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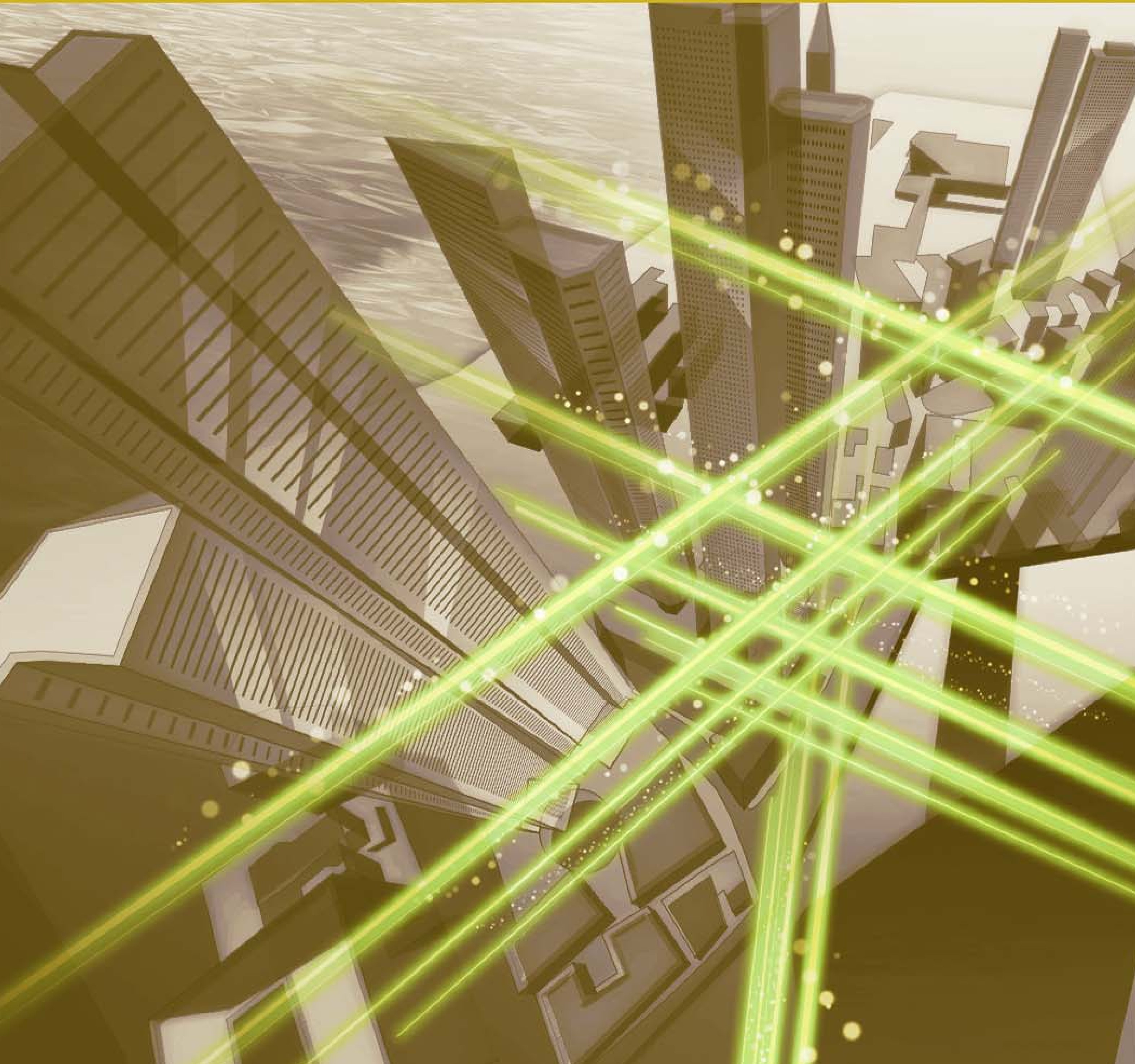

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Face Matters Simply and Honestly While Communicating. Nurture Intuition Underpinned by Proven Results

Shingo Kinoshita
Senior Vice President, Head of Research and Development Planning, NTT Corporation

Abstract

In 2023, NTT Group announced its new medium-term management strategy: "New Value Creation & Sustainability 2027 Powered by IOWN." To execute this strategy, NTT laboratories are committed to pursuing the world's best research and development (R&D) under the following guiding principles: keep researchers motivated and excited, research and develop powerful technology to benefit society in a scalable and sustainable manner, create the future rather than predict it, and nurture intuition and be creative. We interviewed Shingo Kinoshita, NTT senior vice president, head of Research and Development Planning, about the strengths of NTT's R&D and his mindset as a top executive.

Keywords: R&D, large language model, IOWN

NTT's research and development (R&D) has over 70 years of history and a wealth of world-class human resources

—Over a year has passed since you became head of the Research and Development Planning Department. Could you tell us about the current state of R&D at NTT?

Since I was appointed head of the Research and Development Planning Department in June 2023, it has been busy but fulfilling days as the research we have been focusing on is now moving into the phase of practical application and business development. For example, after we launched the first commercial service of the Innovative Optical and Wireless Network (IOWN), IOWN1.0, in March 2023, in November that year, we announced NTT's large language model (LLM) called "tsuzumi," and in March 2024, we launched a commercial service of tsuzumi.

Since we are in the critical phase in which the results of our research are developed into a business, we have been collaborating with many people, including our customers and NTT operating companies. Generative artificial intelligence (AI) is advancing rapidly, and to meet the needs of society, R&D must keep up with that pace. We have therefore accelerated R&D on tsuzumi and announced it six months ahead of schedule.

NTT's R&D expenditures and the number of researchers are actually not that large compared with other global information and communication

technology (ICT) companies. Currently, NTT has approximately 2200 researchers, and R&D expenditures are approximately 120 billion yen. Although these numbers are large in Japan, compared with GAFAM (Google, Apple, Facebook (currently Meta), Amazon, Microsoft), we have a fraction of the number of researchers, and our R&D expenditures are several tenths of theirs.

—How NTT can compete with global companies that have unparalleled resources in terms of R&D expenditures and the number of researchers?

One of NTT R&D's strengths is our abundant human resources, namely, a large number of talented researchers. To make up the above-mentioned difference in R&D expenditures, we are making creative efforts to achieve results, and we in management are supporting our researchers in terms of funding and human resources to the maximum extent possible.

Among ICT-related companies, NTT is ranked ninth in the world in terms of the number of papers published, which is a measure of research capability. In the fields of optical communications, information security, neural engineering, speech recognition, and quantum computing, the number of papers published by NTT ranks first or second in the world, which puts us ahead of Google and IBM. Achieving this ranking in spite of the fact that the number of our researchers and scale of R&D expenditures are significantly smaller is truly down to the high capability of our researchers. To solidify our position as a world leader in research, we hope to raise our ranking in terms of the number of papers published to fifth place in the next few years.

In addition to having outstanding human resources, NTT's R&D has a history of more than 70 years. GAFAM, for example, have not existed for very long, and their personnel are sometimes in flux. In contrast, we have a long history of research, the fundamentals of which have been handed down from senior to junior researchers over a period of nearly 70 years. At NTT laboratories, researchers from a very wide range of fields, from networking to AI and quantum computing, can interact with each other as colleagues, which facilitates synergy. Interacting with external researchers is called "open innovation," but we can generate a wide range of innovations within NTT laboratories.

High motivation among researchers is also the strength of NTT's R&D. For researchers, financial rewards are important; however, the most-important factors are the freedom of choosing a research theme, a comfortable research environment, and connection with co-researchers. NTT laboratories are home to many world-class researchers in various fields, such as NTT Fellow Tatsuaki Okamoto, who is a world authority on cryptography and blockchain, NTT Fellow Yutaka Miyamoto, who is an expert in high-capacity and scalable optical transport network technology, and NTT Fellow Takehiro Moriya, who is an expert in speech and audio signal processing and coding. These "top runners" act as role models to pass on their spirit and style of research, and this practice has become the unifying force for our researchers and has formed the foundation of our history. In this sense, NTT's R&D is a treasure trove of human resources.

Toward the social implementation of IOWN and tsuzumi

—Could you tell us about current major R&D initiatives?

Let me first introduce NTT's LLM "tsuzumi," which we announced at a press conference in November 2023. The key features of tsuzumi are lightweight, high linguistic proficiency (especially in the Japanese language), flexible customization, and multimodality.

Regarding the first feature, lightweight, two versions of tsuzumi are available: "tsuzumi-0.6B," an ultra-lightweight version with 600 million (0.6B) parameters, and "tsuzumi-7B," a lightweight version with 7 billion (7B) parameters. OpenAI's GPT-3, a representative LLM, requires a large-scale computer. For example, training a GPT-3-class model requires an hour's worth of electricity produced by a single nuclear plant, and using it requires multiple high-end graphics processing units (GPUs). With tsuzumi, both power consumption and the number of GPUs can be reduced to a few tenths of those amounts.

Regarding the second feature, high linguistic proficiency, when comparisons of tsuzumi with GPT-3.5 and other LLMs were made using the Rakuda benchmark, a performance-evaluation method for generative AI, tsuzumi beat GPT-3.5 at over an 80% win rate and beat the four top-ranked Japanese LLMs at an overwhelmingly high win rate.

Regarding the third feature, flexible customization, LLMs are good at answering general questions; however, questions specific to an industry or company can be difficult to answer. To address this difficulty, tsuzumi supports a variety of tuning methods.

Regarding the fourth feature, multimodality, while a typical LLM is asked and answers questions in language, tsuzumi understands not only language but also visual and auditory inputs, such as charts, pictures, and audio.

I should explain why an LLM with these excellent features could be developed in such a short period—it is largely due to the technical capabilities of NTT laboratories. For example, NTT is top ranked in the world and first in Japan in terms of the number of papers presented at the most prestigious international conference in the field of natural language processing, which is one of the most important fields concerning AI. NTT has also won first place in global competitions in machine translation and other fields as well as numerous awards from domestic research associations.

To develop an LLM, it is necessary to prepare a large amount of high-quality training data, and we have prepared training data containing more than one-trillion tokens (the smallest unit used in text analysis), including not only Japanese and English but also 21 other languages and programming languages, for pre-training. This dataset covers a very wide range of fields, from various specialties to entertainment. For instructional tuning that follows pre-training, we created a wide range of new data and used existing training data accumulated over 40 years of research on natural language processing, including translation, summarization, dialogue, and reading comprehension.

—We can't wait to see tsuzumi put into practical use. How will IOWN play a role in that? Could you tell us about the progress in the IOWN initiative?

Since the announcement of IOWN in 2019, we have advanced research, development, and practical application of it and launched "IOWN1.0," the first commercial service, in March 2023. We are currently conducting R&D with the aim of deploying IOWN in society. Specifically, we are working on the practical application of photonics-electronics convergence (PEC) devices and their application to communications and computing as well as Digital Twin Computing and next-generation general-purpose AI to maximize the use of those devices and applications.

Let me introduce the next milestones, namely, IOWN2.0, 3.0, and 4.0. In IOWN1.0, optical connections are made between datacenters without optical-to-electrical conversion. In IOWN2.0, optical connections will be made between computer boards in datacenters by using second-generation PEC devices. IOWN3.0 will enable optical connections between semiconductor packages inside a computer board by using third-generation PEC devices, and IOWN4.0 will enable optical connections between dies (chips) inside a semiconductor package by using fourth-generation PEC devices. The application area of optics will be expanded to the inside of semiconductor packages in a manner that achieves overwhelmingly high speed, wide bandwidth, and low power consumption.

IOWN also plays an important role in the R&D of LLMs. For example, during the development of tsuzumi, the training data was located in Yokosuka City (Kanagawa Prefecture) and the GPU cluster was located in Mitaka City (Tokyo), and by connecting the locations with the IOWN1.0 All-Photonics Network, we were able to create an efficient training environment for an LLM that makes the 100-km distance seem irrelevant.

After introduction of IOWN2.0 and beyond, IOWN will become even more important in the R&D of LLMs. Current computing systems have a fixed architecture consisting of central processing units (CPUs) and GPUs, and in some cases, the performance of GPUs cannot be fully exerted due to CPU intervention. On the contrary, IOWN allows the necessary number of CPUs and GPUs to be directly connected by optics on a per-component basis in a flexible architecture. Therefore, dynamic control of combinations of CPUs and GPUs optimized for LLM training and inference will become possible.

Looking further into the future, we pursue an "AI constellation" as NTT's vision for the world of AI. An AI constellation is a next-generation AI architecture in which multiple, small, and specialized LLMs are combined, rather than creating one huge, monolithic LLM, that are smarter and more efficient than a gigantic LLM.

For example, we are thinking of creating a system by which AI with various personas, such as a student, senior citizen, elementary-school teacher, parent raising children, and doctor, could discuss the question, "What is needed to revitalize our community, which is experiencing a decline in population?" Each persona could give their own opinion, and those opinions could be combined or a consensus could be reached while a real person could occasionally step in to interact and help reach a consensus. IOWN will play an important role in efficiently coordinating a large number of distributed AIs.

Create an environment in which everyone can evaluate each other fairly under four guiding principles

—Given your journey thus far, could you tell us what you value as a top executive?

I started my career at NTT as a researcher in 1991. At that time, NTT had just been privatized, and the Internet was in its infancy. Although I had majored in physics at university, I felt the difficulty in research on physics, and the newness of privatized NTT and computers appealed to me, so I jumped at the chance to join an NTT laboratory.

To be honest, I had no knowledge of telecommunications, so I had quite a hard time after I joined that NTT laboratory. Even so, my outstanding senior researchers taught me a lot of things, and I immediately fell in love with research. Because I like new things, when I encountered a new research theme, I got as excited as a child who had received a new toy, and I was very happy when my papers were accepted by academic conferences or cited by other researchers.

I also directed a large-scale project of practical application of research—involving several hundred people—for the Tokyo Olympics. The pleasure of research differs in accordance with the research phase, but each phase, whether research, development, or practical application, has its own unique charms. I'm very happy to be able to contribute to society through the results of our research.

Now as the head of the Research and Development Planning Department, I'm striving to create an environment in which each researcher can engaged in their research activities by assigning them to research groups in a well-balanced manner while taking into account their individual joys, purposes, and characteristics.

I value simplicity and honesty when dealing with matters. When working in an organization, as a result of consideration and coordination in many directions, matters may become more complicated than necessary or deviate from what they should be. Therefore, researchers should value a well-honed simplicity that is easy to understand and satisfactory to everyone.

When matters become complicated, it can be difficult to correct course, so you may have no choice but to accept that situation. From a medium- to long-term perspective, however, going back to the starting point and returning things to their ideal state is a shortcut to success. I want to face things honestly without giving up on anything.

—How do you think NTT's R&D will develop in the future?

My guiding principles for NTT laboratories are fourfold: keep researchers motivated and excited, research and develop powerful technology to benefit society in a scalable and sustainable manner, create the future rather than predict it, and nurture intuition and be creative.

At the time when research on telecommunication networks and computers was in its infancy, if companies could make a high-speed product inexpensively, people were sure to use it. In other words, if researchers researched, developed, and commercialized what they considered to be "good products," they were able to benefit society. However, society is changing rapidly and becoming more complex, and people's values are diversifying, so the "good products" that researchers think of and the "good products" that society demands do not necessarily match. This state of affairs is especially true in the global market.

Under this circumstance, I want to lead our R&D under the guiding principles that we set forth while keeping in mind the words of Goro Yoshida, the first director of the Electrical Communication Laboratory, "Do research by drawing from the fountain of knowledge and provide specific benefits to society through practical application." In other words, we will draw from the fountain of knowledge to solidify our position as the world's best research institute, implement IOWN in society by pursuing practical application, and provide specific benefits to society by striking the right balance between a market-in approach, in which we plan and promote research on the basis of market needs, and product-out approach, in which we promote research to create a future that the market has not even noticed.

I also value intuition. In the world of research, there is intuition that only researchers who have mastered a research field can have. Intuition underpinned by proven results has the power to move people. That is why I expect our researchers to accumulate results. At the same time, we in management intend to continue developing our ability to accept the intuitions of our young researchers who are accumulating results. We will produce numerous research results in an environment where we can fairly evaluate each other as researchers. I ask our partners and members of society to make the most of our researchers, who are conducting world-class R&D, and make full use of the results of their research.

Interviewee profile

■ Career highlights

Shingo Kinoshita joined NTT in 1991. In 2008, he became a senior manager in charge of human resources at NTT Information Sharing Platform Laboratories; in 2012, he became a senior manager of the R&D Planning Group at NTT Research and Development Planning Department; and in 2021, he became vice president, head of NTT Human Informatics Laboratories. He assumed his current position in June 2023.

Leading the World in Optical Devices and Photonics-electronics Convergence Devices While Promoting Our Technology and Increasing the Number of Like-minded Researchers

Shinji Matsuo
NTT Fellow, NTT Device Technology Laboratories and NTT Basic Research Laboratories

Abstract

All-Photonics Network (APN) IOWN1.0 was launched in March 2023, marking the first commercial service of the Innovative Optical and Wireless Network (IOWN). In accordance with the IOWN roadmap, optical interconnections between racks, between boards, inside a board, inside a package, and inside a chip will be sequentially achieved, and optical devices and photonics-electronics convergence devices play key roles in these interconnections. To implement these devices in commercial networks, it is necessary to achieve Moore's law—an empirical rule that the number of devices (such as transistors) in an integrated circuit doubles about every 18 months—in optical devices. We asked Shinji Matsuo, an NTT Fellow at NTT Device Technology Laboratories and NTT Basic Research Laboratories, about the development of membrane optical devices, which integrate compound semiconductors on a silicon-photonics circuit through heterogeneous integration, and his thoughts on fostering young and mid-career researchers.

