each base station cannot be easily expanded. In environments with mobile stations traveling at high speeds, this means that the time during which a mobile station is present in that area is short, which in turn means frequent switching between base stations.

Based on the above, an important requirement for providing high-speed communications for multiple mobile stations traveling at high speeds is to maintain stable high-speed communications even during a switchover between base stations while suppressing inter-mobile-station interference. To this end, we here report on the development of Massive MIMO experimental equipment using digital

*1 Millimeter waves: Radio signals in the frequency band from 30 GHz to 300 GHz as well as the 28 GHz band targeted by 5G all of which are customarily called "millimeter waves."

*2 Path loss: The amount of attenuation in the power of a signal emitted from a transmitting station until it arrives at a reception point.

*3 BF: Technology for increasing/decreasing signal power in a particular direction by giving directionality to the transmission signal. It includes analog beamforming that forms directionality by phase control of multiple antenna elements (RF equipment) and digital beamforming that performs phase control in the baseband section.

BF in the millimeter-wave band as opposed to implementing BF using analog circuits (hereinafter referred to as "analog BF") as a base station function.

In general, analog BF operates by having the base station select the beam to be used from a set of beam candidates determined beforehand. The advantage here is that information only on beam direction is sufficient thereby simplifying equipment structure. On the other hand, the beam is not optimized to radio wave propagation conditions.

In contrast, digital BF performs communication by calculating the optimal beam shape (number of individual beams and directions) according to radio wave propagation conditions. In this way, an improvement in communications quality can be expected, but other problems arise; that is, information on the propagation channel must be estimated, but tracking of wildly fluctuating radio wave propagation conditions in an environment with mobile stations traveling at high speeds is difficult. However, the fact that digital BF is achieved by digital signal processing means that suppression of inter-mobile-station interference can be incorporated in beam generation and control and that optimal BF can be performed even in an environment with multiple mobile stations, all of which make digital BF a key technology for enhancing communications performance in the future. Additionally, as examples of base station cooperation, information (received power, degree of spatial multiplexing available for transmission, etc.) obtained from channel information used for digital BF can be used for instantaneous switching to the base station best suited for communication, or multiple base stations can be controlled to perform simultaneous transmissions. Such base station cooperation can achieve stable and high-speed communications within an area.

2.2 Overview of Digital BF

In contrast to analog BF, digital BF generates and controls beams by digital signal processing. Analog BF uses a phase shifter*5 and amplifier*6 connected to each antenna element to achieve strong radio wave directionality in a particular direction by superimposing radio waves emitted from each of those elements. The problem here, however, is that the superimposing of radio waves always results in the same beam shape in whatever the direction. Digital BF, on the other hand, generates beams by using channel information between the base station and mobile station, calculating the weighting factors to obtain maximum received power, and multiplying the transmission signal by those factors by digital signal processing. In this way, digital BF can deal with a situation in which the mobile station's peripheral environment is fluctuating though the mobile station itself may be stationary by reforming an optimal beam according to that fluctuation. Digital signal processing also enables high-accuracy MIMO multiplexing of multiple signals and suppression of inter-mobile-station interference. A conceptual diagram of interference suppression is shown in **Figure 1**. In analog BF, when a beam faces a particular direction as shown in Fig. 1 (a), the shape of that beam always has a fixed pattern. As a result, interference can occur between mobile stations depending on the environment and communication performance can greatly deteriorate if the effect of that interference is large. Digital BF, though, can

*4 Massive MIMO: MIMO systems transmit radio signals overlapping in space by using multiple antenna elements for transmission and reception. Massive MIMO systems aim to achieve high-speed data communications with greater numbers of simultaneous streaming transmissions while securing service areas. They achieve that aim by using antenna elements consisting of super multi-element arrays to create sharply formed radio beams to compensate for the radio path losses that accompany high-frequency band usage.

*5 Phase shifter: A circuit that can change the phase going to each antenna element.

*6 Amplifier: A circuit that amplifies the signal.

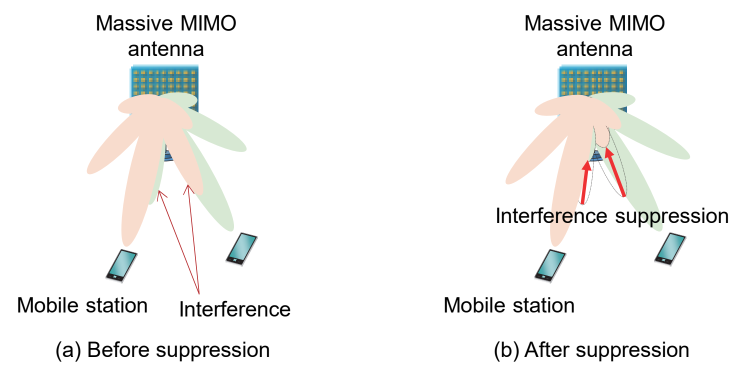


Figure 1 Conceptual diagram of interference suppression by digital BF

perform beam shaping correctly according to the peripheral environment. In Fig. 1 (b), the beam shape is formed so as to suppress inter-mobile-station interference, which can improve communication quality compared with no interference suppression.

However, channel information between the base station and mobile station must be determined in detail to achieve digital BF. This channel information is estimated from the channel matrix, whose number of rows is equal to the number of antenna elements and number of columns is equal to the number of base stations. In 5G, a base station turns out to be a massive-element antenna, so it is necessary to estimate a matrix of enormous size. Additionally, if the temporal fluctuation of the mobile station and peripheral environment is gentle, it should be possible to estimate channel information, but if this temporal fluctuation is intense as in a high-mobility environment, a discrepancy will emerge in channel information between the time of estimation and the time at which the signal is actually transmitted. As a result, an optimal beam cannot necessarily be formed.

With the aim, therefore, of exploiting the benefits of digital BF while contracting the size of the matrix to be estimated, we adopted technology that first forms multiple beams in predetermined directions using a many-element antenna and then estimates channel information between those multiple beams and the mobile station [2]. With this approach, the size of the matrix to be estimated can be reduced from number of mobile station elements × number of base station elements to number of mobile station elements × number of beams. In this way, by performing digital signal processing using a matrix of a size equal to number of mobile station elements × number of beams, it become possible to estimate channel information in a relatively short time while minimizing quality degradation from the use of all elements. With this approach, digital signal processing as in forming and controlling beams and suppressing inter-mobile-station interference can still be performed thereby enabling transmission by digital BF even in a high-mobility environment.

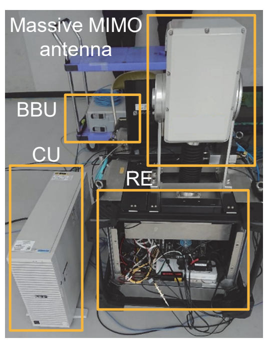
2.3 Overview of Experimental Equipment

External views of base-station and mobile-station experimental equipment that we developed are shown in **Photo 1** and main specifications of this equipment are listed in **Table 1**.

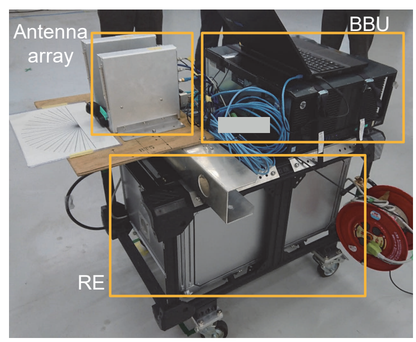
The base station features a 240-element Massive MIMO antenna connected to a BaseBand Unit (BBU)*7 that performs digital BF weight calculations. In addition, the Central Unit (CU)*8 connects to multiple BBUs with the role of performing a control function in multi-base-station cooperation.

The mobile station, meanwhile, features four antenna arrays*9 each having 15 vertical elements. Among these four arrays, only two panels for a total of 30 elements are used for transmitting a reference signal*10, but in reception, all four panels are used to increase receive gain. These antenna arrays connect to the BBU via Radio Equipment (RE)*11.

With this experimental equipment, the base station uses the reference signal periodically transmitted by the mobile station to estimate channel



(a) Base station



(b) Mobile station

Photo 1　Experimental equipment

Table 1　Equipment specifications

Center frequency	27.6 GHz
Bandwidth	100 MHz (100 MHz × 1CC)
No. of base-station antenna elements	240 (15 vertical × horizontal 16)
No. of mobile station antenna elements	60 (15 vertical × horizontal 4) *30 elements during transmission
No. of streams	2
Max. base-station transmission power	27 dBm
Max. mobile station transmission power	18 dBm
Max. mobile station transmission rate	705 Mbps

*7　BBU: One component of base station equipment performing digital signal processing of transmit/receive information when communicating with a mobile station.

*8　CU: Equipment that connects to a baseband unit and performs radio resource control.

*9　Antenna array: An arrangement of multiple antenna elements or panels forming an antenna group.

*10　Reference signal: A known signal from base stations, configured in UE.

*11　RE: The equipment that connects with the baseband processor via the fronthaul.

information. It then generates digital BF weights based on the results of that estimation and transmits a maximum to two streams per mobile station. A mobile station can achieve a maximum throughput of 705 Mbps with a total of two streams. Additionally, once the mobile station begins to receive signal streams, it calculates a receive filter*12 at its BBU, detects transmitted signals, and measures throughput.

3. Overview and Results of Millimeter-wave Outdoor Experimental Trials

3.1 Experimental Environment

In outdoor experimental trials targeting multiple mobile stations traveling at high speeds, we performed transmission experiments to evaluate throughput under base station cooperation [3]. The experimental setup is shown in **Photo 2**. In these experiments, we used three base stations each temporarily installed in the bed of a truck. We also used two mobile stations each installed in a vehicle and had them travel at high speed. At this time, antenna height was set at 2.2 m for both the base stations and mobile stations.

