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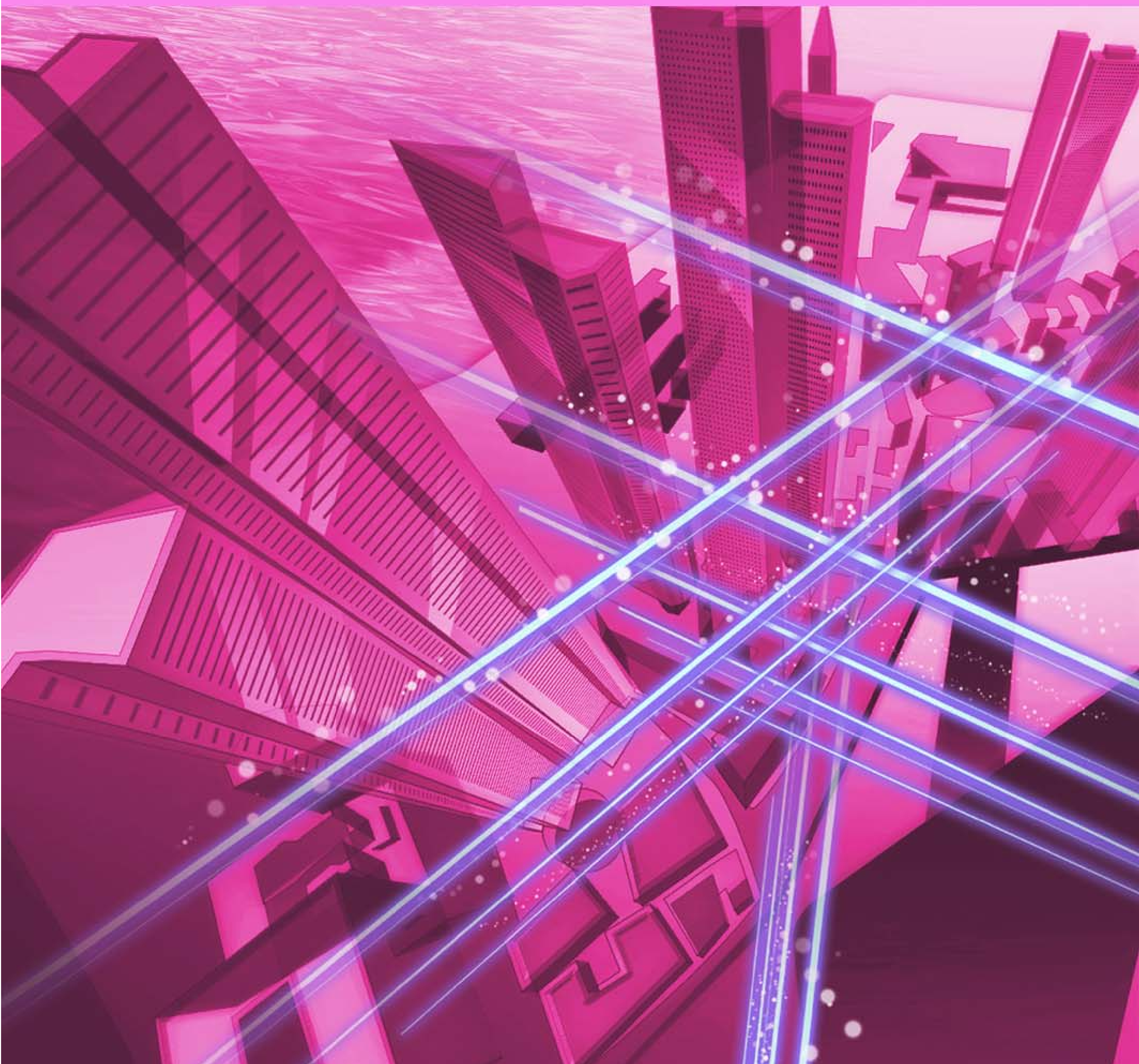

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NTT Technical Review

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Try It Yourself and Pursue the Truth

Hideaki Ozawa
Chief Operations Officer and Chief Technology Officer, NTT Research, Inc.

Overview

NTT Research focuses on cutting-edge basic research in the fields of quantum computing, cryptography, blockchain, and medical/health informatics with partners around the world. Two years after its establishment, it has won several prestigious awards, including the International Association for Cryptologic Research (IACR) Test-of-Time Award, SPIE Maiman Laser Award, and IACR Crypto 2020 Best Paper Award. The institute's achievements also include solving the 20-year-old problem of program obfuscation. We interviewed Hideaki Ozawa, chief operations officer and chief technology officer of NTT Research, about the progress of research and the art of management.

Keywords: basic research, NTT Research, Inc., R&D management

Finding the seeds of new technologies

—Two years have passed since NTT Research was established. Could you give us an overview of the institute and the progress of research?

NTT Research was established in July 2019 in Silicon Valley, USA, to focus on basic research and advance technologies to bring positive change to human life by assembling scientists and experts around the world. It is composed of three laboratories: the Physics & Informatics Laboratories (PHI Lab), whose main research area is quantum physics, including quantum computers based on optical technology, which will form the basis of the novel technologies required in the future beyond the era of the Innovative Optical and Wireless Network (IOWN); the Cryptography & Information Security Laboratories (CIS Lab), whose main research area is information and mathematics theory, including cryptography necessary to promote the safe use of various data such as personal information; and the Medical & Health Informatics Laboratories (MEI Lab), whose main research area is medical and health information, which will be required to individualize and revolutionize healthcare services.

These three laboratories aim to create a new technological direction toward business creation over the next 10 to 20 years by combining the basic technology fields that NTT's research and development (R&D) labs have cultivated over many years in Japan with the wisdom of scientists and experts around the world. From April 2020, our 68 papers were accepted and published, and 16 patents (PHI Lab: 4; CIS Lab: 11; and MEI Lab: 1) were filed.

PHI Lab aims to develop optimal systems by combining the advantages of parallel quantum computing with those of classical digital computing. It is developing the world's most-advanced quantum computer, centered on a Coherent Ising Machine, which can operate at room temperature by using the quantum phenomenon of light. It has formed a joint research team with 14 research institutes in the US, including universities (Stanford University, Massachusetts Institute of Technology (MIT), Cornell University, Harvard University, etc.) and national research institutes such as National Aeronautics and Space Administration (NASA). In 2020, PHI Lab took up a

new research theme, the "quantum approximate optimization algorithm," and began joint research on it with MIT, the University of Chicago, and the University of Waterloo.

CIS Lab researches (i) strong cryptography that can maintain security even if a quantum computer that overrides the security of existing cryptography is created, (ii) high-functionality and flexibility encryption technology that ensures the security of encrypted information, and (iii) highly secure blockchains. In the last two years, NTT has become the organization with the highest number of accepted papers at Crypto and EuroCrypt, the world's most prestigious conferences in the field of cryptography. CIS Lab accounts for about 70% of the papers accepted as NTT. Dr. Brent Waters, who invented "attributed-based encryption," received the Test-of-Time Award from the International Association for Cryptologic Research (IACR). Similarly, Dr. Mark Zhandry and Dr. Brent Waters were awarded the Best Paper Award at EuroCrypt 2019 and Crypto 2020, respectively.

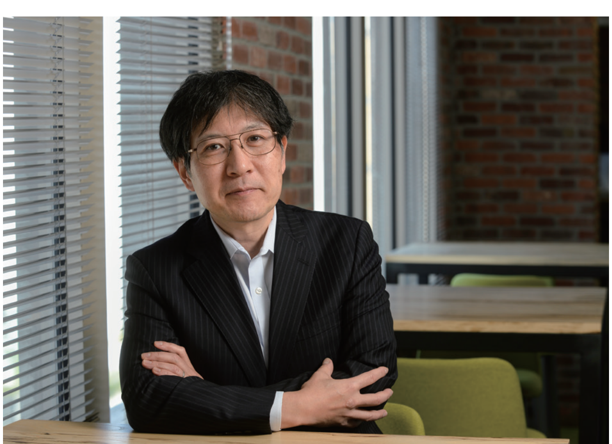
MEI Lab aims to develop physician-support systems and autonomous therapeutic systems by constructing bio digital twins, which apply Digital Twin Computing to the human body, as well as developing micro/nano devices that can be implanted in the human body. MEI Lab has started joint research with the Technical University of Munich on electrodes that can extract electrical signals from the human body and have experimentally implanted the electrodes in laboratory animals (insects, etc.) to verify their effectiveness.

—You have achieved a lot in a short period.

As chief operations officer and chief technology officer, I oversee the entire staff of the laboratories, and for the past two years, I've been focusing on improving our basic R&D capabilities, technological capabilities of the entire group, and corporate value of the group. One of our most urgent tasks was to establish the organization in regard to, for example, recruitment of human resources and conclusion of joint-research agreements with many universities and other institutions. The directors of PHI, CIS, and MEI Labs are world-renowned and who have made significant achievements in their respective fields. By using their human networks, we have invited outstanding researchers worldwide to work in research areas that support the unique technologies that NTT has accumulated and formed research teams that collaborate with researchers in the United States and abroad. The number of researchers has grown from a dozen or so at the time of establishment to 38. Of those researchers, 35 have doctorates, and two are licensed physicians. We have strengthened diversity over the past two years by hiring an increasing number of non-Japanese. We now have 12 from North America, 2 from Europe, and 24 from Asia-Oceania, half of whom are from India, Singapore, Australia, and South Korea, and the other half are Japanese. We have also established a branch in Munich, Germany, to carry out joint research with the Technical University of Munich.

We have set the following three key performance indicators (KPIs): (i) improvement of our basic R&D capabilities, (ii) improvement of the technical capabilities of the entire group, and (iii) improvement of the corporate value of the group. Regarding (i), we have set a target for the average number of papers accepted per researcher per year as one and average impact factor of each paper as 5.0 or more. Regarding (ii), we have set a target of applying for more than ten patents per year and developing human resources by taking on one to three people per year. Regarding (iii), we have set a basic-R&D-capability indicator based on an average number of citations of 6.0 or more for at least five years after the publication of a paper and holding a global R&D workshop once a year. As a result of our efforts, I believe we have met all three KPIs: (i) we have achieved a mean impact factor of 6.3, (ii) accepted more than 25 interns from universities in the US and abroad, and (iii) in September 2021, we held a two-day global R&D workshop that was a hybrid meeting of online and on-site, attracting a total of about 2000 views online and about 130 participants on-site.

I believe that one of the main reasons we have been able to achieve these results is because talented researchers assemble and inspire each other centered on world-class researchers having a unifying cohesive power. However, it is not enough to simply have the world's top-class group of researchers. It is also necessary to have researchers who support the top-class researchers in each research field. In the quantum and medical fields, we need people who can support experimental research. Therefore, we are also hiring young researchers such as those who have just completed their doctoral course. In light of these factors, I believe that we have created an almost ideal environment for basic research.



From the perspective of using the results of basic research for the benefit of society, applied research is necessary; however, since NTT Research focuses on basic research, we will consider how to transfer the results of basic research to applied research.

Take a bird's-eye view and find the excesses and deficiencies

—It is said that the location of work has become no longer an issue during the coronavirus pandemic. Under such circumstances, what is the significance of NTT having research bases abroad?

NTT's business has changed dramatically over the past 20 years. Currently, NTT Group's revenue is about 12 trillion yen, of which about 2 trillion yen is generated outside Japan as our business expands globally, mainly through mergers and acquisitions (M&As).

When I was working at an NTT operating company in Japan and approached overseas companies for global business collaboration, they would ask, "Where are you doing your R&D, Japan or the US?" At that time, I realized the importance of not only taking the results of Japanese R&D overseas but also conducting R&D and turning it into business at and in the style of the location where the business would be rolled out. In this sense, I believe that expanding our global business through M&As and creating the technologies necessary for our business on a global scale is an appropriate way for NTT to grow its global business. As you said, remote work has become widespread, and it is now possible to conduct business without visiting the site. Business is fundamentally based on communication between people, and from that viewpoint, as long as seamless communication is achieved, it might not matter whether business is done face-to-face or remotely.

For R&D, however, the situation is a little different from that of business. An important factor in conducting the best research is to have an environment with the best resources (i.e., people and equipment). Silicon Valley offers exactly such an environment, and it is one of the reasons that NTT Research chose to locate in Silicon Valley. Although there has been much talk about the spread of remote work in the wake of the coronavirus pandemic, researchers have been using email as well as online discussions and other activities long before the pandemic. However, research activities require experimentation and verification. Accordingly, a research base should be established where the resources for experiments and verification are located. Silicon Valley has the best resources needed for research at PHI, CIS, and MEI Labs. When we talk about the necessity of establishing overseas bases, I believe whether the location is overseas or in Japan is unimportant; instead, it is important to determine the essence of the research activity and where to conduct such activity.

—Expectations concerning what NTT Research has to offer are high. Do you have any difficulties in your position as a uniter of the world's top researchers?

For me, life in the US is a good fit, and I'm happy working here. I've had a rather unique career in NTT's R&D labs. I first engaged in R&D as a researcher for about nine years, then in business at an operating company for about 15 years, and recently in R&D management. When I switched from R&D to business then to R&D management, I felt that everything I experienced in my previous job was useful in my current job, and I was gradually understanding the truth of things as I gained more experience. I feel that through interaction with a variety of professions and people, I was able to recognize turning points and understand how to use experiences, and such accumulation of knowledge would lead to success. Of course, there are some failures and disappointments, but I am trying to focus on positive aspects of my experiences.

From my experience, I'd say that the job of top management is to create an environment in which people can work happily, define the concept of operations, create a roadmap, and build a team by acquiring human resources. Moreover, I think the most important role of management is to look at the whole picture from a bird's-eye view and find out the excesses and deficiencies from there. It is also important to change the way of managing the organization depending on the organization, mission, and quality of work. For example, one time, I was seconded to a subsidiary of Kadokawa Shoten Publishing Co. Ltd., whose mission was to develop and operate web services to ensure that work was carried out efficiently to meet release dates for the weekly local guide magazine and website, so a certain degree of strong management was necessary. When I was the head of NTT Media Intelligence Laboratories, however, it

was important for the laboratory staff to come up with new added value on their own, so strong management was not necessary. Here at NTT Research, I don't think strong management is necessary because too much control can reduce the originality of researchers and their ability to advance R&D. I think as long as the direction of research does not deviate significantly, I'll only focus on the results of the research.

NTT Research has been operating for only two years, so I think we still have some omissions and shortcomings in the management of the organization. I'd like to improve and revitalize our institute with a more comprehensive and bird's-eye view of the whole picture.

Management that makes everyone involved feel confident

—So management style differs completely depending on the subject, right? What matters most to you in business or management?

What matters most for me is to be of service to others, and that fundamental part of my life will never change. I think that work is what humans do, and what humans plan and do to achieve what they want is work. I believe that even though our positions and roles differ, work is about producing some kind of result and having an impact on society.

With that in mind, what I aim to do is to try it myself. I want to create an environment in which my colleagues can all feel confident in their work. Therefore, I'll continue to challenge myself to do new things while making myself, team, and customers all happy through their work. To meet that challenge, I first challenge myself and show them what I can do myself to some extent then ask them to challenge themselves to go beyond that. For example, when any of my staff or teams were about to give up and say, "I can't do this," I'd first try to work on the problem myself and show them that they can solve it if they try. Then I'd step back and let them to work on it.

—Do you have a message for researchers and engineers inside and outside the company?

The first is to challenge yourself every day. There are many talented people in the world, and I want you to aim to take on challenges with them. For example, I heard that Sakichi Toyoda, the founder of Toyota Industries Corp., the predecessor of Toyota Motor Corporation, faced a lot of concerns from within the company when he decided to expand his business overseas. On hearing those concerns, he said, "Open your mind, and look at the great world outside." I want many researchers and engineers to see the wide world.

The common quality among world-class researchers is a strong spirit of inquiry. For example, I don't think Einstein started his research on relativity because it would have a high impact factor, as we would say today, and I've also heard that his papers on relativity were first published in journals that didn't attract much attention. I encourage researchers to conduct their research activities not simply to submit papers to journals with high impact factor but to investigate the essence of their research problems. I believe that what is most important in any job is to pursue the truth.

Interviewee profile

■ Career highlights

Hideaki Ozawa joined Nippon Telegraph and Telephone Corporation (NTT) in 1991. After engaging in research and practical application of multimedia processing technologies at NTT Human Interface Laboratories and Cyber Solution Laboratories, he joined NTT WEST (seconded to Walkerplus, Inc.) in 2000, where he was involved in the provision of local multimedia information. He then joined NTT Resonant Inc. in 2004, where he worked on the development and management of "goo" internet services including its search engine and the establishment of mobile-search business, and became head of the Search Business Division in 2011. After serving concurrently as president of NTT Resonant Technology, Inc. from 2013, he became vice president, head of NTT Media Intelligence Laboratories in 2015 and head of the Global Business Promotion Office at NTT TechnoCross Corporation in 2018. He assumed his current position in June 2019.

Where There Is Will, There Is a Way. Researchers, Be Long-term Optimists

Shiro Saito
Senior Distinguished Researcher,
NTT Basic Research Laboratories

Overview

Quantum information technology is attracting attention as a source of technological innovation that will bring about major changes in the future economy and society. Countries around the world, including Japan, the United States, Europe, and China, are positioning research and development of quantum information technology as one of their national strategies. We interviewed Shiro Saito, a senior distinguished researcher at NTT Basic Research Laboratories and who is making a significant contribution to the development of quantum information technology, about the progress of his research and his attitude as a researcher.

Keywords: quantum information technology, superconducting flux qubit, macroscopic quantum phenomena

Research on new devices that contributes to the development of quantum information technology

—Please tell us about your current research.

Quantum mechanics is applied in various devices—ranging from semiconductor devices to lasers and magnetic resonance imaging systems—and I am researching quantum information technology using superconducting quantum circuits. Quantum information technology provides high-performance functions unattainable with conventional technology by skillfully controlling quantum states, which are vulnerable to external noise and have a short lifetime.

Superconducting quantum circuits, which are composed of superconducting elements with quantum properties, have been extensively researched with the aim of developing quantum computers. As a result of the improvement in quantum-state-control techniques, applications of superconducting quantum circuits to quantum devices other than quantum computers, such as quantum sensors, have begun to be explored.

The origin of research on superconducting quantum circuits is the question, "Does the violation of realism that occurs in the world of quantum mechanics occur in the macroscopic world we live in?" Clarifying the question will lead us to the creation of quantum computers that enable massively parallel computing without consuming high energy and quantum sensors that enable highly sensitive sensing that exceeds the limits of the past.

Realism or violation of realism means, for example, if you roll a die under a paper cup, the die's dots are determined even if you do not observe them from the outside, as shown in **Fig. 1**, and this phenomenon is called *realism*. However, in the world of quantum mechanics, violation of realism occurs, that is, the

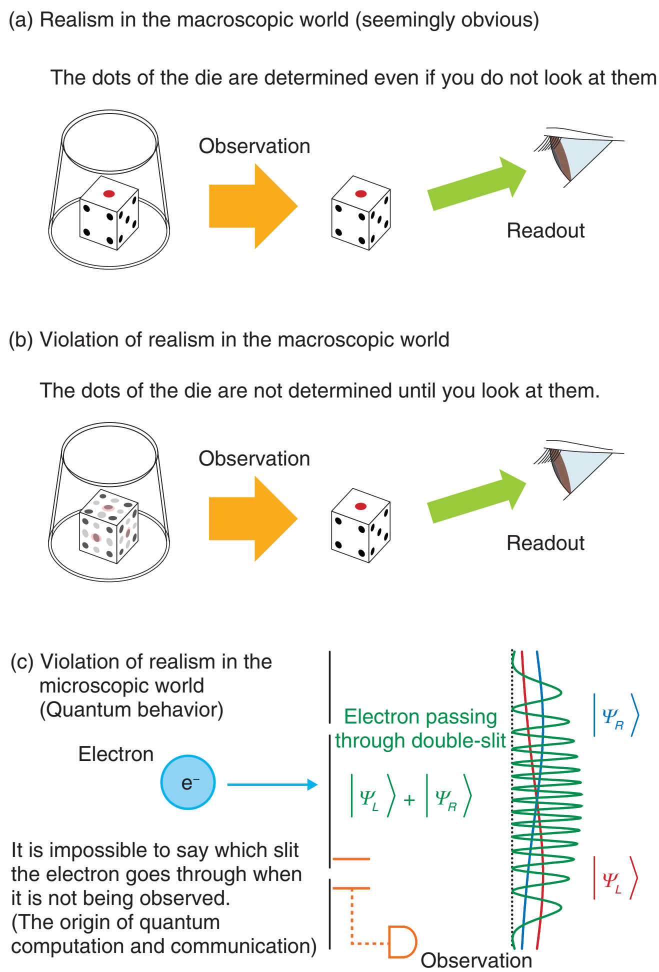


Fig. 1. Realism and violation of realism in the macroscopic world and violation of realism in the microscopic world.

dots on the die under the cup are in a superposition state and determined only when they are observed with the eye by lifting the cup.

In an experiment we conducted, a single electron was sent through a double-slit one by one. When we took a number of measurements of the position of the single electron by using a detector placed at a certain position behind the slit, the position of the electron came together to form a wave pattern (i.e., interference fringes). This phenomenon can be explained as follows. Each time the single electron passes through a double-slit, a state called "superposition" occurs, namely, the electron is superposed between one through the upper slit and the other through the lower slit every time it is sent, and the place where the electrons gather is determined by the interference effect. The interference fringe is a proof of the superposition state, namely violation of realism. However, when we try to measure which slit the electron passed through, the interference fringe disappears. The travel direction of the electron is determined at the moment its passage through the slit is measured, and the electron does not travel in the direction to form the interference fringe. This is the consequence of realism.

Violation of realism has been confirmed in the nanometer-sized microscopic world of electrons, atoms, etc., and the origin of research on superconducting quantum circuits has been whether such phenomenon occurs in the macroscopic world.

—I heard that you have achieved pioneering results. Please tell us about your recent achievements.