Keywords: optical interconnection, membrane optical device, silicon photonics

An optical version of Moore's law: membrane optical devices

—Would you tell us about the research you are currently conducting?

Since joining NTT in 1988, I have been researching photonics-electronics convergence devices, focusing on technologies for the integration of heterogeneous materials. NTT announced the concept of the Innovative Optical and Wireless Network (IOWN) in 2019, and photonics-electronics convergence devices are key for implementing the All-Photonics Network (APN), a component of IOWN. Such devices will contribute significantly to reducing power consumption. Regarding photonics-electronics convergence in IOWN, we have thus far developed devices for replacing electrical-based interconnections between racks and between boards with optical interconnections (first and second generations, respectively). We are currently conducting research and development and practical applications of devices for optical interconnections inside a board (third generation), inside a package (fourth generation), and inside a chip (fifth generation). To put these devices into practical use, the development of an integrated circuit (chip) that can cope with the explosive increase in the number of devices while reducing cost and power consumption will be a challenge. Overcoming this challenge is what we are trying to achieve Moore's law—an empirical rule that states the number of devices (such as transistors) mounted on a single chip doubles every 18 months—in optical devices, including light-emitting devices such as laser diodes (LDs), which are essential for optical interconnection.

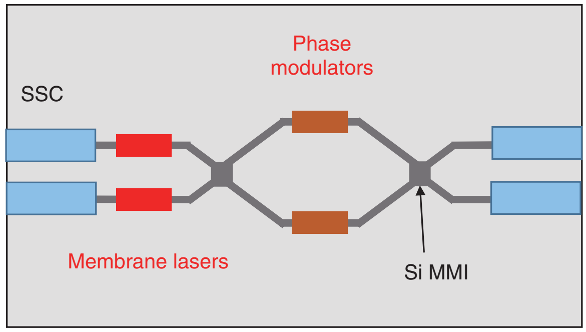
Moore's law regarding semiconductors has held true for more than 50 years thanks to the use of large-area fabrication and microfabrication technologies such as silicon complementary metal-oxide-semiconductor. To achieve Moore's law in optical devices, it is important to use silicon (Si)-photonics technology that uses optical waveguides, etc. using Si. However, optical devices, such as lasers and highly efficient optical modulators, cannot be fabricated using Si; therefore, we fabricate them using indium phosphide (InP)-based compound semiconductors, and large-scale integration of such optical devices is achieved through heterogeneous integration. Integrating Si and compound semiconductors, however, is difficult because they have different lattice constants, which represent the size of the unit lattice of a crystal lattice, and coefficients of thermal expansion, which represent the relationship between changes in length and volume due to changes in temperature. With that difficulty in mind, using Si-photonics technology combining NTT's proprietary thin-film technology and direct-bonding technology, we developed a thin-film (membrane) directly modulated LD fabricated on a Si substrate as a light source for intra-board optical interconnection [1]. We discussed this LD in the previous interview (September 2021 issue) in this journal.

—How is your research on membrane optical devices progressing?

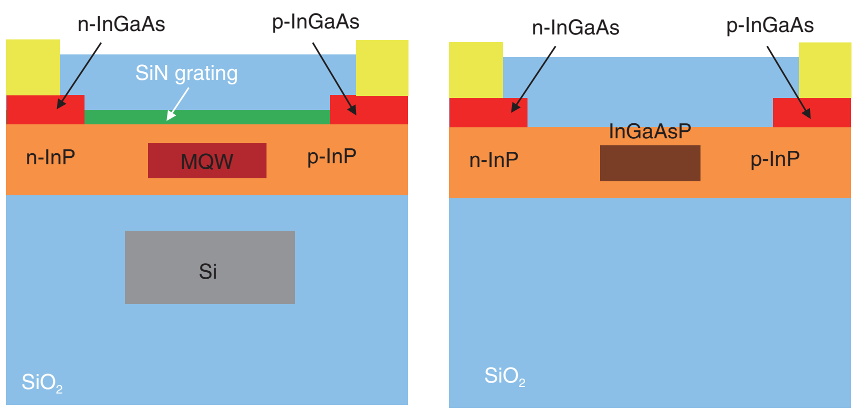
Regarding membrane directly modulated LDs, our research and development is continuing to increase the number of channels and improve stability and reliability to put them into practical use. We are also researching and developing membrane optical modulators, which do not directly modulate the laser but use the laser as a bias light source and use a separate modulator from the light source with higher speeds and a higher temperature range.

Optical modulators can be classified into two types: phase modulators, which primarily modulate the refractive index, and intensity modulators, which modulate the absorption coefficient. A phase modulator is used as a Mach-Zehnder (MZ) modulator in combination with an MZ interferometer, which measures the phase difference between two parallel beams derived from a single light source. By combining multiple MZ modulators and modulating the phase, intensity, and polarization, it is possible to achieve long-distance transmission with increased capacity exceeding 1 Tbit/s per wavelength. Typical materials used for phase modulators are lithium niobate ($LiNbO_3$), Si, and InP-based compound semiconductors. Due to the increases in traffic, optical interconnections will increase in importance in short-distance transmission (2 km or less) such as in a datacenter. Therefore, it is necessary to reduce the transmitter cost by reducing the device size and integrating many devices on a single chip. Indium-phosphide-based compound semiconductors, which are one order of magnitude more efficient than $LiNbO_3$ and Si, are considered key materials to satisfy this requirement.

Regarding intensity modulators, InP-based compound semiconductors and germanium silicon (GeSi) are typically used. Since intensity modulators use only the intensity change as a signal, the transmission capacity is generally smaller than that of MZ modulators;



(a) Schematic of a photonic integrated circuit composed of InP-based compound semiconductor lasers (membrane lasers) and phase modulators



(b) Cross-sectional view of membrane laser (c) Cross-sectional view of phase modulator

A multiple quantum well (MQW) is used for the laser's core layer and InGaAsP is used for the modulator's core layer.

InGaAsP: indium gallium arsenide
MMI: multimode interferometer
SiN: silicon nitride

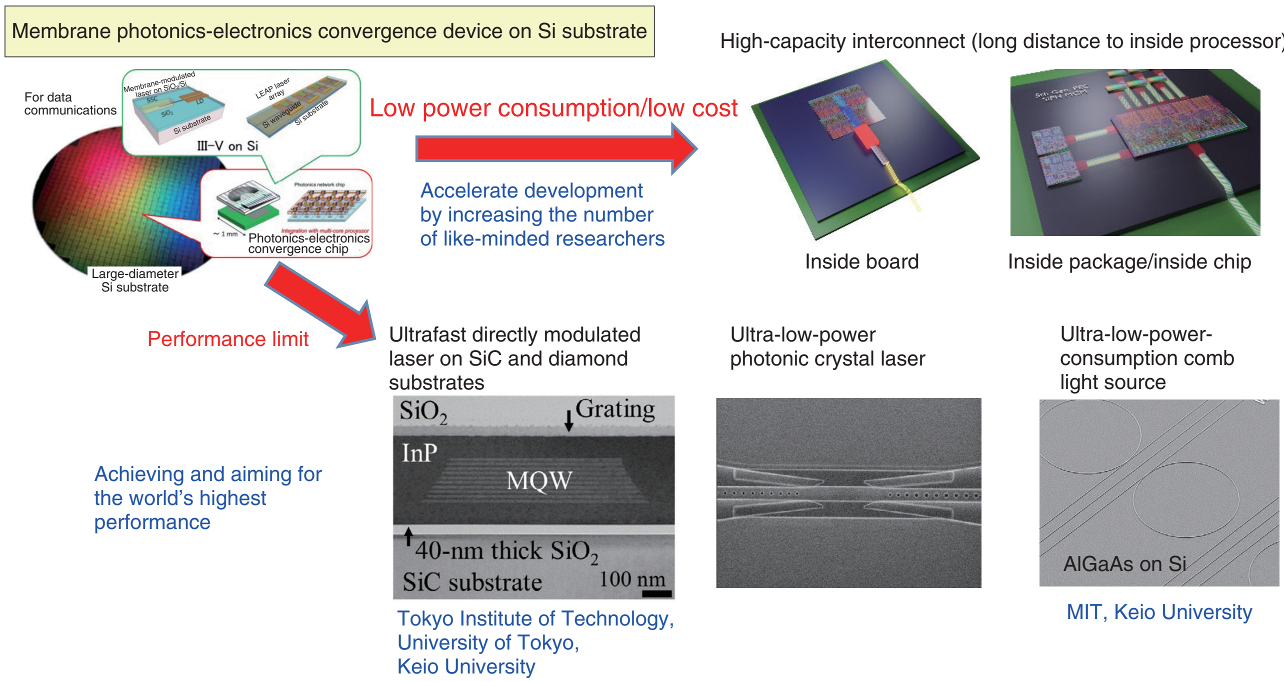
Fig. 1. Photonic integrated circuit composed of InP-based compound semiconductor lasers and phase modulators integrated on Si waveguide.

however, their simple and compact configuration is of importance when a large number of transmitters are required for short-distance transmission. Considering the use of intensity modulators in the 1.3-µm wavelength used in datacenters, there is currently a problem in the crystal growth of GeSi; thus, InP-based compound semiconductors have an advantage.

Figure 1(a) shows a schematic of a photonic integrated circuit we fabricated, which integrates an MZ modulator consisting of a Si MZ interferometer and InP phase modulators with membrane lasers through heterogeneous integration.

By integrating spot size converters (SSCs), which convert the light spot size of a Si waveguide to that of a silicon oxide (SiO_x) waveguide, it is possible to efficiently assemble a device with optical fiber by butt-coupling without using a lens. The cross-sectional views of a membrane laser and phase modulator are respectively shown in **Figs. 1(b)** and **(c)**. Since the lasers for biasing the modulators require continuous light with high output power and stable single-mode lasing, it is important to minimize the optical confinement factor in the laser's core layer. Therefore, a Si waveguide is placed under the laser's core layer.

We also fabricated an electro-absorption modulator (EAM) using InP-based semiconductors. An EAM



AlGaAs: aluminum gallium arsenide
LEAP laser: lambda-scale embedded active-region photonic crystal laser

Fig. 2. Development of future technologies.

exploits the phenomenon that the band gap shifts to the longer-wavelength side and the absorption coefficient changes when an electric field is applied to a semiconductor with a band gap near the operation wavelength. Since the EAM directly changes the amount of electric field absorbed, there is no need to use an interferometer such as an MZ modulator, which results in a very simple configuration. These devices (i.e., membrane lasers, phase modulators, and EAMs) will be key for third-generation photonics-electronics convergence and beyond for short-distance, high-throughput optical interconnection.

Due to the above achievements, in 2022, I was elected as an Optica Fellow for "pioneering contributions to ultra-high-speed and low-power-consumption membrane lasers," and in 2023, I received the IEEE Photonics Society William Streifer Scientific Achievement Award for "contributions to ultra-high-speed, low-power-consumption membrane lasers and their heterogeneous integration."

Our team is also working on practical application of these devices and accelerating joint research with partners, such as Furukawa Electric, to make these devices have low power consumption and low cost toward developing the third- to fifth-generation photonics-electronics convergence devices for IOWN. We are also conducting joint research on ultrafast directly modulated lasers on silicon carbide (SiC) substrates with Tokyo Institute of Technology, the University of Tokyo, and Keio University, with the aim of achieving the world's highest performance while developing ultra-low-power-consumption photonic crystal lasers in collaboration with NTT Basic Research Laboratories. We also intend to build an ecosystem for expanding the market for photonics-electronics convergence devices into the fields of computing and inexpensive, high-performance sensing (**Fig. 2**).

Everything requires a sense of balance

—What do you keep in mind as a researcher?

In the previous interview, I said that I try to collect information and explain my research to people so that they can understand it, and that mindset has basically not changed. I became an NTT Fellow in April 2023, and that status has made me more aware of my expected contribution to IOWN and the fostering of young and mid-career researchers.

My way of thinking slightly differs between basic research and applied research and practical applications regarding fostering researchers. In regard to basic research, I encourage researchers to have a long-term perspective and proactively take on challenges on the basis of that perspective. When people start to worry about their evaluation within a company, they inevitably pursue short-term results; thus, their perspective becomes short-term. This tendency seems to be especially prevalent among young people. From my experience, basic research takes time—in some cases, 20 or 30 years—to produce results. If we seek short-term results, we will achieve neither significant development nor true results as basic research. That is why we need a long-term perspective. Nonetheless, if we think about it in the long term, we might end up following a set path that is exactly as we originally envisioned. However, due to changes in the surrounding environment, the path is not always pointing in the correct direction, so its trajectory must be corrected, and in some cases, it may be necessary to make major corrections to the trajectory. In that case, by actively taking on challenges, we can expect new discoveries and major progress.

In regard to applied research and practical applications, it is necessary to solve the problems in front of you one by one as a team while taking into account the schedule and your own role within the team, applying teamwork to complement each team member, and polishing your execution ability. My team covers the entire process from basic research to applied research and practical applications, so we need both long-term and short-term perspectives. I therefore strive to encourage each team member to be aware of these two perspectives in accordance with their role.

—You have served on the boards of many international conferences and academic societies. How have those experiences affected researcher development?

At the Institute of Electrical and Electronics Engineers (IEEE), I served as the chair of the Steering Committee of the Si Photonics Conference 2024 and as the board of governors of the Photonic Society from 2023 to 2025. At the Optical Fiber Communications Conference and Exhibition (OFC), I served as the program chair in 2020 and general chair in 2022. For Compound Semiconductor Week 2019, I served as the chair of the Steering Committee. At OFC, while involved in the management of the conference, I noticed that the way of thinking and behavior of people from other countries differs from what Japanese people are aware of. For example, when it comes to supporting women in terms of gender balance, people from Europe and the USA are more proactive and explicit than Japan. They are also careful to maintain a balance among regions such as South America, Africa, and Asia. This was a new experience for me because we in Japan consider the gender ratio, but we are not so aware of regional and other balances.

I often talk to young people about how it is important to know what people around the world—not just Japan—value. To attain such knowledge, it is helpful to get involved in organizing international conferences from a young age, so I encourage them to participate in these activities as much as they can. These activities will help them understand not only technology but also ways of thinking and cultural aspects of people from different countries.

The field of optical devices and photonics-electronics convergence devices is one of the most-advanced fields of research. The number of researchers in this field is still small, thus we have the opportunity to lead the world. We are actively participating in conferences to promote our technology and persuade more researchers to join us in this field. Therefore, the number of people researching something similar to our field will gradually increase, and a new trend will be created. If you are too far ahead and others cannot keep up, you will not be able to make connections with other researchers and will become isolated. However, if you stick too close to others, you are more likely to be overtaken. In other words, it is necessary to strike a balance between these two situations, and I believe that understanding the way of thinking and cultural aspects of people from around the world will help us strike that balance.

—What is your message to younger researchers?

Regarding basic research, I urge young researchers to take a long-term perspective. NTT's research laboratories are unique in that although they are corporate laboratories, they also conduct basic research. Basic research, which is one of our strengths, is the result of endeavors of ten or more years. Of course, you will make achievements along the way, but they will be mid-term and short-term results as milestones toward achieving the goal in mind from a long-term perspective. These medium- and short-term milestones will satisfy internal evaluations, but focusing too much on them can lead to losing sight of the ultimate goal.

Regarding applied research and practical applications, it is necessary to achieve results while aiming toward short- and mid-term goals. You should therefore change your perspectives in accordance with your current position. Some researchers switch between basic research and applied research and practical applications. For our team, the two are in direct contact. Therefore, it is important to take a balanced approach in understanding each person's perspective and position.

Reference

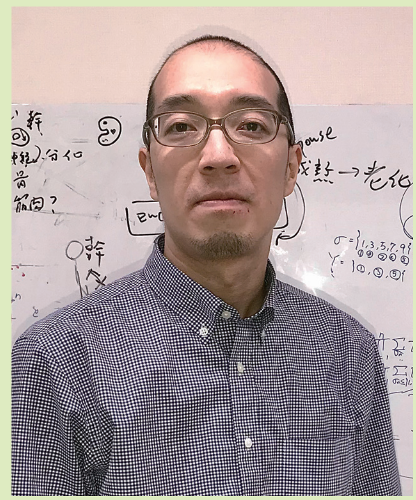
[1] T. Hiraki, T. Aihara, T. Fujii, K. Takeda, T. Segawa, and S. Matsuo, "Development of Membrane Optical Modulators for IOWN," NTT Technical Review, Vol. 20, No. 8, pp. 28–34, Aug. 2022. https://doi.org/10.53829/ntr202208fa3

■ Interviewee profile

Shinji Matsuo received a B.E. and M.E. in electrical engineering from Hiroshima University in 1986 and 1988, and Ph.D. in electronics and applied physics from Tokyo Institute of Technology in 2008. In 1988, he joined NTT Optoelectronics Laboratories, where he researched photonic functional devices using multiple-quantum-well pin modulators and vertical cavity surface emitting lasers. In 1997, he researched optical networks using wavelength division multiplexing technologies at NTT Network Innovation Laboratories. Since 2000, he has been researching high-speed tunable optical filters and lasers at NTT Photonics Laboratories, NTT Device Technology Laboratories, and NTT Basic Research Laboratories. He is a member of Japan Society of Applied Physics and Institute of Electronics, Information and Communication Engineers, and a fellow of IEEE and Optica.