Experimental configuration is shown in **Figure 2**. In the experiments, two mobile stations each pass by three base stations while traveling at a uniform speed of 90 km/h. These three base stations are positioned at distances of 0, 200, and 400 m, respectively. At this time, it is assumed that two streams are transmitted to each mobile station and that distributed MIMO technology is applied to transmit each stream from a different base station. Specifically, base station #1 transmits the 1st stream of each mobile station continuously while base station #2 and base station #3 transmit the 2nd stream. Transmitting different streams from multiple base stations in this way causes the correlation of channel information from each base station to drop making it easy to separate MIMO spatially multiplexed streams. In addition, two methods of base station cooperation were implemented here: high-speed switching to base station #2 and base station #3 and simultaneous transmission from base station #2 and base station #3. In these

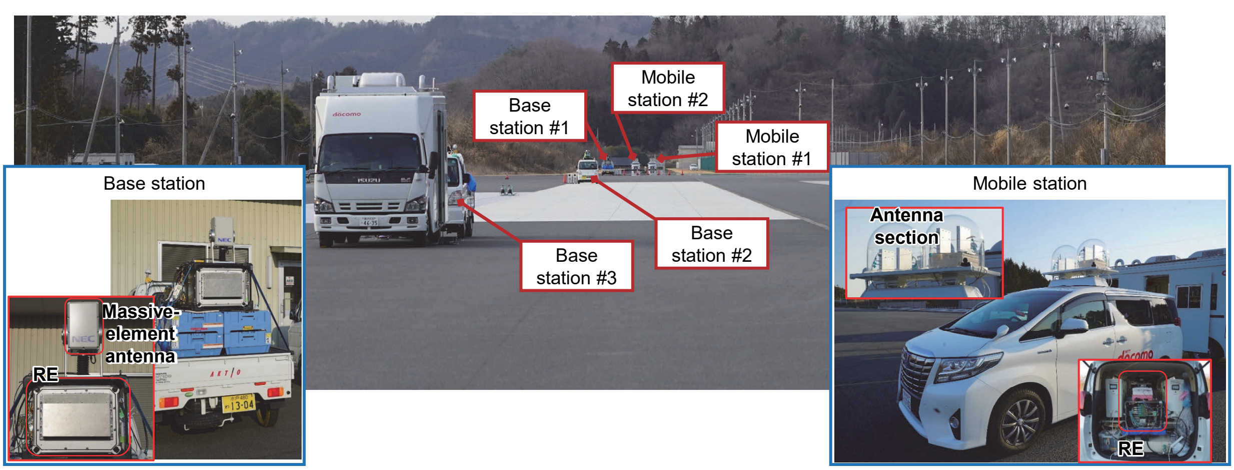


Photo 2 Experimental setup

*12 **Receive filter:** In MIMO communications, transmitting/receiving by multiple antennas enables the transmission of multiple streams and an improvement in received power of the desired signal. On the other hand, the information in multiple streams through transmitting/receiving by multiple antennas is received in a complicated overlapping state, so a filter is used to mitigate that overlapping and make it easier to estimate the desired signal.

experiments, we evaluated downlink throughput for mobile stations traveling at a high speed of 90 km/h.

3.2 Experimental Results

1) Base Station Cooperation Experiment

To test the effects of base station cooperation, we compared the case of not using base station #2 in Fig. 2 (no base station cooperation) and the case of using all base stations (cooperation between base station #2 and base station #3). To examine only the effects of base station cooperation, we used only mobile station #2 in this experiment traveling at a speed of 90 km/h. Here, base station #1 transmits the 1st stream while base station #2 or base station #3 transmits the 2nd stream, and when performing base station cooperation, the base station from among base station #2 and base station #3 that CU judges most capable of improving communication quality based on channel information will transmit the 2nd stream.

Throughput versus mobile station position from 0 to 400 m is shown in **Figure 3**. It can be seen

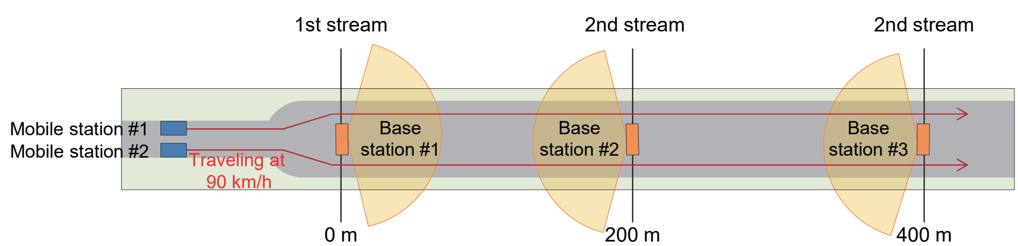


Figure 2　Experimental configuration

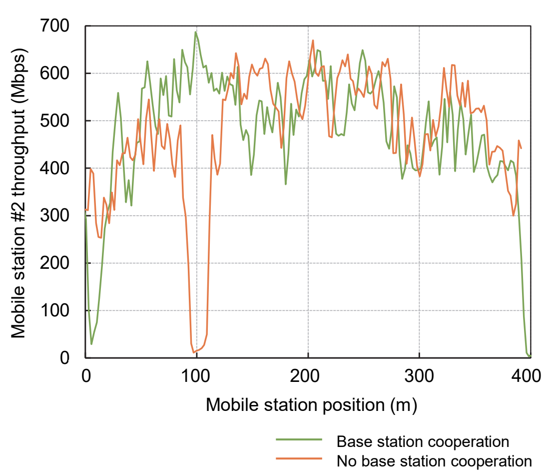


Figure 3　Effects of base station cooperation

from these results that throughput deteriorated at the 100 m position when not performing base station cooperation. However, communications could be achieved without this drop in throughput when performing base station cooperation. This was the effect of installing base station #2 at the 200 m position and performing base station cooperation (base station high-speed switching) so that communications could be continued from a different base station even in an environment or at a mobile station position where the communication performance of a certain base station had deteriorated. This result demonstrates that base station cooperation can achieve high-speed communications over a wide area within the coverage area.

2) Base Station Cooperation Experiment (Base Station High-speed Switching) during Two-mobile-station Multiplexing

Figure 4 shows throughput for a total of two streams transmitted to each of two mobile stations during high-speed switching between base station #2 and base station #3 depending on communication quality. Since the antenna array of base station #2 is facing to the left in Fig. 2, we consider that a mobile station will switch from base station #2 to base station #3 near the 200 m position. Consequently, on checking throughput near 200 m, no major deterioration in throughput can be observed for either mobile station #1 or mobile station #2 showing that base station switching could be achieved in a relatively stable manner.

From these results, it can be seen that stable and high throughput can be achieved within the coverage area through base station switching while achieving simultaneous communication with two mobile stations by suppressing inter-mobile-station interference through digital BF. This holds even in an environment in which two mobile stations are traveling at a high speed of 90 km/h.

3) Base Station Cooperation Experiment (Base Station Simultaneous Transmission) during Two-mobile-station Multiplexing

Throughput when having base station #2 and base station #3 perform simultaneous transmission

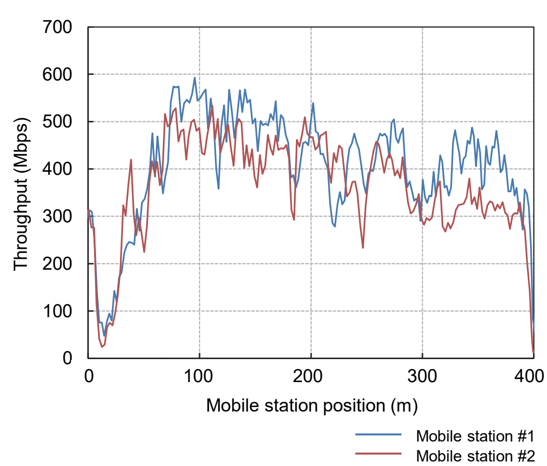


Figure 4 User throughput for base station switching at 90 km/h

is shown in **Figure 5**. Basic conditions are the same as those of Fig. 4, but with respect to the 2nd stream, base station #2 and base station #3 transmit the same signal simultaneously, so an improvement in received power can be expected at the mobile stations.

Examining throughput in the range of 0 – 200 m, it can be seen that simultaneous transmission operated without a problem. Furthermore, on comparing these results with those of Fig. 4, it can be seen that throughput was improved if only slightly in the range, for example, of 0 – 50 m. We offer two reasons for this, one that received power increased by simultaneous transmission, and another that deterioration in communication quality could be suppressed overall even if the quality of the signal from one of the base stations deteriorated due to the peripheral environment since there was also a signal from the other base station. However, at positions from 50 to 200 m, throughput in Fig. 5 could not necessarily maintain higher values than throughput in Fig. 4. This is because, in this experimental environment, line-of-sight waves are dominant and radio waves on which signals of base station #2 and base station #3 are superimposed cancel each other out at some positions. Nevertheless, we consider that throughput in a high-mobility environment can be made stable through simultaneous transmission.

The results of this experiment demonstrate the effectiveness of simultaneous transmission as a form of base station cooperation.