In 2016, in collaboration with the University of Illinois, USA, we successfully demonstrated violation of realism concerning superconducting currents

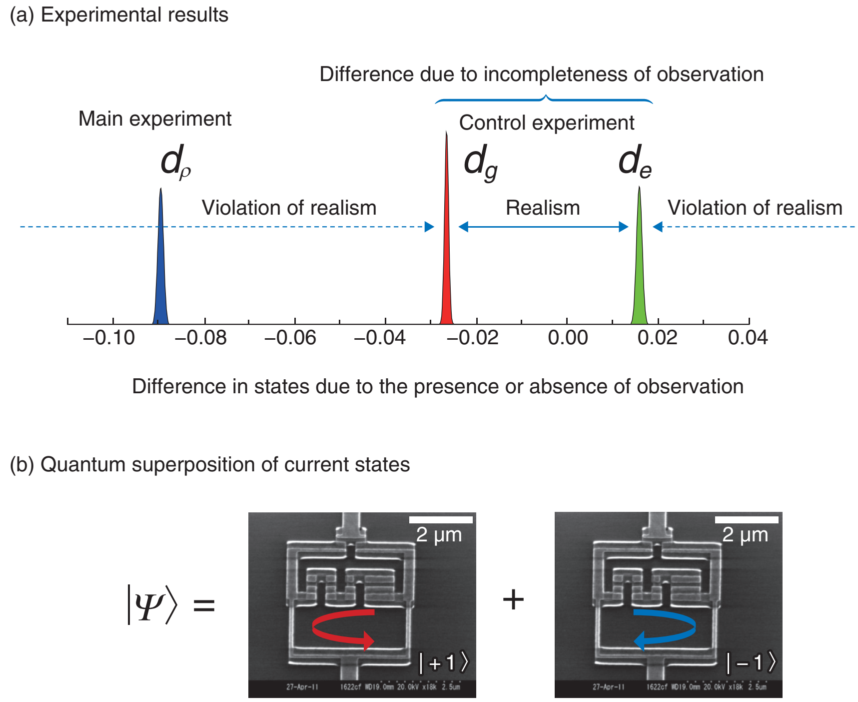
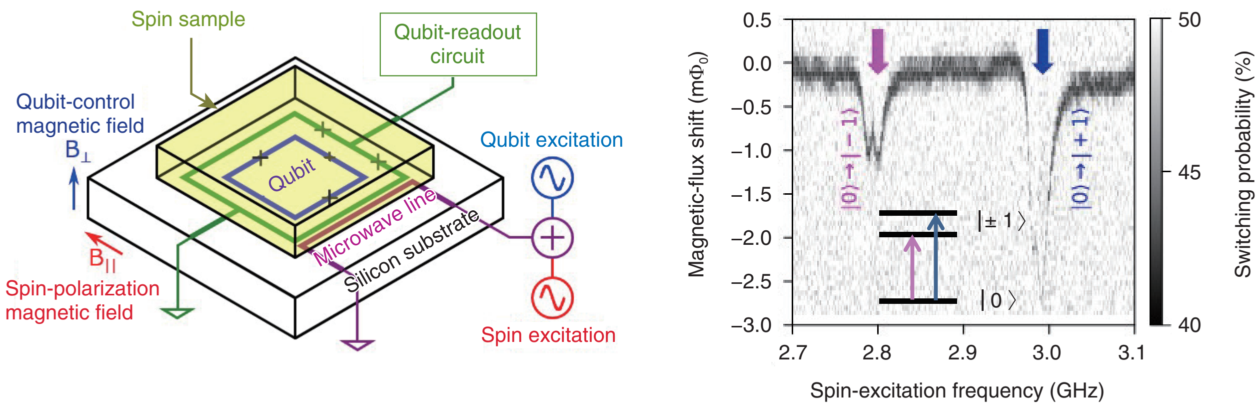


Fig. 2. Experimental results concerning quantum superposition of current states.

using a superconducting flux qubit (**Fig. 2**). As I mentioned with the earlier question, if the macroscopic world follows quantum mechanics, violation of realism should also occur. The question of whether this violation occurs in the macroscopic world or whether it is not owing to the limitations of quantum mechanics (i.e., the macroscopic realism problem) has been an unsolved problem since the dawn of quantum mechanics. A current of 170 nA (equivalent to 10^{12} electrons flowing per second) flows through a superconducting flux qubit. Our recent results indicate that realism is violated in this current, and our demonstration that quantum mechanics is applicable on the macroscopic scale, i.e., current states, will significantly contribute to the field of fundamental physics. It also confirms that superconducting flux qubits can work as quantum devices that use true quantum properties. The results were published in the online edition of the British scientific journal Nature Communications [1].

In 2019, we demonstrated electron-spin resonance using a superconducting flux qubit, which makes it possible to analyze a small-volume sample containing several dozens of electron spins (**Fig. 3**).

This research on quantum sensing using superconducting qubits is part of the "Creation of Innovative Quantum Technology Platform Based on Advanced Control of Quantum States" project supported by the Japan Science and Technology Agency's Core Research for Evolutional Science and Technology (CREST) program [2]. Electron-spin resonance spectroscopy is one analytical method for investigating the properties of electron spins in materials and is widely used for analysis of molecular structures. However, analysis with a current electron-spin-resonance spectrometer requires a sample containing a large number of electron spins, namely, about 10^{13}, and a sample volume of several milliliters. As a result, the samples that can be analyzed are limited. A superconducting flux qubit functions as a highly sensitive magnetometer. We have demonstrated electron-spin resonance spectroscopy by using this magnetometer to detect electron spins, which have the properties of a tiny magnet. We succeeded in detecting about 400 electron spins in a 0.05-pL sample volume. The development of a new electron-spin-resonance spectroscopy method that can be used to analyze a material sample containing a small number of spins in a minute volume is considered to contribute to a wide range of fields from basic science to material characterization, bioanalysis, and medical applications. This achievement was published in 2019 in the online



(a) Local-electron-spin-resonance spectrometer using flux qubit

(b) Electron-spin-resonance spectra due to the nitrogen-vacancy (NV) center in diamond. The inset shows the energy levels of the NV center.

Fig. 3. Demonstration of electron-spin resonance.

version of the British scientific journal Communications Physics [3]. Then, in 2020, the detection volume reached 0.006 pL, and the detection sensitivity reached 20 electron spins [4].

We are currently working on the “Development of Integration Technologies for Superconducting Quantum Circuits” project as part of the national Moonshot Research & Development Program launched in December 2020 entitled “Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050” [5, 6].

Curiosity toward macroscopic quantum phenomena

—How do you feel about the expansion and fulfillment of your research field?

Looking at the field of superconducting quantum circuits as a whole from the perspective of a pioneer, I feel that this field is evolving ever more rapidly. In the beginning, the activities were small scale and slow, but as the potential of this field was revealed, researchers from academia and industry, as well as outstanding researchers in a wide variety of fields other than superconductivity, joined the field. This situation has created an interesting trend; for example, when high-temperature superconductivity was in vogue, researchers in the field of quantum circuits studied high-temperature superconductivity as a primary theme then returned to quantum circuits to advance them dramatically.

Starting from pursuing the question of violation of realism by creating macroscopic superposition, in 2016, we were able to answer that question not only phenomenologically but also mathematically. During that time, quantum technology had matured, and the quantum field had become a focus of public attention. Twenty years ago, only a handful of researchers were working on superconducting quantum circuits; however, a huge number of groups are now working on them, and new papers are being published every day. On reading those papers, I feel a difference between the volume of resources we have and those of the USA, Europe, and China. In the field of quantum computing, the USA—led by Google, IBM, and others—is investing heavily and seems to have the upper hand.

Under these circumstances, I believe that Japanese research institutes must join forces in the field of quantum research. If each research lab were to work on its own, it would be left behind by the rest of the world; therefore, it is necessary for each lab to take charge of a research theme it has expertise in and combine them to compete with the rest of the world.

Having played a pioneering role in this field, I try to conduct research that is one step ahead and will be useful in the future. My participation in the Moonshot project on quantum error correction is one example of such research. Although our resources in terms of both funding and human resources may be an order of magnitude less than those overseas, I believe that my role is to draw a picture that attracts outstanding researchers by effectively promoting new initiatives and using the achievements as material.

In drawing such a picture, I feel that it was very meaningful to participate in the new projects of CREST and Moonshot that I mentioned earlier. Quantum technology is a hot topic attracting much attention, and I think it is important to demonstrate the unique characteristics of NTT.

I think that this field is now in the phase of thinking about what can be done with new ideas. When considering the overall development of the field, I believe that we shouldn't put too much pressure on researchers; instead, we should give them a certain degree of freedom. If we put excessive pressure on them, their ideas will be meager, and that situation will affect the development of the field as a whole.

—What has supported you in your pursuit of quantum technology for the past 20 years since you joined NTT?

My starting point was curiosity about macroscopic quantum phenomena. When I was at university, I studied superconductivity; however, neither the environment nor the technology needed to investigate macroscopic quantum phenomena was available, so I joined NTT because I admired its environment and system. Researchers should be motivated to work on something because they are interested in or because there is an unknown in a particular field.

For example, the main reason that I'm devoted to quantum technology is that when I was a university student, I admired the research of Prof. Yasunobu Nakamura (who is currently at the University of Tokyo), who was the first person in the world to demonstrate quantum superposition in a superconducting circuit. I was hooked by the wonder of creating superpositions in the macroscopic realm.

Prof. Nakamura is now in a position to coordinate research on quantum computers in Japan, and I'm now able to tackle such research from a different angle. One time, Prof. Nakamura said to me, "I remember a student who asked me questions in particular detail during a special lecture, and it turned out it was you, Prof. Saito." That explains how much I admired Prof. Nakamura's research. With that memory in mind, I try to convey to students who come to NTT for training that research is an interesting world.

Perhaps the way of thinking behind the saying "Where there is a will, there is a way" can support our research life. I think researchers need to be "long-term optimists." Although I have always believed in that saying and have always believed that any problems can be solved, I was unable to achieve success for a while after joining the company. It was around the time when the qubit I created had a short lifetime and could not be superposed. Still believing that "Where there is a will, there is a way" and that if I make improvements steadily, the lifetime of the qubit will be extended, I continued to improve the samples and measurement system. Then, in the middle of the night at the laboratory, I saw Rabi oscillations in the qubit signal indicating superposition. I was really excited when I was able to confirm the data for the first time; I even jumped for joy in our large, empty gymnasium-like laboratory alone. I think experiencing that kind of success makes us expect to achieve further success.

Cherish your connections with people

—What do you keep in mind when determining a research theme?

When determining a new theme, I first analyze the current situation then select a theme that will allow me to find a new method or novelty. For example, it is important to (i) understand your strengths and the trends being followed by other researchers in your research area by comparing their strengths with yours and (ii) narrow down the theme you should pursue while considering the direction in which you can come up with something new.

Although it depends on the research phase and field, the current field of superconducting circuits, for example, is quite broad, so it is necessary to survey how far each area within it has progressed. The number of papers published in the field is considerable, so it may be difficult to keep track of the overall research. Even so, if you do not keep track properly, you may go in a wasteful direction or even if you produce results, they might not receive proper appraisal.

I also tried my hand at creating macroscopic superposition by trial and error. However, time is not infinite, so I try to get a general idea of the direction of the field of superconducting quantum circuits by reading papers, including references, published by groups who are making progress in the field. The references are particularly very useful for obtaining an overview of the field since they contain most of the relevant papers in the field.

You should select the theme you are interested in. Regarding macroscopic superposition, it is necessary to extend the lifetime of the qubit. Therefore, I was excited to see that the lifetime of the qubit had recently begun to extend again, and that excitement confirmed that I do really like studying macroscopic superposition.

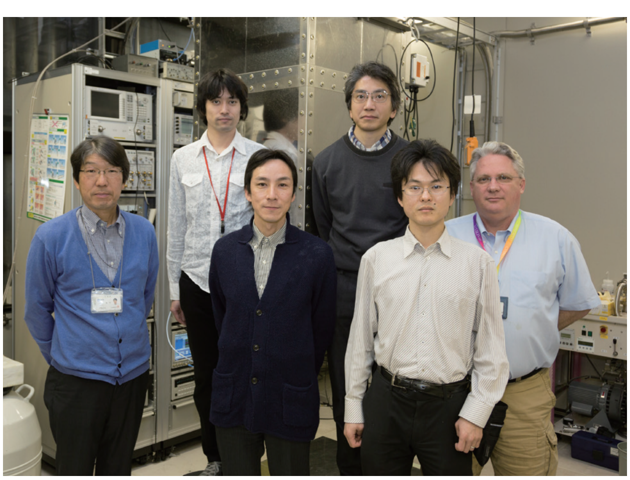
In addition to being aware of this emotion, it is also important to be interested in what is right and new. For example, I'm exploring a new direction called "bosonic codes" and am applying my accumulated knowledge of qubits to build a new quantum system based on bosonic codes. I want to make the most of the foundations that we have built but also want to look for new things.

—What would you like to say to our young researchers?

Young researchers, cherish your connections with people. I say that because connecting with people gives us new knowledge, and collaboration with researchers in completely different fields can bring new perspectives. For example, when we were trying to develop a bosonic code in the Moonshot project, I was looking to collaborate with researchers fabricating a high-Q (quality factor) cavity for storing bosonic qubit information and was able to connect with certain collaborators as a result of casual conversation that took place in a symposium.

As another example, I was considering using diamond as a material that might improve the limit on coherence time (i.e., the timescale over which the quantum information stored in the qubit is lost) of the superconducting qubit. Coincidentally, around that time, a superior of mine casually started a conversation with a researcher sitting next to him at lunch during a conference, and it turned out that the researcher was an expert on diamond. Following the advice given by that expert led us to achieve outstanding results. These experiences made me recognize the importance of showing up at places where researchers gather and connecting with them. Therefore, I hope that you will value your interactions with others—both inside and outside NTT.

During your research activities, you don't have to be bound by the purpose of your research. A research goal can have derivation and detours. There are many different ways to achieve goals, and I think it is good to have a variety of offshoots. If you put 90% of your energy into your research theme and the remaining 10% into something completely unrelated, you will be able to broaden the scope your research. Convey to people what you want to do. Opportunities even lie in casual conversations in daily life. I encourage you to pursue a research theme that you are interested in while maintaining your curiosity.



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■ **Interviewee profile**

Shiro Saito

Senior Distinguished Researcher and Group Leader of Superconducting Quantum Circuits Research Group, NTT Basic Research Laboratories.

He received a B.E., M.E., and Dr.Eng. in applied physics from the University of Tokyo in 1995, 1997, and 2000. He joined NTT Basic Research Laboratories in 2000. Since then he has been engaged in quantum information processing using superconducting circuits. He was a guest researcher at Delft University of Technology from 2005 to 2006 and a guest associate professor at Tokyo University of Science from 2012 to 2020, where he is currently a guest professor. He was appointed as a distinguished researcher of NTT in 2012 and senior distinguished researcher in 2021. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.

Studying Multimodal Interactions: Understanding Dialogue Mechanisms through Combined Observation of Speech, Language, and Body Movement

Ryo Ishii
Distinguished Researcher, NTT Human Informatics Laboratories

Overview

Digital Twin Computing is one of the three key fields of technology in the IOWN (Innovative Optical and Wireless Network) vision. In order to build a digital-world representation of a person that includes not only their external aspects, but also their internal aspects, such as consciousness and thought, it is essential to understand and model the mechanisms of human communication. In this article, we speak to Distinguished Researcher Ryo Ishii, who works with multimodal information including speech, language, and body movement with the aim of understanding the mechanisms of human communication, for example in how a person conveys their mental state.

Keywords: human communication, multimodal interaction, dialogue system

Communication is born of the interaction between multiple modalities such as speech and gestures

—What kind of research field is multimodal interaction?

When people talk with others, they communicate using more than just their voice and language. They use multiple modalities, such as gaze, facial expression, and gestures, communicating what we call "multimodal information." These modalities are used in combination, and the modalities influence each other as people use them to communicate information. These interactions using multimodal information are called "multimodal interactions." What's particularly important about these interactions is that the transmitted multimodal information is dealt with as a whole. For example, during a conversation someone might say, "Don't joke about that." Looking at the written words alone, you can't tell whether the speaker is angry or joking. But when you listen to the

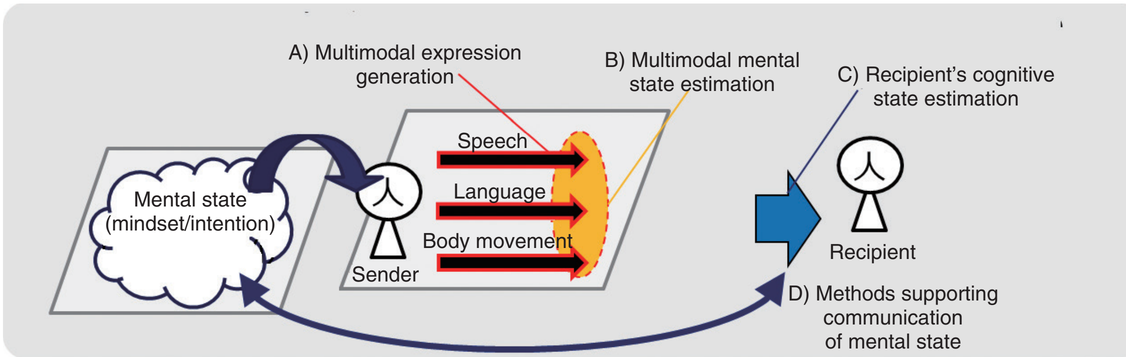


Fig. 1. The field of multimodal interaction.

tone of their voice and look at their facial expression, you know that if they are speaking softly with a big smile, they're probably not serious. One major research topic is comprehensively processing this multimodal information to understand the intentions and messages that people convey, and understanding and modeling the mechanisms for how this information is transmitted between people. Another major research topic in multimodal interactions is using this understanding and these models to support communication between people and enable smooth communication between people and dialogue systems.

In this research area, I am carrying out a multifaceted study of mechanisms for expressing and recognizing multimodal information (**Fig. 1**). This involves A) "multimodal expression generation," which is researching and modeling the mechanisms for generating speech, language, and physical motion to transmit the current mental state; B) "multimodal mental state estimation," which is estimating the mental state of the sender through their speech, language, and body movement; and C) "recipient's cognitive state estimation," which is looking at how the recipient interprets the sender's mental state. In addition, I am carrying out practical research into D) "methods supporting communication of mental state," which involves recognizing discrepancies between the sender's state of mind and their state of mind as perceived by the recipient, and enabling the sender's state of mind to be correctly conveyed to the recipient.

—What are you researching specifically?

As an example, one topic I worked on at NTT Communication Science Laboratories was predicting the next speaker and timing of speech. In the future, dialogue systems will need to quickly predict who should talk next, enabling them to speak at the appropriate time during conversations with people. So, we built a model that predicts who will speak next and when, based on subtle behavior like people's eye movements, head movements, and breaths taken before speaking. Since there were no existing studies that measured people's respiration during a conversation and analyzed it in relation to speech behavior, our paper presenting this research was given an Outstanding Paper Award at the ACM International Conference on Multimodal Interaction, the leading conference in this research field.

In addition, we work closely with internal and external researchers to conduct a variety of research related to multimodal interactions. This includes work on the "MoPaCo Window Interface," which creates three-dimensional video from video conferencing systems to encourage users to interact using natural gaze and body movement, "body movement generation technology," which automatically generates gestures based on the speaker's speech and language, and "personal characteristic/skill estimation technology," which accurately estimates the personal characteristics and communication skills of participants based on speech, language, and image information from their conversation.

—What are the current challenges you're facing?

One useful approach is applying machine learning technology, which is already widely studied and used, to the field of multimodal interactions. This can help us understand and model how humans' intentions are conveyed, and the mechanisms of how we transmit information to each other. Machine learning technology generally requires a large amount of data anyway, but when dealing with human communication, there's a massive diversity of communication methods due to the large number of variables, such as different situations, number of people, cultures, relationships, and locations. This makes collecting the necessary data a difficult task that requires a huge amount of work.

For example, when gathering data from a conversation, the first step is to record the content of the speech by listening to it and manually writing up the timing and what was said. For example, "XX was said between XX seconds and XX seconds" (although speech recognition technology can be used for preprocessing). To some extent, we can automatically gather data on facial expressions, gaze, and posture from images of the speakers. However, for some modalities this method isn't accurate enough, so each image must be checked manually, by checking who's looking at who and labeling the eye movement, for example. A one-second video usually consists of about 30 still images, which makes the manual process time consuming and cumbersome. For these reasons, it takes a lot of work to construct corpus data (in this case, a data group for dialogue research) containing multimodal information for human conversations, and in many cases, we're unable to collect all of the data and we have to conduct our research using only a small amount of data from a particular situation.

Researchers nowadays say that once the data are collected, the research is 70% or 80% done. It may be a bit of an exaggeration, but collecting data is a very important and very expensive task. Being able to efficiently collect large amounts of data from human conversation is a major challenge, but if it is overcome, I think research in this field will take a huge leap forward.

Aiming for an all-encompassing model for communication

—What are the plans for future research?

As a new approach, we are carrying out research into modeling all aspects of human communication in order to gain a deep understanding of the communication mechanisms. Current communication modeling technology defines a human behavior as input X and a single state such as a human emotion, a personal characteristic, or a location as output Y, and only works to understand the relationship between the two. These individual studies are very enlightening and interesting, but from the perspective of understanding and modeling the entire mechanism of human communication, they only cover a tiny number of phenomena. I have started to work on forming an integrated understanding and model of the relationships between the various phenomena that occur in human communication.

As an example, a person may express (or "transmit") multimodal information such as speech, language, and body movement through their actual behavior, but before they get to that point, they will have a certain internal mindset and intention. People will also have individual characteristics, such as a personality and values. In addition, the dialogue will be influenced by personal relationships, roles, and the atmosphere during the conversation. **Figure 2** shows a simple example of this relationship. We have modeled the entirety of natural communication in four different layers: a "high-order layer" that holds people's relationships, roles, and the atmosphere of the conversation; an "actual-behavior layer" for multimodal information transmitted and received through actual behaviors such as speech, language, and body movement; a "mental layer" that holds internal information such as people's mindsets and intentions; and a "personal-characteristics layer" that holds information such as personality and values.

As mentioned above, there have been many studies carried out in the past on things like using one behavior to predict the next, and estimating individual personal characteristics and relationships from behavior, but essentially, communication can be thought of as a model in which the four layers are interrelated and act in combination with each other. In addition, Fig. 2 shows the communication status at one point in time, but this model will change over time.

The current goal is to create an ultimate, all-encompassing model of communication by looking at the relationships between these layers and the changes over time.

—What kinds of possibilities will this technology unlock?

If we can create this ultimate, all-encompassing model of communication, the system will not only be able to accurately understand the state of the conversation, but will also be able to predict and simulate the future state. We expect this to enable three main things.

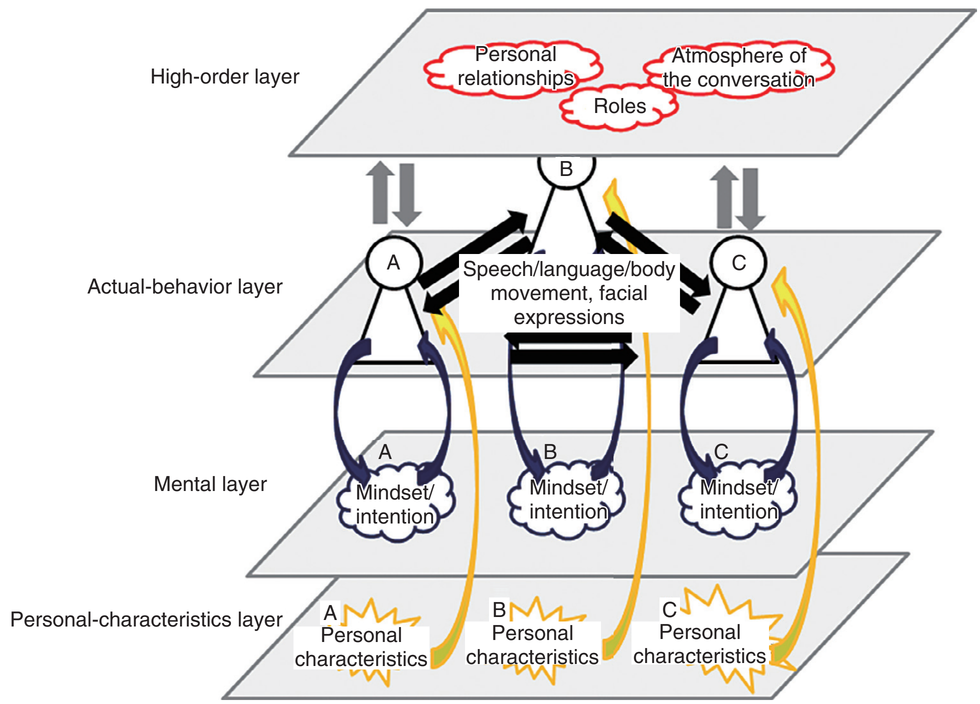


Fig. 2. Communication model devised by Dr. Ishii.