Bayesian Nonparametric Methods for Analyzing Ever-increasing Infinite Data

Masahiro Nakano
Distinguished Researcher, NTT Communication Science Laboratories and NTT Basic Research Laboratories



Abstract

One field of research that is gathering attention today is statistical machine learning that aims to apply analytical data to real-world problems. Conventional analysis has mainly used methods that manually set the scale and parameters of a statistical model or training model based on the data given and that involve costly tuning. These methods, however, incur massive amounts of time and labor, so using them to analyze data that will only continue to expand from here on is difficult. To solve this problem, there is a strong demand for a new technique that automatically adjusts model scale and parameters according to the quality and volume of data. In this article, we talked with NTT Distinguished Researcher Masahiro Nakano about his research on Bayesian nonparametric methods for solving problems faced by today's data society.

Keywords: statistical machine learning, Bayesian nonparametric methods, extremal combinatorics

Establishing a new technique for analyzing relational data of infinite size

—Mr. Nakano, could you first tell us what kind of technology is "Bayesian nonparametric relational data analysis"?

The volume and scale of data in today's society continue to increase on a yearly basis while the types of data being processed are becoming increasingly diverse. In such an environment, the conventional approach has been to manually set appropriate model parameters each time and to perform various types of processing. This approach, however, requires a massive amount of time and labor, which will make it hard for this approach to deal with further development of the data society. Bayesian nonparametric methods that I introduce here is a means of solving this problem. This technology adjusts the scale and parameters of a statistical model or training model in a data-driven manner (automatically according to the quality and volume of data) thereby reducing the massive amount of time and labor incurred by manual means that has been a problem in the past.

A technology called "relational data analysis" can be offered as one example of applying Bayesian nonparametric methods. Let's consider the problem of "indefinite complaints" in modern society as an

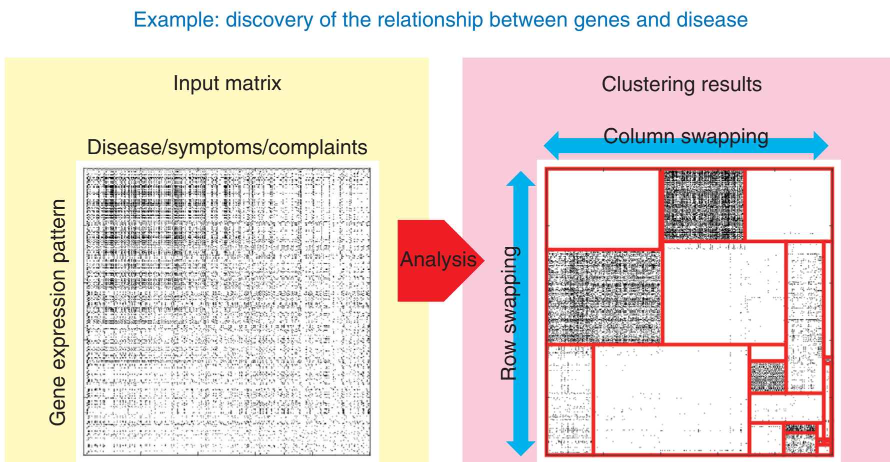


Fig. 1. Overview of Bayesian nonparametric relational data analysis.

application example. An indefinite complaint corresponds to a state in which a medical exam performed in response to subjective symptoms describing a physical or mental disorder is unable to identify the underlying disease or determine an effective method of treatment. Such symptoms are wide ranging and may appear in a composite manner as in "I'm feeling sluggish," "I can't stop feeling tired," and "My arms feel dull," which makes it difficult to identify disease in units of individual patients, presenting a social problem. However, if relational data between such a large number of patients and symptoms could be collected and analyzed, it would be possible to clarify correlations among individual items of data and uncover some sort of common features through data science.

However, there is a major problem in carrying out such an analysis. Specifically, if the number of data items that can be collected is (nearly) infinite, dealing with such a large volume of data is difficult. For example, the number of subjective symptoms is quite large including symptoms that differ from person to person, and the number of patients with indefinite complaints is potentially immeasurable. As such, there is the possibility that the relational data of patients and symptoms could become infinitely large along the rows and columns of a table, making data analysis extremely difficult.

To potentially analyze such data, technology that applies "uncertainty" to the infinite possibilities lying behind data in a data-driven manner is called "Bayesian nonparametric methods," which was created in 2000 as a field in machine learning. A specific result of this technology was the "discovery of the relationship between genes and disease." This was achieved by partitioning the data into rectangles when analyzing that data based on clustering (the grouping of data based on similarities between data) and constructing a new probabilistic generative model that could generate all possible combinatorial patterns for those grouping candidates (**Fig. 1**). Additionally, adjusting and clustering optimal rectangular partitions in accordance with the given data achieved an efficient data analysis method. This approach made it possible to analyze all sorts of "nearly infinite" data according to the quality and volume of data, which could not be done by conventional techniques.

—What other technologies are you working on in your research?

In parallel with the technology I just described, I have been researching "super-Bayesian relational data analysis" since 2022. In simple terms, this technology relaxes the feature of "dealing with infinity" in Bayesian nonparametric relational data analysis.

In actuality, the greatest barrier to achieving Bayesian nonparametric relational data analysis has been the construction of an inference algorithm. Let me explain why this is so. By proactively using "infinity" on a computer, the construction of an inference algorithm for use in data analysis will be accompanied by "infinity," and as a result, the possibility of some sort of infinite loop must be avoided, which makes it all the more difficult to design a model for performing analysis. This is a problem stemming from the use of

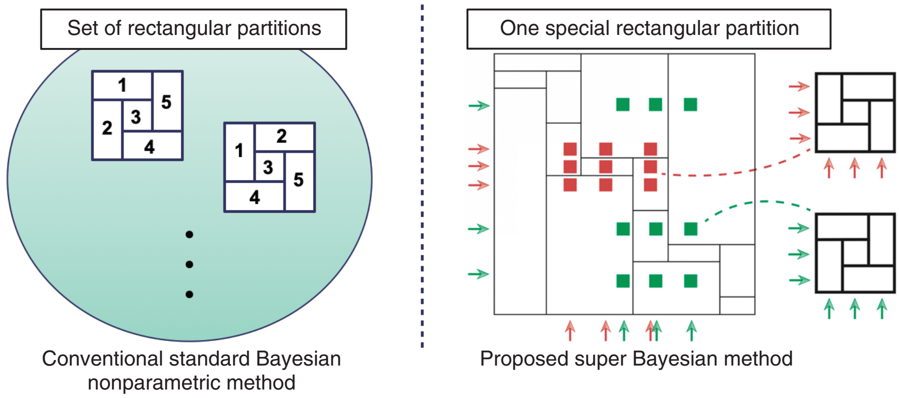


Fig. 2. Comparison of Bayesian nonparametric relational data analysis and super Bayesian method.

stochastic operations by the inference algorithm in Bayesian nonparametric relational data analysis. In general, when talking about probability, the total probability of the occurrence of candidate events must always be 100%. However, with an infinite number of cases, even if total probability is 100%, the probability of each number of cases itself is 0%. In other words, by making a partial collection of an "infinite number of cases" from the entire "infinite number of cases," we would have a positive probability. Consequently, if one should carelessly think "I can ignore this event since its probability is zero," the probability of that neglected event could become positive without realizing it, which means that there is a risk of a breakdown without total probability becoming 100%.

Soon after I started out on my research path, the sales pitch then being given for Bayesian nonparametric relational data analysis was that it was "capable of handling infinity in a virtual manner." For me, this was a magic-like quality that I found very appealing. This was the 2000s, the time of the first boom of Bayesian nonparametric methods, and the emergence of new techniques on practically a daily basis was very stimulating to me as a researcher. However, around 2012, excitement began to grow around artificial intelligence (AI) in parallel with the third boom in neural networks, and at the same time, the excitement surrounding Bayesian nonparametric methods appeared to calm down relative to its early days. Personally, I believe the reason for this, in a few words, is that "it was not technology that could be applied in practice." Given that the key feature of Bayesian nonparametric methods is the capability of "handling infinity in a virtual manner," they turn out to be models that are quite difficult to handle on computers. From the perspective of actual applications, the level of difficulty of constructing Bayesian nonparametric relational data analysis is often high, and it's no exaggeration to say that first trying out a method based on existing deep learning technology is the most promising approach.

On the other hand, similar to the way that deep learning rose to prominence from 2012 on thanks to the third boom in neural networks, I began to wonder whether there was a method that could satisfy both ease of construction and practical use in relational data analysis. A breakthrough in my search occurred when I encountered "extremal combinatorics" in 2021–2022.

Extremal combinatorics is a field of study that deals with order arising from a certain kind of redundancy. For example, when considering a tremendously long numeric sequence (more precisely, a uniform random permutation), it is known that all kinds of short permutations, such as 14523 or 8245361, have a high probability of appearing as a partial series of that sequence. An important insight obtained from extremal combinatorics is that "if you prepare a massive thing with sufficient redundancy, more than enough things of various types can be expressed." In short, in the case of Bayesian nonparametric relational data analysis, I noticed that an alternative to something thought to require "infinity" might be possible by replacing it with a "sufficiently redundant and large thing" and proposed the "super Bayesian method" (**Fig. 2**). Additionally, since no infinity is involved in such a "sufficiently redundant and large thing," it holds the possibility of making construction of an inference algorithm much easier. By incorporating

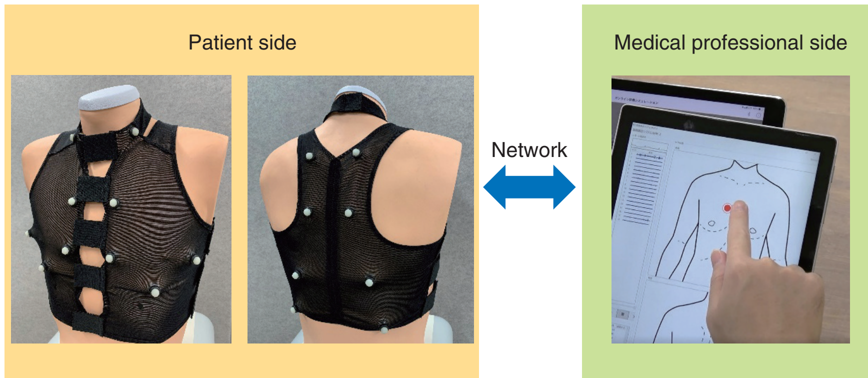


Fig. 3. "Telestethoscope" initiative.

insight on extremal combinatorics, I expect the super Bayesian method to become a technology that can be applied in practice while having the power of Bayesian nonparametric relational data analysis, and as such, to lead the way to future developments.

The super Bayesian method shows much potential as a new branch of Bayesian nonparametric relational data analysis, and taking advantage of the opportunity I had in making an oral presentation (top 4%) at AISTATS 2022, a major conference in this field, I have been putting effort into this method since then. Machine learning methods that proactively use such extremal combinatorics was still unexplored territory at that time, so I was fortunate in receiving a positive response from reviewers and the audience too, all of which encouraged me to continue with my research. In contrast to all the excitement surrounding the machine learning and AI field at present, research laboratories that are working on Bayesian nonparametric methods are relatively few in number. Research is something that makes progress through the efforts of mankind on the whole. By therefore continuing with this type of research and attracting more attention in this field, I hope to increase the size of my research team with an eye to further progress as a joint effort.

Making use of knowledge gained to contribute to NTT's Medical and Health Vision

—What is the outlook for your research going forward?

Looking to the future, I would like to make some sort of contribution to NTT's Medical and Health Vision, which aims for a future in which everyone is always healthy with a hopeful outlook. At NTT, Digital Twin Computing, one of the key elements of the Innovative Optical and Wireless Network (IOWN), will be used to make a detailed mapping of a person's physical and mental state (bio-digital twin). Additionally, by predicting a person's physical and mental state sometime in the future, bio-digital twins will contribute to a future vision of medical care. I myself feel that I can contribute to making NTT's vision a reality by making good use of the knowledge I have gained through my work to date on Bayesian nonparametric relational data analysis and the super Bayesian method.

As a specific initiative in this regard, the Biomedical Informatics Research Group that I currently belong to is researching a device called a "telestethoscope" (**Fig. 3**). Based on the concept of a wearable/visible stethoscope, this technology transmits the data of a patient wearing the stethoscope to a remote location. To begin with, this capability enables auscultation by a medical professional with no risk of infection from the COVID-19 virus. Additionally, it enables early detection of any abnormalities when assessing the urgency of patient care for a remotely located patient while also promoting an understanding and awareness of one's own body on the patient's side.

Of course, research of bio-digital twin does not stop here. At NTT Communication Science Laboratories that I belong to, we are working on a long-term research goal of constructing human organs as digital computer models through a co-creation project with

Osaka University called "PRIMe." In this way, by searching for and implementing a variety of applications in addition to the telestethoscope, I will move forward with my research with the aim of contributing to NTT's Medical and Health Vision and creating a world in which many people can live a highly enriched life.

—Mr. Nakano, please leave us with a message for researchers, students, and business partners.

I have been blessed with many connections even from the time prior to entering NTT. Professor Shigeki Sagayama, my academic advisor at the laboratory that I belonged to in graduate school, was originally from NTT, and I had the opportunity of receiving guidance from NTT Senior Distinguished Researcher Hirokazu Kameoka during joint research with NTT while I was a graduate student. Known globally from that time as a top research institute in the field of Bayesian nonparametric relational data analysis, NTT Communication Science Laboratories (in particular, Visiting Fellow Dr. Naonori Ueda and Takeshi Yamada, former head of NTT Communication Science Laboratories) made important contributions to the field even in those early days, so it was an attractive research institute for me from my student days onward.

Additionally, after entering NTT, I came to feel that NTT laboratories were an environment that, instead of restricting a researcher to only short-term choices or concentrations, actually welcomed the selection of diverse themes and challenges tailored to that person's enthusiasm and passion. For example, around 2011 when I entered NTT, the third neural network boom was heavily influencing computer science around the world. However, NTT was able to avoid getting swept up in that tide, and I myself was able to continue with my research on Bayesian nonparametric relational data analysis. Of course, it's important to grasp global happenings and research trends, but on the other hand, a researcher may obtain unexpected results through research involving diverse and wide-ranging fields. As a researcher, I find this NTT environment that welcomes a variety of themes as a medium- and long-term investment to be very appealing.

At present, moreover, I am fortunate in having many occasions to serve as a mentor to junior researchers. In the course of giving all sorts of guidance, I have observed junior researchers launch research themes from up close, so based on this experience, I would be happy to give advice to any young researchers that happen to be reading this article. Specifically, in research, it is important to try out "something that you may think to be a waste" many times. Of course, it must be said here that the correct way of conducting research and boosting motivation differs from person to person. In recent years, there has been much emphasis on "cost performance" and "time performance," which is opposite to my way of thinking.

However, when attempting to draw a new picture on a totally blank canvas, for example, it may happen that your brush does not move at all when faced with white paper having not a single mark. At this time, anything is fine, so once you dive right in and mark up the paper in some way, you will immediately feel better and your hand will start to move. Research is much the same. Even if you should erroneously mark up a sheet of paper at first, you will stop worrying about those marks as you come to overwrite them with a picture. Furthermore, as in the "sunk cost effect" that is often talked about, there is psychology at work here in that a person who invests any type of cost such as money, time, or effort into some sort of project will look back and find value in doing so. If you are having a problem in which your research is not progressing at all, my advice is to "start with small things." Putting yourself to work beginning with what is familiar to you and from what you are capable of doing will expand possibilities. In this way, I would like you to open up the way to a new future!

■ Interviewee profile

Masahiro Nakano received his M.E. from the Graduate School of Information Science and Technology, The University of Tokyo in 2011 and entered Nippon Telegraph and Telephone Corporation (NTT) in the same year. He is currently assigned to NTT Communication Science Laboratories and has been concurrently working at NTT Bio-Medical Informatics Research Center since 2020. He is engaged in the study of statistical machine learning and its application to biomedical information processing using stochastic processes (stochastic models using infinite-dimensional parameter space) and universal objects in extremal combinatorics.

Achieving IOWN/6G and Creating New Value with World-leading Technologies

Kazunori Akabane, Kohei Mizuno, Koichi Takasugi, Kenji Suzuki, and Yoshiaki Kisaka

Abstract

NTT Network Innovation Laboratories (NIL) is committed to the practical application of IOWN (the Innovative Optical and Wireless Network) with its world-leading technological capabilities. NIL also conducts research and development with the mission of enhancing the competitiveness of the NTT Group by developing the world's first and most advanced technologies to bring about social change and create new value. This article provides an overview of the technologies being researched and developed by NIL.

Keywords: All-Photonics Network (APN), optical transmission technology, wireless transmission technology

1. Introduction

NTT Network Innovation Laboratories (NIL) is engaged in research and development (R&D) with the aim of establishing communication technologies that enable long-distance, high-speed, and large-capacity information transmission over a wide range of areas, including optical fibers, air, underwater, and other communication media, using physical waves in various frequency bands such as optical, radio, and acoustic waves.

Figure 1 shows the areas of NIL's R&D efforts. While focusing on optical communications in optical fibers, radio communications in air and space, and acoustic communications in water, we are also developing communication technologies in the boundary region between radio waves and light, such as free-space optical communications (FSO).