4. Conclusion

This article described research and development for 5G evolution with the aim of providing stable throughput with wide coverage by applying base station cooperation technology while suppressing interference between multiple mobile stations by applying digital BF in the millimeter-wave band. On developing millimeter-wave band

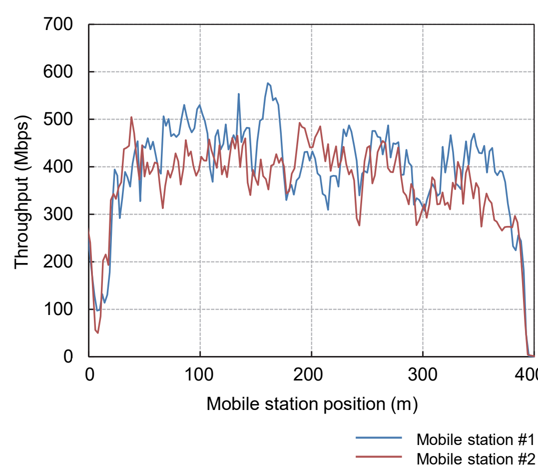


Figure 5　User throughput for simultaneous base station transmission at 90 km/h

experimental equipment incorporating base station cooperation technology by digital BF and performing outdoor experimental trials, it was shown that high-speed switching among three base stations could be achieved while suppressing interference between two mobile stations moving at a high speed of 90 km/h. It was also shown that stable and high throughput could be provided over a wide area by performing simultaneous base-station transmissions through base station cooperation. In future research, we plan to test the effects of base station cooperation technology with a variety of base-station arrangement methods.

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Technology Reports

Agile | Remote Work | App Development

Migrating an Agile Application Development System to an Efficient Remote Work Environment - A Case Study

Communication Device Development Department Takashi Fukuzono Eiko Onuki
Kiki Wakayama

Usually in agile development, members gather at the same location to work. However, to avoid the spread of the novel coronavirus, development systems that incorporate remote work are necessary. Therefore, to maintain efficiency in development, NTT DOCOMO began combining related tools such as those for Web task management and automation, and Web conferencing tools for remote work. This has made it possible to maintain product quality and release products with the same short cycles as before the coronavirus pandemic.

1. Introduction

The docomo TV terminal is a TV device sold by NTT DOCOMO. By connecting it to a TV, the user can watch various video services such as Hikari TV for docomo.

The docomo TV terminal app is a smartphone app for operating the docomo TV terminal, and has numerous functions such as remote-control operation of docomo TV terminal and viewing recorded content in other locations. Also, to support the constant upgrades to video services made in response to changes in the market environment, it is effective to develop the docomo TV terminal app using agile development, which prioritizes and develops required functions in short cycles.

Agile development requires an environment that enables close communications because of its short development cycle and often takes place in the same location. For the docomo TV terminal app, our development team gathered at one location and carried out development in an environment that enabled such close communications.

However, due to an increase in the number of people infected with the new strain of coronavirus in the Tokyo metropolitan area, and in light of the risk of infection with the new strain of coronavirus within the agile development team, it was decided that, in principle, all development members would work remotely from February 2020, after development tools and communication methods were improved.

This article describes the case study of agile development of the docomo TV terminal app and the innovations involved in remote development.

2. Agile Development Overview

2.1 Framework for Agile Development

Agile development is a general term for software development methods that repeat development in short periods of time. It began when notable persons in agile development declared values and principles of behavior common to agile software development as the Manifesto for Agile Software Development [1].

Because agile development proceeds through repeated development in short periods of time, it is more robust to change than waterfall development*1 and can respond quickly and flexibly to changes in market user needs.

There are various frameworks for agile development, such as Scrum, Extreme Programming*2 and Kanban*3, etc. For our development, we adopted Scrum, a framework that is lightweight and easy to understand (but difficult to learn).

The theory and definitions of Scrum are described in the "Scrum Guide" [2]. Its content is revised as needed. Scrum defines three roles, five ceremonies, and three artifacts based on the three principles of "inspection" to make sure the team is progressing correctly, "adaptation" to improve the process as a result of the inspection, and "transparency" to make sure all the current status and problems are visible.

2.2 Overview of the Scrum Process

1) The Three Roles in Scrum (**Figure 1**)

(1) Product Owner (PO): Responsible for maximizing the value of the product produced by the Scrum team. Responsible for the product, creates and prioritizes the product backlog, which describes the requirements for all product functions.

(2) Scrum Master (SM): Responsible for promoting the understanding and practice of Scrum and ensuring that the process runs well. Ensures that the Scrum team is effective by leading them to become self-managed and cross-functional by removing obstacles to their progress and helping them to improve.

(3) Development member: Development members realize the product. There is no hierarchy. The ability to create products is fulfilled when everyone aligns. The team makes every effort to complete the product backlog items agreed upon with the PO, and is responsible for constant improvement.

2) The Five Ceremonies in Scrum

(1) Daily Scrum: A place where the status of the development team is examined daily with

*1 **Waterfall development:** A development method in which the processes of definition of requirements, design, implementation and evaluation are performed in order.

*2 **Extreme Programming:** A type of agile software development methodology that takes rules of thumb to the extreme for efficient development.

*3 **Kanban:** A type of agile software development method in which work items are visualized in a list called "Kanban" to continuously implement and improve the work.

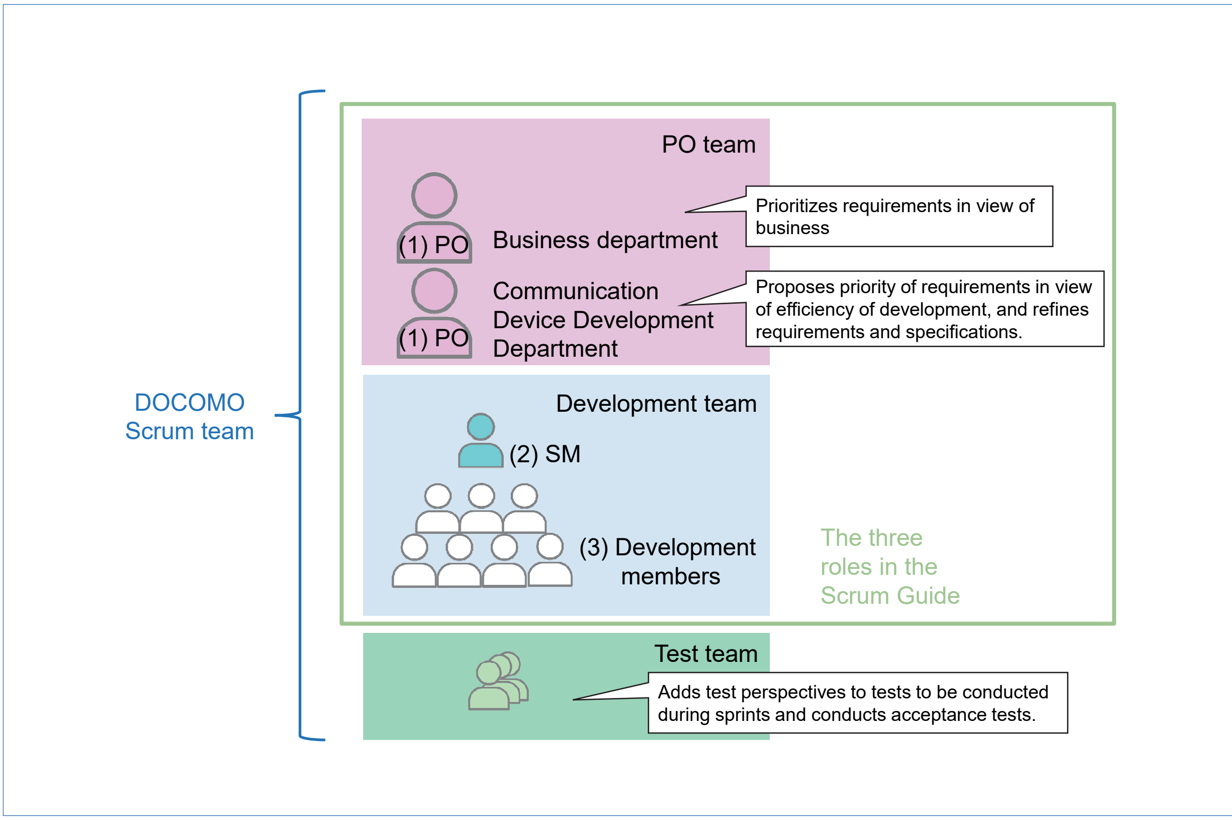

Figure 1 Organization chart

three questions (what was done yesterday, what needs to be done today, and are there any obstacles?). 15 minutes maximum, no extensions.

(2) Sprint*4 review: A place for the PO to review the development team's sprint artifacts (apps). These are presented to the relevant stakeholders. After that, the team may get feedback and revise the apps.

(3) Sprint planning: Also called a planning meeting, and where a development plan for a sprint is made. The PO talks about the what and why of the product backlog, and the development team talks about the how. The development team also talks about how likely they are to achieve the requirements of the product backlog in this sprint.

(4) Sprint retrospective: This ceremony is also called a "look back" and is used to repeat improvements so that the work can be done even better. The ceremony entails sorting out what went well in the sprint and what can be improved in the future. Rather than fixing bugs, fix the processes in which bugs are created. In our project, we use the KPT method*5 to share and agree with members on what to continue and improve in the following sprints.

(5) Backlog refinement*6: Maintenance of the product backlog for subsequent sprints.

*4 Sprint: A short development period, limited by the Scrum Guide to no more than one month.

*5 KPT method: A framework for reviewing the progress of a project, in which "Keep (good things)," "Problem (issues)," and "Try (improvement measures for problems)" are listed and reviewed for approaches and procedures during a sprint period.

*6 Backlog refinement: One of the events defined in Scrum. The process of cleaning up the product backlog for subsequent sprints.

3) The Three Artifacts in Scrum

(1) Product backlog: A description of the requirements for each function of the entire product, the so-called wish list. Prioritizes and arranges the features with the highest value so that they are developed in order from the top of the list. Priorities need to be constantly updated so that they are the latest.