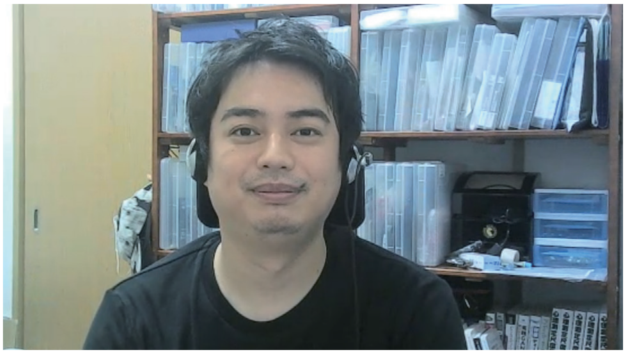
The first is the provision of real-time support for human communication. During a conversation, for example, if someone is a little upset, the system can follow up with them, or if one person is talking all the time it can ask what others think to try and switch the speaker and facilitate conversation, making the situation more harmonious and encouraging communication.

The second is the creation of the ultimate dialogue system. This dialogue system will be able to understand its conversation partner and the communication situation, and communicate appropriately just like a person.

The third is training people's communication skills. We are currently working on research into estimating how well we compliment people and automating training for this skill. Complimenting people is an important skill, and many people are concerned about how to do it best. With the all-encompassing communication model, it will be possible to evaluate how effective a person is at complimenting their conversation partner based on a wide range of perspectives such as their mindset and intention, their personal characteristics, the circumstances of the conversation, and the personal characteristics of their partner. Based on these evaluations, the system will give advice like, "A conversation partner with XX personality has XX intentions in XX situation, so complimenting XX more will help you build a better relationship." The aim is to use this ability to create applications that can improve people's communication skills.

—Do you have any messages for people aiming to become researchers?

What I'm aiming toward and what I want to achieve hasn't changed much since I was a student. I think my current research topic is my life's work, and I'm pretty invested in it. I think it's really important to spend your life in pursuit of what you want to achieve, and not to give up. There are opportunities for research and development in universities, companies, and various other places, but I don't think there's any environment where you will be 100% satisfied. At times, you may have to work on research topics that don't match your own aims. I think it's a real waste if you let yourself get dissatisfied in that kind of situation, and lose your motivation for research and your appetite for developing your personal skills. Whatever situation you find yourself in, you should think hard about what you can learn to help you reach your



final goal, how to achieve results efficiently, and how to make the most of your own abilities to succeed. And I think it's very important to build up your achievements one by one. In doing so, I believe that opportunities to pursue the research topics you're interested in will come around, and you will also have opportunities to start up the research yourself.

I also think it's important to involve other people. I am currently conducting four joint research projects with researchers from outside the company, and I have lots of other talented colleagues outside the company who I can work together with to help further my research. There are real limits to what you can achieve on your own. I think it's very important that you build up a group of colleagues who can work together to help each other achieve their goals.

I think multimodal interaction is a great research area for those who like people and are interested in communication. Multimodal interaction is an interdisciplinary field that involves a wide range of academic areas, including humanities and engineering. That means a single area of expertise alone is not enough for the creation of good technology, and a wide range of expertise is required. It's not easy to gain expertise across such a broad area, and this is still a new field that's under development. In order to break new ground in this field and succeed as a researcher, you need a strong desire to understand the mechanisms of human communication and to change the world through these new interaction technologies. You may not have the necessary expertise at the start, but I think if you have a strong drive to get stuck into the research, you'll be able to succeed in this field.

■ **Interviewee profile**

Ryo Ishii

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He received a B.S. and M.S. in computer and information sciences from Tokyo University of Agriculture and Technology in 2006 and 2008, and a Ph.D. in informatics from Kyoto University in 2013. Since joining Nippon Telegraph and Telephone Corporation (NTT) in 2008, he worked for NTT Cyber Space Laboratories (2008–2012), NTT Communication Science Laboratories (2012–2016), NTT Media Intelligence Laboratories (2016–2021, including as a visiting researcher at Carnegie Mellon University from 2019–2020). He has been with NTT Human Informatics Laboratories since July 2021 and with NTT Digital Twin Computing Research Center since January 2021.

Trends and Target Implementations for 5G evolution & 6G

Yoshihisa Kishiyama, Satoshi Suyama, and Satoshi Nagata

Abstract

In Japan, commercial 5th-generation mobile communication systems (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.

Keywords: 5G evolution & 6G, requirements, wireless technology

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 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 4G with Long Term Evolution (LTE) technology capable of speeds in excess of 100 Mbit/s supported the explosive spread of smartphones. Then in March 2020, Japan's first 5G services were launched, offering maximum transmission speeds of over 4 Gbit/s.

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 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, NTT 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 standardization

*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).

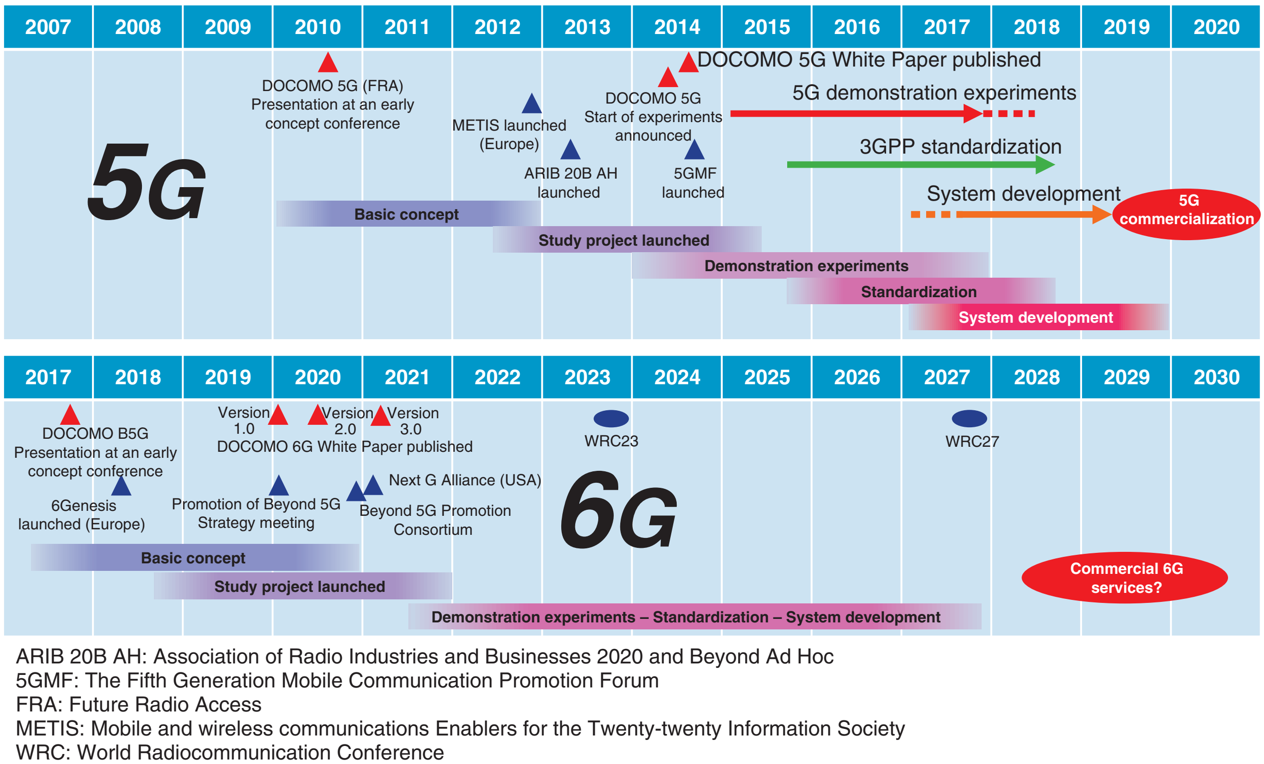

Fig. 1. 5G development history and 6G schedule.

of 5G began at the 3rd Generation Partnership Project (3GPP) 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 to make terahertz waves*2 available for research purposes [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*3, 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 industry, academia, and government on 6G technology [5].

At NTT 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. 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

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

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

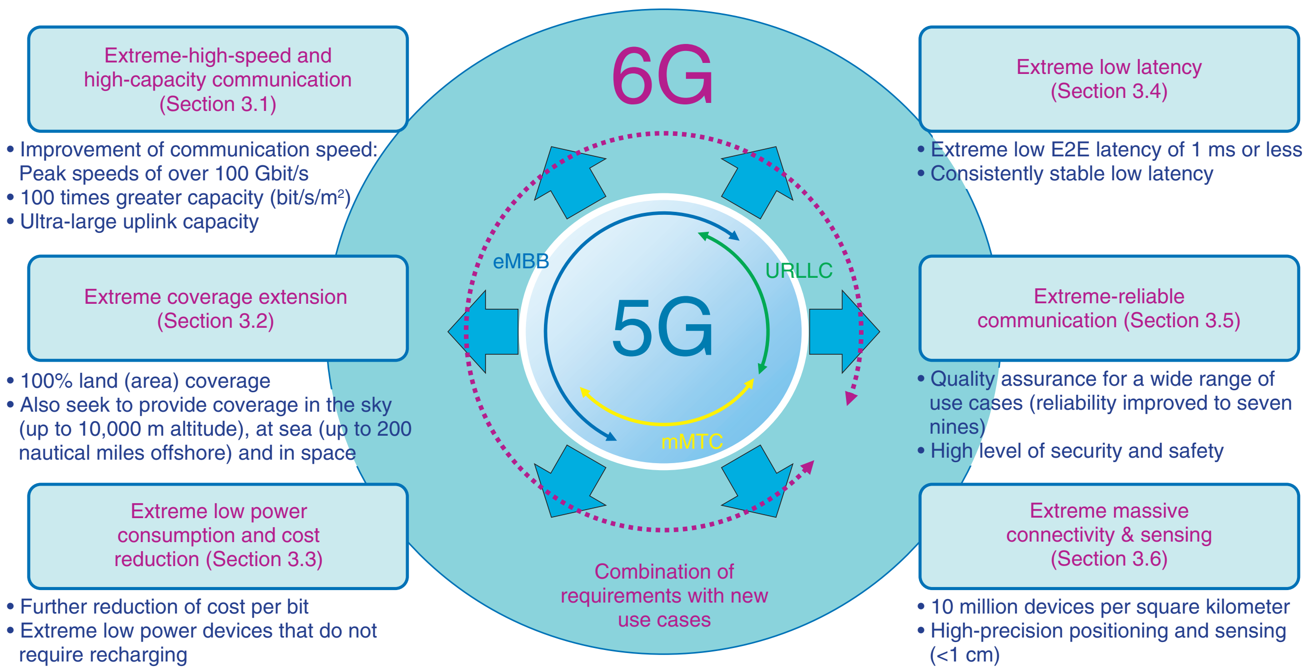

Fig. 2. Requirements for 6G.

experiments and international standardization efforts will be promoted with the aim of introducing 6G commercial services by 2030.

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 2** 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 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 three-dimensional 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*4 because it will be necessary to transmit diverse real-world information in real time to the cloud and AI processes that constitute the

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

"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 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), 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 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.

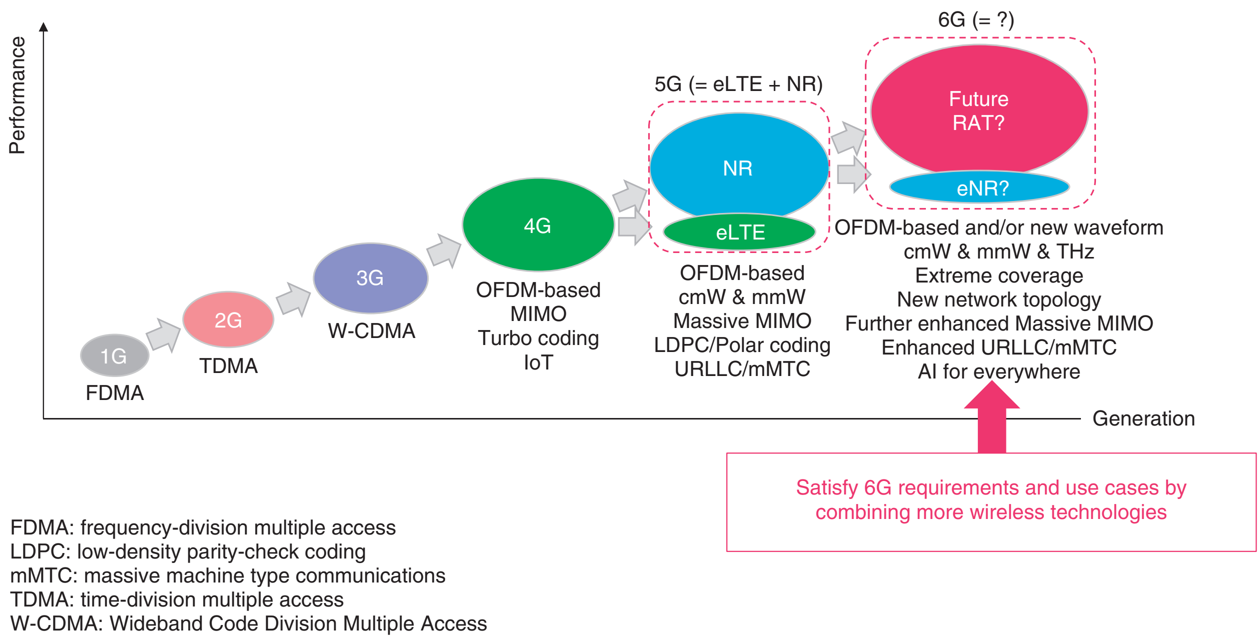

Fig. 3. Technological development of mobile communication systems towards 6G.

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 3 illustrates the development of technology from previous mobile communication generations to 6G. Earlier generations had a single representative technology (RAT: radio access technology)[*5] that they used for radio access, but since 4G, mobile communication has used multiple technologies based on orthogonal frequency division multiplexing (OFDM).[*6] 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[*7] close to the Shannon limit[*8], while the requirements for mobile communication systems, frequency bands, and use cases are

*5 RAT: Radio access technologies such as New Radio, LTE, W-CDMA, and GSM (Global System for Mobile Communications).
*6 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.
*7 Frequency utilization efficiency: The number of bits of information that can be sent per unit time and unit bandwidth.
*8 Shannon limit: The theoretical maximum rate at which information can be transmitted through a communication channel of a given bandwidth and signal-to-noise ratio.

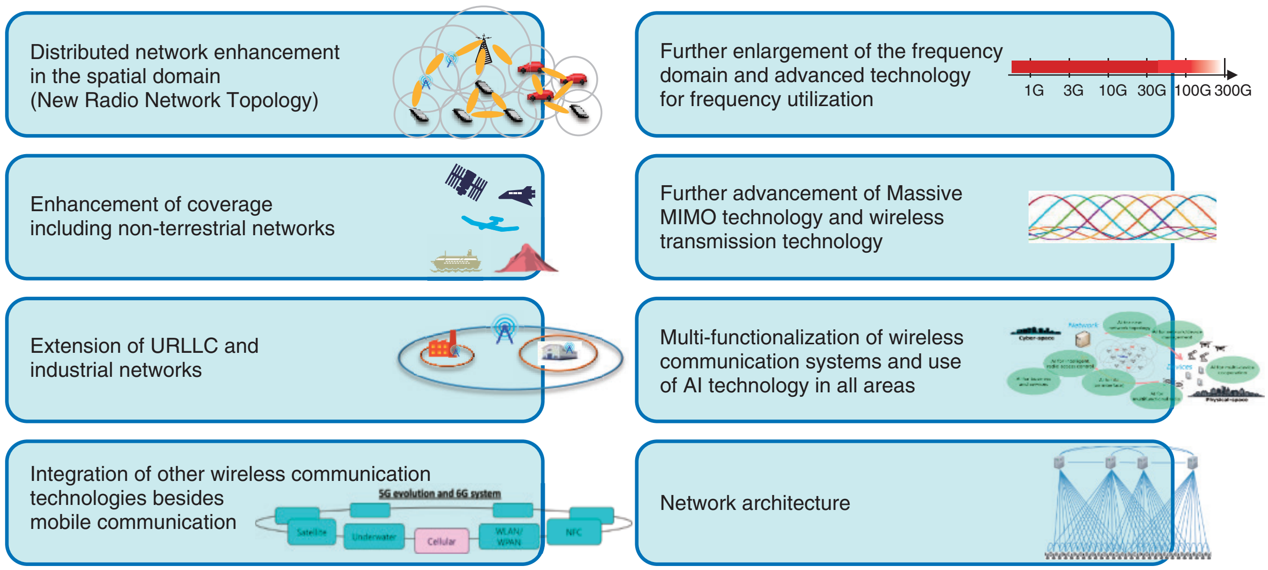

Fig. 4. Technology areas that need to be considered for 5G evolution & 6G.

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)*9, 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 **Fig. 4** [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*10 in the spatial domain.

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.

*9 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.

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

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 details of each technical area, discussions of related research and development activities can be found elsewhere in this issue [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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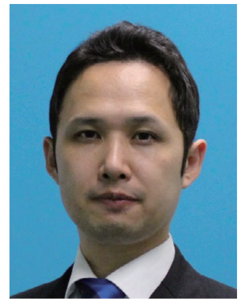

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Research of Transparent RIS Technology toward 5G evolution & 6G

Daisuke Kitayama, Yuto Hama, Kensuke Miyachi, and Yoshihisa Kishiyama

Abstract

The introduction of the 5th-generation mobile communications system (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 the intelligent radio environment (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 the reconfigurable intelligent surface (RIS), an important component of IRE, and metamaterial/metasurface technologies as elemental technologies of RIS.

Keywords: 5G evolution, millimeter wave, metasurface

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 through 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 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 & 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.

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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.

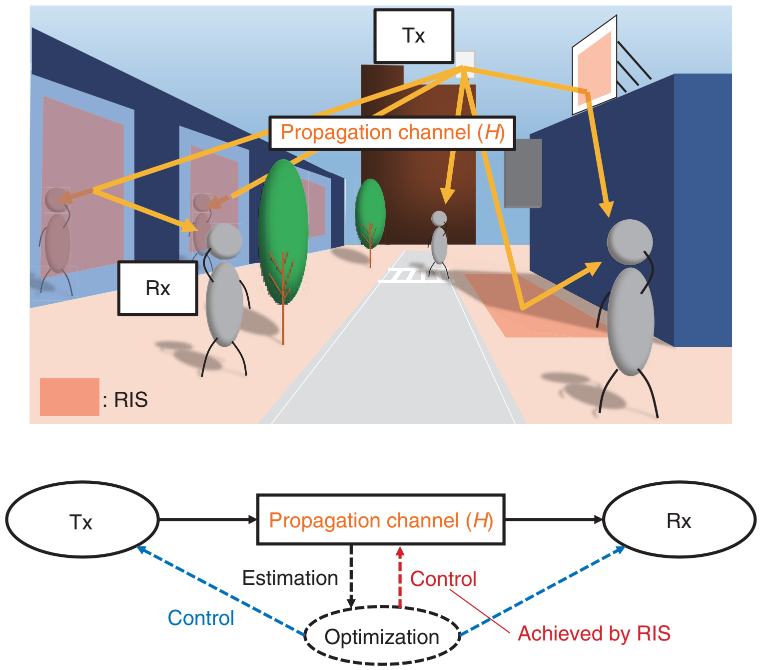


Fig. 1. Conceptual diagram of IRE.

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 **Fig. 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

*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.

following operations.

- Estimate the radio channel characteristics required for determining RIS operation.
- 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.

2.2.1 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 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.

- Receiving a direct wave with a BS – MS of 200 m
- 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 **Fig. 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 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.

2.2.2 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

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

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

*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.

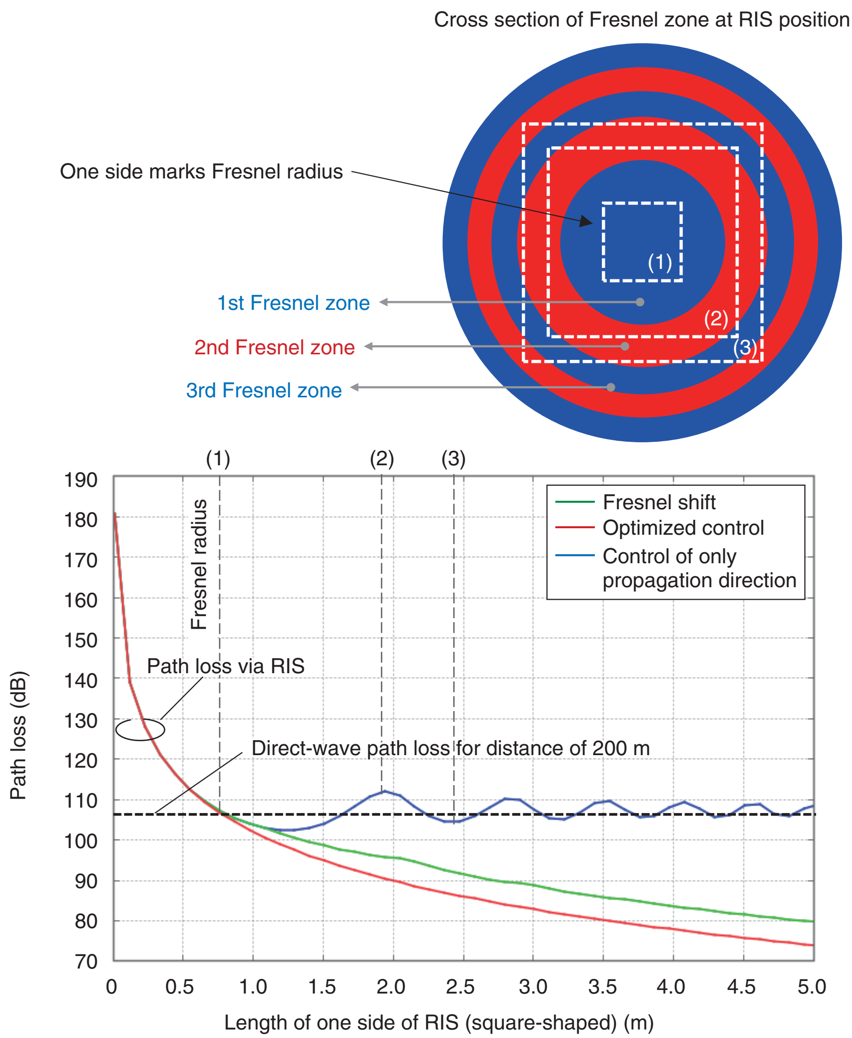


Fig. 2. Relationship between RIS size and path loss.