NIL is promoting the R&D of the All-Photonics Network (APN) to implement the Innovative Optical and Wireless Network (IOWN) promoted by NTT. The APN IOWN1.0 service was launched in March 2023, in which users can exclusively use optical wavelength end-to-end, providing high-speed, high-capacity, low-latency, and low-jitter networks. For this APN IOWN1.0 service, we developed an optical transport network (OTN) transmission system called OTN Anywhere that embodies a delay-managed network that can freely control communication delays.

NIL is conducting R&D to improve the performance and convenience of IOWN in the directions shown in **Fig. 2**. Toward IOWN2.0, which is expected to be implemented in 2025 or later, we are developing OTN Anywhere to accommodate a wider variety of client signals and manage delays at a finer granularity. We are also engaged in R&D on elemental technologies that contribute to improving the usability of IOWN, such as the development of a digital signal processor (DSP) that enables large-capacity transmission of 1.6-Tbit/s class by using digital coherent optical transmission technology, automatic optical path provisioning (AOPP) and remote control technology, a secure optical transport network that provides secure network services using post-quantum cryptography (PQC), and an IOWN infrastructure processing unit (IPU) board that

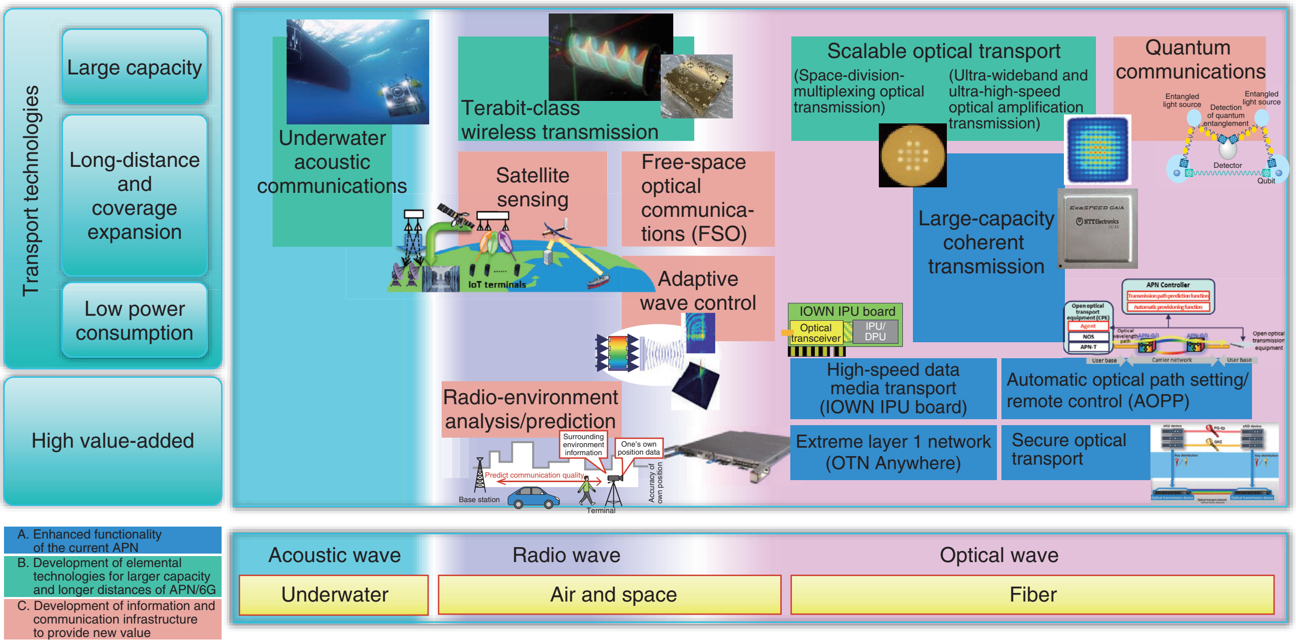


Fig. 1. Areas of R&D by NIL.

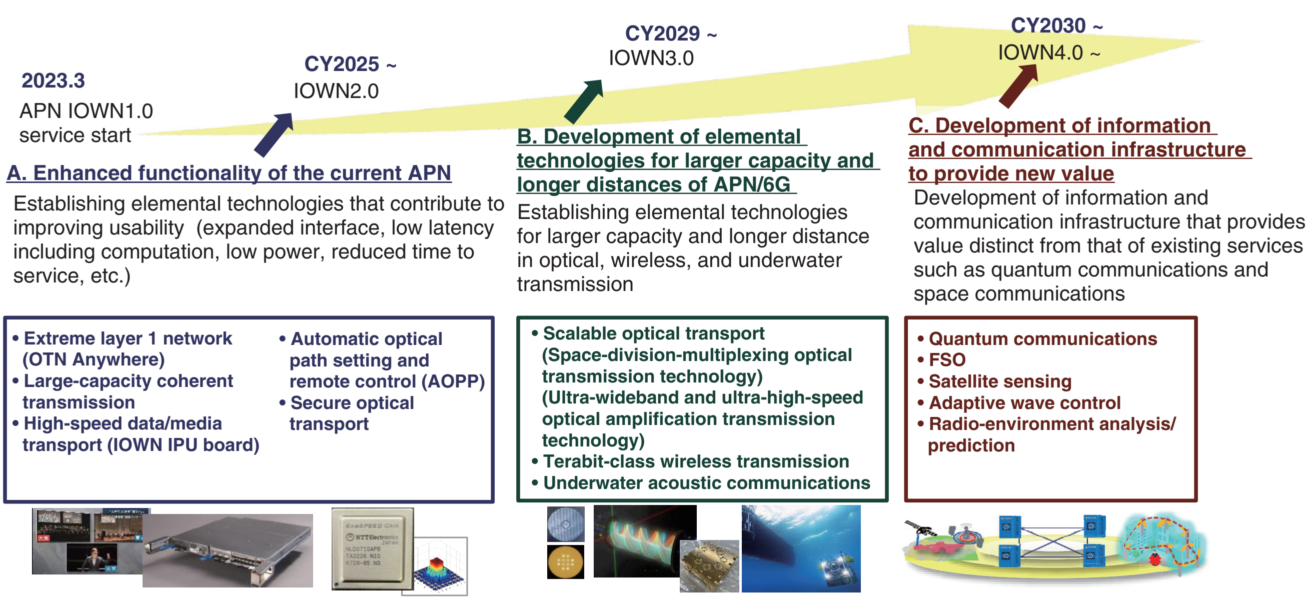


Fig. 2. Directions for R&D promoted by NIL.

achieves ultra-low and deterministic delay data transmission.

Toward IOWN3.0, which we aim to implement in 2029 or later, we are developing elemental technologies for further increasing the capacity and distance of the IOWN APN, such as the development of space-division-multiplexing technology and scalable optical transport technology to achieve petabit-class transmission throughput in the APN, terabit-class wireless transmission technology for wireless xHaul

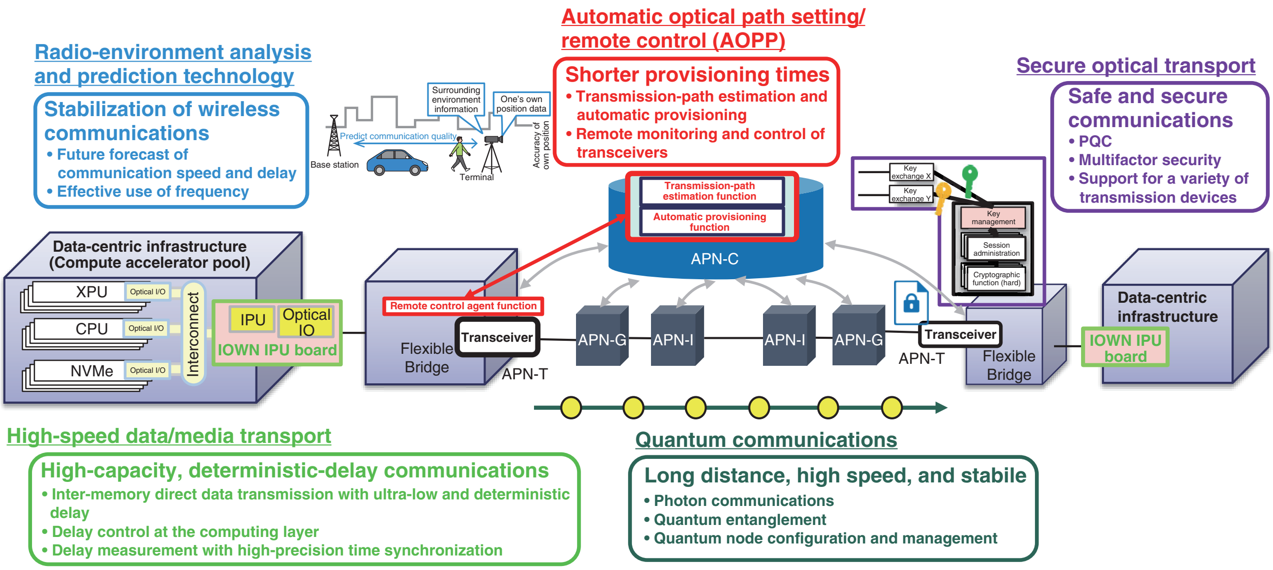


Fig. 3. Overview of frontier communication technologies.

supporting IOWN/6th-generation mobile communication system (6G), and underwater acoustic communication technology to achieve large capacity, multiplexing, and security.

Toward IOWN4.0, which we aim to implement in the 2030s, we are engaged in R&D to develop an information and communication infrastructure that provides new value distinct from that of existing services, such as R&D of a scalable quantum network using quantum repeaters and adaptive wave control technology that forms a free wireless space with high precision.

In the following sections, we introduce the cutting-edge technologies we are developing, which can be categorized as frontier communication technologies, wave propagation technologies, and optical transport innovation technologies.

2. Frontier communication technologies

The outline of the frontier communication technologies is shown in **Fig. 3**. To create mission-critical services, such as smart cities, medicine, and finance, by using widely distributed computing resources, we will develop transport and control technologies and quantum communications that transmit qubits.

2.1 High-speed data/media transport (IOWN IPU board)

We established technology to transmit data and media with ultra-low and deterministic delay on the IOWN APN to provide services with high real-time performance such as smart cities, medical care, and finance [1]. In high-speed data transport, we will implement the IOWN IPU board to enable data transmission with ultra-low and deterministic delay between memories as well as software development kit (SDK) to enable applications to determine the transmission-processing delay through delay measurement with high-precision time synchronization. High-speed media transport enables ultra-low-latency media transmission such as uncompressed video and three-dimensional video.

2.2 Automatic optical path setting and remote control (AOPP)

To achieve datacenter exchange (DCX) that dynamically connects datacenters in response to user requests by using the IOWN APN, automatic provisioning that sets optical wavelength paths on demand will be achieved.

This is achieved by setting the parameters of optical wavelength paths on the basis of the result of the transmission-path estimation between multi-user bases under different conditions such as device vendors and propagation characteristics on demand [2]. By implementing the remote control agent function on optical transponders installed at user sites, it will be possible to set up the parameters of optical transceivers and monitor the status of the transceivers

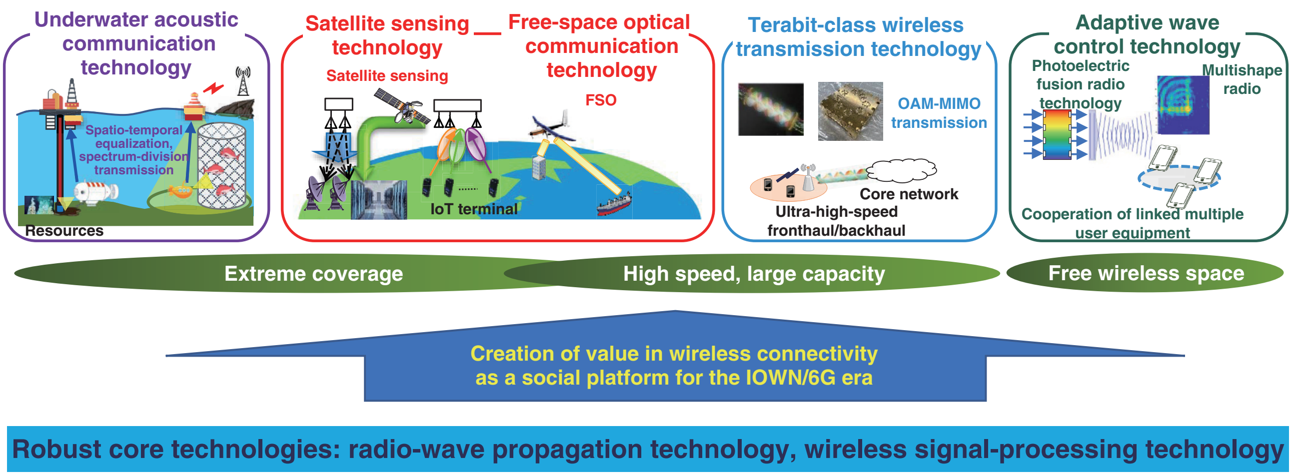


Fig. 4. Overview of wave propagation technologies.

from telecommunication carrier facilities. By advancing the standardization of the monitoring and control interface, we aim to provide DCX services using open and multi-vender optical transponders.

2.3 Secure optical transport

In anticipation of future eavesdropping and tampering by using quantum computers, we are developing a technology to guarantee the safety of optical wavelength paths in the APN by means of PQC. To expand security functions in line with future advances in security and transmission technologies, this technology has a functional architecture that disaggregates key-exchange functions, key-management functions (software processing), and cryptographic functions (hardware processing) and achieves strong security (multifactor security) by synthesizing multiple keys with different reliability bases obtained using different key-exchange methods.

2.4 Radio-environment analysis and prediction technology

Using a variety of physical-space information, including non-communication sensor devices such as cameras and sensors, we are developing technologies to predict the future communication quality of a few seconds ahead and always ensure broadband and low-latency radio communications. This will promote the effective use of frequency resources in high-frequency bands, such as millimeter waves, and be applied to mission-critical use cases such as robot control, which have traditionally been difficult in the radio environment.

2.5 Quantum communication technology

To network many quantum computers and exponentially improve computing power, we are developing quantum communication technology that transmits quantum bits handled by quantum computers. We aim to establish photon communication and quantum entanglement communication technologies to achieve stable long-distance and high-speed communications, and quantum node configuration and management technology to implement quantum networks.

3. Wave propagation technologies

We are developing wave propagation technologies to create value in wireless connectivity as a social platform for the IOWN/6G era (**Fig. 4**). In underwater acoustic communication technology and satellite sensing technology, we are aiming for extreme coverage expansion to expand communication areas into the ocean, space, and sky in addition to terrestrial communications. We are also investigating high-speed, large-capacity transmission that improves communication speed through FSO technology and terabit-class wireless transmission technology. We are also investigating adaptive wave control technology as the ultimate wireless communications that can freely control the communication area and form a highly accurate wireless space.

3.1 Underwater acoustic communication technology

Expectations to improve operational efficiency by using communications in industrial fields, such as seabed resource development, port facility construction, and marine facility inspection, are increasing due to the expansion of extreme coverage into the ocean, which has been an unexplored area as a mobile communication system. Through the establishment of spatio-temporal equalization technology and environmental-noise-resistance-improvement technology for achieving high-speed, long-distance, and stabile underwater acoustic communications, high-speed transmission of 1-Mbit/s class was achieved, and the world's first wireless remotely operated vehicle equipped with this technology was demonstrated in an open experiment [3]. In cooperation with various partners in the industrial field, we are studying the applicability of technology to more specific operations and conducting various R&D projects such as on underwater acoustic positioning and wide-area communication networks.

3.2 Satellite sensing technology

We are developing the basic technology of a satellite sensing platform that collects Internet of Things (IoT) data using general low-power wide-area terminals that are widely used on the ground without using satellite-specific equipment or frequencies [4]. We aim for sensing on a global scale by using extreme-coverage communication platforms that cannot be covered by terrestrial networks, such as in mountainous areas and oceans.

3.3 FSO technology

We are engaged in research on spatial optical communication technologies with the aim of establishing new communication infrastructure technologies that enable the provision of ultra-high-speed wireless links to locations and mobile devices where optical fibers are difficult to install. We are aiming for ultra-high-speed, large-capacity transmission by high-efficiency fiber coupling using wavefront compensation technology for atmospheric turbulence caused by atmospheric propagation and to apply it to rapid temporary network recovery in the event of a disaster.

3.4 Terabit-class wireless transmission technology

The fronthaul and backhaul in the IOWN/6G era are expected to require terabit-class wireless transmission technology. To achieve this, we are investigating high-speed, large-capacity wireless transmission by increasing the bandwidth and number of spatial multiplexes. We have demonstrated the world's first high-capacity wireless transmission of 1.4 Tbit/s by orbital angular momentum (OAM) multiplexed transmission using ultra-high bandwidth in the sub-terahertz band [5]. We aim to demonstrate long-distance transmission over 100 m, assuming various applications in the real world.

3.5 Adaptive wave control technology

In the wireless system of IOWN/6G, it is assumed that a wide variety of devices will be connected wirelessly, which will increase interference between users and power loss due to utilization of high frequency bands. As elemental technologies contributing to the resolution of these issues, we are developing multi-shape wave control technology that bends and straightens the propagation area on the basis of wave-control, terminal-coordinated user-centric radio access network technology that adaptively forms a wireless space by cooperating with terminals, and optical matrix wireless beamforming technology that uses photoelectric fusion to enable wireless beamforming in large-scale array antennas with circuit saving.