(2) Sprint backlog: The division of the product backlog into specific tasks.

(3) Sprint artifact: Created by the development team on a sprint-by-sprint basis and is an artifact for which release decisions can be made. In app development, this means a working app and documentation.

2.3 Structure of Our Project

For our project, the business department and the Communication Device Development Department are acting as the PO team on Scrum development. The Communication Device Development Department is responsible for proposing priorities based on development efficiency, while the business department is responsible for final prioritization based on business. The SM and development team consist of members from the development contractor, and the test team consists of members from the test contractor (Fig. 1).

3. Scheme for Short-cycle Release

3.1 Requirements Definition Phase

1) Development Prioritization

The business department assigns business priorities to the development requirements, and the Communication Device Development Department and the development team arrange the development requirements in detail in order of highest priority. Requirements arranged in detail are fed back to the business department to determine development priorities.

(1) Business priority assignment

For each development requirement, the business department explains to the Communication Device Development Department and the development team the priority of the requirement and how it will benefit the business. By doing so, the entire team gains common recognition of the objective, and the Communication Device Development Department and the development team are able to arrange requirements into details and prioritize the development appropriately in subsequent processes.

(2) Arranging requirements in detail

The Communication Device Development Department and the development team refine the requirements in order of priority of development requirements assigned by the business department, and further divide functions. The Communication Device Development Department assigns development priorities to the functions arranged in detail judged on business effects, development scale and development efficiency. The divided detailed functions and development priorities are fed back to the business department, which makes the final decision on development priorities.

2) Integrated Ticket[*7] Management

Efforts are made to efficiently update and share

*7 Ticket: A task or issue that arises in a development project.

tickets with all members, from the PO team to the development team (**Figure 2**). After the PO team describes the requirements (what, why) as parent issues in the ticket management tool, the development team describes the details of the work (how) to realize these as sub issues. In addition, by discussing how to implement the changes on the source code review tool and linking it to the ticket management tool, it is now possible to understand and manage changes in the source code due to which requirements and which tasks in an integrated manner.

As a result, misunderstandings and omissions in requirements, tasks, and source code modifications are less likely to occur, which means reduced reworking.

(1) Requirements

In the requirements stage, the PO team not only describes the details in the ticket management tool in as much detail as possible, but also focuses on the background and purpose of why the development requirement was made. As a result, we created an environment in which each member of the development team can actively consider the design from a business perspective when the team moves into doing specific tasks.

(2) Work details

The parent issue is the requirement, and the development team describes the work required to implement the software based on the requirement as sub issues. Linking

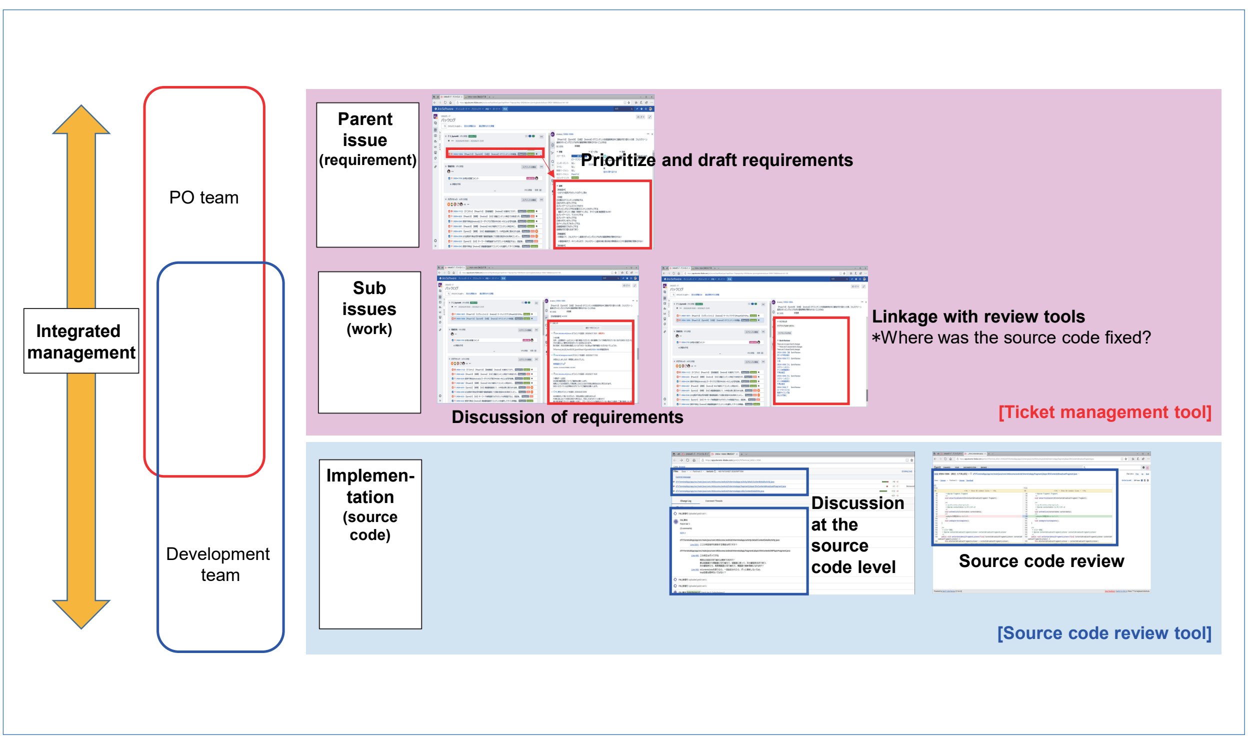

Figure 2　Integrated ticket management

requirements to work details ensures that no content to be implemented is omitted.

Also, linking work content with the source code review tool makes it possible to understand processes in later reviews by mapping modifications in the source code.

(3) Supplement with text chat tools

Tickets are not created for minor Q&A, etc., so instead, text chat tools are used to conduct Q&A. Compared to e-mail and ticketing tools, text chat tools do not require greetings and can be used to ask questions without strict classification of the content. This has the effect of reducing communication costs such as time spent on writing, and even when details have not yet been decided, the content is solidified as the chat continues, which is useful for aligning members' thinking before ticketing and for detailing ticket content.

3.2 Development Phase

For the development phase, we have built a system that does not distribute information such as documents and source code necessary for development to individual work terminals, but stores such information on the cloud so that members can share it. The system can also be linked to tools that need to be executed continuously, such as post-build signing, so that builds*8 can be executed automatically on a regular basis.

1) Development Tools in the Cloud

(1) Cloud management of source code

The source code is stored in the cloud and can be easily accessed from each person's work terminal regardless of location, so that the same source code can be shared by the entire development team. Also, by explicitly displaying commercial branches*9 and development branches, we also devised a way to prevent regression*10 and other problems.

(2) Review circulation tool

Although the source code is reviewed by experts from the development team, we introduced a tool to track the log of who circulated the code and what was pointed out and corrected so that the opinions of the team can be widely confirmed. This helps to eliminate omissions of revisions and also enables full management of review progress within teams.

(3) Source code analysis and obfuscation*11

Before a build, static parsing*12 of the source code is performed. Previously, results were not shared because we performed this on each person's work terminal. Currently, the results of the analysis are displayed in the cloud so that each person can check them and they can be deployed horizontally.

Apps are also obfuscated before being made commercially available to avoid analysis by reverse engineering*13. To ensure that there are no obfuscation omissions, obfuscation is performed using a tool in the cloud, and the results are logged on a server so that the status of obfuscation can be shared among development team members.

2) Tool Automation

(1) Automatic build execution

In general, development team members often build applications individually as needed,

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*8 Build: A process or operation to create files executable on a terminal or distribution packages based on source code.

*9 Branch: In version control, a branch from the master history that is recorded. For example, a commercially available version is called a commercial branch, and a version that is not yet commercially available and still under development is called a development branch.

*10 Regression: Reduced performance or function degradation that occurs with software upgrades, mainly caused by the revival of past defects.

but in such cases, there are issues such as the version to be verified being different for each member. For this reason, we introduced a rule that the system would automatically run builds on a regular basis (specifically, once a day at night) and work the next day with that app as the latest version. This means the entire team can now share the most recent app version, and hence there is no more regression caused by proceeding with verification work on old apps. In addition, by keeping and sharing the history of the changes as a log on the server, the entire development team is made aware of source code changes and the number of missed changes has been reduced.

(2) Signing automation

To clarify to the user that apps are for services provided by NTT DOCOMO, apps are given a signature. Until now, apps built by the development team have been uploaded to the signature granting server by the Communication Device Development Department for signature granting. However, to eliminate the hassle of transferring files to and from the development team and to speed up development, the Communication Device Development Department is now responsible for building source code stored as a commercial branch in the cloud. In addition, the manual signature granting process was eliminated by creating a script*14 that automatically sends apps to the signature granting server after a build and grants them signatures.

3.3 Test Phase

Conventionally, after the final sprint when development of all requirements was complete, operation of all requirements was checked as an acceptance test and a market release decision was made. This required lots of time required for acceptance testing, and many defects were detected at the end of development. This approach resulted in rework and time needed to fix problems before market release, making it impossible to achieve short release cycles.

Therefore, to detect defects as early as possible in the development stage, we decided to conduct some of the tests, which had been conducted collectively in acceptance tests, in front-end processes during the sprint period.

1) User Scenario Testing

As shown in **Figure 3** (a), before improving the test phase, user scenario testing was conducted after the final sprint when all functions had been implemented, which resulted in long test time and detection of many defects at the end of development. Therefore, we changed to a policy of conducting user scenario testing of developed requirements in each sprint (Fig. 3 (b)). This resulted in early detection and solving of problems early in the development process. The time required for testing was also shortened by changing requirement verification after the implementation of all functions to exploratory testing*15.