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].

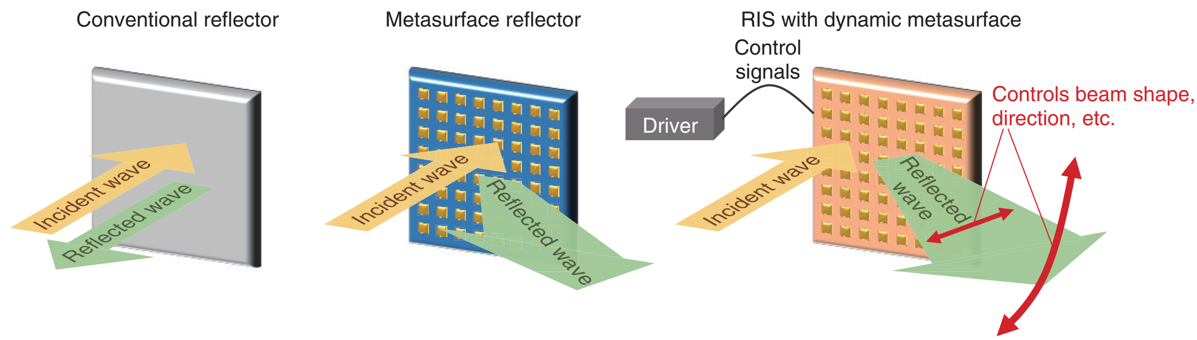


Fig. 3. Conceptual diagram of RIS using metasurface technology.

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 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 (**Fig. 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.

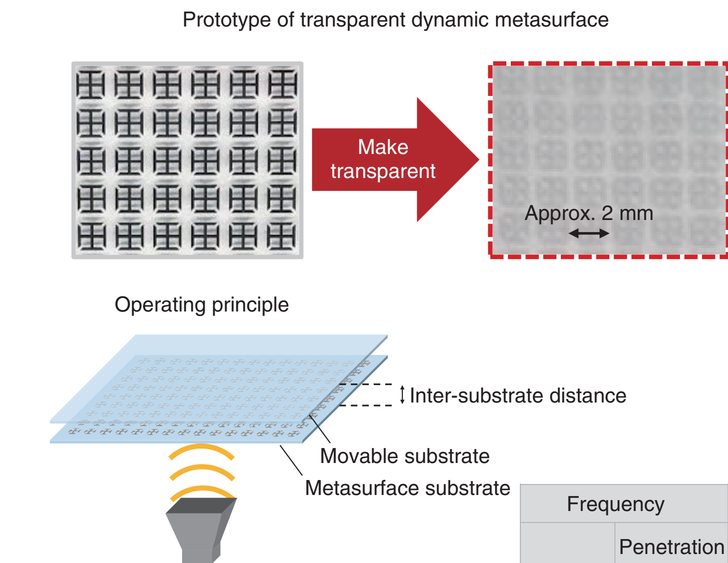
3.1 Transparent dynamic metasurface

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

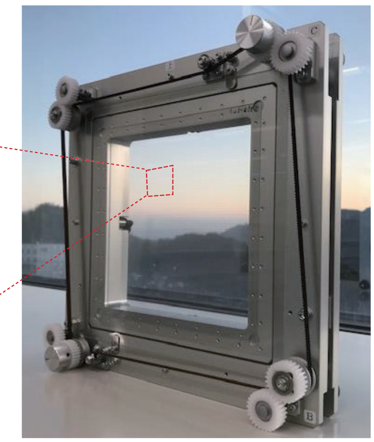
In response to the above issues, we have been developing and studying a “transparent dynamic metasurface” in cooperation with AGC Inc. as a RIS prototype that can dynamically control the reflection and penetration of radio waves while maintaining high transparency (**Fig. 4**) [9]. The metasurface substrate 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

*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.



	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

Fig. 4. Transparent dynamic metasurface initiative.

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).

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.

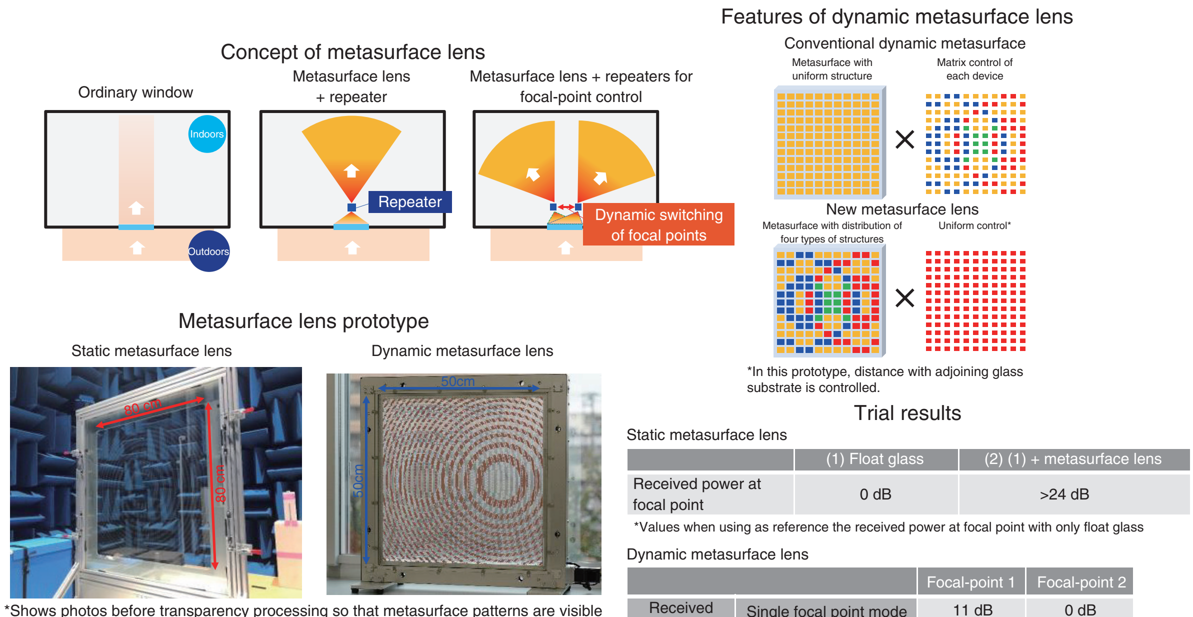
3.2 Making windows into radio-wave lenses by transparent metasurface lens

Compared with radio waves in the frequency bands currently used in LTE (Long Term Evolution) and the Sub-6[*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 (**Figs. 5** and **6**). In a trial using this metasurface lens, we found that the received power at the focal point could be improved by 24 dB or more compared with the case of an ordinary transparent glass.

*11 Sub-6: 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.



	(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

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

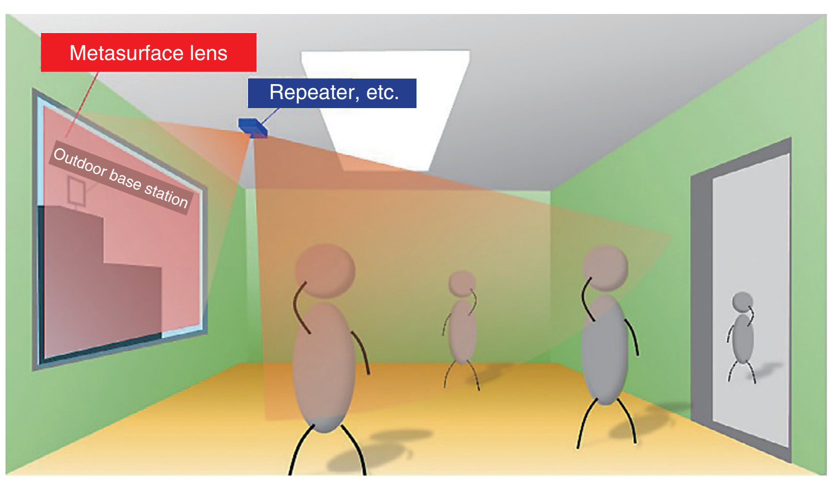


Fig. 6. Example of using a transparent metasurface lens.

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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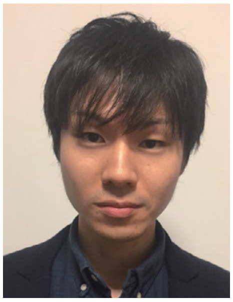

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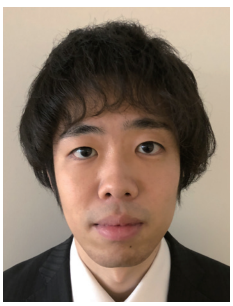

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Research on NTN Technology for 5G evolution & 6G

Yuki Hokazono, Yoshihisa Kishiyama, and Takahiro Asai

Abstract

In the 5th-generation mobile communication system (5G) evolution & 6G, extreme coverage extension is being studied for use cases in all places including air, sea, and space. Non-terrestrial networks using geostationary satellites, low earth orbit satellites, and high-altitude platform stations 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.

Keywords: NTN, HAPS, extreme coverage extension

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 **Fig. 1**, NTT DOCOMO is conducting research and development aimed at achieving extreme coverage extension whereby mobile communication can be made available in all locations,

Fig. 1. Extreme coverage extension.

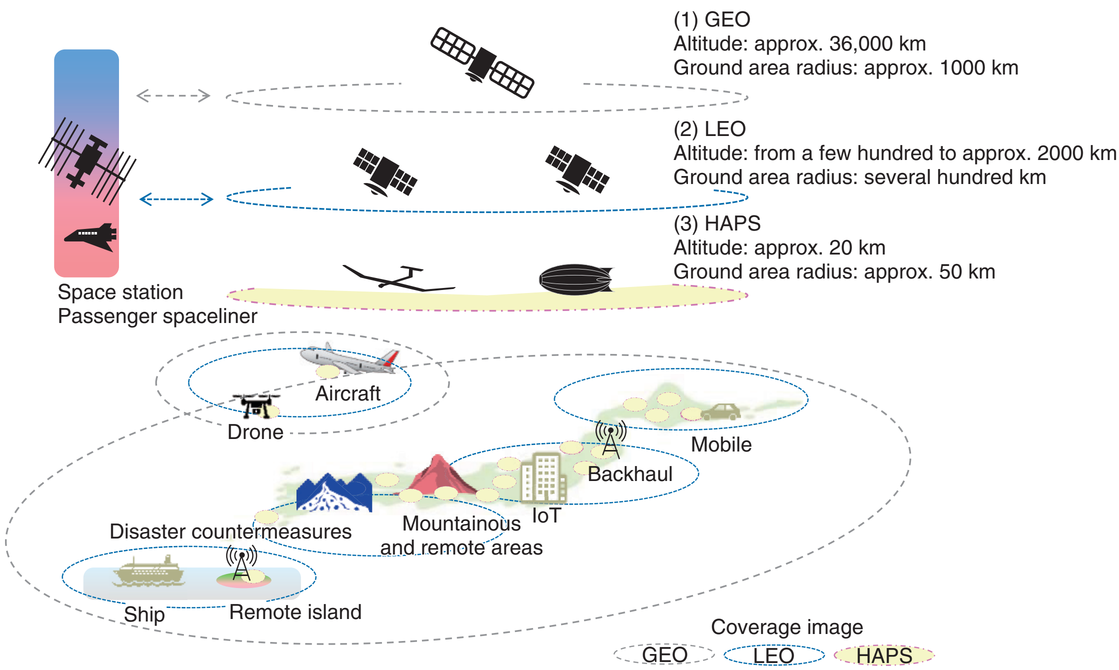


Fig. 2. Illustration of how satellites and HAPS can be used to extend coverage to the sky, sea, and space.

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)*1 technology using satellites and high-altitude platform stations (HAPS)*2. 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 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 **Fig. 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) GEO satellite

A GEO satellite 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

*1 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.

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

networks by providing a mobile backhaul[*3]. Since additional network capacity will be required in the 6G era, very high throughput satellites are being studied with the aim of improving system capacity by optimizing the allocation of power and frequency across multiple beams [3].

(2) LEO satellite

An LEO satellite orbits the Earth at an altitude ranging from a few hundred km to about 2000 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[*4]. 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)[*5] technology, and for high-capacity, low-latency backhauls in satellite constellations that form networks through cooperation between multiple satellites [4].

(3) HAPS

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[*6] 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)[*7] to NTNs [6].

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 **Fig. 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[*8] 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 **Fig. 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 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 Gbit/s per service link[*9]. Furthermore, to provide multiple simultaneous service links, the feeder link[*10] will have to be capable of even faster communication speeds (several Gbit/s to several tens of Gbit/s) and must operate as stably as possible regardless of weather-related effects.

It is also necessary to flexibly control lines so that

*3 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.

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

*5 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.

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

*7 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 Internet of Things (IoT).

*8 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."

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

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

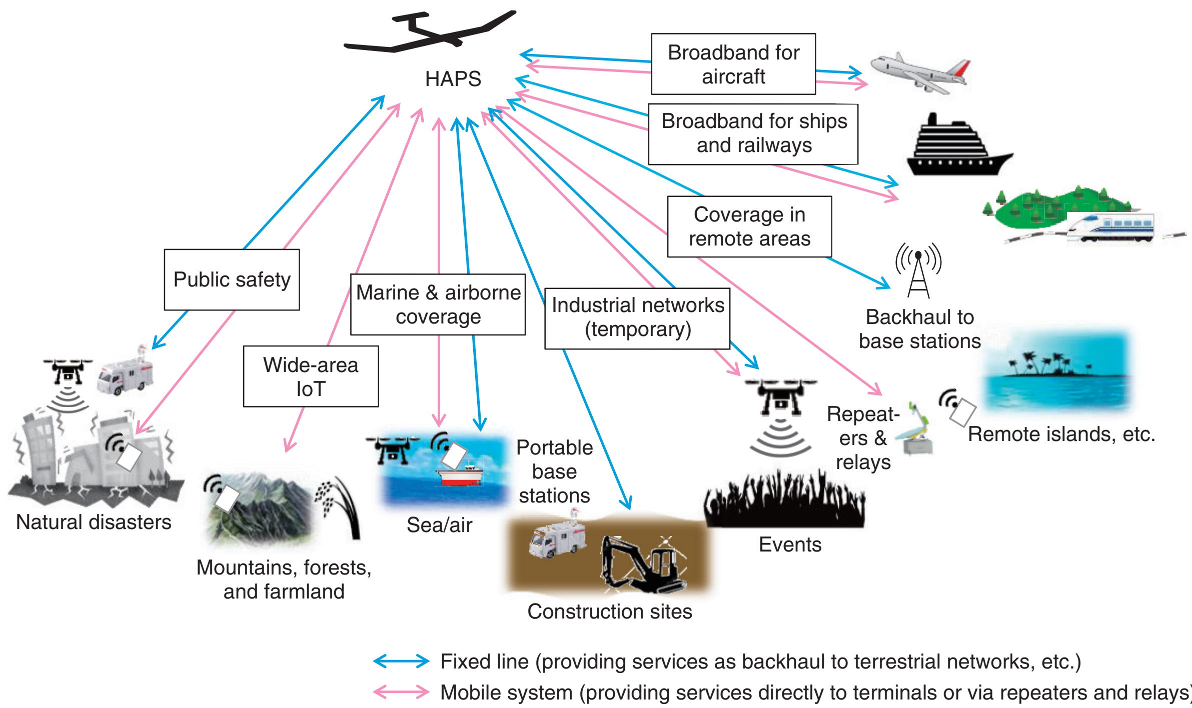


Fig. 3. Various use cases expected for HAPS.

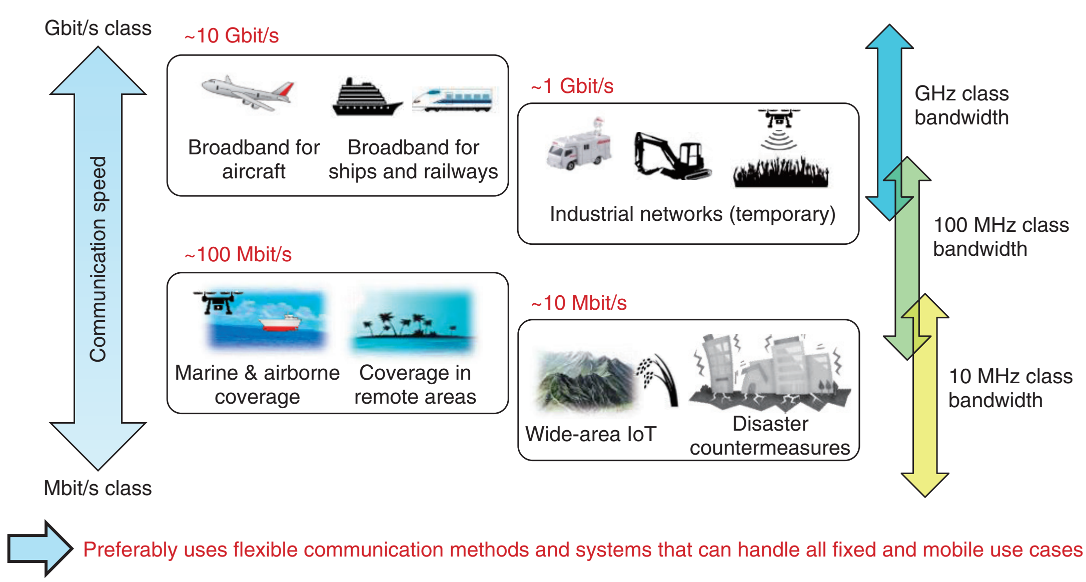


Fig. 4. Requirements for each HAPS use case.

they can be adapted from normal business applications to public safety*11 applications in the event of a disaster. Current disaster countermeasures are geared towards providing basic communication services

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

such as voice calls and short message services, 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

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

(1) Relay station type

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

(2) Base station type

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.

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 communication systems, and their ability to cooperate with GEO/LEO satellites.

3.2.2 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 **Fig. 5**. Here, the distributed unit (DU)*12 and radio unit (RU)*13 of the 5G base station are mounted on the HAPS in accordance with Open RAN (O-RAN)*14 Alliance specifications [9]. In this configuration, availability is ensured by installing a centralized unit (CU)*15 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 without the need for intervening relay stations. As a further extension, site diversity*16 can be implemented by using multiple CUs on the ground side to reduce the impact of bad weather and natural disasters, and mobility support*17 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*18 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

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

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

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

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

*16 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.

*17 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.

*18 Standalone: A deployment scenario using only NR, in contrast with non-standalone operation which uses Long Term Evolution (LTE)-NR Dual Connectivity to coordinate existing LTE/LTE-Advanced and NR.

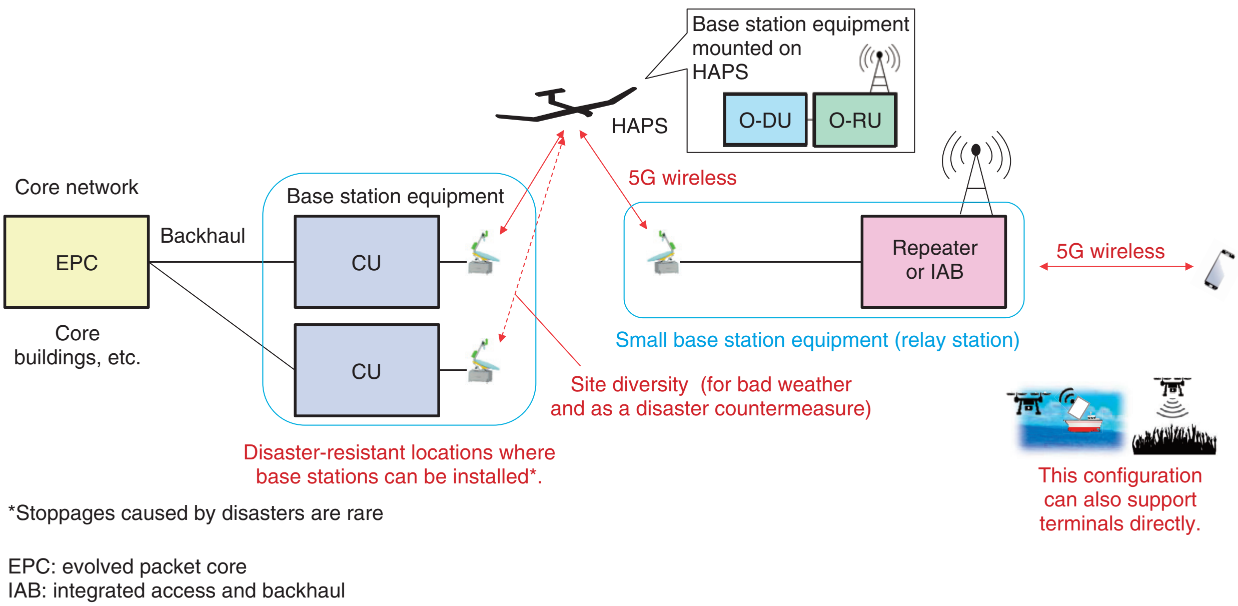


Fig. 5. Example of cooperative configuration when HAPS is used for backhaul.

various attributes such as mobility support, site diversity technology and frequency sharing technology*19, 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

*19 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.

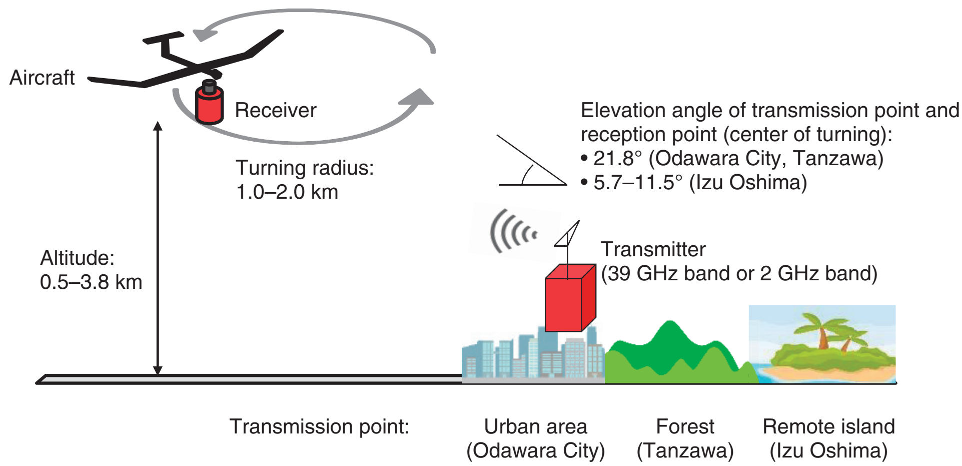
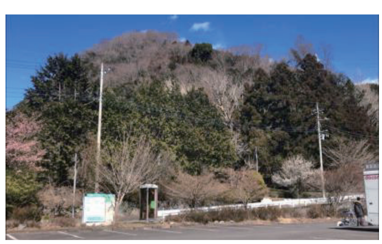


Fig. 6. Illustration of the airborne propagation measurement test.

(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

Fig. 7. Test environments with various obstacles.

and trees in each use case, as shown in **Fig. 7**.