4. Optical transport innovation technologies

Toward the implementation of the APN, which forms the basis of IOWN, we are engaged in R&D on optical transport innovation technologies that will improve the added value and increase the capacity of optical networks (**Fig. 5**). To advance APN services and expand use cases, we are promoting R&D of extreme layer 1 network technologies that bring new value to users and operators. We are also developing high-capacity coherent transmission technology to achieve high-capacity and low-power optical paths and developing scalable optical transport infrastructure technologies that achieve Pbit/s-class transmission throughput per link to efficiently accommodate a huge amount of future communication traffic.

4.1 Extreme layer 1 network technology (OTN Anywhere)

By creating elemental technologies that bring value to users and operators through layer 1 networking, we aim to contribute to the advancement of APN services and expansion of use cases. We are conducting R&D on a delay-managed transmission system (OTN Anywhere) that measures and controls network delays with high precision and layer 1 hit-less switching technology that changes the network configuration without bit loss of communication data to provide

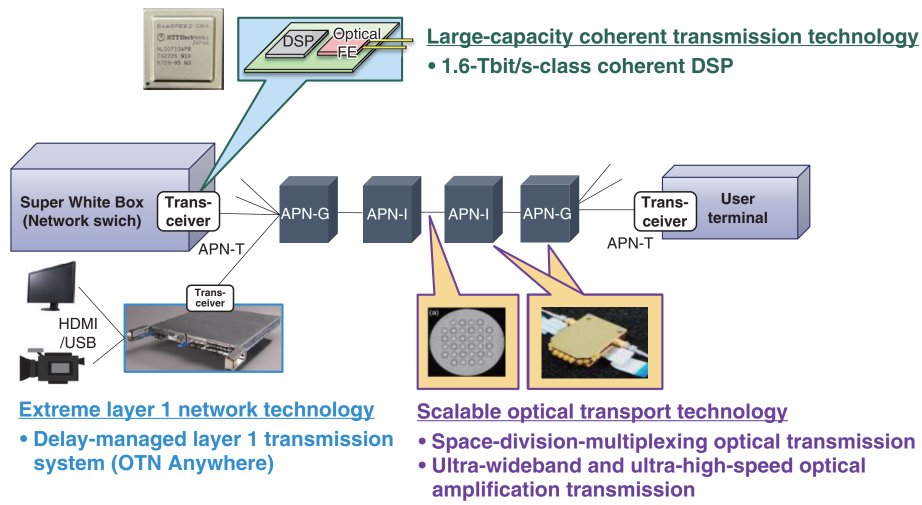


Fig. 5. Overview of optical transport innovation technologies.

new value-added functions for high-capacity, low-latency layer 1 communication paths and bring about changes in user experience. We are expanding the use cases through demonstration experiments such as remote surgery using these technologies and fair eSports remote competition.

4.2 High-capacity coherent transmission technology (coherent DSP)

We are aiming to establish a digital coherent optical transmission technology that will enable high-speed large-capacity optical transmission over 1 Tbit/s per wavelength, which is essential for APN construction, to extend transmission distance and reduce power consumption. We are researching and developing technologies for providing optimal optical paths by flexibly changing the transmission scheme and compensation processing in rapidly expanding application areas, which are applied not only to conventional long-distance transmission for carriers but also to short-distance transmission such as datacenter interconnect. We are also developing a digital signal processing circuit (coherent DSP) for 1.6-Tbit/s-class optical communications, which is a key device for achieving high-capacity coherent transmission at low power.

4.3 Scalable optical transport technology

To construct Pbit/s-class optical networks that can accommodate communication traffic, which will rapidly increase in the future due to the development of high-speed mobile access and the spread of artificial intelligence services, we aim to establish a scalable optical network technology of 1-Pbit/s-class capacity per link by developing innovative ultra-high-capacity transmission technologies and optical signal processing technologies. As elemental technologies to achieve large-capacity transmission, we are engaged in R&D on basic technologies such as large-capacity space-division-multiplexing transmission technology [6, 7] using core and mode multiplexing and wide-band optical-amplification and wavelength-band conversion technologies [8] using wide-band parametric optical amplification.

5. Conclusion

We outlined the efforts of NIL on cutting-edge technologies toward IOWN/6G. Toward the deployment of IOWN/6G scheduled for 2030, we will continue to collaborate with business partners and specialists in a variety of industries to achieve early establishment of various elemental technologies.

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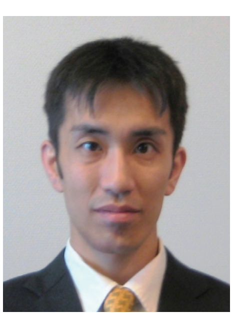

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Remote Robot Control with Haptic Feedback Enabled by Low-latency Transport and Precision Bilateral Control Technologies

Junki Ichikawa, Takuro Yamaguchi, Yasuhiro Mochida, Hitoshi Masutani, Yoshihide Tonomura, and Hirokazu Takahashi

Abstract

The anticipation for advancements in remote robot control technology has been growing. NTT and Sony Group Corporation have collaborated to develop and demonstrate a new remote robot control technology that includes the sensation of touch, such as the feeling of pressure and weight, using low-latency transport and precision bilateral control technologies. This technology provides detailed feedback to operators located remotely, making it feel as though they are physically interacting with objects from afar. This article discusses the potential applications of this technology in various fields, including healthcare and manufacturing.

Keywords: remote robot control, RDMA communication, precision bilateral control

1. Expectations for remote collaborative robots

Demand for robots that cooperate with humans, known as collaborative robots, or cobots, is increasing. These robots are capable of complex cognition and decision-making tasks, as well as precise manipulations that can be complemented by human operators, leading to their anticipated utilization across a wide range of industries. In the construction industry, for example, construction robots can perform tasks that are challenging for human workers, while operators can focus on quality control and machine management, enhancing productivity and improving working conditions. In the medical field, surgical robots provide precise operational assistance, while doctors can make clinical decisions during procedures. Providing operators with the robot's sense of force (the sensation of pressure and weight when touching objects) also allows for even more delicate manipulations. There are various methods for enabling force feedback, but bilateral control, which coordinates the robot with the operator's movements to provide force feedback, is well-known. Thus, in this article, we refer to these robots as "bilateral control robots."

As the demand for collaborative robots continues to rise, remote robot control has also garnered increasing attention as a solution to mitigate the impact of the pandemic and labor shortages. For instance, doctors in Tokyo are able to carry out surgical procedures remotely on patients in rural areas (see **Fig. 1**). Although surgeries can be conducted despite the physical distances separating the doctor and patient, a high-quality network is essential to connect the locations.

Requirements for networks and applications are expected to differ significantly on the basis of the operations they support. The specific requirements

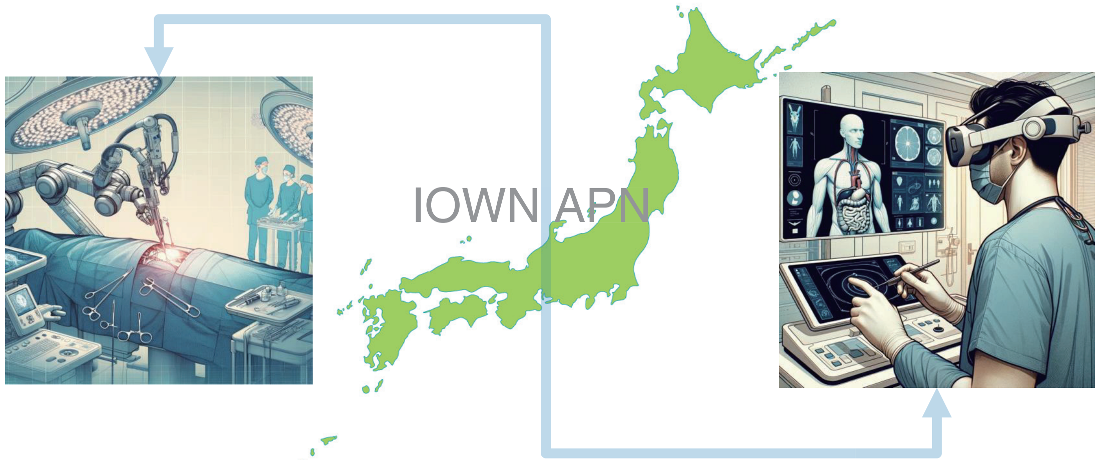


Fig. 1. Remote surgery by teleoperated robot.

Table 1. Network requirements for remote robots.

		Construction robots	Remote surgery robots	Bilateral control robots
Requirements	Position accuracy	Order of centimeters	Less than order of millimeters	Less than order of millimeters
	Latency	Order of several hundred milliseconds	Less than 100 milliseconds	Order of several dozen milliseconds
	Jitter	–	Order of several hundred microseconds	Order of 100 microseconds

for construction robots, remote surgery robots, and bilateral control robots are detailed in **Table 1**. The requirements for remote surgery robots, which necessitates precise control, are more stringent than those for construction robots. The requirements for bilateral control robots, which provide haptic feedback through synchronization, are even more demanding. This is due to the need for these robots to maintain synchronization within microseconds.

2. Technical overview

To enable remote robot control, the integration of robotic technology and communication technology is essential. Therefore, NTT and Sony Group Corporation have combined their respective technologies to undertake a demonstration of remote robot control that incorporates a new tactile experience. This section provides an overview of NTT's low-latency transport technology and Sony's precision bilateral control technology.

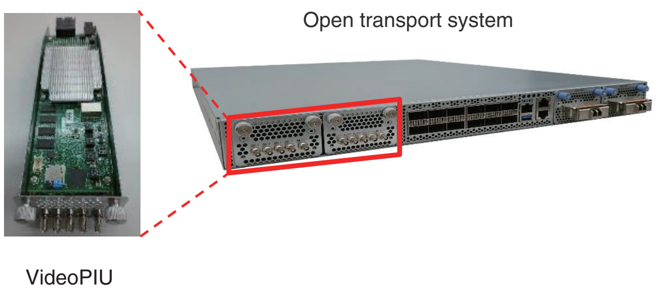
2.1 Low-latency transport technology

NTT is advancing the development of the All-Photonics Network (APN) as part of its commitment to implementing the Innovative Optical and Wireless Network (IOWN)*1, a next-generation communication technology. In APN IOWN1.0, the network can provide a stable, low-latency physical infrastructure by exclusively dedicating optical wavelengths from end-to-end, crucial for mission-critical services. However, it is essential to extend this low latency and stability to robot-side applications. To fully leverage the capabilities of the IOWN APN, our research and development (R&D) efforts are focused on developing low-latency transport technologies that ensure high-quality data delivery directly to the application layer.

2.1.1 Uncompressed video transmission technology [1]

Uncompressed video transmission technology is a

*1 IOWN: An innovative network based on photonics technology, openly developed through collaborative architecture formulation at the IOWN Global Forum.



VideoPIU specifications

FPGA	type	Intel Stratix 10 SX
	clock	200 MHz
	logic	Encap: 237,707 ALM Decap: 193,205 ALM
	DRAM	8 GB
Video	resolution	7680 x 4320 pixels
	frequency	59.94 Hz
	color sampling	YCbCr 4:2:2
	bit depth	10 bits
	buffering	33 ms
Audio	channel	16 ch / SDI
	frequency	48 kHz
	bit depth	16 bits
IP	version	IPv4
	protocol	SMPTE ST 2110 SMPTE ST 2022-7
Power		50 W

Fig. 2. Uncompressed video transmission plug-in unit (VideoPIU) and specifications.

method that enables low-latency feedback of visual information from remote robots to operators. With the recent increase in network capacities, although the required transmission bandwidth becomes larger compared with buffering and compressing video frames, the ability to transmit video with low latency has become more advantageous in real scenarios.

Traditional optical transmission devices were offered as integrated solutions by individual manufacturers, including both hardware and software functions, which made it difficult for service providers to flexibly add additional functionalities for video transmission. In contrast, new open optical transmission devices have started to emerge with a disaggregated configuration. These devices allow for the separation of various functions and the addition of flexible configurations and enhancements through standardized interface control. We have seized this trend and developed an uncompressed video transmission plug-in unit (VideoPIU) that can be used with disaggregated open optical transmission devices (**Fig. 2**).

VideoPIU converts serial digital interface (SDI) signals*2 directly into SMPTE ST2110 streams [2], the standard for Internet protocol (IP)-based video transmission, allowing direct video-signal transmission through open optical transmission devices. VideoPIU is also implemented in hardware, reducing the delay from video input on the transmitting side to video output on the receiving side to within 1 ms. It can process 8K60p video*3 per image and, by linking two images, can achieve 8K120p transmission. It also supports seamless protection (SMPTE ST2022-7 [3]), ensuring continuous delivery without interruption even in the event of network disruptions or temporary failures by using two different optical paths.

2.1.2 Remote direct memory access acceleration technology

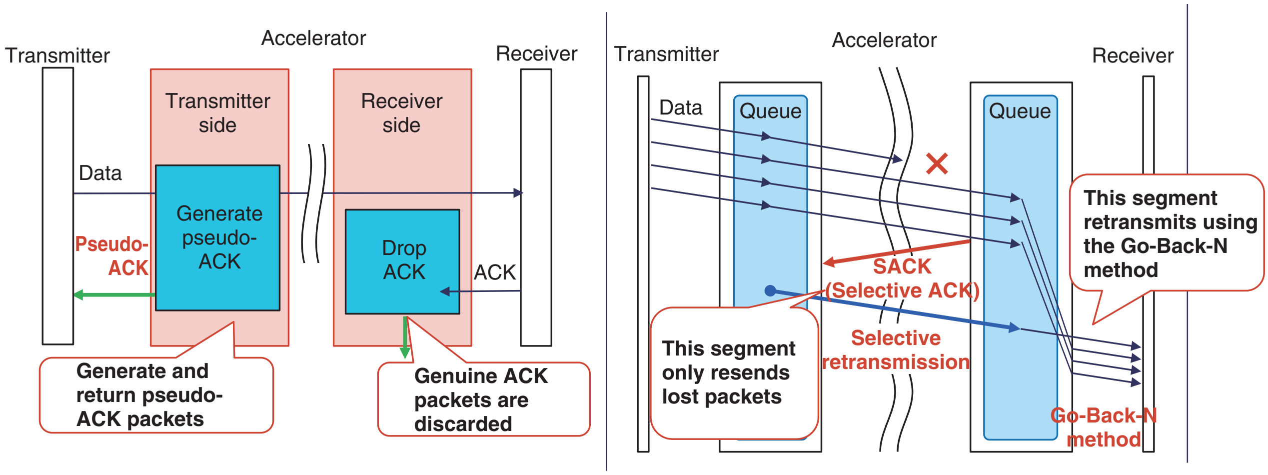
Remote direct memory access (RDMA) communication is widely used in datacenters and high-performance computing domains as a method for achieving high-bandwidth and low-latency data access between computers. RDMA allows for the direct transfer of data from memory to the network without central processing unit (CPU) intervention, making it a highly promising technology for fast, low-latency data transfers essential for time-sensitive and real-time services.

However, RDMA reliable connection, which facilitates reliable data transfers, is primarily designed for short-distance communications within datacenters. This design limitation has historically led to performance issues when adapted for medium to long-distance communications. The latency induced by longer distances typically results in increased waiting times at the requester due to slower acknowledgement (ACK) reception from the responder, subsequently lowering throughput.

To address this issue, we devised a method for

*2 SDI signal: A video transmission method using coaxial cables, widely used in broadcasting equipment.

*3 8K60P video: A video format that transmits ultra-high-resolution video at a resolution of 7680 x 4320 pixels, with a refresh rate of 60 frames per second, delivering clear and detailed visuals.



(a) Configuration of the pseudo-ACK packet method

(b) Segment-based retransmission mechanism

Fig. 3. Technical highlights of RDMA accelerator.

generating pseudo-ACKs near the requester, allowing for the early release of the requester's work queue element and enabling the acceptance of subsequent work requests. This method helps prevent performance degradation by reducing wait times and maintaining throughput (**Fig. 3(a)**).

This innovative method places accelerators near both the requester and responder, bridging long-distance networks. These accelerators create pseudo-ACKs using connection establishment data and request packets, effectively minimizing the waiting period for transmissions. However, this initially resulted in disabled packet-loss detection and retransmission mechanisms, posing significant reliability concerns. To resolve these, we implemented a suitable retransmission mechanism for the communication segments (**Fig. 3(b)**). This mechanism uses the Go-Back-N and selective retransmission strategies by segment, enabling quick recovery from packet loss while maintaining high-speed communication over long distances.

We conducted simulation evaluations of the above method. In the evaluations, we simulated propagation delays typical of long-distance networks and compared the throughput with traditional RDMA communications. The results indicate that under conditions simulating a 1000-km delay, with and without packet loss, there was an average improvement in throughput of 10 and 40 times, respectively, for a message size of 4 KiB (**Fig. 4**).

2.2 Precision bilateral control technology

We have sought collaboration with Sony, which is developing precision bilateral control technology. Sony possesses advanced bilateral control technology capable of flexibly adapting to changes in the external environment in response to human operations and controlling very minute forces with extreme accuracy. This section outlines the overview of the precision bilateral control technology.

Precision bilateral control technology is achieved by synchronizing the actions of two robots: a leader and follower. The follower robot moves in response to the leader robot's actions, and when the follower robot touches an object, the reactive force is transmitted back to the leader robot [4] (**Fig. 5(a)**).