2) Regression Testing

Similar to user scenario testing, before test phase improvements, regression testing was started after the final sprint when all functions had been implemented, and defects were detected at the end of development (Fig. 3 (a)).

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*11 Obfuscation: Processing of source code to make it difficult for humans to understand without changing the behavior of the program so that malicious users cannot easily decipher or tamper with the application.

*12 Parsing: Analyzing source code to find out where it violates rules or syntax.

*13 Reverse engineering: The study and clarification of the technical information of an application by observing the behavior of its software or analyzing its source code.

*14 Script: A simple programming language for describing programs for simple processes. A program described by a script may also be called a script.

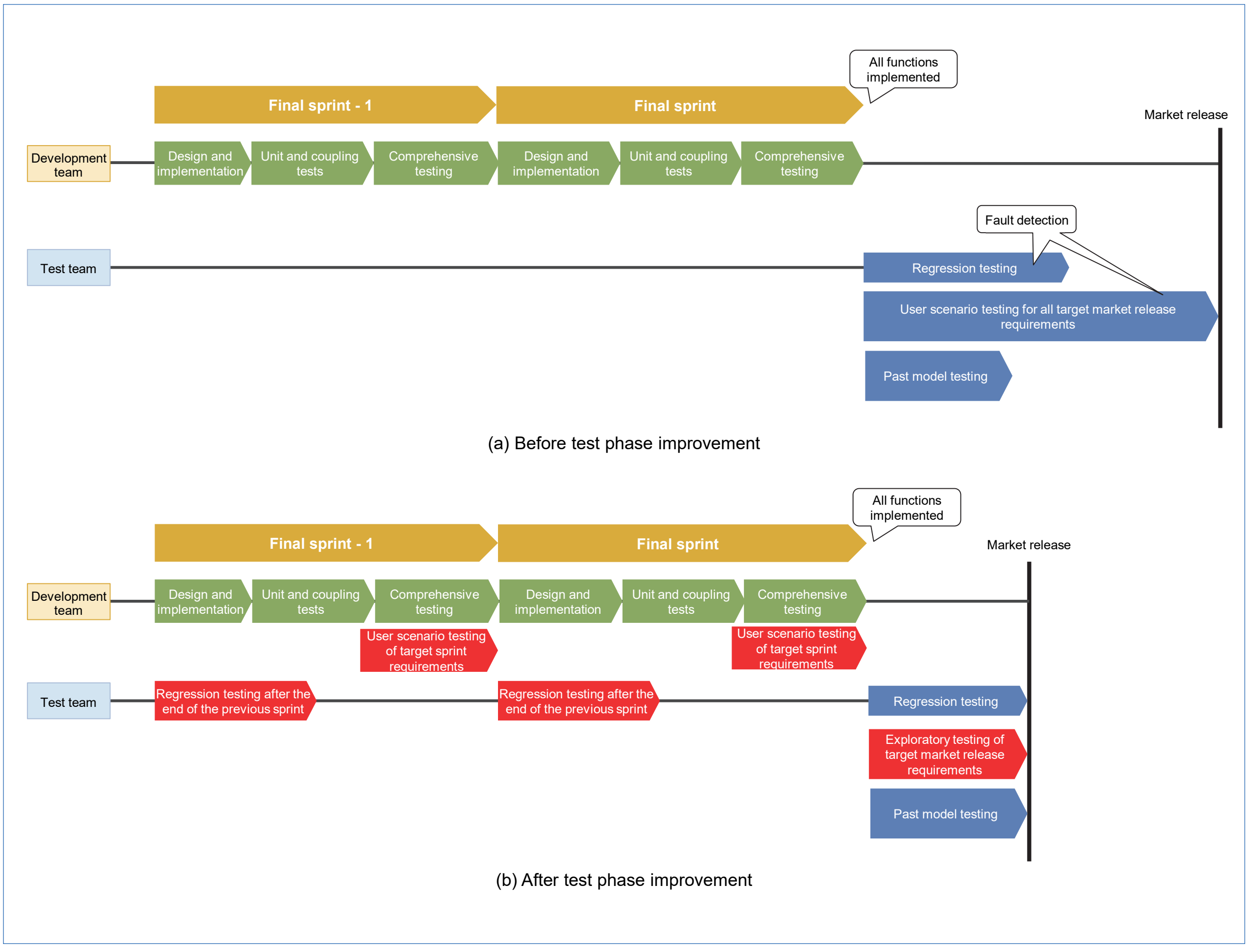

Figure 3　Shortened test time with improved test phase

Therefore, we changed the policy to conduct regression testing on artifacts at the completion of each sprint. In consideration of the number of man-hours required for testing, we also automated regression testing. This made it possible to detect and correct defects in the early stages of development. Defects are now rarely detected at the end of development (Fig. 3 (b)).

3) Effectiveness

Since we had already confirmed that artifacts were up to the market quality level at the completion of each sprint, after implementation of all functions was complete, only the minimum operation check was conducted as the final quality check before market release. Testing used to take about a month on average after implementing all functions, but this has been reduced to about three business days.

4. Changes Associated with Remote Development

4.1 Overview

Considering the risk of a mass outbreak of the

*15 Exploratory testing: A method of executing tests while checking software behavior and test results, rather than creating test cases in advance. Since it does not involve prior test design or pattern exhaustive testing, exploratory testing can be conducted more quickly than conventional descriptive testing and is well suited for agile development.

novel coronavirus in the agile development team, the team shifted to remote work development. This involved various Scrum ceremonies also being changed from face-to-face meeting to methods suitable for remote development. Although there were some issues unique to remote work, such as communications and security, we were able transition smoothly by devising methods that did not compromise productivity.

4.2 Examples of Migration to Remote Work

1) Various Scrum Ceremonies

(1) Daily Scrum

Before transitioning to remote work, all members would gather in front of a large screen monitor displaying the ticket management tool to check the progress of each member. After the transition to remote work, a Web conference system was introduced to check the progress of each member while sharing the ticket management tool on the screen so that the daily Scrum can be held as it was before transitioning to remote work.

(2) Sprint planning, sprint retrospective

For these two ceremonies, we are conducting Web conferences in which participants can see each other's faces, as these are Scrum ceremonies with a lot of discussions among members. Early in the transition to remote work, we would hold Web conferences without showing our faces, but since we could not read each other's reactions and thoughts through audio alone, we gradually lost the ability to have active discussions due to anxiety and the impact this had on motivation.

Therefore, we made it a rule in principle to participate in Web conferences showing our faces. By showing our faces to each other we can obtain additional visual information from non-vocal information such as facial expressions, gestures and eye contact. As a result, we are now able to have active discussions to a degree similar to before the transition to remote work.

For sprint retrospectives, before the transition to remote work, the KPT method was used with labels and simili paper. While physical tools are no longer available due to the transition to remote work, sprint retrospectives can be operated in the same way as before the transition to remote work by using spreadsheets*16 instead. As a side effect of using spreadsheets, it became easier to check past history because it was electronic.

(3) Sprint review

Before the transition to remote work, operations were checked using the actual device at the sprint review and the PO team made the acceptance decision on the spot. In contrast, since the transition to remote work, we have been using a test distribution tool to distribute the app as a sprint artifact so that each member can download the app to an actual device at home and check its operation. We also have prepared demonstration videos and play them during sprint reviews to prevent any discrepancies in perception among members.

These initiatives have made it possible for the PO team to make acceptance decisions

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*16 Spreadsheet: A type of Web application that can be edited by multiple people at the same time. Because it can be known who is editing which part of the sheet in real time, a spreadsheet can be used as a substitute for sticky notes or simili paper and hence enables efficient work.

at sprint reviews, just as they did before the transition to remote work.

(4) Backlog refinement

Backlog refinement, which used to be conducted in person before the transition to remote work, can now be conducted in the same way as before the transition thanks to the introduction of the Web conference system.

2) Others

(1) Communication outside Scrum ceremonies

The entire team is always connected by voice during working hours by using a tool that has a voice chat function. This enables member to feel free to talk to each other even when minor questions arise and communicate closely similar to when everyone was at the same location before the transition to remote work.

Other than voice, we also use text chat as a real-time communication method. To facilitate communications when complex explanations are required for operating procedures or causes of problems for example, text chat can be used as a supplementary tool to voice communication. Before the transition to remote work, we used a white board to align members' thinking, but since the transition to remote work, we use text chat instead.

(2) Workshop

We have deepened relationships among the members and promoted self-organization*17 by holding regular workshops where each group discusses issues related to development and feeds back the results to the development. Since it became difficult to hold face-to-face meetings after the transition to remote work, relationships cultivated during development at our base are being utilized even after the transition to remote work and have led to the maintenance of productivity even under remote work by fostering an atmosphere where opinions can be frankly discussed.

In the future, we are also considering holding workshops remotely so that we can continue to maintain these relationship even when members are replaced.

(3) Security

Information security risk is an important factor in remote work development. When the development was done in groups at our base, an ID card was required to enter the room, and people who were not involved in the project were not allowed in. However, when development is done at home, people who are not involved in the project, such as family members, may be able to enter and leave workrooms. Similar to physical measures, it is important to set certain rules and ensure that development team members follow those rules. The Telework Security Guidelines from the Ministry of Internal Affairs and Communications recommend the implementation of measures that balance rules, people and technology [3]. From early on in our project, we have been working with the development team to study countermeasures against information security risks, as described below.

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*17 Self-organization: Instead of having a manager, team members manage projects autonomously. Members make plans themselves, share daily progress and solve problems.

(a) Formulation of rules for secure operations

In formulating the operation rules, we referred to the content of the guidelines set by the security departments of the companies involved in the project.