For the transmitting antenna, we selected a product that was able to cover the turning range of the aircraft within the beam width*20, 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*21 designed to cause almost no propagation loss*22 was secured to its base. We also performed an initial experiment in which neither of the transmitting or

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

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

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

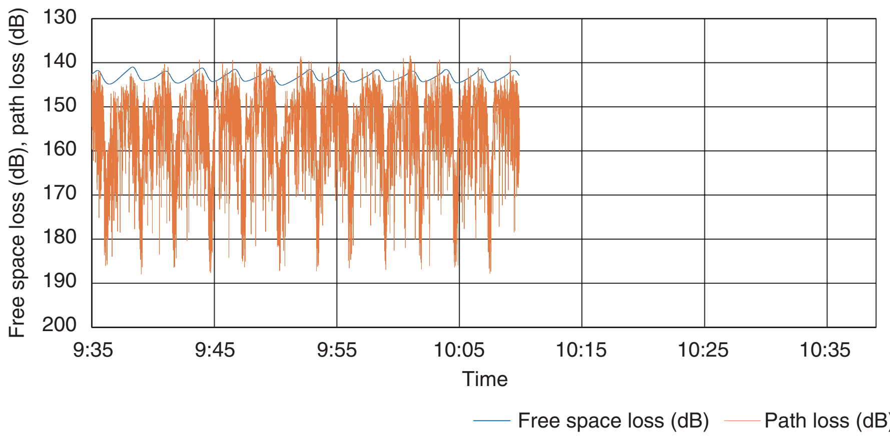


Fig. 8. Propagation loss time series data in the 39 GHz band at Odawara City (line of sight)/2 km turning diameter.

receiving antennas were provided with tracking functions, and the receiving antenna was fixed directly to the underside of the aircraft.

4.2 Evaluation

4.2.1 Overview

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 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.

4.2.2 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. 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 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*23, and the obstruction of radio waves by the aircraft itself when the underside of the aircraft was facing away from the transmission point.

In the building-occluded environment, the 39 GHz propagation loss has a mean value about 17 dB larger and a median value about 19 dB larger compared with the line-of-sight environment. 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, 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 toward implementing extreme coverage extension, which is one of

*23 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.

the important issues for 5G evolution & 6G, we have described NTN technology, especially 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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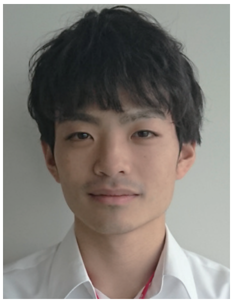

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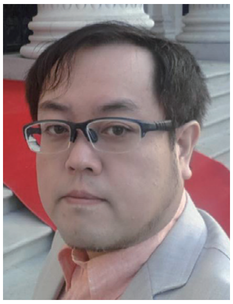

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Improving Communication Performance in High-mobility Environments by Millimeter-wave Base Station Cooperation for 5G evolution

Tatsuki Okuyama, Satoshi Suyama, Nobuhide Nonaka, and Takahiro Asai

Abstract

Although the 5th-generation mobile communications system (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 cooperation 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.

Keywords: digital beamforming, base station cooperation, outdoor experimental trials

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

*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 (radio-frequency equipment) and digital BF that performs phase control in the baseband section.

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 communications 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 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 communication 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 communication 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

*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.

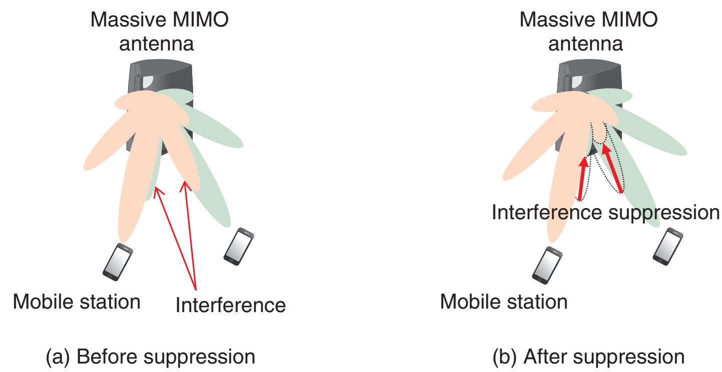


Fig. 1. Conceptual diagram of interference suppression by digital BF.

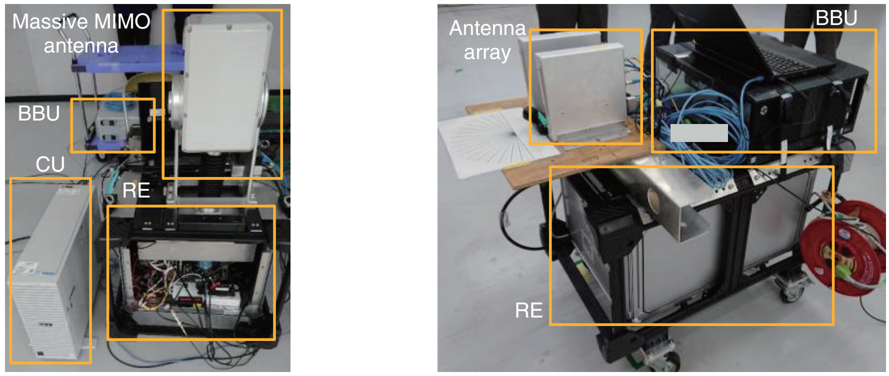
BF uses a phase shifter*5 and amplifier*6 connected to each antenna element to achieve strong radio wave directionality in a particular direction by superimposing radio waves emitted from each of those elements. The problem here, however, is that the superimposing of radio waves always results in the 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 **Fig. 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 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 becomes 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

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

*6 Amplifier: A circuit that amplifies the signal.



(a) Base station (b) Mobile station

Fig. 2. Experimental equipment.

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 **Fig. 2**. 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 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 Mbit/s 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 **Fig. 3**. 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 **Fig. 4**. 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

*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 user equipment.

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

*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.

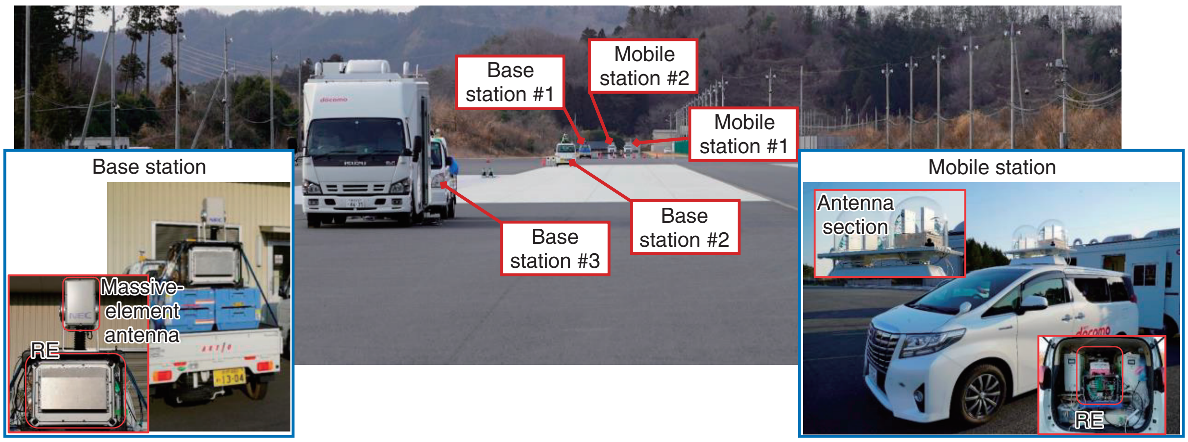


Fig. 3. Experimental setup.

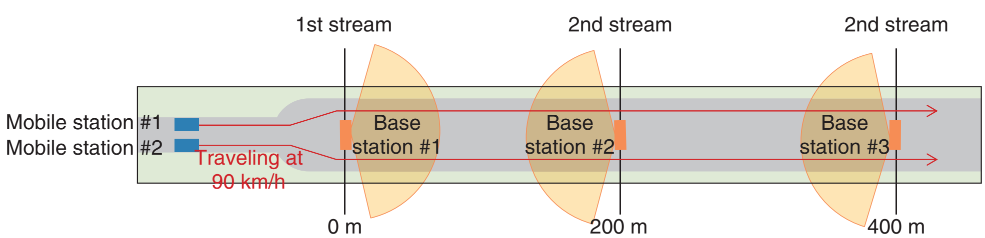


Fig. 4. Experimental configuration.

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

3.2 Experimental results

3.2.1 Base station cooperation experiment

To test the effects of base station cooperation, we compared the case of not using base station #2 in Fig. 4 (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 **Fig. 5**. It can be seen 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)

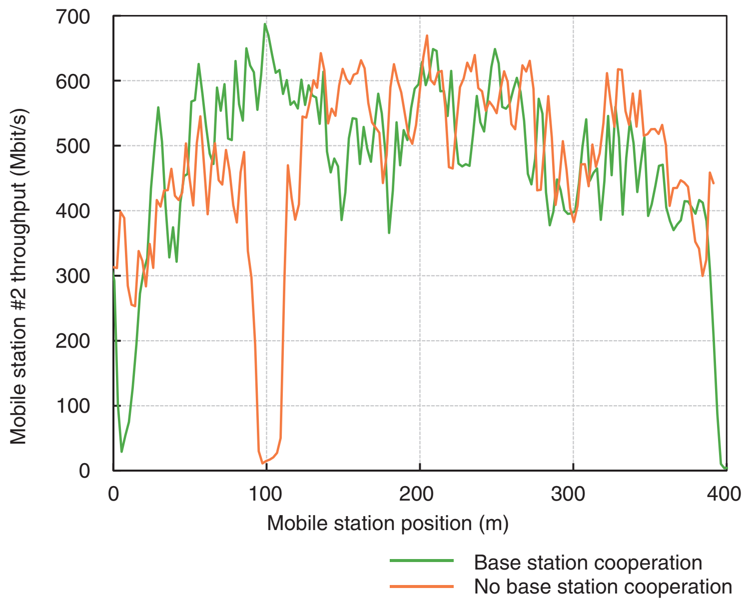


Fig. 5. Effects of base station cooperation.

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.

3.2.2 Base station cooperation experiment (base station high-speed switching) during two-mobile-station multiplexing

Figure 6 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. 4, 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 communications 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.

3.2.3 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 is shown in **Fig. 7**. Basic conditions are the same as those of Fig. 6, 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. 6, 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. 7 could not necessarily maintain higher values than throughput in Fig. 6. This is

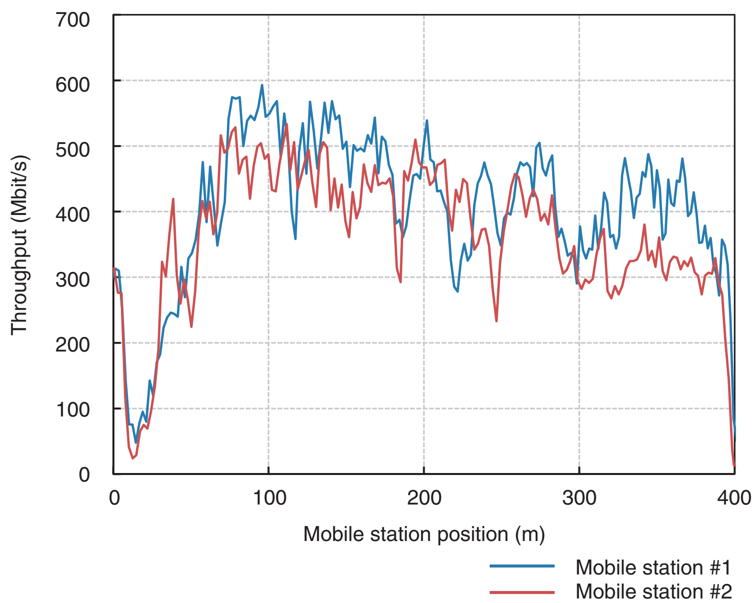


Fig. 6. User throughput for base station switching at 90 km/h.

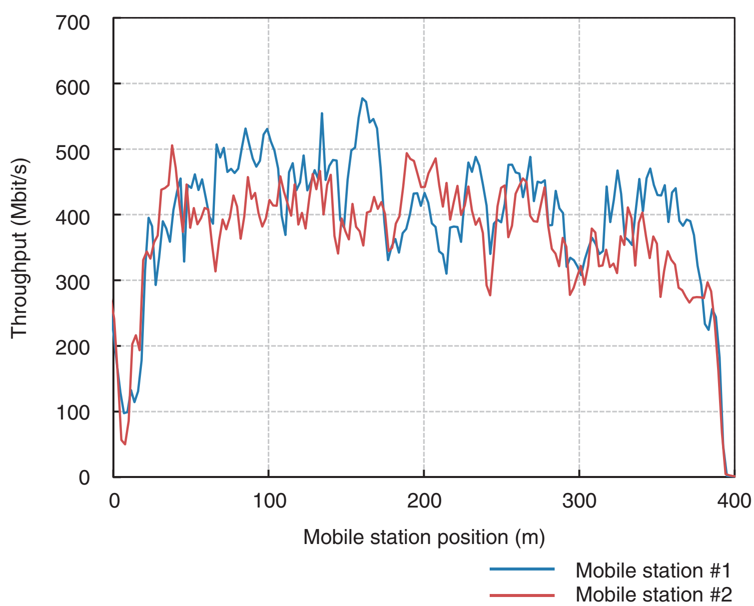


Fig. 7. User throughput for simultaneous base station transmission at 90 km/h.

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 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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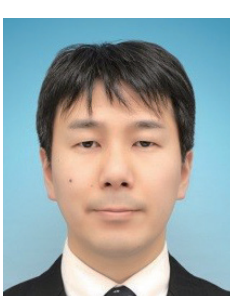

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High-gain Optical Parametric Amplifier Module by Using a PPLN Waveguide and Its Application to Quadrature Squeezing

Takahiro Kashiwazaki, Takeshi Umeki, Takushi Kazama, Koji Enbutsu, Osamu Tadanaga, and Kei Watanabe

Abstract

Optical parametric amplification is expected as a key technique for high-speed optical fiber communication and optical quantum computing. We developed a high-gain and broadband optical parametric amplifier (OPA) module by using a periodically poled lithium niobate (PPLN) waveguide, the single-mode core of which is directly bonded to a lithium tantalate substrate. The OPA is assembled as a pump-combiner-integrated module with four optical-fiber input/output ports. By improving the fabrication processes of the PPLN waveguide and the assembly techniques of OPA modules, we achieved over-30-dB phase sensitive amplification with a continuous-wave pump. By using the PPLN waveguide, we successfully obtained over-6-dB squeezed light, the spectral bandwidth of which was 2.5 THz. This high-gain broadband OPA module will help build an advanced information society.

Keywords: periodically poled lithium niobate, optical parametric amplifier, squeezed light

1. Introduction

The explosive spread of information and communication technologies makes it possible to build an intelligent social and economic system that intricately combines various technologies, such as artificial intelligence and robotics technologies. These information technologies will not only improve our lives but will also promote the sustainable development of the global environment. To ensure this prediction, higher-capacity lower-latency communication and higher-speed lower-power-consumption computation are needed as the technological infrastructure for a future society. However, these techniques are approaching several limits. In optical fiber communication, we are facing limits such as the standard quantum limit for optical linear amplifiers [1] and nonlinear Shannon limit, which determines the practical capacity of optical fiber communication [2]. In the computing field, we are facing the limit of Moore's law for semiconductor microfabrication [3].

To break these limitations, we conducted research on nonlinear optical devices and their applications to optical fiber communication and optical signal processing. Nonlinear optics describe various nonlinear responses of properties such as frequency and phase of light with strong interaction in nonlinear media [4]. By handling a wide variety of these nonlinear optical phenomena, it is possible to break through the limitations in optical communication and computation mentioned above. For example, by using phase sensitive amplification (PSA) with an optical parametric amplifier (OPA), we can break the standard quantum limit of conventional optical linear amplifiers on the basis of stimulated emission in long-haul fiber communication [5]. Optical phase conjugation by using an OPA can compensate for the nonlinear distortions in optical fibers, which is one factor causing the nonlinear Shannon limit [6]. Wideband optical wavelength conversion also contributes to the expansion of communication resources of wavelengths without reconverting to electrical signals [7]. Regarding computation, OPAs play key roles in non-von Neumann computers, such as a coherent-Ising machine (CIM) [8] and optical quantum computers [9]. In a CIM, an OPA is located in an optical fiber loop and generates artificial spins that have a 0 or π relative phase of light. With the use of time-domain multiplexing and measurement feedforward techniques, the CIM can find solutions for NP (nondeterministic polynomial time)-hard problems such as maximum cut problems. OPAs are also used for quantum light sources for various types of optical quantum computing (QC). For discrete-variable QC, OPAs can generate entangled photon pairs by spontaneous parametric down conversion processes [10]. OPAs also play an important role in continuous-variable (CV) QC because they generate a broadband squeezed vacuum state of light, which is an essential state to generate CV quantum entanglement [11]. Studies have shown the possibility of using OPAs in quantum measurement without electrical circuits [12]. This will be a key technique to achieve ultra-fast QC.

With the demand of OPAs for such applications, we developed OPA modules that are based on a periodically poled lithium niobate (PPLN) waveguide [13]. Thanks to its second-ordered nonlinearity, a PPLN waveguide has advantages as an OPA media compared with third-ordered nonlinear media such as high-nonlinear optical fibers. A PPLN-based OPA operates at room temperature without Brillouin scattering under high-power-pump injection, which often becomes a problem with third-ordered nonlinear media, and has the capability of integration in optical circuits. In this article, we introduce our PPLN-waveguide-based OPA module and its application for PSA and optical quadrature squeezing. Our PPLN-waveguide-based OPA module has high pump-power durability, low insertion loss, and high optical parametric gain. The module will be key for future optical communication and computation.

2. PPLN-waveguide-based OPA module

For various applications, an OPA should have a fiber-pigtailed configuration with pump combiners. Fiber-pigtailed devices can be used with various reliable optical components, which are sophisticated in optical communication technologies. The configuration promises easy installation into an optical communication system and various quantum technologies for out-of-lab application.

2.1 Waveguide fabrication

For achieving high-gain optical parametric amplification, a PPLN waveguide should have a small core and high durability for a high-power pump and maintain the phase matching condition along it. **Figure 1(a)** shows the fabrication process of our PPLN waveguide. First, a periodically poled structure is formed by the electrical poling process [14] for an LN wafer. The poling period is about 18 μm. We used a zinc oxide (ZnO)-doped LN wafer because of its high resistance to photorefractive damage [15]. After poling, the wafer was directly bonded to a lithium tantalate wafer. This directly bonded structure also allows us to use high-power light to obtain high nonlinearity [16]. The upper side of the PPLN layer was polished into a thin layer with a thickness of about 5.0 μm. Then, by using photolithography and a dry etching technique, the waveguide structure was obtained. **Figure 1(b)** shows a cross-sectional view of a fabricated waveguide taken using a scanning electron-beam microscope. To avoid several problems due to the existence of higher-order modes in the waveguide, our waveguide is designed as a single-mode waveguide for light in the communication wavelength band. The waveguide has a length of about 45 mm, as shown in **Fig. 1(c)**. The second-harmonic generation (SHG) efficiency at the phase-matched wavelength is 1200%/W, as shown in **Fig. 1(d)**, which was acquired under 3-mW light injection with a wavelength of 1550 nm. Thanks to the fine processing, the phase matching curve is close to the ideal sinc-squared shape. This means the waveguide's core has a uniform shape.

2.2 Module assembly

We assembled the fabricated PPLN waveguide as a pump-combiner-integrated OPA module with four optical-fiber input/output (I/O) ports [17]. **Figure 2(a)** shows an overview of the module. The module houses the fabricated PPLN waveguide, six lenses, four dichroic mirrors, and four pigtailed optical fibers, as shown in **Fig. 2(b)**. To suppress optical loss between the waveguide and optical fibers, we designed a spot-size-convertor at both input and output end regions of the waveguide. Thanks to the optimum coupling of both signal and pump lights with the use of two

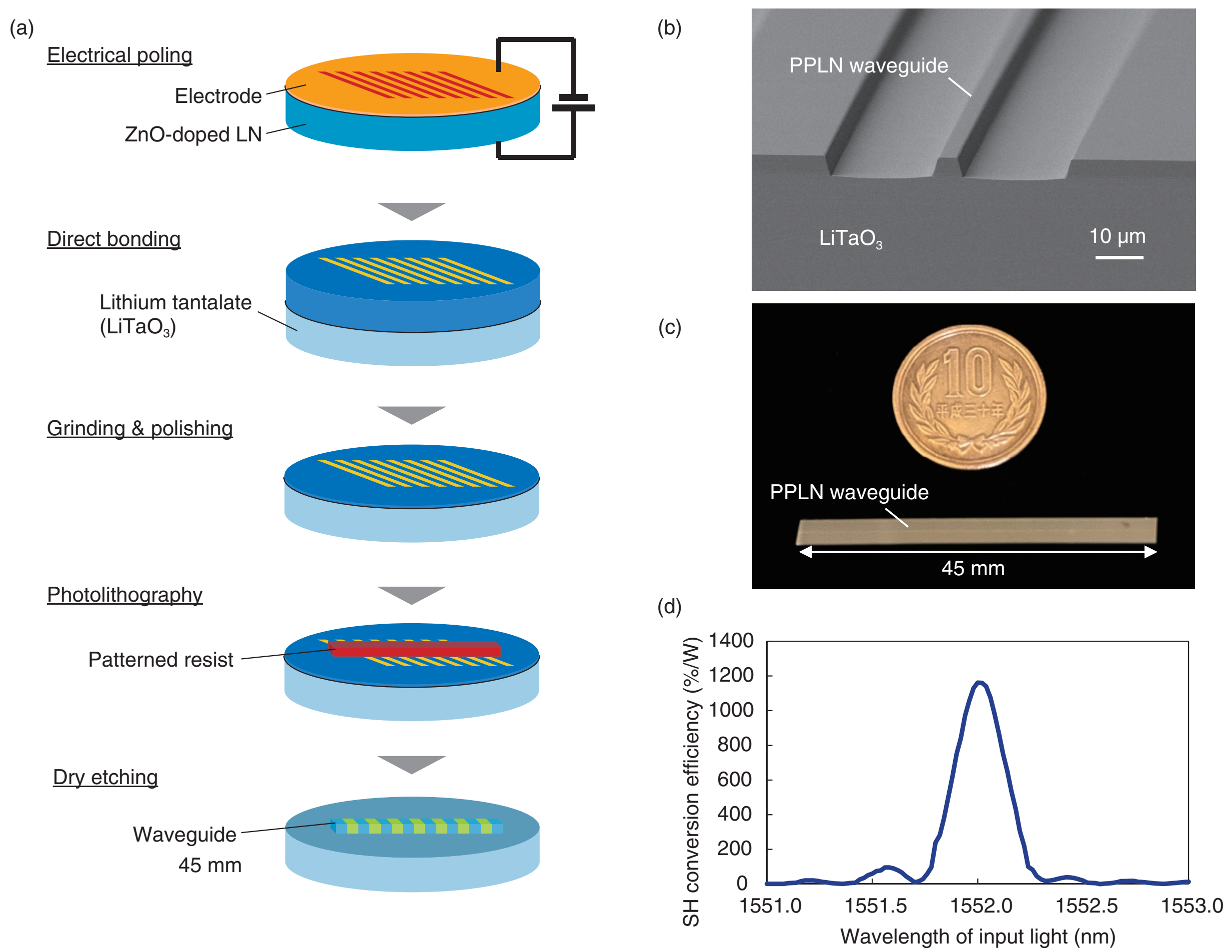

Fig. 1. (a) Fabrication process of our PPLN waveguide by using direct bonding and dry etching techniques. (b) Schematic image of PPLN waveguide taken using scanning electron microscope. (c) Photograph of fabricated PPLN waveguide. (d) SH conversion efficiency [9].

lenses, we obtained coupling losses of 0.5 dB at 1550 nm and 0.7 dB at 775 nm on each side. The total module insertion losses are 2.0 and 2.3 dB for the wavelengths of 1550 and 775 nm, respectively, which include waveguide losses. To maintain the phase-matching condition at any environmental temperature, we placed a Peltier device under the waveguide.