2.2.1 High-sensitivity force sensing technology [5]

To feedback the sensation of touching human soft tissues to the operator, it is necessary to detect minute force changes as small as 1 gf (gram-force, equivalent to 0.0098 N) at the tool tip. However, incorporating force sensors into the system resulted in inertial forces being observed as noise, which made it challenging to detect slight changes in tip force. To address this issue, Sony has applied an optical strain sensor called a fiber Bragg grating (FBG) sensor, which features a diffraction grating etched into part of an optical fiber. Despite its ultra-fine fiber shape, the FBG sensor can measure the strain in the sensor part with high sensitivity. By mounting an ultra-sensitive FBG sensor at the tool tip and improving the algorithm that estimates the three-dimensional force

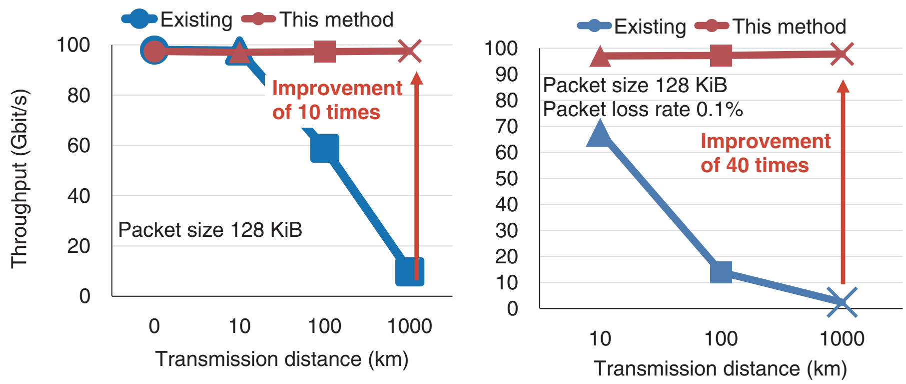
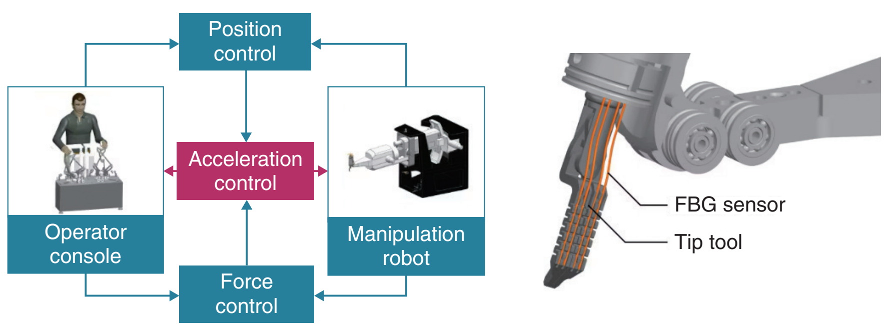


Fig. 4. Effect of accelerators in RDMA communications.



(a) Overview of precision bilateral control

(b) Force-sensor-equipped tip tool

Fig. 5. Precision bilateral control technology.

applied to the tool tip from the sensor's strain amount, Sony has significantly reduced dynamic noise. This advancement allows for the precise detection of even minute force changes as small as 1 gf (**Fig. 5(b)**).

2.2.2 Precision position and force control technology

To achieve precise bilateral control, precise management of both position and force is essential. Traditional algorithms are affected by modeling errors due to variations in the robot's posture, leading to degraded position-tracking performance and vibrations when interacting with external environments. To address this issue, Sony has incorporated its proprietary technology, the generalized inverse dynamics (GID) library*4, into their systems. This integration minimizes the impact of modeling errors caused by changes in robot posture, significantly enhancing responsiveness and operational stability, achieving position accuracy of less than 1 mm.

High-speed real-time processing is crucial for the signal processing involved in precise bilateral control. These signal processing tasks have traditionally been implemented on generic CPUs within a host personal computer (PC), which could not meet control system specifications due to communication delays and interrupt processing delays. To overcome these challenges, Sony has implemented part of the electrical processing on a field programmable gate array (FPGA), which is suitable for high-speed parallel processing. A proprietary protocol has also been developed for communication between the host PC and FPGA, resulting in a system that is 50 times faster than previous systems. By cascading multiple FPGAs using optical fibers, it is now possible to

*4 GID library: A model-based control algorithm that executes optimization calculations considering various constraints to accurately determine the necessary actuation in robots for specific tasks, along with a library that implements this algorithm.

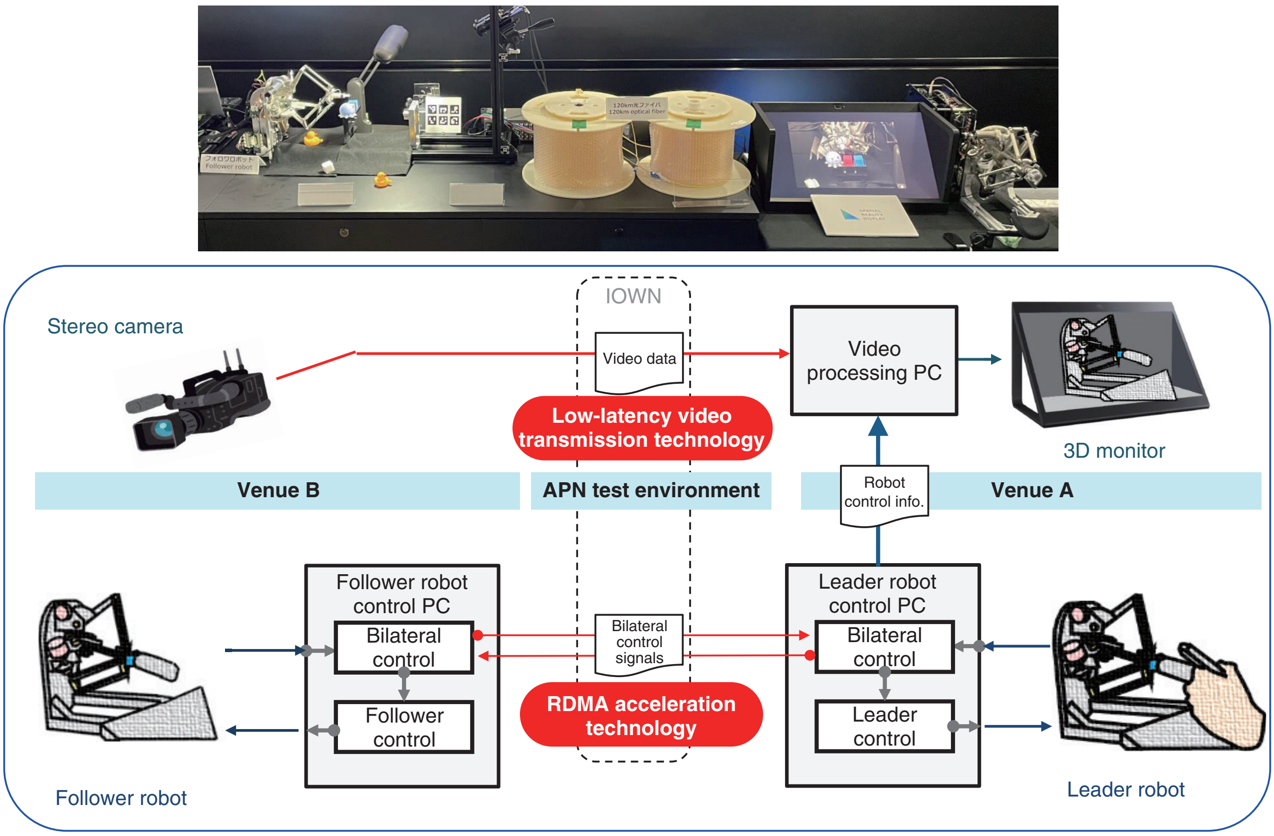


Fig. 6. Configuration and setup of the remote robot control demonstration experiment.

transmit signals with minimal delay in multi-degree-of-freedom systems such as the precision bilateral control system composed of leader and follower robots.

3. Results of the joint demonstration experiment

We conducted a demonstration experiment to verify whether remote robot control with haptic feedback is functional over distances exceeding 100 km. The experiment was carried out in an APN testing environment established at the NTT Musashino R&D Center. This testing environment included configurations such as APN-G (Gateway) and APN-I (Interchange) [6], as discussed in the IOWN Global Forum, representing a projection of future service environments. For this experiment, approximately 120 km of optical fiber was used to connect the setup. The configuration and setup of the experiment are illustrated in **Fig. 6**.

In the demonstration, the leader and follower robots were connected using Sony's precision bilateral robots. The robot control PCs on both the leader and follower sides were equipped with RDMA transfer capabilities, facilitating the transmission and reception of bilateral control signals via an RDMA accelerator. Regarding the visual feedback, side-by-side stereo video was transmitted using VideoPIU and displayed on Sony's ELF-SR2 spatial reproduction display, which enables unaided stereoscopic viewing. It is important to note that the FBG sensor was not used in this experiment as additional tests beyond force feedback evaluation were required.

3.1 Communication evaluation results

Throughout the long-distance demonstration experiment spanning 120 km via the APN, video was transmitted with a remarkably low total latency of 1.6 ms, broken down as 1 ms of video-processing delay and 0.6 ms of APN-transmission delay for the 120 km. For the bilateral control signal communication via RDMA, the total latency was maintained at 1 ms, with an accelerator-processing delay of 0.4 ms, APN-transmission delay of 0.6 ms, and jitter of only 10 µs.

This setup allowed for exceptionally stable and low-jitter communication due to the elimination of CPU intervention, confirming the feasibility of achieving the high stability required by the bilateral control robots, as outlined in Table 1.

3.2 Operational evaluation of bilateral control robots

The operational evaluation revealed that the operator could not perceive any significant distance between themselves and the follower robot, enhancing the sense of immediacy and responsiveness. In this experiment, interactions with objects of varying hardness were performed remotely through the bilateral control robot, enabling the operator to discern even subtle differences in the object's surface texture. The ELF-SR2 spatial-reproduction display also provided natural stereoscopic vision enabled by head tracking, allowing the operator to carry out natural manipulations with a clear sense of spatial depth.

4. Future initiatives

In this initiative, a joint demonstration was conducted in an APN test environment, merging NTT's low-latency transport technology with Sony's precision bilateral control technology. This was aimed at achieving remote control operations that do not let users feel the distance, even when performed over distances exceeding 120 km. The results confirmed that it is possible to meet the stringent requirements demanded of bilateral control robots, allowing operators to feel as though they are directly touching objects in front of them.

Going forward, we plan to expand the scope of precise remote operations beyond geographical limitations by conducting demonstration experiments tailored to specific use cases. Through these efforts, we aim to contribute to the creation of a richer society.

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R&D Activities of Core Wireless Technologies to Implement the Social Infrastructure for IOWN/6G

Hirofumi Sasaki and Seiji Ohmori

Abstract

NTT and NTT DOCOMO are working together to implement "5G Evolution & 6G powered by IOWN," a combination of 6th-generation mobile communication system (6G) networks and the Innovative Optical and Wireless Network (IOWN). In this article, we introduce NTT Network Innovation Laboratories' initiatives for the IOWN/6G era, including orbital angular momentum multiplexing transmission technology in the sub-terahertz band for ultra-high-speed, large-capacity communications and underwater acoustic communication technology for extreme coverage extension.

Keywords: 5G Evolution & 6G powered by IOWN, orbital angular momentum multiplexing, underwater acoustic communication technology

1. Introduction

Nearly four years have passed since the commercial launch of 5th-generation mobile communication system (5G) services in 2020, and its adoption is gradually increasing. In 2023, the national 5G population-coverage ratio reached 96% in Japan [1], and the proportion of 5G smartphones in total smartphone shipments increased to 95% [2]. The mobile communication system, which is essential to the information and communication infrastructure, undergoes a generational change approximately every ten years. Various initiatives and research and development (R&D) efforts are currently underway in many countries and organizations for 6G, which is expected to be implemented in the 2030s. The Innovative Optical and Wireless Network (IOWN), which is promoted by the NTT Group, is an initiative for the next-generation communication infrastructure, to be practically implemented around 2030, similar to 6G, and will be an important communication-infrastructure foundation in the 6G era. The fusion of the 6G network, IOWN, and information-processing technologies is expected to evolve into a social infrastructure that can address various social issues and provide diverse value. This convergence of 6G and IOWN technologies is called "5G Evolution & 6G powered by IOWN," on which NTT and NTT DOCOMO are working closely [3]. The following technical requirements for 6G are described in detail in the DOCOMO 6G White Paper [4]: extreme high data rate, high-capacity communications, extreme low latency, extreme coverage, extreme high reliability, extreme low energy and cost, and extreme massive connectivity and sensing.

In this article, we introduce NTT Network Innovation Laboratories' initiatives for the IOWN/6G era, including orbital angular momentum (OAM)*1 multiplexing transmission technology in the sub-THz band*2 for ultra-high-speed, large-capacity communications, and underwater acoustic communication technology for extreme coverage extension.

*1 OAM: OAM is one of the physical properties of radio waves and is expressed as the product of the positional coordinate and its conjugate momentum. Radio waves with different OAM are uncorrelated and can be superimposed and separated independently.

*2 Sub-THz band: The sub-terahertz band refers to the frequency range between 100 GHz and 1 THz. It is characterized by extremely short wavelengths (ranging from several hundred micrometers to several millimeters) and strong linearity.

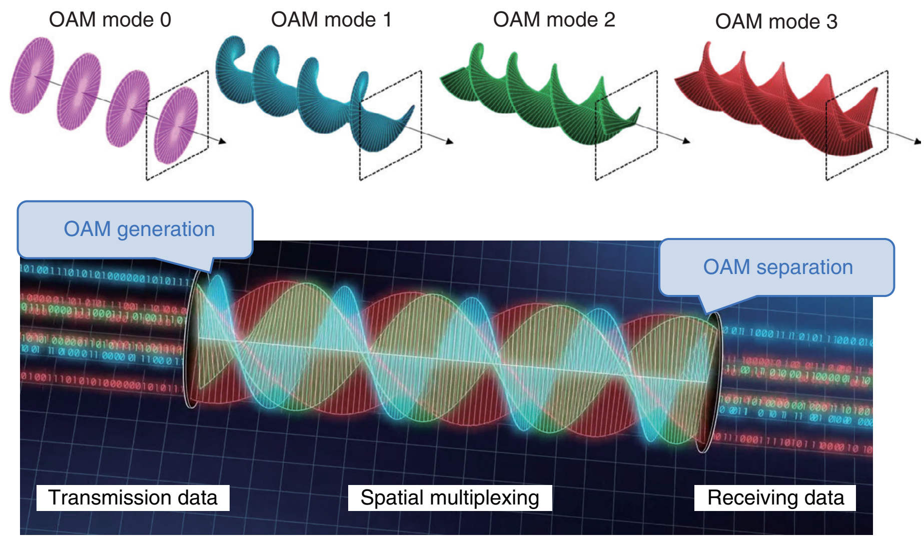


Fig. 1. Schematic of OAM multiplexing transmission technology.

2. OAM multiplexing transmission technology in the sub-THz band

The demand for wireless communications is increasing exponentially and will continue to grow even after 5G. 5G has introduced high-frequency bands called millimeter-wave bands for the first time, providing high-speed wireless communication services by broadening the transmission bandwidth.

In these high-frequency bands, however, radio waves show high straightness and are strongly affected by shielding and propagation losses, requiring base-station facilities and antennas to be placed at higher density. Thus, a more flexible network configuration and higher installability will be required for xHaul*3 connecting base stations and core networks. Wireless transmission technology is a good option to meet these demands and can be used in various scenarios, such as high-density deployment of fixed or temporary base stations in environments where fixed optical wiring is difficult, to take advantage of the flexibility and installability of wireless connection. Considering the functional sharing among base-station facilities and the subordinate connection of multiple facilities, xHaul requires extremely high transmission capacity exceeding 1 Tbit/s. NTT is engaged in R&D of terabit-class wireless transmission technology to support the high-capacity network and information-processing infrastructure of IOWN/6G and prepare for the increasing future demand for wireless communications.

There are three directions that can be taken to increase capacity in wireless communications: increase the spatial multiplexing*4 order, broaden the transmission bandwidth, and increase the modulation level. NTT is taking the approach of increasing the spatial multiplexing order through the use of a new principle based on electromagnetic waves having OAM and broadening the transmission bandwidth using the sub-THz band.

OAM is a physical property of radio waves, and radio waves with OAM (so-called OAM waves) have identical phase trajectories with a helical structure that spirals in the propagation direction (**Fig. 1**). The phase of an OAM wave propagates in a rotation symmetrical to the propagation axis, and OAM waves with integer multiple of the phase rotations are orthogonal to each other. Accordingly, multiple OAM waves with different spiral structures can be superimposed and separated without them interfering with each other if we use a receiver that can receive each OAM wave with its corresponding phase rotation.

NTT takes an approach using an analog circuit called a Butler matrix to increase the spatial multiplexing order by multiplexing multiple OAM waves.

*3 xHaul: General term for transmission networks, such as fronthaul, mid-haul, and back-haul, that connect base-station facilities and core networks.

*4 Spatial multiplexing: A transmission method with which multiple data series are transmitted in parallel by using multiple spatially independent radio waves simultaneously and in the same frequency band.