Specifically, work is to be done in a secure environment such as an isolated private room, the use of loaned PCs is mandatory, the use of personal PCs is prohibited, free software is not to be installed, and PCs are not to be taken outside the home, etc.

These operational rules were made into an itemized checklist. The entire team first reads the document, and then each person is asked to check it once a month to ensure that individuals regularly reacquaint themselves with it and that it is being used appropriately.

(b) Source code and documentation management

The source code is stored in the cloud. To maintain security, the development environment on the cloud is accessed via a Virtual Private Network (VPN) connection*18 after authentication with an ID, password, and client certificate assigned to each individual.

Documents such as specifications and design documents are stored on a server at the development vendor base. The information on the server can be viewed and edited using a remote desktop, which allows remote control of the PC at the base from the home. It is prohibited to physically take the information home.

(c) Device management

For remote work development, it was decided to prohibit the use of individually purchased computers and to mandate use of computers loaned by the company. The development of the docomo TV terminal app also requires verification of operations on various smartphones and tablets. This meant it was necessary for each member to also take home smartphones or other devices to check the app. To manage and ensure that these devices are in proper working order, a visual check is conducted every morning via video call to check where PCs and devices are and ensure that they can be turned on. This reduces the risk of loss or malfunction, and also enables quick response in case of loss or malfunction.

5. Productivity and Quality in Agile Remote Working

5.1 Productivity

We examined team productivity when they were developing together at the base and after the transition to remote work.

1) Velocity Trends

In Scrum development, there is a number called velocity. The average amount of work that a Scrum team completes during a sprint is expressed by a unit of "story point," A value expressed in this way is called "velocity." Velocity is a relative value and is used as a reference to see how much work (tickets) can be completed in the next sprint, and to understand the growth of the team.

*18 VPN connection: A method of connecting to a public network such as the Internet using a virtual dedicated line environment protected by authentication and encryption technologies.

Figure 4 shows the velocity of the docomo TV terminal app development team and the trend in corresponding story points per person. In this project, the number of people in the development team changed at the same time as the transition to remote work, so we checked the story points per person trend before and after the transition to remote work rather than the velocity of the entire team. Immediately after the switch to remote work, there was a temporary drop in the trend, but this recovered and stayed at the same level as before the switch, indicating that the team was able to operate without losing productivity.

Since we were able to operate without losing productivity, there has been no impact on release schedules or frequency of app releases.

2) Happiness Level Trends

Happiness level is a five-point score of how happy individuals feel based on their work content, role and ease of working, and is an indicator of whether the organization is a vibrant place to work. In our project, we interviewed members of the development team about their level of happiness in each sprint, calculated the average, and analyzed this trend (**Figure 5**).

Immediately after the transition to remote work, many people were confused by the change in environment and were temporarily depressed but later recovered. We heard many positive comments about working on development from home, such as having more time to spend with family. In agile development, it is said that the higher the happiness level of the team, the higher the productivity. It can be seen that the happiness level trend is similar to the velocity trend shown above.

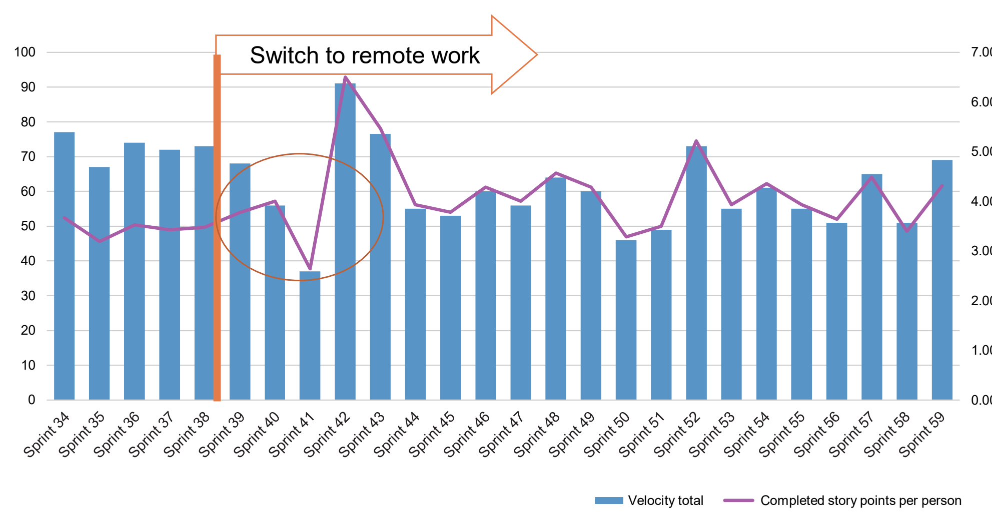

Figure 4　Trends in velocity

5.2 Quality

To verify whether there was any change in the quality of the app before and after the transition to remote work, **Figure 6** shows the bug detection rate per number of kSteps added during the development phase. The quality target for the app is less than 1 item/kStep. We achieved less than 1 item in all sprints, meaning that compared to before, there was no decline in quality after the switch to remote work.

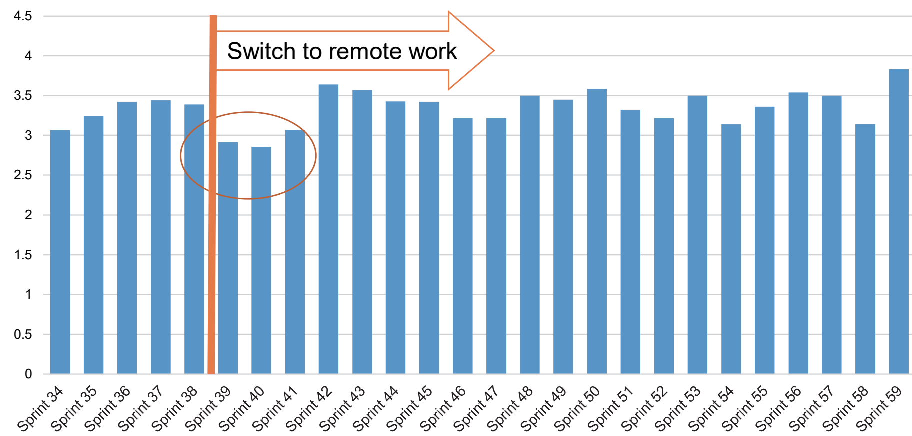

Figure 5　Trends in happiness level

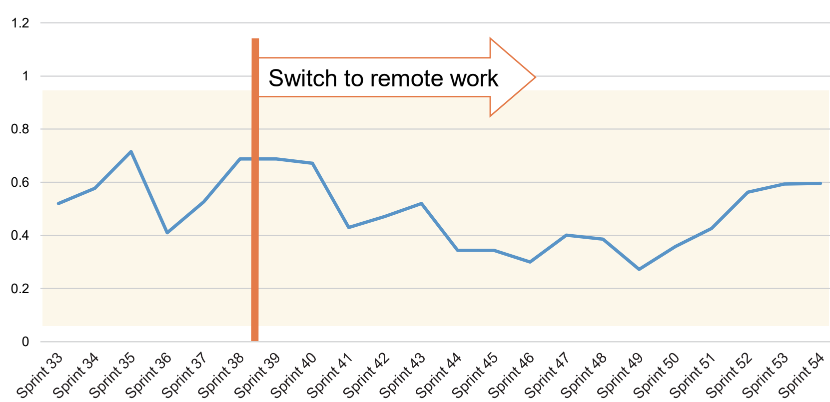

Figure 6　Trends in bug detection rate per kStep added in the development phase

6. Conclusion

In this article, we described a case study of an agile development project's transition to efficient remote development. With remote development, we were able to achieve short release cycles while maintaining quality and productivity. Agile development is a method that involves continuous improvement. Hence, we will continue our efforts to improve it and achieve more efficient development going forward.

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Technology Reports

UWB | Ranging Technology | Osaifu-Keitai

Study on Practical Application of the Touchless Function to Osaifu-Keitai Using UWB Ranging Technology

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In recent years, as there has been a push to make payments cashless, the use of new technologies such as QR/barcode payments has been expanding. NTT DOCOMO has been providing a contactless payment service called "Osaifu-Keitai" for some time, but with the aim of realizing even greater convenience and new user experiences, we are currently studying practical application of Osaifu-Keitai technology to support a touchless function that enables users to make payments simply by standing or passing by a designated location, using UWB, a radio technology that enables highly accurate range measurement. This article describes the details.

1. Introduction

In recent years, Ultra Wide Band (UWB), a medium-range radio technology, has been gaining attention as it has started to be incorporated into a variety of smartphones. UWB holds promise for use in a variety of use cases because of its highly accurate ranging function that takes advantage of radio wave characteristics. Japan is also evolving toward cashless payment systems and the use of QR code/barcode payments are expanding on the existing credit cards and electronic money. In light of these circumstances, NTT DOCOMO is aiming to combine the Osaifu-Keitai it currently provides with UWB to realize Osaifu-Keitai that supports the touchless function as a new means of payment. This article describes studies, technical verifications, and issues for creating new use cases and User Experiences (UX)*1 in the payment field utilizing UWB ranging technology.

*1 UX: A general term for the experiences gained through the use or consumption of certain products or services.

2. "Payment: Touchless-enabled Osaifu-Keitai" Using UWB

2.1 What is UWB?

UWB is an ultra-wideband medium-range radio communication technology. Institute of Electrical and Electronics Engineers (IEEE)*2 802.15.4a, which is the standard specification for UWB, defines it as communications using the 3.1 to 10.6 GHz band. As well as high-speed communication using a wide bandwidth, UWB has the ability to measure the distance and angle of objects with high accuracy. This ranging function uses a method called "time of flight," which measures the time it takes for a signal to propagate, and calculates the distance by multiplying the time by the propagation speed.