3. Application

Our PPLN-waveguide-based OPA module can be used for various applications. In this article, we focus on degenerate PSA for long-haul optical fiber communication and optical quadrature squeezing for CV optical QC.

3.1 Over-30-dB PSA

Figure 3(a) shows the experimental setup for degenerate PSA [18]. We used a continuous wave at 1551.6 nm as a signal and pump source. The pump light was amplified using an erbium doped fiber amplifier (EDFA) and launched into a PPLN module for SHG. The generated SH pump was launched into the four-port PPLN module with the signal light to cause optical parametric amplification. The relative phase between the signal and pump was locked using a lead zirconate titanate (PZT)-based fiber stretcher in accordance with the error signal from an optical phase-lock-loop. The output signal light from the PPLN device was detected using an optical spectrum analyzer. **Figure 3(b)** shows the input and output spectra of degenerate PSA. The difference between the input spectrum and output spectrum without

(a)

(b)

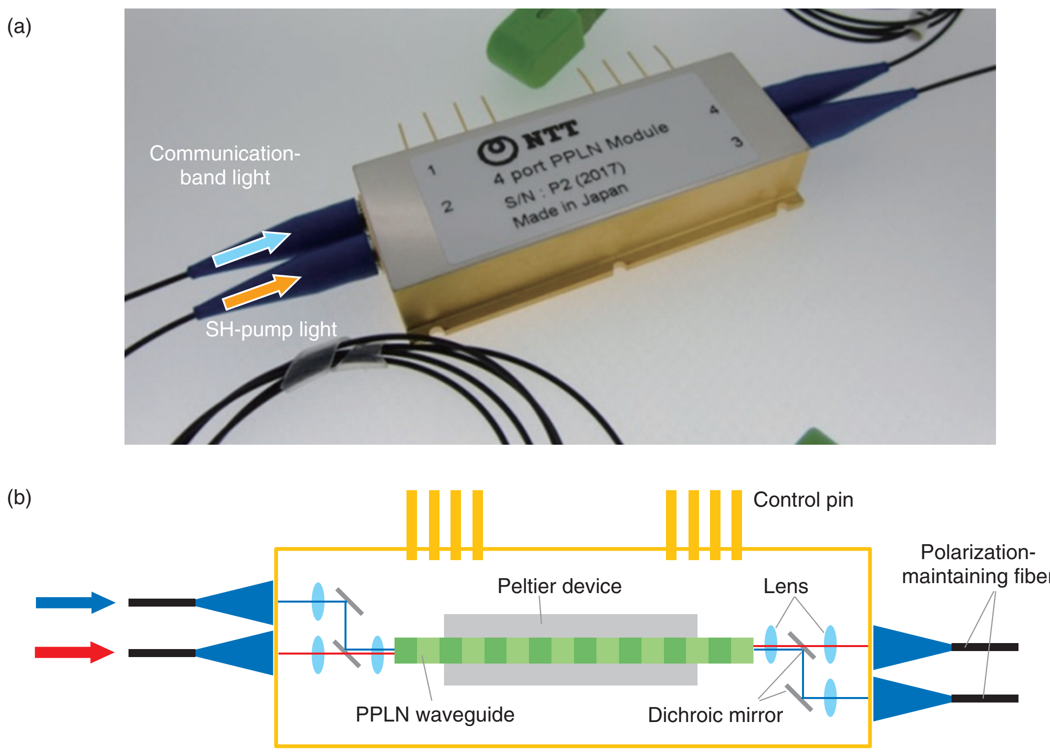

Fig. 2. (a) Overview of fabricated PPLN-waveguide-based OPA module, which has four pigtailed optical fibers as I/O ports. (b) Schematic of inside the fabricated module. The PPLN-waveguide length is 45 mm. The waveguide temperature is controlled with a Peltier device mounted under it.

pump corresponds to the insertion loss of 2.0 dB. The input spectrum is amplified with the external gain of 32.3 dB when the injected pump power is 1.35 W. **Figure 3(c)** shows the external gains as a function of the input pump power. The PSA gains are exponentially increased due to the increase in the SH-pump power without any degradation due to photorefractive damage. This means that our module showed high durability against the high-power SH pump to operate with a continuous-wave-pump power of over 1 W.

3.2 Optical quadrature squeezing

A squeezed vacuum state of light is a non-classical state, which has a reduced quantum uncertainty in a specific amplitude quadrature compared with that of the vacuum state [19], as shown in **Fig. 4(a)**. This state should be used as an essential resource for various optical quantum technologies. For example, by using squeezed light, optical beamsplitters, and optical delay line interferometers, we can generate multipartite optical entanglement, namely an optical cluster state, that is multiplexed in the time domain [20]. This is one of the most important calculation resources in measurement-based QC, which has potential for high-speed large-scale fault-tolerant operation [21]. For achieving this large-scale universal and fault-tolerant QC, a highly squeezed state of light is desired because it results in high-fidelity CV quantum gates and high-dimensional quantum entanglement. For high-speed QC, broadband squeezed light is desired because the maximum clock rate of QC is limited by the bandwidth of the quantum resource. A squeezed light is generated by pumping an OPA and is typically characterized by measuring the variances of the electrical field with balanced homodyne detection [22]. **Figure 4(b)** shows the measured noise intensities of squeezed light and the vacuum state of light. In accordance with the scanning of the relative phase between the local oscillator and squeezed light, squeezed and anti-squeezed noise are shown one after the other. However, the noise of the vacuum state, namely shot noise, shows a constant value despite the phase scanning. This is because, in the coherent vacuum state, quantum noise equally exists in two optical quadratures. The squeezed level shows over-6-dB noise reduction compared with the vacuum noise.

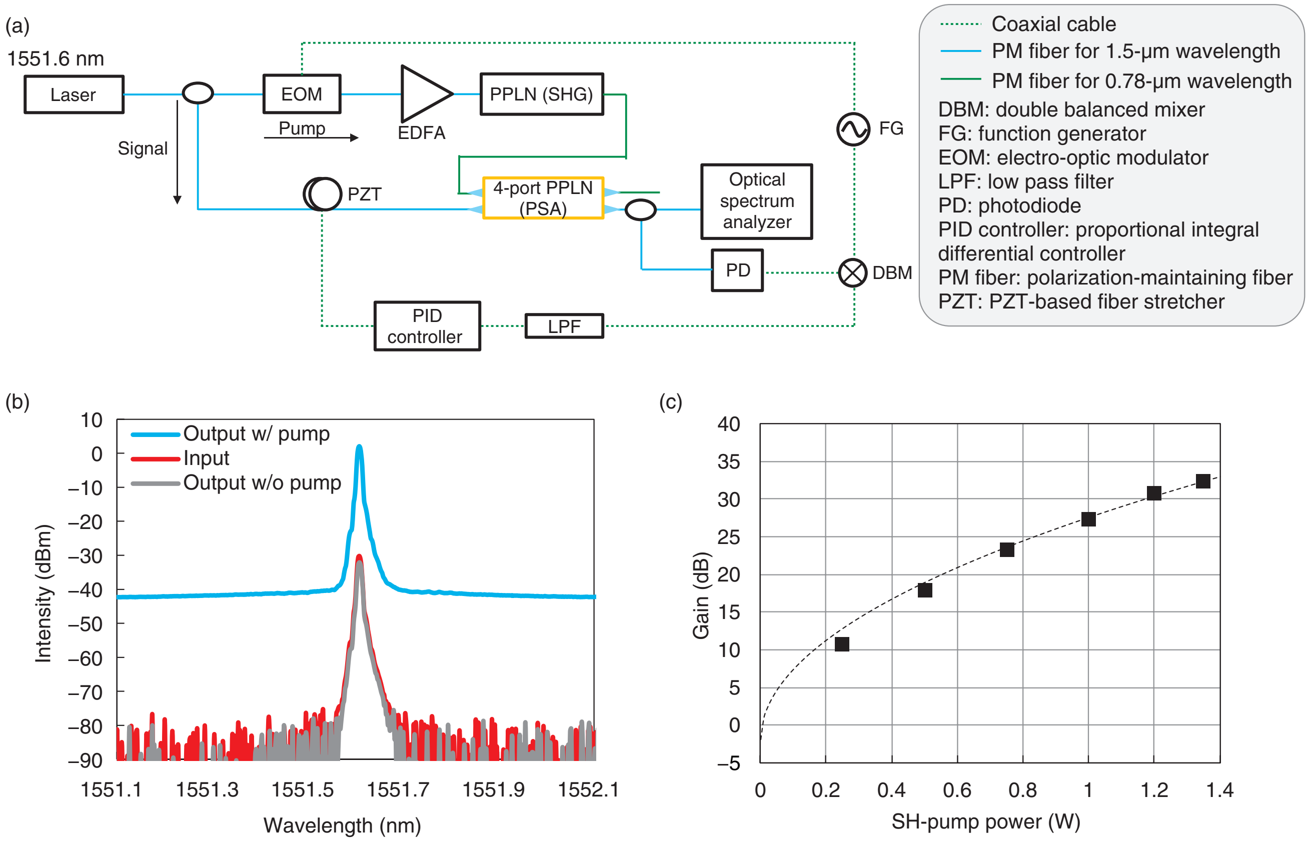

Fig. 3. (a) Experimental setup for degenerate PSA. (b) Measured spectrum of amplified light [18]. (c) External gain of PSA as a function of the input pump power [18].

This value exceeds 4.5 dB, which is required for the generation of a two-dimensional optical cluster state. The squeezed light also shows 2.5-THz spectral bandwidth, as shown in **Fig. 4(c)**. This broad bandwidth indicates the possibility of THz-order clock-rate QC. The squeezed light will lead to the development of a high-speed on-chip quantum processor using time-domain multiplexing with a centimeter-order optical delay line.

4. Conclusion

We introduced our broadband high-gain OPA module assembled with a ZnO-doped PPLN waveguide. The PPLN waveguide was fabricated by direct bonding and photolithography. Thanks to the fine process, we can obtain a uniform waveguide and SHG efficiency of 1200%/W. Its directly bonded core enabled us to use over-1-W of pump light to achieve a high-gain optical parametric process without pump-induced degradation. The waveguide is assembled into a pump-combiner-integrated OPA module with four optical-fiber I/O ports. By using this OPA module, we demonstrated over-30-dB PSA even with a continuous-wave pump. This value is sufficient for the amplification gain in long-haul optical communication. We also used the waveguide as an optical quadrature squeezer and obtained over-6-dB squeezed light. This value is sufficient for generating a two-dimensional optical cluster state, which enables multi-qubit computation. The squeezed light also has a 2.5-THz spectral bandwidth. This broad bandwidth indicates the possibility of THz-order clock-rate QC, shortens the length of a flying qumode into sub-millimeter, and enables the implementation of optical delay line interferometers into an integrated optical chip. This broadband high-gain OPA module will break the limits in optical communication and computation.

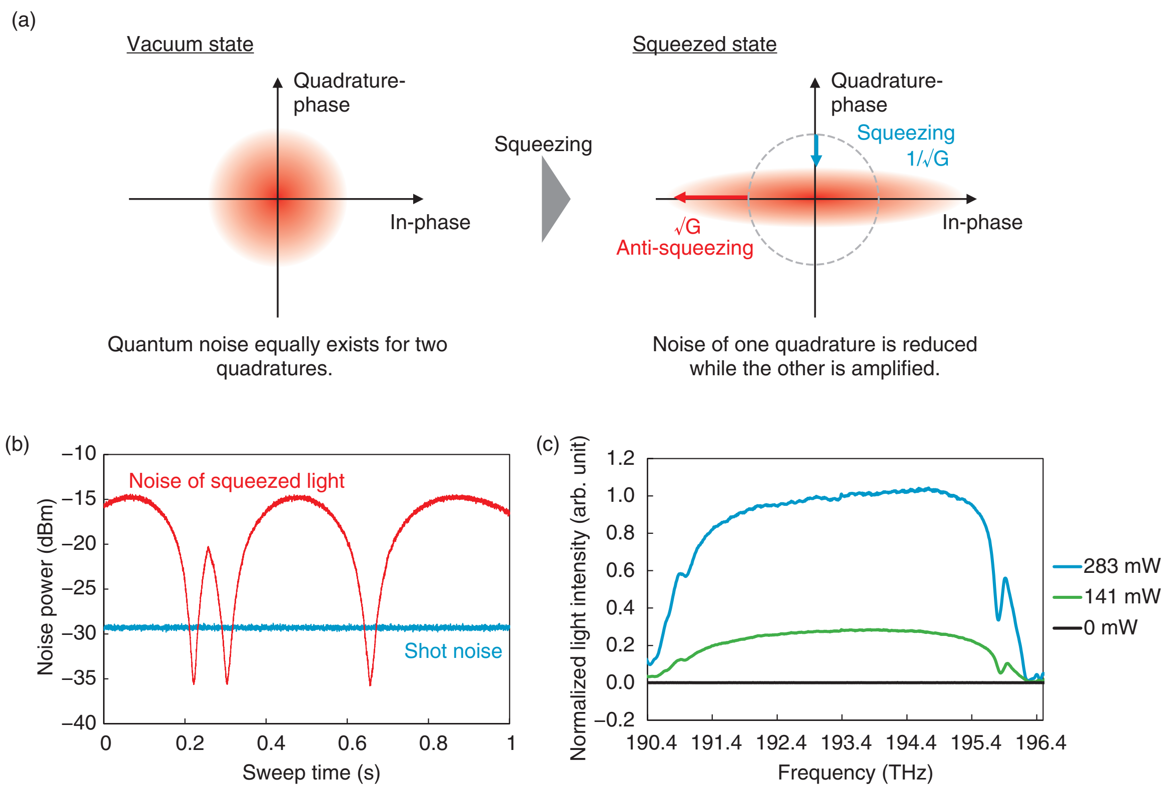

Fig. 4. (a) Schematics of vacuum noise and squeezed vacuum noise. (b) Noise intensities of a squeezed state of light and vacuum state measured using a spectrum analyzer with balanced homodyne detection [8]. (c) Optical spectra for squeezed light with various pump power [8].

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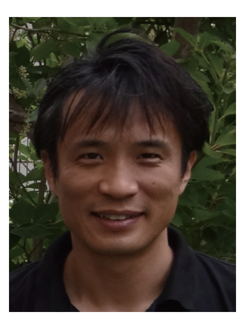

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Development of Beyond 100G Optical Cross Connect (B100G-OXC) System

Takeshi Kawasaki, Takeshi Seki, Ken Ito, Yasutaka Sugano, Hiroki Date, Hiroki Kawahara, Daisaku Shimazaki, and Hideki Maeda

Abstract

The rapid increase in Internet traffic is expected due to the spread of network services such as 5G (fifth-generation mobile communication), Internet of Things, and cloud. To economically expand the capacity in the core network of the NTT Group, NTT Network Innovation Center developed the Beyond 100G Optical Cross Connect (B100G-OXC) system, which enables beyond 100-Gbit/s per wavelength optical transmission. This article gives an overview of this system.

Keywords: optical transport, DWDM, multi-level modulation

1. Capacity enhancement in the core network

NTT has expanded the capacity of optical transport systems to build both an efficient and economical optical transport network to address the constant increase in communication traffic in the core network, as shown in **Fig. 1**. In the current optical transport system, which has been deployed, we achieved a maximum of 8-Tbit/s capacity by multiplexing 80 channels of an optical signal with 100-Gbit/s per wavelength through the use of digital coherent technology*1. To further enhance system capacity, we developed the Beyond 100G Optical Cross Connect (B100G-OXC) system as a higher-capacity optical transport system by increasing the signal speed.

2. Technical features of B100G-OXC system

The system configuration of the B100G-OXC system is shown in **Fig. 2**. It is an optical transport system based on dense wavelength-division multiplexing (DWDM) and digital coherent technology (DWDM is the technology to transmit multiple wavelengths in a single fiber).

The B100G-OXC system is also called ROADM (reconfigurable optical add/drop multiplexer) since it can configure optical nodes as "add," "drop," or "through" for any arbitrary optical path in a maximum of eight directions. The main technical features of the B100G-OXC system are as follows:

- 400-Gbit/s multi-carrier optical transmission
- Long-distance transmission of 100-Gbit/s optical signals
- Adaptation to low-loss optical fiber for longer-distance transmission
- Accommodation of the 400 Gigabit Ethernet (GbE) client interface

2.1 400-Gbit/s multi-carrier optical transmission

There are several ways to enhance capacity. One is to increase the number of wavelengths for multiplexing, and the other is to increase the signal speed of the optical channel per wavelength. In addition, there are mainly three ways to increase the signal speed of an optical channel [1]:

1. Increase the rate of modulation

*1 Digital coherent technology: The technology that improves both sensitivity and spectral efficiency by using a coherent detection scheme with which an optical signal is treated as a wave. It also provides high-speed signal processing that can compensate for the distortion of waveforms when transmitting through optical fiber.

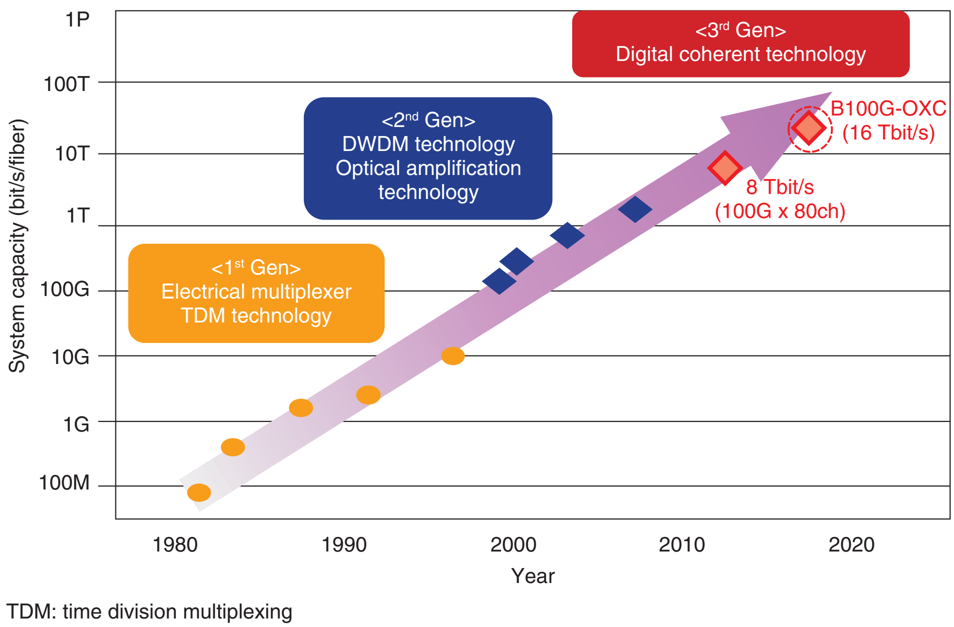


Fig. 1. Development history of optical transport systems at NTT.

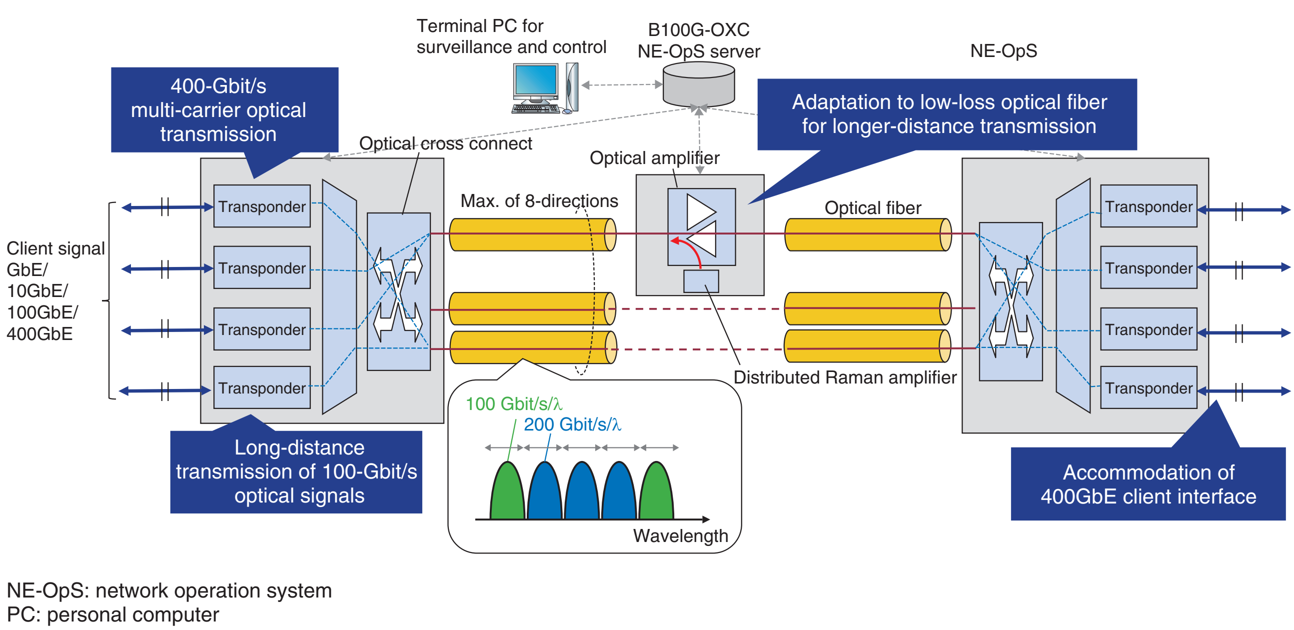
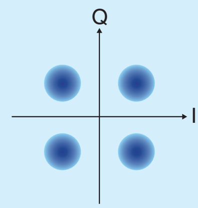
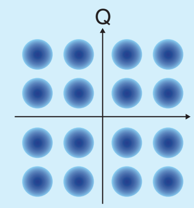
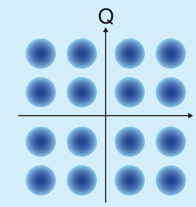
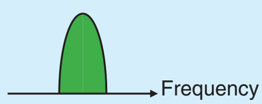
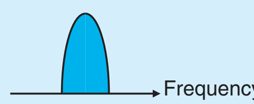
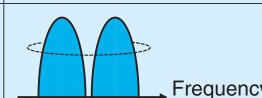


Fig. 2. Overview of B100G-OXC system.