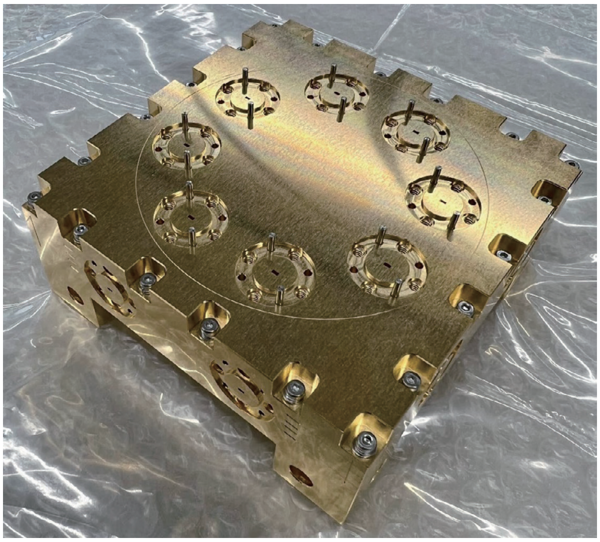
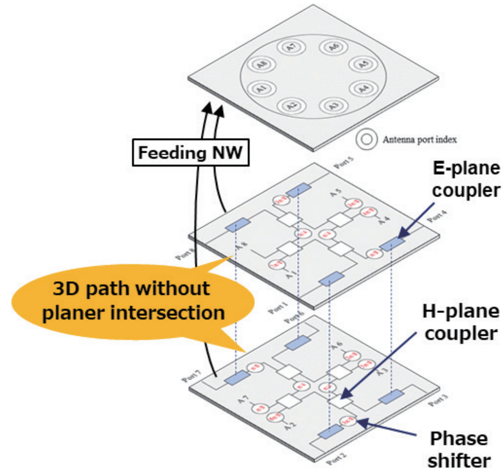


Fig. 2. An antenna-integrated Butler matrix developed for the sub-THz band.



NW: network

Fig. 3. Schematic of multilayer 3D path of the Butler matrix.

This approach reduces the enormous amount of digital signal processing required to eliminate interference between multiplexed data streams in high-capacity communications exceeding 1 Tbit/s. NTT has promoted R&D of sub-THz-band waveguide technology and developed an antenna-integrated Butler matrix that operates with a wide bandwidth and low loss (**Fig. 2**). The antenna-integrated Butler matrix is designed to simultaneously generate and separate eight different OAM waves over a very wide bandwidth, i.e., 135 to 170 GHz, which can be used to multiplex and transmit eight data signals. By executing OAM multiplexing transmission with two different polarizations, it is possible to multiplex and transmit twice as many data signals simultaneously without them interfering with each other.

To transmit eight OAM waves simultaneously by using the Butler matrix, the phase of the radio waves must be controlled with extremely high precision. Since the phase of radio waves varies with frequency, it is extremely difficult to control the phase uniformly over a wide bandwidth by using an analog circuit. We first analyzed the unique radio-wave propagation in a waveguide, which is different from free space, and developed a phase shifter that can theoretically align the advance of phases uniformly over a wide bandwidth.

By designing a multilayer three-dimensional (3D) path (**Fig. 3**) that includes the aforementioned phase shifter so that all paths are electrically equal in length and planar intersections in the circuit (which degrade performance) are eliminated, we developed a prototype Butler matrix that can provide the necessary phase for each OAM mode over 35-GHz width. One characteristic of this Butler matrix is that it is designed as a hollow waveguide, and compared with general dielectric-substrate circuits, it can prevent dielectric loss and radio-wave leakage, achieving low loss despite being a high-frequency circuit.

We conducted transmission experiments using the antenna-integrated Butler matrix and achieved the world's first high-capacity wireless transmission totaling 1.44 Tbit/s in the sub-THz bands of 135.5 to 151.5 GHz and 152.5 to 168.5 GHz in March 2023 [5] (**Fig. 4**), and 1.58 Tbit/s was achieved by further reducing waveguide losses [6]. The next step in this research is to establish and demonstrate terabit-class wireless transmission technology over longer distances exceeding 100 m while envisioning various application scenarios of this technology as xHaul.

3. Underwater acoustic communication technology

3.1 Background

6G, which is being researched and developed for implementation in the 2030s, is expected to not only upgrade mobile communication systems on land but also extreme coverage extension by developing communication areas including air, sea, and space, which have been unexplored areas concerning mobile

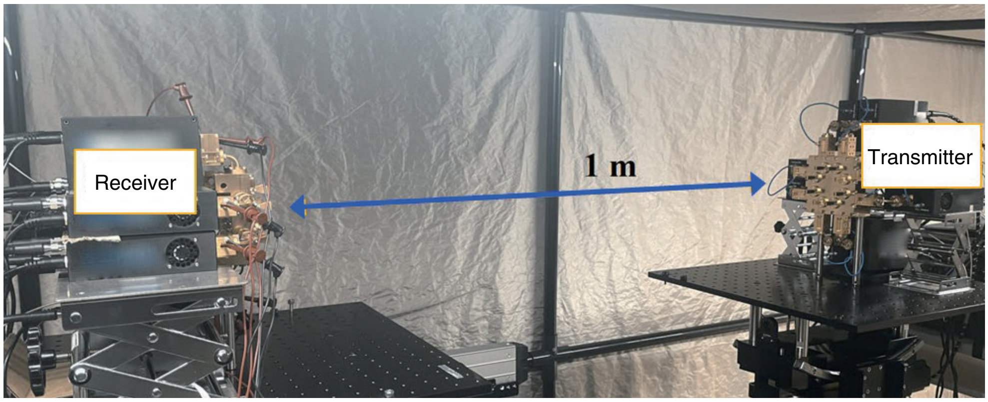


Fig. 4. OAM multiplexing transmission experiments using the Butler matrix.

communication systems [4]. Regarding the sea, it is necessary to improve efficiency by using information and communication technology in sea-based industrial fields such as underwater-resource exploration and port-facility construction, but the use of wireless communications has been difficult.

NTT has been engaged in R&D of underwater acoustic communication technology to enable underwater wireless communications. In November 2022, NTT succeeded in transmitting 1 Mbit/s at 300 m using this technology for the first time and developed a fully wirelessly controlled remotely operated vehicle (ROV) [7, 8].

3.2 Proof of concept for submarine-communication-cable maintenance service

Submarine communication cables are the cornerstone of communications between continents, and most modern international Internet communications are conducted through these cables. The maintenance and inspection of these cables is important, and in the NTT Group, NTT World Engineering Marine (NTT-WE Marine) conducts such maintenance and inspection. Preventive maintenance is important to prevent large-scale communication failures such as disconnection of submarine communication cables. The risk of failure is particularly high in shallow sea areas within a water depth of 30 m, and there is a risk of damage to the exterior and protective pipes as well as the cutting of cables, so inspection is essential. However, inspection divers manually conduct all inspections, which involve risks and is not practical. Therefore, NTT-WE Marine and many other companies are making efforts to improve the inspection efficiency of submarine communication cables by using underwater robots such as ROVs.

However, ROVs are currently controlled through wired connections because wireless communications are difficult under water. In the inspection of submarine communication cables, the inspection range is often from a few meters to a few hundred meters. In shallow waters within a depth of 30 m, where most preventive maintenance is carried out, not only marine structures such as ships and buoys but also rocks and corals on the seafloor become obstacles. Therefore, the operation of the control cables of wire-controlled ROVs is a major challenge.

In September 2023, NTT and NTT-WE Marine conducted a proof of concept (PoC) to investigate an actual submarine communication cable using a fully wirelessly controlled ROV equipped with NTT's underwater acoustic communication technology. **Figure 5** shows an overview of this PoC. A controller for controlling a wireless ROV and underwater-acoustic-communication device are installed in a cable-laying ship, and the wireless ROV is controlled using underwater acoustic communications from the ship. The underwater video captured with the wireless ROV is wirelessly transmitted through underwater acoustic communications, and the condition of the underwater communication cable on board is confirmed. **Figure 6** shows the communication quality and a video frame showing video quality. The submarine-communication-cable inspection with the wireless ROV was carried out for about 1 h, and the success rate of video-frame transmission during that time was about 96%, confirming that submarine-communication-cable inspection with a wireless ROV is possible.

To further improve the performance of the underwater

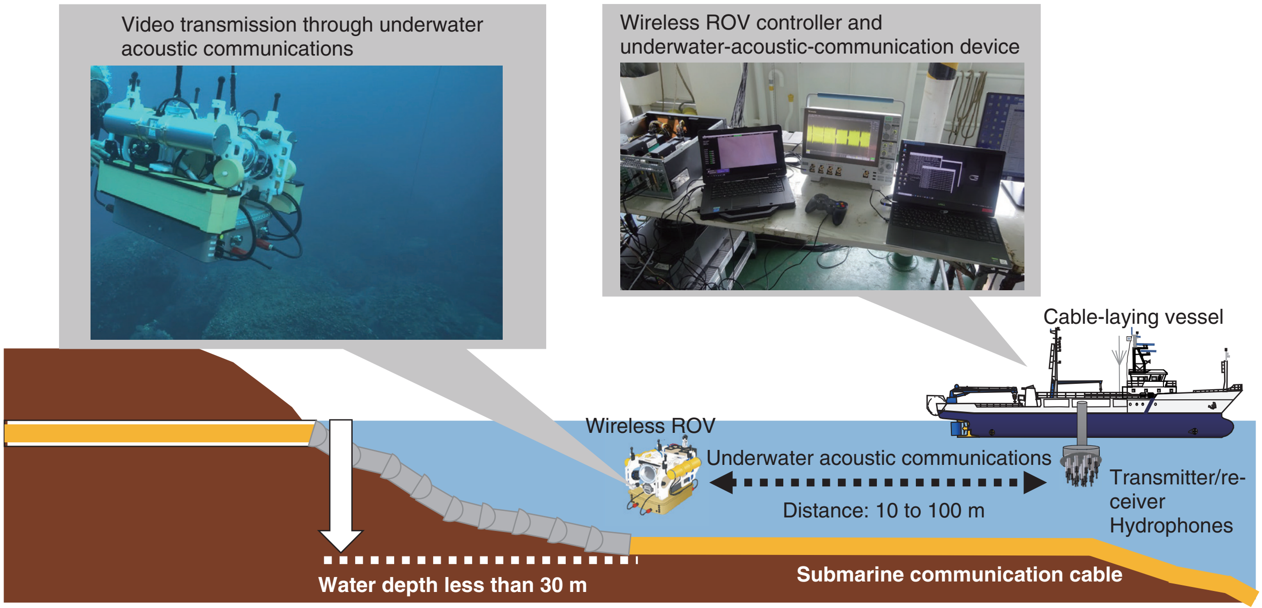


Fig. 5. Overview of PoC of submarine-communication-cable inspection using a fully wirelessly controlled ROV.

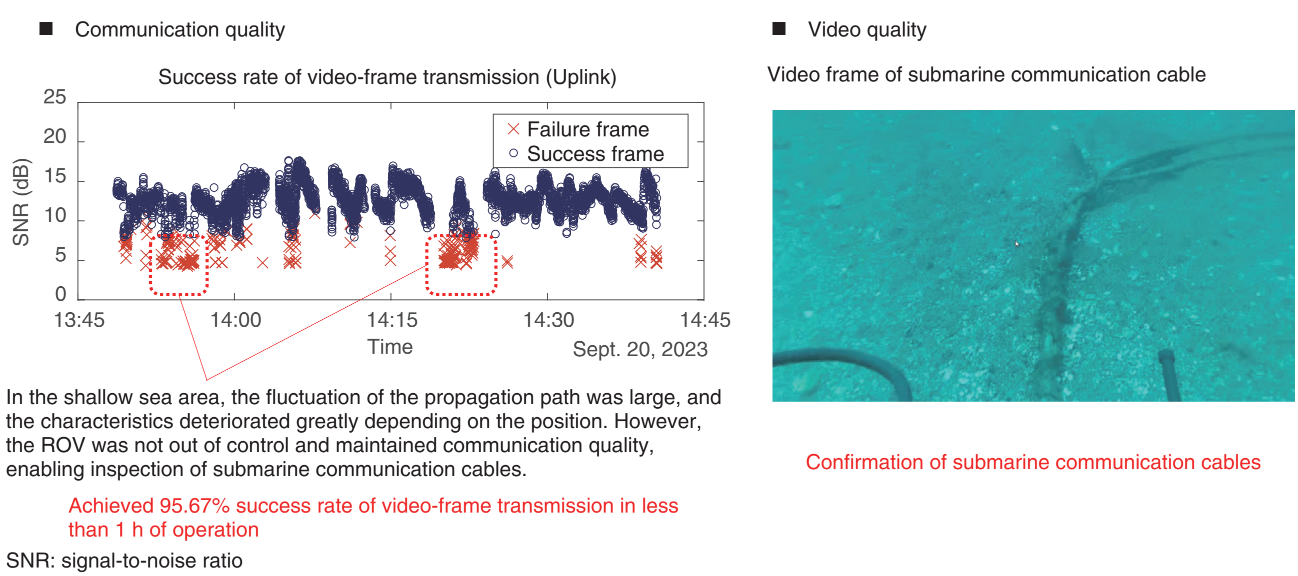


Fig. 6. PoC results.

acoustic communication technology, we will investigate underwater positioning technology to identify where inspection points are located on the seafloor where the Global Positioning System cannot reach and improve the efficiency of inspection work for submarine communication cables.

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Research and Development of 1.6-Tbit/s-class Ethernet Optical Transmission Technology Supporting Large-scale Datacenter Networks

Hiroki Taniguchi, Fukutaro Hamaoka, Kohki Shibahara, Takayoshi Mori, Masashi Kikuchi, and Teruo Jyo

Abstract

To improve the scalability of large-scale datacenter networks, it is necessary to achieve a 10-km transmission of 1.6-Tbit/s optical signal per fiber, which is more than 4 times the conventional practical level. In this article, we introduce a digital-signal-processing technology developed by NTT that is excellent in resistance to waveform distortion due to transmission systems, an ultra-wideband baseband amplifier integrated circuit module, and optical signal transmission experiment in which 400-Gbit/s optical-intensity-modulation signals were transmitted in 4-parallel spatial division multiplexing using a multi-core fiber cable installed at NTT laboratories.

Keywords: optical transmission technology, datacenter network, intensity-modulated direct detection method

1. Large datacenter networks and high-speed Ethernet

Due to the explosive growth in video streaming services, the expansion of cloud services, and the spread of 5th-generation mobile communication system (5G) services, communication traffic is expected to continue increasing. Therfore, traffic within and between datacenters is expected to increase due to the large number of users accessing datacenters.

In datacenter networks, the Ethernet standard is applied as a data-signal transmission method, and the standardization up to 400 Gbit/s was completed as the Institute of Electrical and Electronics Engineers (IEEE) 802.3 standard. Discussions on Ethernet standards of 800 Gbit/s and 1.6 Tbit/s have also started as the next standard [1]. **Figure 1** shows the specific configuration of the standardized Ethernet standards (green) and next Ethernet standards (black). Many Ethernet standards use a multi-lane distribution system for parallel transmission to achieve higher Ethernet speeds. For 400-Gbit/s Ethernet signal transmission, for example, four lanes of 100-Gbit/s signals are transmitted in parallel. The method of parallelization is wavelength division multiplexing (WDM)*1 or using parallel single-mode fiber (PSM)*2. The 1.6-Tbit/s Ethernet standard currently under discussion is a configuration in which 200-Gbit/s signals are multiplexed with 8 lanes of PSMs.

As datacenter network traffic increases, Ethernet switches with a huge capacity are installed, and an increase in the number of ports for Ethernet modules is inevitable. Therefore, for future large-scale datacenter networks, an economical 1.6-Tbit/s high-capacity

*1 WDM: A system that transmits signals in parallel using multiple wavelength channels.

*2 PSM: A system that transmits signals in parallel using multiple optical fibers.

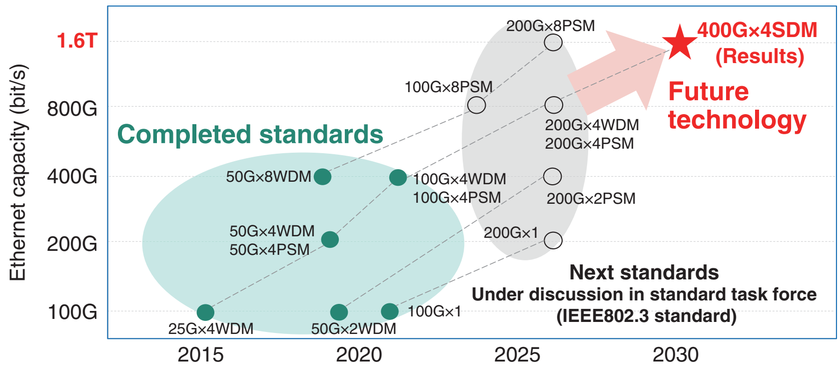


Fig. 1. Trends in Ethernet standard standardization and positioning of results.