UWB was institutionalized in Japanese Radio Law for communications applications (3.4 – 4.8 and 7.25 – 10.25 GHz bands) in 2006, for automotive radar applications for collision prevention (22 – 29 GHz band) in 2010, and for sensor applications (7.25 – 10.25 GHz band) in 2013. However, the applications for communications and sensors have been limited to indoor use. Later however, with expectations for various applications and increasing needs for outdoor use, the law was amended in May 2019 to allow outdoor use in the 7.587 – 8.4 GHz band. With this amended law, UWB has started to be installed in a variety of smartphones and peripheral devices.

2.2 Activity Status of Standardization Organizations

Even since before the amendment of the Radio Law in Japan, the activities of standardization organizations related to UWB have been getting busier. The following summarizes the activities of each of these organizations.

- IEEE802.15.4 [1]

  IEEE802.15.4 defines physical layer*3 and logical layer*4 specifications to enable low data rate radio connectivity and precise ranging between devices that do not require batteries or require very limited battery power. Standardization of UWB is underway in the IEEE802.15.4 working group.

  802.15.4a [2] establishes the physical layer for ranging, and 802.15.4z [3], which was released in August 2020, strengthens the security of the physical layer defined in 802.15.4a and establishes the logical layer.

- Car Connectivity Consortium (CCC) [4]

  CCC is an international industry organization that formulates use cases for smartphone-linked vehicles and related specifications for the service layer*5. Based on IEEE802.15.4z, it is planning to formulate next-generation specifications for digital keys that use UWB and Bluetooth Low Energy (BLE)*6. As of March 2021, 129 companies, including automobile, in-vehicle equipment, component and smartphone manufacturers are currently participating in the organization.

- FiRa Consortium (FiRa)

  FiRa is an industry group that aims to ensure interoperability among UWB products to realize UWB use cases. It is planning to establish a certification program based on IEEE802.15.4z. 65 companies (as of March 2021) that use UWB (component, smartphone and electrical equipment manufacturers, etc.) are currently participating.

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*2 IEEE: The world's largest technical professional organization (international academic society) dedicated to the advancement of technology in the field of electrical and information engineering.

*3 Physical layer: Defining physical connections and transmission methods, the first layer of the OSI reference model. The OSI reference model classifies and defines communication functions.

*4 Logical layer: Defining methods for identification and collision avoidance so that communications between physically connected devices are performed smoothly, a part of the second layer of the OSI reference model. The OSI reference model classifies and defines communication functions.

Currently, the most specified use case of UWB, and the one that is on the verge of practical application, is the use of UWB as a digital key fob for vehicles, which is being discussed in the CCC. Conventional digital key fobs for cars use Low Frequency (LF)*7 radio waves to unlock the door, but there have been incidents of cars being stolen by relay attacks, in which the thief intercepts and retransmits the radio waves transmitted by the key fob to unlock the door when the owner is away. In this regard, UWB can prevent relay attacks because the distance from the real key fob cannot be falsified thanks to the time of flight ranging function.

Although various other use cases for UWB are under development by FiRa, and the use of UWB is being considered for a wide range of applications such as unmanned shops and house locks, as of March 2021, practical application is still some way off.

2.3 How Conventional Osaifu-Keitai Works

Osaifu-Keitai is a contactless payment service that uses a mobile FeliCa®*8 chip embedded in a mobile handset. The underlying technology is FeliCa, a contactless IC card technology developed by Sony Corporation. Feature phones or smartphones equipped with FeliCa chips offer a high level of convenience by enabling multiple payment services on a single handset. These chips also incorporate safety and security features such as unlocking through identity authentication. The chips were first installed in the mova 506i series in July 2004, have since been installed in many i-mode handsets, and were made available for Android handsets in 2010. Today, not only NTT DOCOMO handsets but also many handsets of other telecommunications carriers and subscriber identity module (SIM)-free*9 handsets distributed in Japan are compatible with Osaifu-Keitai.

There are two main hardware components that make Osaifu-Keitai possible: embedded Secure Element (eSE) and Contactless Frontend (CLF) (**Figure 1**). eSE is a tamper-resistant*10, highly secure chip that executes security-critical applications and stores data. The CLF is a radio chip that controls the front end of contactless communications with the outside of the handset. Its radio technology complies with Near Field Communication (NFC) Forum*11 specifications, and uses radio waves in the 13.56 MHz frequency band to send and receive FeliCa commands when the handset is within a few centimeters of a reader/writer. The FeliCa commands are then sent to the eSE, and the mobile FeliCa application in the eSE performs a series of processes such as interpreting and responding to commands and updating recorded e-money balance information. This makes payment operations equivalent to those of a standalone FeliCa card possible on mobile handsets.

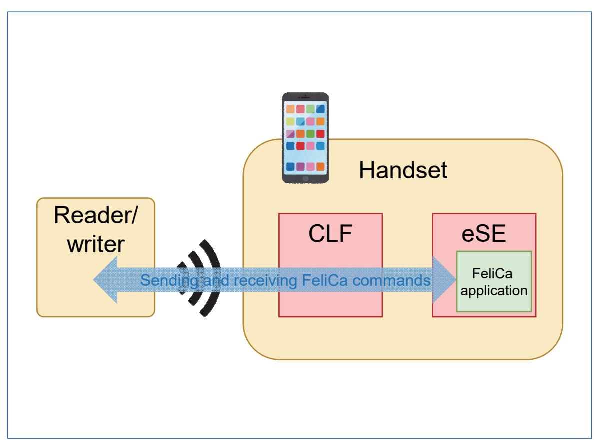

Figure 1 Configuration of Osaifu-Keitai

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*5 Service layer: The layer that specifies the protocols to be used by services.

*6 BLE: A short-range radio communication technology standard with low power consumption and low cost.

*7 LF: Long wave. Radio waves in the frequency band of 30 to 300 kHz.

*8 FeliCa®: A contactless IC card technology developed by Sony Corp. A registered trademark of Sony Corp.

*9 SIM-free: Having no restrictions on the use of a SIM from a different telecommunications carrier when inserted into a handset.

Originally, NTT DOCOMO used eSE, which was developed exclusively for mobile FeliCa. However, from 2019, we have increasingly been using general-purpose secure chips compliant with the standard specifications specified by the GlobalPlatform*12. This has made it possible to standardize handset hardware between global models and models for the Japanese market, making it even easier for handset manufacturers to support Osaifu-Keitai. It is also worth noting that such general-purpose eSE chips can be used for service applications other than Osaifu-Keitai, opening up possibilities for a variety of secure services other than FeliCa-based payment services, such as digital keys and identity authentication.

2.4 Changes from Traditional Osaifu-Keitai to Touchless-enabled Osaifu-Keitai

NTT DOCOMO is considering touchless support combining UWB and Osaifu-Keitai, because we want to provide UX that enables easy payment even when it is not easy to take out the smartphone and hold it over a reader/writer, such as when the user's hands are full, when the user keeps the smartphone in the back of their bag, or when making a payment in a drive-through.

The act of holding a handset over a reader/writer not only exchanges payment data, but also confirms the user's intention to make a payment. Therefore, in the case of a touchless system, confirmation of the user's intention to make a payment must be obtained through some other action. To solve this problem, we decided to use UWB, which has highly accurate ranging performance, to set up a specific area for payment, and view the user as expressing intention to make a payment by staying in or passing through that area. **Figure 2** shows the different methods of confirming

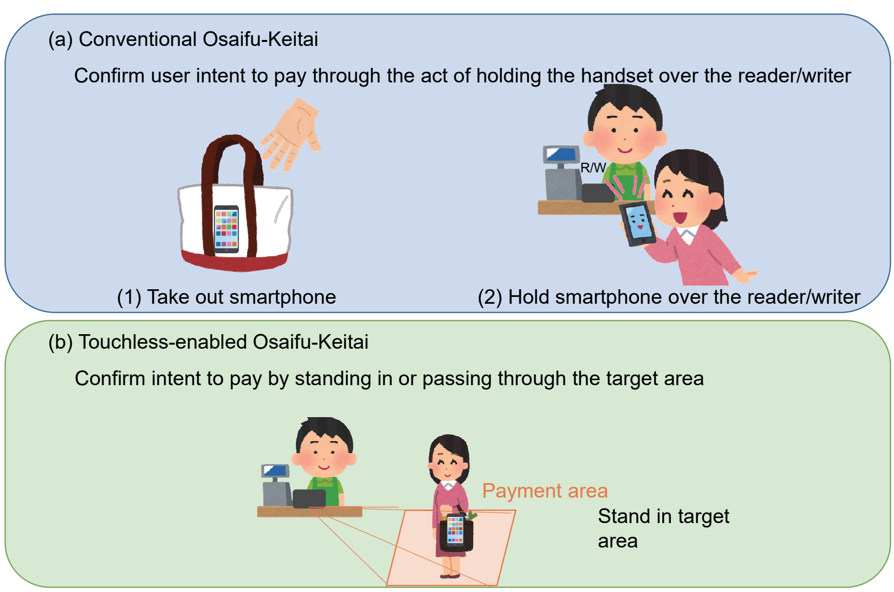

Figure 2　Different methods of confirming payment intention

*10 **Tamper-resistant:** A property that prevents integrated programs, data and other digital information from unauthorized referencing or rewriting.

*11 **NFC Forum:** An international standardization organization that aims to promote and develop technical specifications for the short-range radio technologies known as NFC.

*12 **GlobalPlatform:** An international standardization organization that formulates trials for IC cards and security technologies, including credit cards and SIM cards.

such intention.