2. Increase the degree of the multiple modulation/ demodulation scheme
3. Enable multi-carrier optical transmission

With the B100G-OXC system, we increased the transmission rate per wavelength from 100 to 200 Gbit/s by changing the modulation scheme from dual polarization-quadrature phase shift keying (DP-QPSK), which is used in the conventional 100-Gbit/s-based optical system, to DP-16 quadrature amplitude modulation (QAM), maintaining the baud rate at 32

Table 1. Modulation scheme for the B100G-OXC system.

Data rate	100G	200G	400G
Modulation format	DP-QPSK	DP-16QAM	DP-16QAM (Multi-carrier optical transmission)
Constellation map			
Baud rate at single wavelength	32 Gbaud	32 Gbaud	32 Gbaud
Number of symbols (bit/symbol)	2	4	4
Number of optical carriers	1	1	2
Image of optical spectrum			
Transmission distance	Approx. 1000 km	Approx. 500 km	Approx. 500 km

Gbaud, which is that of the conventional system (**Table 1**). We also achieved maximum 500-km transmission at a 400-Gbit/s data rate with no regeneration by using 2 x 200-Gbit/s optical signals.

2.2 Long-distance transmission of 100-Gbit/s optical signals

In the core network, long-distance transmission is as critical as capacity enhancement in terms of building a network more economically. There is generally a trade-off between increasing the transmission rate (higher-capacity transmission) and transmission distance. Although we can achieve a higher rate of transmission by increasing the degree of the multi-level modulation scheme (for example, from DP-QPSK to DP-16QAM), transmission distance can be decreased. In the B100G-OXC system, we adopted DP-QPSK, which is the same modulation scheme as in the conventional 100-Gbit/s-based optical transport system to achieve 1000-km transmission without regeneration, which is almost double that of the conventional system. The B100G-OXC system also enables us to change the mode of the modulation scheme as well as transmission rate through software, so it is possible for us to select the optimum type of modulation more flexibly on the basis of the target distance of the route.

2.3 Adaptation to low-loss optical fiber for longer-distance transmission

We attribute 400-Gbit/s multi-carrier 500-km transmission to the fact that we adapted the B100G-OXC system to the new cutoff shifted fiber (CSF, complied with ITU-T*2 G.654.E) as well as single mode fiber (SMF, compliant with ITU-T G.652) or dispersion shifted fiber (DSF, compliant with ITU-T G.653). CSF offers a lower loss profile than that of the other types of fibers for longer transmission. It also secures a larger effective area*3 by expanding the diameter of the optical fiber core, which allows us to suppress the degradation of optical signals due to nonlinear effects that can occur during the transmission through the fiber. As a result, we can achieve longer transmission distance. The general optical characteristics of SMF, DSF, and CSF are listed in **Table 2** [2].

We also achieved high-power distributed Raman amplification (DRA) in the B100G-OXC system as a key technology for longer-distance transmission, as shown in **Fig. 3**. DRA amplifies optical signals by using optical fiber as an amplified medium, so its gain

*2 ITU-T: The Telecommunication Standardization Sector of International Telecommunication Union

*3 Effective area: Indicator of how the optical power is distributed around the core in the fiber. The larger its indicator, the weaker the nonlinear effect that occurs in the fiber during transmission since the optical-power density becomes lower.

Table 2. Types of optical fibers and their characteristics.

Optical fiber type	SMF	DSF	CSF
ITU-T standard	G.652	G.653	G.654.E
Cutoff wavelength*1 (Max) (nm)*2	< 1260	< 1270	< 1530
Loss coefficient (Max) (dB/km)*2, 3	< 0.35	< 0.35	< 0.23
Chromatic dispersion (ps/nm/km)*2, 3	16–23	2–8	17–23
Effective area (μm²)*2, 3	–80	–50	110–125

*1 Cutoff wavelength is the minimum wavelength that the light in the fiber can transmit as a single mode. If the wavelength of the light is shorter than the cutoff wavelength, it can transmit as multi-mode.
*2 Above figures are extracted from ITU-T Recommendation, document [2], and manufactures' catalog.
*3 Value at 1550-nm wavelength.

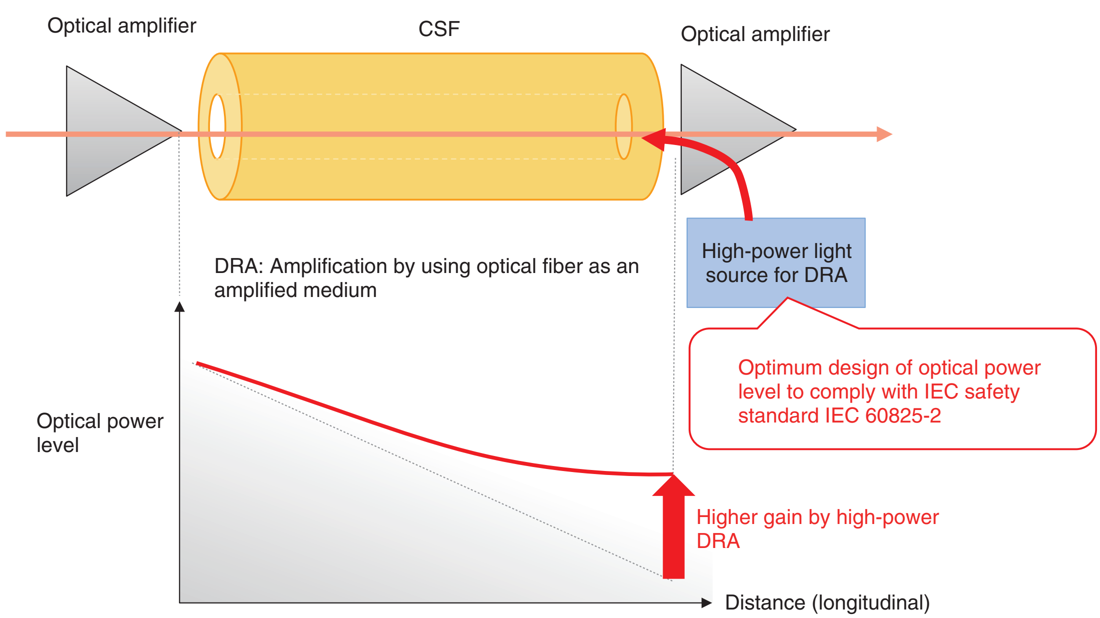


Fig. 3. High-power DRA.

characteristic depends on the fiber characteristics. Initially lower gain of DRA was assumed for CSF since it has a relatively larger core than those of other fibers. We then achieved high-power DRA to obtain sufficient gain even under CSF. Safety design is also important for long-term operation because we need to handle a high-power excitation light source, which has around 100 mW of output power. With the B100G-OXC system, we determined the optimum condition for the excitation light source for DRA to achieve maximum transmission performance while maintaining safety by complying with IEC*4 60825-2, which is the international standard on the safety of optical-fiber communication systems.

2.4 Accommodation of 400GbE client interface

In the B100G-OXC system, we achieved the accommodation of the 400GbE*5 client interface in combination with 400-Gbit/s multi-carrier optical transmission. This allows us to connect with new large-scale routers or Layer 2 switches. The 400GbE interface has been standardized and is now widely used mainly in datacenters. **Figure 4** shows a schematic of how 400GbE is transmitted. The incoming

*4 IEC: International Electrotechnical Commission

*5 400GbE: The new specification for the high-speed Ethernet client interface standardized as international standard (Institute of Electrical and Electronics Engineers (IEEE) 802.3bs). The data-transport speed is 400 Gbit/s, which is quadruple that of 100GbE (compliant with IEEE 802.3ba).

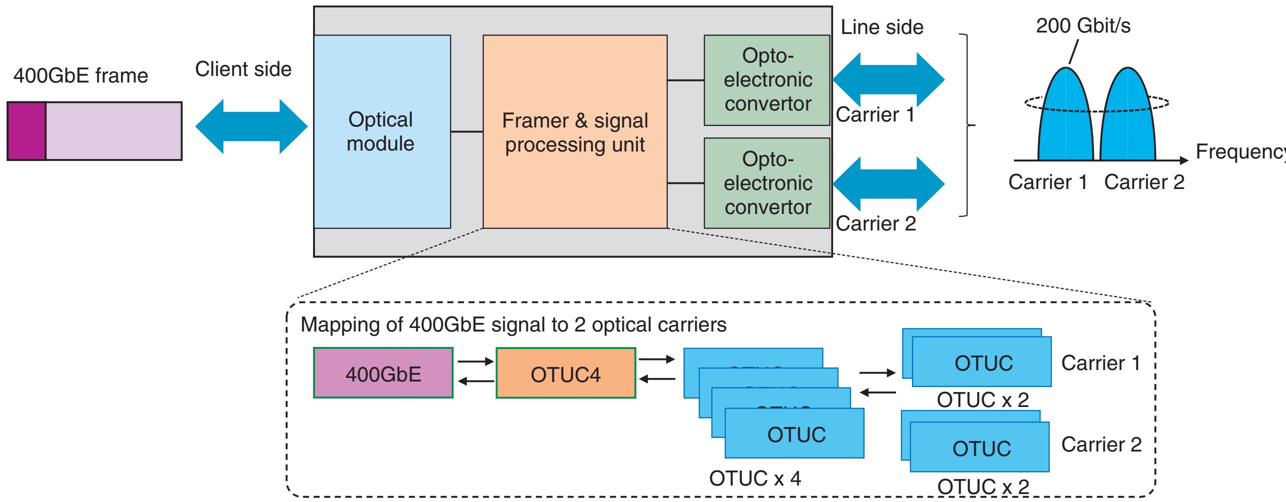


Fig. 4. Multi-carrier transmission of 400GbE signals.

400GbE signal is mapped onto 4 x OTUC*6 frames in the framer and signal processing unit inside the transponder (transceiver). Each OTUC frame has a 100-Gbit/s bit rate. Two OTUC frames are modulated in a single optical carrier, which has a 200-Gbit/s rate, then 400GbE data are transmitted using 2 x 200-Gbit/s optical carriers [3].

3. Conclusion and future perspectives

We achieved both high-capacity and longer-distance transmission to build a core transport network more economically. NTT is now researching and developing the All-Photonics Network [4], which is one of the innovative optical transport platforms to implement IOWN (Innovative Optical and Wireless Network). We are aiming to further increase the speed of optical signals per wavelength such as 400 Gbit/s or 1 Tbit/s. We will also target furthering high-capacity transmission by using multi-band transmission [5] to expand the transmission-wavelength range or using space-division multiplexing technology such as multi-core fibers [6]. We will continue to work on further improving optical transport systems and expanding transmission capacity.

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*6 OTUC: A 100-Gbit/s element (slice) of an optical channel transport unit-Cn (OTUCn). The index Cn denotes n × 100G, where n is a positive integer and C means 100G.

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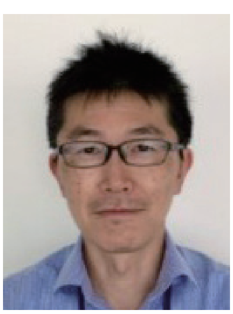

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Standardization Activities in the Asia-Pacific Region—New Management Structure Approved at the 33rd Asia-Pacific Telecommunity Standardization Program (ASTAP) Meeting

Noriyuki Araki

Abstract

The 33rd Asia-Pacific Telecommunity Standardization Program (ASTAP) meeting was held in June 2021 in an online format. ASTAP aims at strengthening standardization activities in the information and communication technology field in the Asia-Pacific Telecommunity and contributing to the establishment of international standards as a region. This article describes the main results of ASTAP-33 and the industry workshop held during the meeting.

Keywords: APT, ASTAP, standardization

1. Introduction

The Asia-Pacific Telecommunity (APT) is an international organization promoting information and communication technology (ICT) sector development in the Asia-Pacific region. It was established in 1979 and has 38 member countries [1].

The APT Standardization Program (ASTAP) was established in 1998 to promote standardization activities in APT [2]. The main objectives are to (1) contribute to international standardization by building a cooperative framework for standardization within the APT region, (2) foster standardization activists within the APT region and support skill development in the ICT field by members within the region, especially members of developing countries, and (3) make APT common proposals to international standardization organizations, such as the International Telecommunication Union (ITU), as regional standardization organizations. It is important to use ASTAP as a platform for building partnerships in the APT region and contributing to developing countries. It is also considered to be an important issue as a strategy for international collaboration on standardization in Japan. The 33rd ASTAP meeting (ASTAP-33) was held from June 7 to 11, 2021, and about 190 people from 17 member countries participated. At the meeting, an industry workshop on the fifth-generation mobile communication system (5G) and emergency communications was held, and 142 people participated.

2. New management structure of ASTAP

The terms of office of the chair and vice-chair of ASTAP are set to allow a maximum of two terms for each term of three years. ASTAP-32 was held in November 2020 at the timing of the expiration of the

Table 1. Organization and management structure of ASTAP.

Group	Chair	Vice-chair
ASTAP	Dr. Hyoung Jun Kim (Korea)	Dr. Hideyuki Iwata (TTC, Japan) Mr. Xiaoyu You (China)
WG Policy and Strategic Co-ordination (WG PSC)	Mrs. Nguyen Thi Khanh Thuan (Vietnam)	Mr. Kaoru Kenyoshi (NICT, Japan) Mr. Wu Tong (China)
Expert Group Bridging the Standardization Gap (EG BSG)	Mrs. Nguyen Thi Khanh Thuan (Vietnam)	Mr. Ki-Hun Kim (Korea) Dr. Hideyuki Iwata (TTC, Japan)
Expert Group Green ICT and EMF Exposure (EG GICT&EMF)	Dr. Sam Young Chung (Korea)	Mr. Min Prasad Aryal (Nepal) Mr. Nur Akbar Said (Indonesia) Mr. Uttachai Mannontri (Thailand)
Expert Group ITU-T Issues (EG ITU-T)	Mr. Kaoru Kenyoshi (NICT, Japan)	Mr. Nguyen Van Khoa (Vietnam)
Expert Group Policies, Regulatory and Strategies (EG PRS)	Ms. Nadia Hazwani Yaakob (Malaysia)	–
WG Network and System (WG NS)	Dr. Joon-Won Leen (Korea)	Dr. Hiroyo Ogawa (NICT, Japan)
Expert Group Future Network and Next Generation Networks (EG FN&NGN)	Dr. Joon-Won Lee (Korea)	Mr. Kazunori Tanikawa (NICT, Japan)
Expert Group Seamless Access Communication Systems (EG SACS)	Dr. Hiroyo Ogawa (NICT, Japan)	–
Expert Group Disaster Risk Management and Relief System (EG DRMRS)	Mr. Noriyuki Araki (NTT, Japan)	–
WG Service and Application (WG SA)	Ms. Miho Naganuma (NEC, Japan)	Dr. Jee-In Kim (Korea)
Expert Group Internet of Things Application/Services (EG IOT)	Dr. Toru Yamada (NEC, Japan)	Dr. Seung-yun Lee (Korea) Ms. Haihua Li (China)
Expert Group Security (EG IS)	Ms. Miho Naganuma (NEC, Japan)	Dr. Heuisu Ryu (Korea)
Expert Group Multimedia Application (EG MA)	Dr. Hideki Yamamoto (OKI, Japan)	Dr. Dong il Seo (Korea)
Expert Group Accessibility and Usability (EG AU)	Dr. Jee-In Kim (Korea)	Ms. Wantanee Phantachat (Thailand)

terms of office of the chair and vice-chairs of ASTAP. A new chair and vice-chairs were elected, and the work plans were confirmed at the meeting of the Working Group (WG), including the review of working methods in response to the worldwide spread of COVID-19 and the confirmation of the continuation of the organizational structure. Due to the COVID-19 pandemic, ASTAP-32 was held online for only 2 days, so the Expert Group (EG) meeting by technology field was not held, and substantive discussion on the new management structure started with ASTAP-33.

Table 1 shows the organization structure of ASTAP and the new management structure. At ASTAP-32, Dr. Hyoung Jun Kim (Electronics and Telecommunications Research Institute (ETRI), Korea) was appointed as the new chair, who served as vice-chair until the previous meeting, and Dr. Hideyuki Iwata (The Telecommunication Technology Committee (TTC), Japan) and Dr. Xiaoyu You (The China Academy of Information and Communications Technology (CAICT), China) were appointed as vice-chairs. The continuation of the chairs and vice-chairs of the WG and EG was also confirmed and approved, respectively. At ASTAP-33, Mr. Kaoru Kenyoshi (National Institute of Information and Communications Technology (NICT), Japan) was newly appointed as vice-chair of WG PSC (Policy and Strategic Co-ordination), and Mr. Noriyuki Araki (NTT, Japan), author of this article, was appointed as chair of EG DRMRS (Disaster Risk Management and Relief System).

3. Industry workshop

At ASTAP-33, the ASTAP vice-chair organized an industry workshop on topics of interest to APT member countries. Based on the results of the questionnaire to APT member countries, ten presentations were made in each session on two topics of 5G and emergency communications from Japan, China, Korea, Thailand, etc. The commercial introduction of 5G has started in APT countries including Japan, China, and Korea, and it is a topic of interest for countries that are about to start commercialization. Natural disasters, such as typhoons and torrential rains, have occurred frequently not only in Japan but also throughout the APT region, and the social impact

Table 2. Industry workshop program.

Industry workshop on "5G & Emergency communications"	
Session 1: 5G	**Introductory Remarks** by Hideyuki Iwata, TTC, Japan Industry Workshop Corresponding Member **Part I: 5G** Chair: Dr. Seungyun Lee, ETRI, Republic of Korea 1. 5G Technology, Standard and Industry Development by Yongming Liang, Huawei, P.R. China 2. Application of 5G in the Industrial Internet by Zongxiang Li, CAICT, P.R. China 3. Pioneering 5G Broadcast: Building on Multiple Generations of Cellular Broadcast Technology Leadership by Michael Seongill Park, Qualcomm, Rep. of Korea 4. 5G Network Deployment and Service Development by Xiaoyin Zhao, China Telecom, P.R. China 5. Moving Towards Autonomous Networks Together by Wong Leon, Rakuten Mobile, Inc, Japan
Session 2: Emergency communications	**Part II: Emergency communications** Chair: Mr. Noriyuki Araki, NTT, Japan 1. The Role of Emergency Messages in Covid-19 and the Future Direction in 5G by Seung-hee Oh, ETRI, Rep. of Korea 2. An intelligent Big Data Analysis System for Fire Management Using NB-IoT by Lun Li, CAICT, P.R. China 3. Enhancing Emergency Medical Service (EMS) Operation with Digital Technology: Case Study in Thailand by Teerawat Issariyakul, National Telecom Public Company Limited, Thailand 4. Himawari Real-Time: A Web Application and Sharing System of Large-scale Data and High-resolution Images of Himawari Meteorological Satellite across Asia-Pacific Region for Disaster Mitigations by Ken Takeshi Murata, NICT, Japan 5. Resilient Information and Communication Technologies by Toshiaki Kuri, NICT, Japan
Conclusion	**Conclusion of Industry Workshop** Mr. Xiaoyu You, CAICT, P.R. China

NB-IoT: narrow band Internet of Things

of COVID-19 continues to grow. **Table 2** shows the program of the industry workshop.

Some of the presentations at the industry workshop were discussed in technically relevant EGs such as EG FN&NGN (Future Network and Next Generation Networks) and EG DRMRS, and new technical documents (APT Report) on related technologies were proposed as future work items.

4. Key output documents

At ASTAP-33, input documents were discussed at WG and EG meetings, and ten APT Reports and two Liaison statements to other standards bodies were approved as output documents at the plenary meeting. **Table 3** lists the main output documents (APT Reports and Liaisons) that have been approved.

Five APT Reports have been proposed by Japan and have led the development of documents, accounting for more than half the documents approved at this meeting. The following two documents were proposed by TTC where NTT serves as an expert committee member:

- "Handbook to Introduce ICT Solutions for the Community in Rural Areas" (OUT-10)
- "APT Report on Traffic Accidental Record and its Analysis Method's Guidelines in Asia" (OUT-18)

The former is a compilation of examples of ICT solution demonstration experiments in rural areas conducted in cooperation with partners in Asian countries and using the APT Project, etc. In this case, we added and revised a medical solution for tuberculosis in Myanmar. The latter indicates the importance of devising countermeasures by recording and analyzing accidents for the purpose of reducing traffic accidents. In this report, we investigated the situation of accident-record collection and analysis in Asian countries and summarized the record items and analysis methods as guidelines.

5. Future plans

Due to the fact that ITU events, such as World Telecommunication Standardization Assembly and World Telecommunication Development Conference, have been postponed until 2022, and that there is a possibility that the schedule will be changed again depending on the COVID-19 situation, we determined that it would be difficult to decide the date and venue of ASTAP-34, and the schedule of ASTAP-34 has not yet been decided. It is hoped that the ASTAP meetings

Table 3. Approved main output documents (APT Reports and Liaisons).

Title	Document number
Handbook to Introduce ICT Solutions for the Community in Rural Areas	ASTAP-33/OUT-10
Guideline on referencing int'l standards in developing national standards	ASTAP-33/OUT-11
Report of the Compliance Label of Communication Devices Implemented by APT Member Countries	ASTAP-33/OUT-12
APT Report on VoLTE Interoperability	ASTAP-33/OUT-13
Liaison Statement to ITU-D SG2 Q5/2	ASTAP-33/OUT-14
APT Report on Requirement of Transmitter in Coherent Radio over Fiber System	ASTAP-33/OUT-15
Revised APT Report on Radio-over-Fiber Relay Link for Indoor Communication Systems	ASTAP-33/OUT-16
APT Report on Traffic Accident Record and its Analysis Method's Guidelines in Asia	ASTAP-33/OUT-18
Security Guidelines for Open Source Software	ASTAP-33/OUT-19
APT Report on interactive multimedia service on IPTV/CATV in the Asia-Pacific Region	ASTAP-33/OUT-20
Liaison Statement to ITU-T SG16, SG9 and ITU-D SG1	ASTAP-33/OUT-21
Report of Surveying Mobile Accessibility in the AP region	ASTAP-33/OUT-24

CATV: cable television
IPTV: Internet protocol television
ITU-D: ITU Telecommunication Development Sector
ITU-T: ITU Telecommunication Standardization Sector
SG: Study Group
VoLTE: voice over Long-Term Evolution

will be held in person to promote standardization activities in the Asia-Pacific region and use ASTAP more effectively as a forum for deepening cooperation with APT member countries.

References

[1] APT, https://www.apt.int/
[2] ASTAP, https://www.apt.int/APTASTAP

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He received a B.E. and M.E. in electrical and electronic engineering from Sophia University, Tokyo, in 1993 and 1995. He joined NTT Access Network Service Systems Laboratories in 1995, where he researched and developed operation and maintenance systems for optical fiber cable networks. He has been contributing to standardization efforts in ITU-T Study Group (SG)6 since 2006. He was the rapporteur of Question 6 of ITU-T SG6 from 2006 to 2008 and the rapporteur of Question 17 of ITU-T SG15 from 2008 to 2012. He also served as the chairman of the ITU-T Focus Group on Disaster Relief Systems and Network Resilience and Recovery. He has been the vice-chairman of ITU-T SG15 since 2013. He also contributes to the activities of International Electrotechnical Commission (IEC) Technical Committee 86 (fiber optic systems). He received the ITU-AJ award from the ITU Association of Japan in 2017. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Event Report: NTT Communication Science Laboratories Open House 2021

Kenichi Arai, Go Kato, Kenta Niwa, Hsin-I Liao, Daiki Nasu, and Tomoki Ookuni

Abstract

NTT Communication Science Laboratories Open House 2021 was held online, the content of which was published on the Open House 2021 web page at noon on June 3rd, 2021. The videos of 5 talks and 29 exhibits presented our latest research efforts in information and human sciences and were played more than 6000 times within the first month after the event.

Keywords: information science, human science, artificial intelligence

1. Overview

NTT Communication Science Laboratories (NTT CS Labs) celebrated its 30th anniversary this year. NTT CS Labs has aimed to establish cutting-edge technologies that enable heart-to-heart communication between people and people and between people and computers. We are thus working on a fundamental theory that approaches the essence of humans and information science, as well as on innovative technologies that will transform society. NTT CS Labs' Open House is held annually to introduce the results of our basic research and innovative leading-edge research with many hands-on intuitive exhibits to those who are engaged in research, development, business, and education.

Open House 2021 was held virtually due to measures to prevent the further spread of COVID-19. The latest research results were published with recorded lecture videos on the Open House 2021 web page at noon on June 3rd [1]. The content attracted many views within a month not only from NTT Group employees but also from businesses, universities, and research institutes. The event content is still available.

This article summarizes the event's research talks and exhibits.

2. Keynote speech

Dr. Takeshi Yamada, vice president and head of NTT CS Labs, presented a speech entitled "No matter how far apart, my heart will always be with you – Exploring the essence of communication that will create a spiritually rich society –," in which he looked back upon the history of NTT and establishment of NTT CS Labs then introduced present and future cutting-edge basic research and technologies (**Photo 1**).

For the past 30 years since its founding on July 4, 1991, NTT CS Labs has been developing innovative technologies such as media processing and machine learning that approach and even surpass human capabilities and seeking out fundamental principles in fields such as cognitive neuroscience and brain science that afford a deeper understanding of humans. After introducing the latest research results of NTT CS Labs from the three perspectives of "how to communicate accurately and efficiently" (information),

Photo 1. Keynote speech (Dr. Takeshi Yamada). "No matter how far apart, my heart will always be with you – Exploring the essence of communication that will create a spiritually rich society –."

"how to communicate by what means" (media), and "what is being indicated" (meaning), Dr. Yamada declared that NTT CS Labs will boldly and persistently tackle new challenges for the next 30 years to enable communication that can be conveyed to the heart through research that only NTT CS Labs can conduct.

3. Research talks

The following three research talks highlighted recent significant research results and high-profile research themes. Each talk introduced some of the latest research results and provided background and an overview of the research. After each talk, we received many questions from participants in real time for the question-and-answer (Q&A) session, confirming that the viewers had a high interest in our research.

(1) "The coming ages when AI becomes our conversation partners – Cutting edge of conversational systems with large-scale neural network models –," Dr. Hiroaki Sugiyama, Innovative Communication Laboratory

Dr. Hiroaki Sugiyama explained chatting dialogue systems for satisfying people's desire for dialogue through natural chatting with people. NTT CS Labs has been researching various dialogue systems for a long time, including research on giving systems personalities and improving the smoothness of dialogue by organically linking multiple dialogue robots. With the recent rapid development in deep learning, English social dialogue systems using large-scale deep learning have been proposed. He introduced details of NTT CS Labs' latest deep learning-based Japanese social dialogue system and its achievements and remaining issues (**Photo 2**).

(2) "Looking more, acting better – New concept of eye-hand coordination for skilled action –," Dr. Naotoshi Abekawa, Human and Information Science Laboratory

Dr. Naotoshi Abekawa explained skillful motor control using the mechanism of coordinated eye and arm motion as an example. One key issue in developing user-friendly information and communication technology is to understand "behavior" or "action," that is, to understand the essence of "motion." Although we seem to control motions easily, motor controls are achieved by sophisticated brain mechanisms, including the control of eye movements to obtain target information and the generation of limb movements. In his talk, he focused on the question, "Why is the eye important for skilled motor actions?", introduced explanations from the literature, and proposed an interpretation based on his findings (**Photo 3**).

(3) "Developing AI that pays attention to who you want to listen to – Deep learning based selective hearing with SpeakerBeam –," Dr. Marc Delcroix, Media Information Laboratory

Dr. Marc Delcroix discussed approaches to achieve computational selective hearing. Selective hearing refers to the ability to focus on listening to a desired speaker, even in a noisy environment such as a cocktail party. He first introduced SpeakerBeam, which is

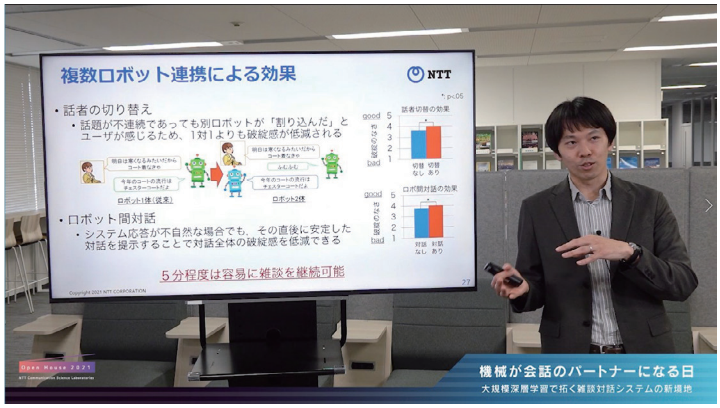

Photo 2. Research talk (Dr. Hiroaki Sugiyama). "The coming ages when AI becomes our conversation partners – Cutting edge of conversational systems with large-scale neural network models –."

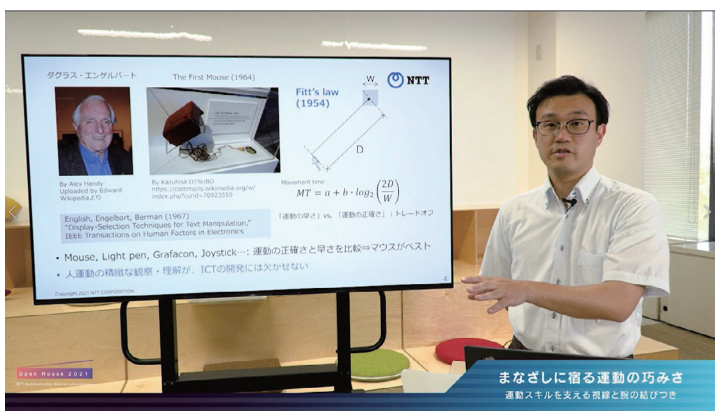

Photo 3. Research talk (Dr. Naotoshi Abekawa). "Looking more, acting better – New concept of eye-hand coordination for skilled action –."

a deep-learning-based method he and his co-researchers proposed to extract speech of a desired target speaker in a mixture of several speakers by using a few seconds of pre-recorded audio data of the target speaker. He then presented recent research on (1) extension to multi-modal processing, where he and his co-researchers use video of the lip movement of the target speaker in addition to audio pre-recording, (2) integration with automatic speech recognition, and (3) the generalization to the extraction of arbitrary sounds (**Photo 4**).

4. Research exhibition

The Open House featured 29 exhibits displaying NTT CS Labs' latest research results. We categorized them into four areas: *Science of Machine Learning*, *Science of Communication and Computation*, *Science of Media Information*, and *Science of Humans*. Each exhibit prepared videos explaining the latest results and were published on the event web page (**Photo 5**). Several provided online demonstrations or demo videos to make them closer to direct demonstrations. We also introduced a Q&A system in which page visitors can freely post questions and comments and CS Labs' researcher can answer them. There were more than 130 public questions, and some expressed the enthusiasm of the visitors, such as long comments and professional questions.

The following list, taken from the Open House website, summarizes the research exhibits in each category.

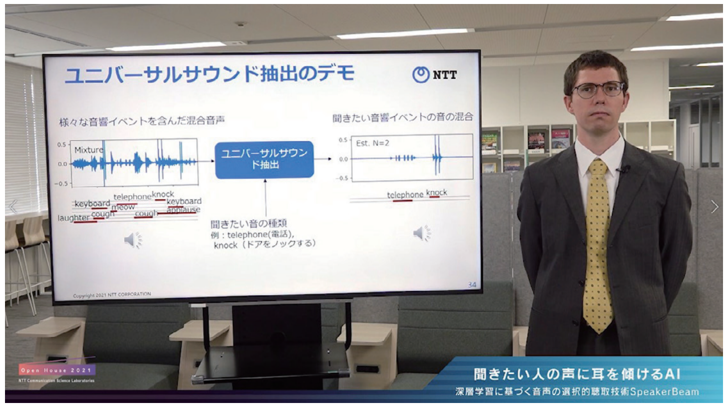

Photo 4. Research talk (Dr. Marc Delcroix). "Developing AI that pays attention to who you want to listen to – Deep learning based selective hearing with SpeakerBeam –."

Photo 5. Exhibition web page.

4.1 Science of Machine Learning

- Learning how to learn from various datasets
  – Meta-learning from tasks with heterogeneous attribute spaces –
- Ask me how to make a fair decision for everyone
  – Learning individually fair classifier based on causality –
- Ask me anything about network structure
  – Indexing graph structure with decision diagrams –
- No labels? Count on me!
  – Self-supervised adaptation for unknown domains/classes –
- Finding groups through connection relationships
  – Relational data model with infinite flexibility –

- Finding features in data fast and accurately
  – Acceleration of feature selection with group regularization –
- Privacy-aware machine learning
  – Distributed learning algorithm and medical application –
- Estimating risk of infection in a city
  – People flow reconstruction based on anonymous sensor data –

4.2 Science of Communication and Computation

- Being greedy makes quantum computers work well
  – Economic rationality makes cloud quantum computing reliable –
- Revealing hidden structures behind sentences
  – Neural rhetorical structure parsing with pseudo-labeled data –
- Two experts, one result
  – Fusing two experts for enhancing their specialties –
- Can a chatbot mediate trust between humans?
  – Bridging doctor-patient rapport through a chatbot –
- Recipes for enjoy-talking conversational systems
  – Development of transformer-based conversational systems –

4.3 Science of Media Information

- Detecting faint sound by light
  – Non-contact sound measurement by precision interferometry –
- Extracting voices out of noise & reverberation
  – Joint signal separation, dereverberation, and noise reduction –
- AI that acquires knowledge just by watching TV
  – Crossmodal learning for concept acquisition of human movements –
- Real-time speech emotion controller using face
  – Emotional voice conversion via facial expression recognition –
- Visualizing touched places for Corona prevention
  – Touched places detection using heat traces by thermography –
- Telestethoscope: Looking into body by listening
  – Biomedical sound analysis utilizing physical characteristics –

4.4 Science of Humans

- Is falling birthrate related to population density?
  – Prediction and demonstration via life history theory –
- Move of magnetic fields, move by magnetic fields
  – Magnetact: A magnetic force-based tactile technology –
- Make hard objects soft, make rough objects smooth
  – Simple method for modulating tactile texture –
- Sense of touch connects our hearts beyond distance
  – Empathetic telecommunication by vibrotactile transmission –
- Why do mothers approach to infants' "crying"?
  – Oxytocin as a neural regulator of maternal implicit approach –
- Auditory attention that appears in the eye
  – Relation between microsaccades and auditory spatial attention –
- Blink pattern of elite car race drivers
  – Professional drivers always blink at the same time over laps –
- Essence of "keeping your eye on the ball"
  – Eye-hand coordination in motor learning –
- How do you define your dominant hand?
  – Quantifying motor-skill performance using a smartphone –
- Brain functions to recognize and hit a fastball
  – Brain mechanisms for quick judgment and motor control –

5. Special lecture

We asked Professor Asa Ito, professor of Tokyo Institute of Technology, to give a special lecture entitled "Bodies in the remote era," have a talk with NTT Fellow Makio Kashino, and review the research exhibitions. In the lecture, based on her research on haptic communication with the visually impaired, she talked about the problems of remote communication and the potential of the body (haptics). As an example of how trust was created through haptic communication, she shared an episode in which she simulated the experience of a visually impaired person being accompanied by a runner, and the rope connected to the runner quickly transmitted subtle information such as emotions and sensations, resulting in a surprising level of trust. She mentioned, however, that remote communication tends to be a one-way transmission of information, making it difficult to build a relationship of trust. She also introduced her research on watching sports with the visually impaired, remotely operated alter-ego robot communication, and memory of sensation and haptic perception. She mentioned that in haptic remote communication, we can sometimes feel the existence of a person because we cannot touch their actual body, and that she has sensed the possibility for a new form of communication.

6. Concluding remarks

Open House 2021 was held as an event to present our latest results on a website. The lecture videos were viewed more than 6000 times in June by various segments of users. Participants provided many valuable opinions that have encouraged us to pursue further research activities through interactive means of communication with CS Labs researchers such as the Q&A system and Q&A session during the lectures. In closing, we would like to offer our sincere thanks to all the participants of this online event.

Reference

[1] Website of NTT Communication Science Laboratories Open House 2021, http://www.kecl.ntt.co.jp/openhouse/2021/index_en.html

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He received a B.S., M.S., and Ph.D. from Waseda University, Tokyo, in 1991, 1993, and 2003. He joined NTT Communication Science Laboratories in 1993 and has been engaged in research on the application of nonlinear dynamics and stochastic systems to signal processing. His current research interests include physical random number generators based on a chaotic laser and the prediction of intelligibility using an automatic speech recognition system. He is a member of the Institute of Electronics, Information and Communication Engineers, the Physical Society of Japan (JPS), and the Acoustical Society of Japan (ASJ).

Go Kato

Senior Research Scientist, Computing Theory Research Group, Media Information Laboratory, NTT Communication Science Laboratories.

He received a doctor of science in physics from The University of Tokyo in 2004. He joined NTT Communication Science Laboratories the same year and has been engaged in the theoretical investigation of quantum information. He is especially interested in mathematical structures emerging in the field of quantum information. He is a member of JPS.

Kenta Niwa

Distinguished Researcher, Learning and Intelligent System Research Group, Innovative Communication Laboratory, NTT Communication Science Laboratories.

He received a B.E., M.E., and Ph.D. in information science from Nagoya University in 2006, 2008, and 2014. Since joining NTT in 2008, he has been engaged in research on microphone array signal processing. From 2017 to 2018, he was a visiting researcher at Victoria University of Wellington, New Zealand and involved with research on distributed machine learning and mathematical optimization. He is especially interested in distributed system optimization, such as model training on edge computing. He also belongs to NTT Computer and Data Science Laboratories. He was awarded the Awaya Prize by ASJ in 2010. He is a member of the Institute of Electrical and Electronics Engineers (IEEE).

Hsin-I Liao

Senior Research Scientist, Human Information Science Laboratory, NTT Communication Science Laboratories.

She received a Ph.D. in psychology from the Department of Psychology, National Taiwan University, in 2009. She joined NTT Communication Science Laboratories in 2012 and has been studying auditory salience, music preference, and preference of visual images. She has also explored the use of pupillary response recording to correlate human cognitive functions such as auditory salience and preference decision. From 2007 to 2008, she was a visiting student at California Institute of Technology, USA, where she studied visual preference using recorded eye movements and visual awareness using transcranial magnetic stimulation. She received a Best Student Poster Prize of the Asia-Pacific Conference on Vision in 2008, a Travel Award of the Association for the Scientific Study of Consciousness in 2011, and a Registration Fee Exemption Award of the International Multisensory Research Forum in 2011. She is a member of the Vision Sciences Society, Association for Research in Otolaryngology, and Japan Neuroscience Society.

Daiki Nasu

Research Scientist, Kashino Diverse Brain Research Laboratory, NTT Communication Science Laboratories.

He received a Ph.D. in medicine from the Graduate School of Medicine, Osaka University, in 2014. He joined NTT Communication Science Laboratories in 2016 and has been engaged in research on human motor control and biomechanics in sports. He has recently been focusing on the relationship between sports performance skill and brain function in athletes. He is a member of the Society for Neuroscience, the Japan Society of Physical Education, Health and Sport Sciences, the Japanese Society of Biomechanics.

Tomoki Ookuni

Senior Research Scientist, Research and Planning Section, NTT Communication Science Laboratories.

He received a B.A. in economics from Kyoto University in 1990 and M.A. in marketing science from Osaka Prefecture University in 2004. He joined NTT in 1990 and has been engaged in managing research and development at both NTT WEST and NTT since 1998. He joined NTT Communication Science Laboratories in 2019.

External Awards

Best Paper Award

Winners: Ryosuke Matsuo, Jun Shiomi, Tohru Ishihara, Hidetoshi Onodera, Kyoto University; Akihiko Shinya, Masaya Notomi, NTT Nanophotonics Center/NTT Basic Research Laboratories
Date: June 3, 2021
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE)

For “Methods for Reducing Power and Area and BDD-based Optical Light Circuits.”
Published as: R. Matsuo, J. Shiomi, T. Ishihara, H. Onodera, A. Shinya, and M. Notomi, “Methods for Reducing Power and Area and BDD-based Optical Light Circuits,” IEICE Trans. Fundamentals, Vol. E102-A, No. 12, pp. 1751–1759, Dec. 2019.

Young Researcher Award

Winner: Yoko Sogabe, NTT Computer and Data Science Laboratories
Date: August 6, 2021
Organization: The Institute of Image Electronics Engineers of Japan

For “Deep Learning-based Image Reconstruction for Compressive Spectral Imaging with Spectrally Varying PSF.”
Published as: Y. Sogabe, M. Miyata, F. Kobayashi, S. Sugimoto, T. Kurozumi, T. Hashimoto, and Y. Hiwasaki, “Deep Learning-based Image Reconstruction for Compressive Spectral Imaging with Spectrally Varying PSF,” Proc. of Media Computing Conference 2021, June 2021.

Infographics VQA runners-up

Winners: Ryota Tanaka and Kyosuke Nishida, NTT Human Informatics Laboratories
Date: September 6, 2021
Organization: 16th International Conference on Document Analysis and Recognition (ICDAR 2021)

For “IG-BERT: Learning Text-Icon-Layout Representations and Arithmetic Operations for Infographic Understanding.”
Published as: R. Tanaka and K. Nishida, “IG-BERT: Learning Text-Icon-Layout Representations and Arithmetic Operations for Infographic Understanding,” ICDAR 2021, Apr. 2021.

Best Presentation Award / Best Industry Presentation Award

Winners: Kenji Tanaka, Yuki Arikawa, Tsuyoshi Ito, NTT Device Technology Laboratories; Kazutaka Morita, NTT Software Innovation Center; Naru Nemoto, NTT Device Technology Laboratories; Fumiaki Miura, NTT Software Innovation Center; Kazuhiko Terada, NTT Device Technology Laboratories; Junji Teramoto, NTT Software Innovation Center; Takeshi Sakamoto, NTT Device Technology Laboratories
Date: September 10, 2021
Organization: The IEICE Technical Committee on Reconfigurable Systems (RECONF)

For “With GPU-FPGA Heterogeneous Computing, Highly Effective Communication for Distributed Deep Learning.”
Published as: K. Tanaka, Y. Arikawa, T. Ito, K. Morita, N. Nemoto, F. Miura, K. Terada, J. Teramoto, and T. Sakamoto, “With GPU-FPGA Heterogeneous Computing, Highly Effective Communication for Distributed Deep Learning,” IEICE-RECONF2020-19, Sept. 2020.

Distinguished Contributions Award

Winner: Yasushi Takatori, NTT Access Network Service Systems Laboratories
Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a sub-editor of EB journal.

Distinguished Contributions Award

Winner: Yusuke Asai, NTT Access Network Service Systems Laboratories
Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a sub-editor of EB journal.

Distinguished Contributions Award

Winner: Wataru Yamada, NTT Access Network Service Systems Laboratories
Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a journal reviewer.

Distinguished Contributions Award

Winner: Tomoki Murakami, NTT Access Network Service Systems Laboratories
Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a journal reviewer.

Distinguished Contributions Award

Winner: Motoharu Sasaki, NTT Access Network Service Systems Laboratories
Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a journal reviewer.

Distinguished Contributions Award

Winner: Takeshi Onizawa, NTT Access Network Service Systems Laboratories
Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a sub-editor of JB journal.

Distinguished Contributions Award

Winner: Hayato Fukuzono, NTT Access Network Service Systems Laboratories

Date: September 14, 2021
Organization: IEICE Communications Society

For his contributions to the IEICE Communications Society as a journal reviewer.

IEICE ComSoc Distinguished Contributions Award
Winner: Tatsuya Shimada, NTT Access Network Service Systems Laboratories
Date: September 15, 2021
Organization: IEICE Communications Society

For his contribution to the IEICE Communications Society as a member of the Council of Technical Committee Representatives.

Papers Published in Technical Journals and Conference Proceedings

Task Clustering Method Using User Interaction Logs to Plan RPA Introduction

Y. Urabe, S. Yagi, K. Tsuchikawa, and H. Oishi

Proc. of the 19th International Conference on Business Process Management (BPM 2021), Lecture Notes in Computer Science, Vol. 12875, pp. 273–288, Springer, Cham., August 2021.

Robotic process automation (RPA) software is a powerful tool that can automate business operations to reduce manual labor while improving operational quality by eliminating input errors. In order to efficiently and effectively improve business operations with RPA, it is necessary to clarify the types and volumes of actual business operations being performed by the employees and improve operations that have a large volume and are performed repeatedly. User interaction (UI) logs consist of users' activities performed on the computer and can be collected regardless of the business system or application to understand how employees work. However, it is difficult to understand the types and volumes of the executed tasks from such data because the task types are not recorded explicitly. In this work, we propose a method that clusters UI logs into task types to help analyzers identify high-volume and repetitive tasks for RPA introduction. As the operation types differ by task type, we utilize this characteristic to analyze the co-occurrence of operations and segment UI logs into a sequence of the same task types. Then, we perform clustering based on the operation types contained in the segments. We evaluated our approach using UI logs generated from actual scenarios in a workplace, and report the results and limitations.

Gaze Control during Reaching Is Flexibly Modulated to Optimize Task Outcome

N. Abekawa, H. Gomi, and J. Diedrichsen

Journal of Neurophysiology, Vol. 126, No. 3, pp. 816–826, Sept. 2021.

When reaching for an object with the hand, the gaze is usually directed at the target. In a laboratory setting, fixation is strongly maintained at the reach target until the reaching is completed, a phenomenon known as "gaze anchoring." While conventional accounts of such tight eye-hand coordination have often emphasized the internal synergetic linkage between both motor systems, more recent optimal control theories regard motor coordination as the adaptive solution to task requirements. We here investigated to what degree gaze control during reaching is modulated by task demands. We adopted a gaze-anchoring paradigm in which participants had to reach for a target location. During the reach, they additionally had to make a saccadic eye movement to a salient visual cue presented at locations other than the target. We manipulated the task demands by independently changing reward contingencies for saccade reaction time (RT) and reaching accuracy. On average, both saccade RTs and reach error varied systematically with reward condition, with reach accuracy improving when the saccade was delayed. The distribution of the saccade RTs showed two types of eye movements: fast saccades with short RTs, and voluntary saccade with longer RTs. Increased reward for high reach accuracy reduced the probability of fast saccades but left their latency unchanged. The results suggest that gaze anchoring acts through a suppression of fast saccades, a mechanism that can be adaptively adjusted to the current task demands.