Instead of using NFC for radio exchange of payment information as in the conventional Osaifu-Keitai as described above, BLE is used as the mechanism to achieve payment in combination with the UWB ranging function. **Figure 3** shows the differences with the conventional Osaifu-Keitai. Here, BLE is used because currently international standardization has not been completed for communications other than ranging data with UWB, so interoperability remains an issue.

3. Actions to Achieve Touchless Compatibility

3.1 Challenges for Practical Application

As mentioned above, UWB holds promise for use in a variety of future cases, although three conditions are necessary for it to actually become popular as social infrastructure around people.

- The first is the development of international standards. In the case of radio devices, "minimum commitments" such as radio performance standards and communications protocol specifications are necessary to ensure that any combination of devices can communicate and operate with each other. Such rules are often specified by international standardization bodies. Organizations that specify technical specifications for UWB include the aforementioned IEEE, CCC and FiRa. While the IEEE has completed the specifications of the base physical and logical layers, CCC and FiRa are currently working on the specifications of the higher layers, related to service specifications.
- The second is popularization of UWB-enabled devices. Broadly speaking, these are either

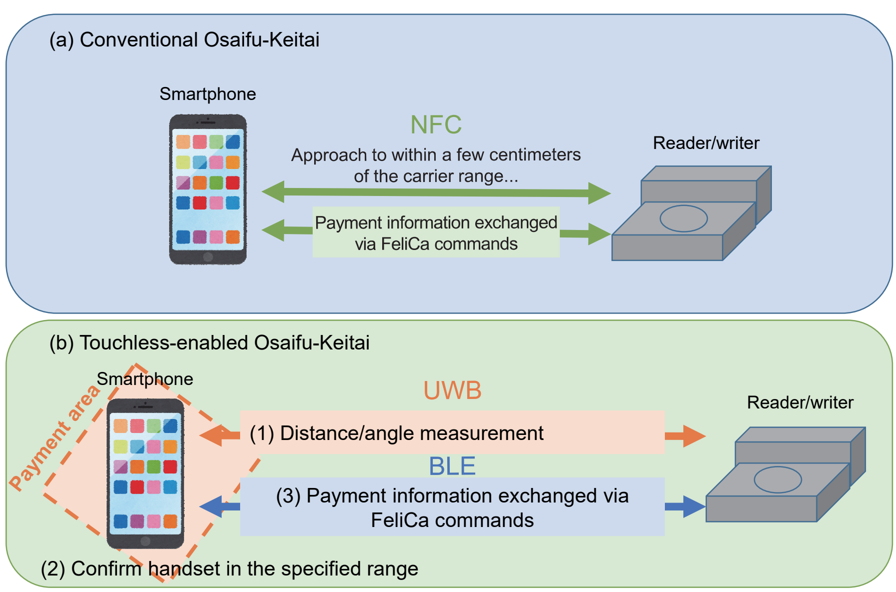

Figure 3　Comparison of methods

smartphone terminals used by end users or reader/writers that serve as communication partners. For the former, some handset manufacturers began installing UWB in smartphones since around 2020, but these are still limited. Thus, it is essential to expand the number of compatible models and supporting manufacturers. As for the latter, there are a variety of devices for different uses such as payment terminals connected to Point Of Sale (POS) registers*13 in retail outlets, in-vehicle devices for digital key door opening and digital signage*14 terminals for displaying advertisements on streets. It is not easy to popularize use of these services due to complex factors such as the needs of each service, commercial flows and cost effectiveness.

- The third is the emergence of service providers using UWB-equipped devices. The mere existence of UWB-equipped devices will not bring benefits to end users. Only when services using these devices are launched will they provide convenience to end users and lead to business profits for service providers. For such business decisions to be made, it is necessary that the set of smartphones and reader/writer devices are sufficiently widespread in the market to form a basis for service provision.

These three conditions will not be satisfied "in sequence." For example, "products can be developed because standard specifications have been decided," "services can be started because smartphones have become popular," "products can be developed because there is demand for services," and "specifications can be matured through trial and error with actual products and services" – similar to the so-called problem of whether the chicken or the egg comes first.

NTT DOCOMO has experienced this kind of issue many times in the business world with the birth of various new technologies and services such as Osaifu-Keitai. Therefore, we will develop working devices for verification first, and from the early stages collaborate with service providers to exchange opinions and think together about how to implement these technologies in their services, with the aim of breaking out of a chicken and egg situation as quickly as possible.

3.2 Development and Evaluation of a Prototype UWB-enabled Smartphone

Working prototypes, or devices that enable verification of touchless-enabled Osaifu-Keitai, are a smartphone equipped with UWB with touchless-enabled Osaifu-Keitai functions, and a reader/writer device capable of communicating with the smartphone using the same radio bands and protocols. Since these two items do not yet exist in the world, we developed hardware and software for verification with the cooperation of four partner companies in the UWB study.

The roles of the four partner companies are as follows:

- Sony Corporation: Development of prototypes of UWB-enabled reader/writer devices and software
- FeliCa Networks, Inc: Development of UWB-enabled FeliCa middleware*15 and applications

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*13 POS register: A system equipped with point-of-sale information management functions to manage money for sales and inventory status of goods in real time.

*14 Digital signage: Advertising media using digital technology. Using displays or projectors to change advertising content in response to time or location, this technology is gaining attention as an alternative to conventional advertising media such as posters, etc.

*15 Middleware: Software positioned between the OS and user applications, and that provides common functions for multiple applications, thereby enabling efficient application development.

- NXP Semiconductors: Provision of IC chips for UWB and development environment/ technical information on UWB
- SHARP Corporation: Development of UWB-enabled smartphone prototypes and software

There are two major points of view for verification of the smartphone and reader/writer devices developed through the above system.

- The first is how to achieve enough ranging accuracy to identify the user's intent to pay. To prevent erroneous payments, we thought that the area where intent to pay is indicated should be limited to the space of a single person, and accuracy targets should be set to +/- 10 cm in distance error and +/- 10 degrees in angle error.
- The second is to solve the problem of installing the technology in smartphones. New UWB radio installation should be specified and designed so that it does not interfere with other radios or consume an extremely large amount of battery power while in use.

Under these objectives, as a result of ranging with the designed and developed prototype smartphone and reader/writer device in a test environment with no obstacles in between and the smartphone fixed, the measurement errors in distance and angle were kept within the target values, and payment processing could be performed within the specified range. We were able to confirm that there were no interference problems with other radios, and battery consumption was kept to a minimum by turning off the UWB chip power when ranging was not being performed.

3.3 Verification with Service Provider Partners

Although the aforementioned performance targets were met, there are still issues to be addressed for practical application. Since it is necessary for users to be able to actually use touchless Osaifu-Keita in any environment with a low probability of failure, it is necessary to test the smartphone in various environments. For example, assuming that the phone is placed in a bag, there are many factors that could affect radio communications such as the direction of the phone in the bag, the material of the bag and its contents, the combination of usage patterns and the environment in which the phone is placed, and distance, etc. Various factors that could affect wireless communication can also be assumed when considering usage scenes where Osaifu-Keitai is already in use, such as in front of cash registers in retail outlets, near ticket gates in stations and in front of vending machines, etc.

With the current specifications of the prototype, it is difficult to detect the smartphone location in cases where a person is between the smartphone and reader/writer device and their body blocks the signal, such as when making a payment with the smartphone in the back pocket of the pants. Such cases require hardware improvements such as antenna relocation. In some usage scenarios, where location determination and payment processing need to be completed while passing through a certain area, the detection range and process start position also need to be reviewed because high processing speed is required.

Going forward, it will be necessary to conduct verification considering use cases in various environments where Osaifu-Keitai is actually used and identify what improvements are necessary.

To achieve this goal, we will continue to build cooperative relationships with various partners and conduct a wide range of verification testing to enable the use of various services.

4. Conclusion

This article has described details of study, technical verification, and issues for providing new UX by creating new use cases of payments with touchless-enabled Osaifu-Keitai using UWB ranging technology. To make the act of payment more seamless through touchless-enabled Osaifu-Keitai, we will focus on the following aspects to verify its practical usage.

- Whether it can be used successfully in a variety of environments (availability)
- Whether payment is processed on the wrong person's handset (security assurance)

Although this article focuses on payment, the high-precision ranging function of UWB is a technology that can be applied to other fields. Hence, we would like to expand UWB use cases (advertisement distribution and digital keys, etc.) in stages. Also, to build hardware environments, we will also actively study the introduction of UWB terminals while observing market trends.

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NTT Received 10th Annual Clarivate Top 100 Global Innovators 2021 Award

In February 2021, NTT received a Clarivate Top 100 Global Innovators™ 2021 award, as selected by Clarivate Plc (headquartered in London, U.K.). This is the 10th consecutive year since 2012 that the award has been given.

This award is given to 100 companies that Clarivate independently selects as being at the top of the innovation landscape based on three indicators: patent success rate (number of inventions and patent acquisition rate), globalization (applications filed in Japan, the United States, Europe, and China), and influence (citation of the company's inventions in applications filed by other companies). This is the 10th consecutive year that NTT has received this prize.

This award is a global recognition of the advanced nature of the Research and Development (R&D) conducted by the entire NTT Group and the value of the inventions and results produced through such R&D.

As a member of the NTT Group, NTT DOCOMO has applied for a number of patents worldwide for basic technologies in the field of mobile communications such as 5th Generation mobile communications systems (5G), and NTT DOCOMO's R&D activities were also recognized as an important factor in this award.

NTT DOCOMO will continue to cultivate its R&D technology capabilities and engage in R&D to open up the company's vision for the future of mobile communications.

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