Ethernet module is required to increase the capacity per port and reduce the number of installations. To achieve this, it is necessary to increase the speed to 400 Gbit/s per lane and transmit signals in parallel with one fiber and a small number of lanes (4 lanes). The use of the intensity-modulated direct detection (IM-DD)[*3] method, which transmits Ethernet data signals in a simple transceiver configuration, is also an effective means of economizing. Ethernet has standards for transmission distances of 2, 10, and 40 km, but in future large-scale datacenter networks, a transmission distance of 10 km, which broadly supports Ethernet connections within and between datacenters, will be important. The latest Ethernet standard achieves a signal of 100 Gbit/s per lane using the IM-DD method by using the 4-level pulse amplitude modulation (PAM[*4]-4) method with a symbol rate[*5] of approximately 53 GBaud. To speed this up to 400 Gbit/s per lane using the PAM-4 method as before, it is necessary to speed up the signal symbol rate to 200 GBaud or higher. To transmit such ultrafast signals with high quality, it is necessary to increase the bandwidth of the electrical amplifier (driver amplifier for driving optical modulators) in the optical transceiver. With the speedup of the signal, digital-signal-processing technology, which compensates for the distorted signal in the optical transmitter/receiver with extremely high precision at the receiver side, is also necessary, and it is difficult to transmit/receive the signal of 400 Gbit/s per lane with the conventional technology. In such ultrafast signals, the effect of waveform distortion generated in the optical fiber transmission line is very pronounced in proportion to the square of the symbol rate (modulation speed), and the signal quality deteriorates significantly. Therefore, when four different wavelengths are multiplexed in one optical fiber as with the conventional method (WDM method), specification of the wavelength channel far from the zero-dispersion wavelength is essential, and it is difficult to achieve 10-km transmission of the wavelength channel.

2. Development trends in high-speed IM-DD signal transmission and reception technology

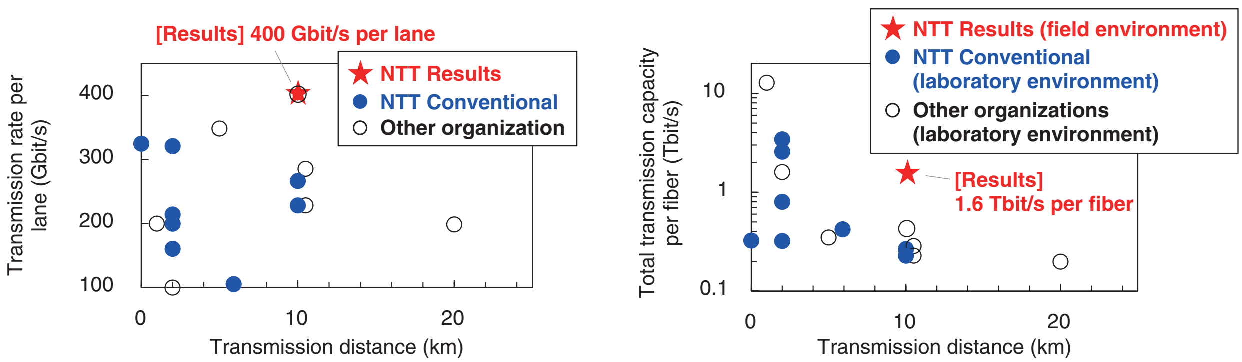
Figure 2 summarizes the research results of IM-DD signal transmission in the Ethernet standard wavelength band (O-band) [2–6]. Figure 2(a) shows the results of a demonstration of a transmission rate of 100 Gbit/s or more per lane, and Figure 2(b) shows the results of a transmission experiment with a total capacity of 0.1 Tbit/s or more per fiber. Transmission experiments with relatively high-speed bitrate per lane (up to 400 Gbit/s [3]) are conducted in a single lane due to the large effect of chromatic dispersion[*6]

*3 IM-DD: Information is added to the light intensity relative to the transmission wavelength. The IM-DD system can be configured with only a semiconductor laser, external optical modulator, driver amplifier, and photodetector, enabling the fabrication of a simple and low-cost optical transceiver.

*4 PAM: A modulation scheme that places information on multiple intensities of signal light. The PAM-4 scheme uses four different light-intensity levels, and the PAM-8 scheme uses eight different light-intensity levels to transmit and receive signals.

*5 Symbol rate: The number of times the optical waveform is switched per second, in baud. The 155-GBaud optical signal achieved in this experiment transmits information by switching the optical waveform 155 billion times per second.

*6 Chromatic dispersion: A phenomenon in which the speed of light propagating through an optical fiber varies with each wavelength. Regarding ultrafast signals, because the signal band to be transmitted is wide and the propagation speed of each wavelength component is different, the effect of signal distortion due to chromatic dispersion becomes significant.



(a) Transmission and reception of 400 Gbit/s ultrafast IM-DD signals by using digital-signal-processing technology excellent in distortion torelance of optical transmitters/receivers, and ultra-wideband baseband amplifier IC module

(b) Successful 10-km transmission experiment of ultrafast IM-DD signals exceeding 1.6 Tbit/s per fiber using field-laid multi-core fibers

Note: As of February 2024 (according to NTT). Experimental results in the wavelength band (O band) of the Ethernet standard in which the IM-DD method is used.

Fig. 2. Results and conventional technology.

[2, 3] (Fig. 2(a)). However, it has been demonstrated that the use of multiple lanes can provide a transmission capacity that exceeds that reported for a single lane, even if the bitrate per lane is relatively low [4, 5] (Fig. 2(b)). For transmission, where the number of lanes to be multiplexed is very large (16 or more), there is concern about the effect of chromatic dispersion even in the O band. Therefore, the space division multiplexing (SDM)*7 method has been combined with the WDM method so that the wavelength range used with the WDM method is not too wide [5].

In an optical transceiver composed of multiple lanes, as described above, an increase in the number of lanes directly leads to an increase in the number of constituent devices and higher prices for the transceiver. Therefore, to develop economical large-capacity Ethernet modules, reducing the number of lanes required by multiplexing high-speed optical signals with low chromatic-dispersion tolerance in multiple lanes is important.

In this experiment, we achieved the transmission and reception of IM-DD optical signals exceeding 400 Gbit/s per lane by NTT's in-house ultra-wideband baseband amplifier integrated circuit (IC) module*8 and ultra-high-precision digital-signal-processing technology (Fig. 2(a)). At the same time, we conducted a 10-km transmission experiment of ultrafast IM-DD signals of 1.6 Tbit/s per fiber with a relatively small number of lanes of 4 (Fig. 1 red and Fig. 2(b)) by implementing chromatic-dispersion management using SDM transmission technology using multi-core fiber [6].

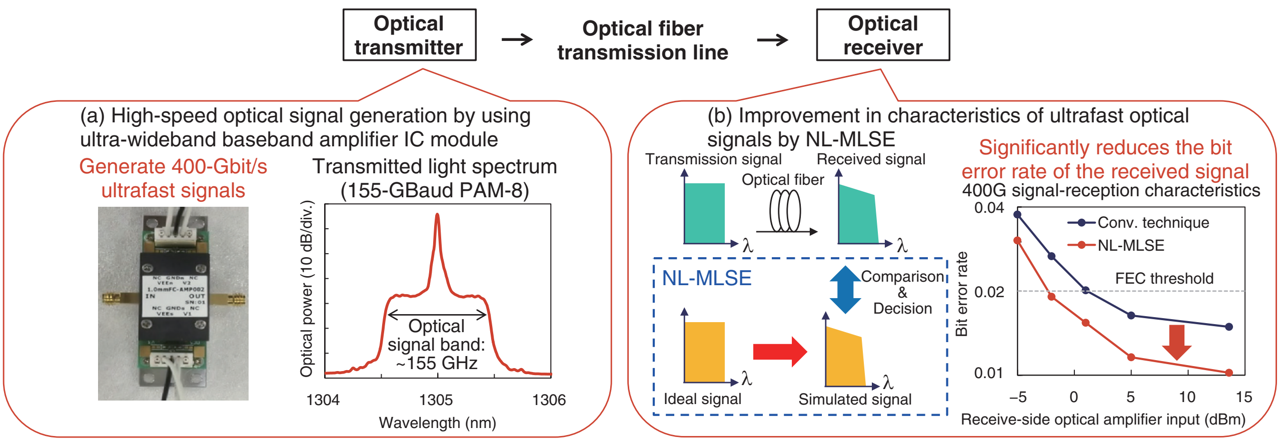
3. NTT proprietary technology details: 400-Gbit/s per-lane ultrafast IM-DD signal transmission/reception technology

An ultra-wideband baseband amplifier IC module [7, 8] corresponding to frequencies up to 110 GHz based on InP-based heterojunction bipolar transistor (InP HBT)*9 technology, which NTT has been researching and developing, was applied as a driver amplifier for driving optical modulators in the optical transmission system. By newly applying the PAM-8 system, which can reduce the symbol rate by 3/4 that with the conventional PAM-4 system, we were able to generate a stable optical signal with an ultrafast IM-DD signal (155-Gbaud PAM-8) of 400 Gbit/s per lane (**Fig. 3(a)**). On the receiver side, NTT's original

*7 SDM: By using multi-core fibers with multiple cores (optical signal channels) in a single optical fiber, multi-mode fibers that propagate multiple modes, etc., it is possible to achieve a dramatically higher communication capacity by using a system that spatially transmits signals in parallel within a single optical fiber.

*8 Ultra-wideband baseband amplifier IC module: An ultra-wideband baseband amplifier IC with the widest bandwidth in the world developed by NTT is mounted in a package with a 1-mm coaxial connector for frequencies up to 110 GHz. InP HBT*9 technology has been used to fabricate amplifier ICs that apply our original high-precision circuit design technology and new circuit architecture technology that enables bandwidth expansion.

*9 InP HBT: A heterojunction bipolar transistor using indium phosphide of a III-V semiconductor. It is a transistor with excellent high speed and breakdown voltage.



FEC: forward error correction

Fig. 3. 400-Gbit/s per-lane ultrafast IMDD signal transmittion and reception technology.

digital-signal-processing technology uses nonlinear maximum likelihood sequence estimation (NL-MLSE)*10 [6] to emulate distorted signals in optical transmitters and receivers and transmission lines with high accuracy. By comparing the emulated signal with the received signal, the bit error rate of the received signal is greatly reduced, enabling the high-quality reception of the ultrafast PAM-8 signal of 400 Gbit/s per lane (**Fig. 3(b)**).

4. NTT proprietary technology details: 10-km multi-core-fiber transmission demonstration of 1.6-Tbit/s ultrafast IM-DD signal per fiber

The ultra-wideband baseband amplifier IC module using InP HBT technology and NL-MLSE developed by NTT enabled transmission and reception of ultrafast IM-DD signals at 400 Gbit/s per lane. For this to be a 1.6-Tbit/s signal, a 400-Gbit/s ultrafast IM-DD signal must be transmitted in four parallel channels. In optical fiber transmission lines, signal waveform distortion occurs due to chromatic dispersion, etc., and the effect becomes more pronounced with higher-speed signals.

To achieve 4-parallel 10-km transmission using the WDM system used in conventional datacenter networks with an optical fiber, a 400-Gbit/s ultrafast, high-multilevel (155-GBaud PAM-8) signal per lane requires severe dispersion management, i.e., verification of specific chromatic dispersion. The specific dispersion range to be considered can be determined from the wavelength range of the wavelength channel defined in the conventional Ethernet standard, range of the zero-dispersion wavelength of the standard single-mode fiber, and dispersion slope, assuming that the system to be considered follows the conventional Ethernet standard [9]. Since the wavelength channel farthest from the zero-dispersion wavelength is more significantly affected by the chromatic dispersion, the narrower the wavelength spacing of each wavelength channel, the better. The narrowest wavelength spacing among the wavelength channels defined by the conventional Ethernet standard is local area network (LAN)-WDM with a frequency spacing of 800 GHz. The chromatic dispersion to be determined takes into account the LAN-WDM wavelength range (1294.5 to 1310.2 nm). Under the above assumptions, the chromatic dispersions for 2- and 10-km transmissions are −5.7 to 1.9 and −28.1 to 9.3 ps/nm, respectively, as shown in the red area in **Fig. 4**. Assuming that 200 Gbit/s (106-GBaud PAM-4), which is scheduled for the next Ethernet standardization, can be multiplexed by 4 lanes of WDM for 10-km transmission, the allowable range of chromatic dispersion for 400-Gbit/s (155-GBaud PAM-8) transmission is determined by considering the difference in baud rate and modulation format and is shown in the green area in Fig. 4 (−5.6 to 5.6 ps/nm). These

*10 NL-MLSE: Maximum likelihood sequence estimation is a technique that improves the accuracy of symbol decision at the receiver by comparing multiple received signals (signal sequences) with multiple candidate sequences that simulate the received signals. In NTT's original NL-MLSE, it is possible to further improve the symbol-decision accuracy by reflecting the nonlinear distortion, which is caused by complex changes in waveform distortion depending on input strength, in the candidate signal sequence in the maximum likelihood sequence estimation.

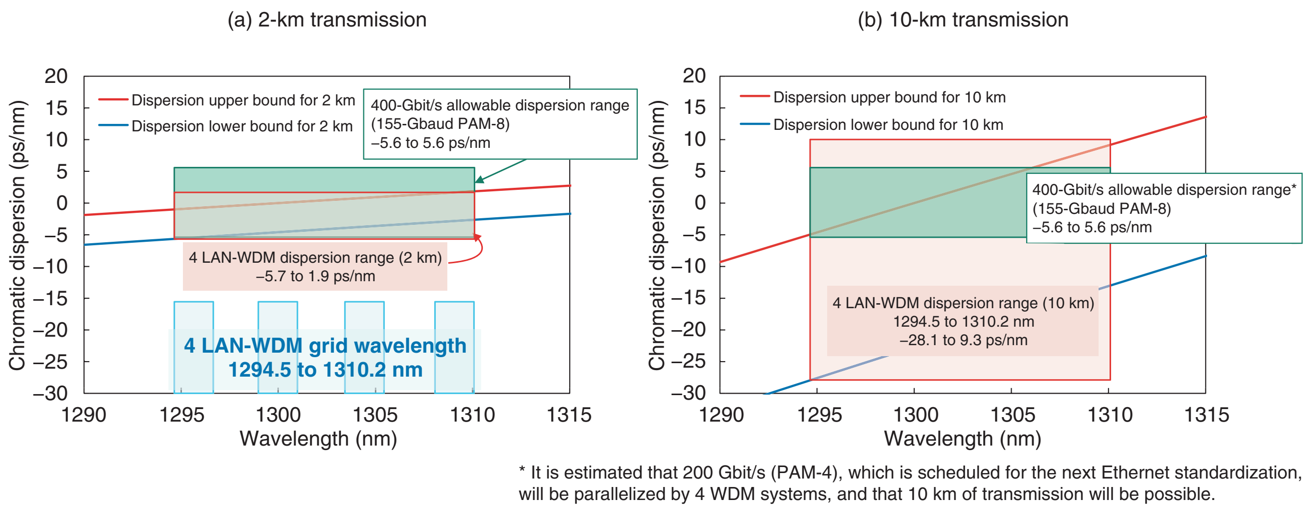


Fig. 4. Chromatic-dispersion characteristics by transmission wavelength and transmission distance.

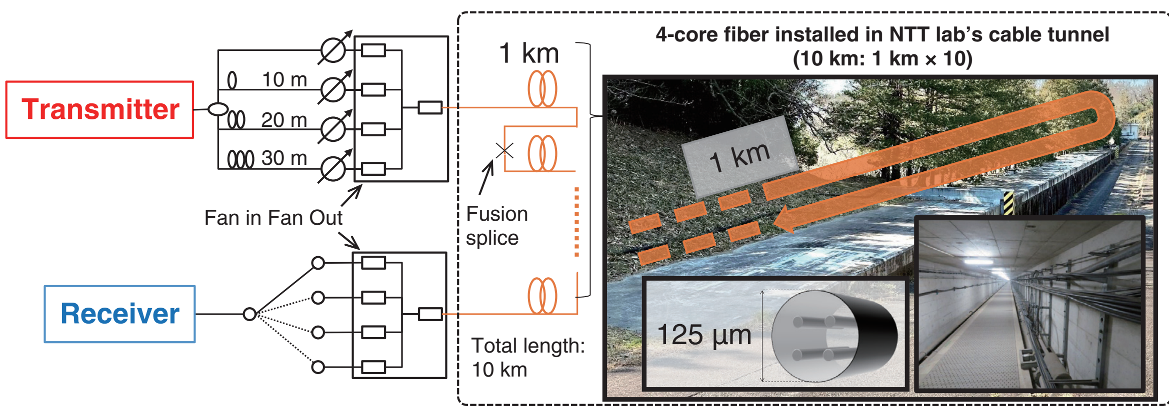


Fig. 5. Experimental 10-km transmission system of 1.6-Tbit/s ultrafast IM-DD signal per fiber.

results indicate that, in 2-km transmission, LAN-WDM can transmit 1.6-Tbit/s signals with 4 lanes of 400-Gbit/s per lane (Fig. 4(a)), except for the fiber with the chromatic-dispersion characteristic where the zero-dispersion wavelength is the longest. In 10-km transmission, however, the range of the chromatic-dispersion amount that must be considered is very wide, and the range of the allowable chromatic dispersion amount of 400 Gbit/s is greatly exceeded; thus, parallelization with the WDM method is not practical (Fig. 4(b)). When wavelength channels are evenly spaced near the zero-dispersion wavelength, the narrower the distance between the wavelength channels, the greater the crosstalk between lanes due to nonlinear optical effects.

In this experiment, we solved these problems by adopting an SDM system using multi-core fibers. Specifically, by assigning one wavelength to each core, we set each of the four cores to a wavelength that is less affected by chromatic dispersion, thereby suppressing the occurrence of nonlinear optical effects (**Fig. 5**). By upgrading the optical signal format from the conventional 4-level (PAM-4) to the 8-level (PAM-8), the symbol rate is reduced by 3/4, and by applying NL-MLSE signal processing, signal-waveform distortion due to chromatic dispersion is greatly reduced.

The transmitters and receivers shown in Fig. 3 were used one by one, and the 400-Gbit/s signal was parallelized by four branches of the optical signal output

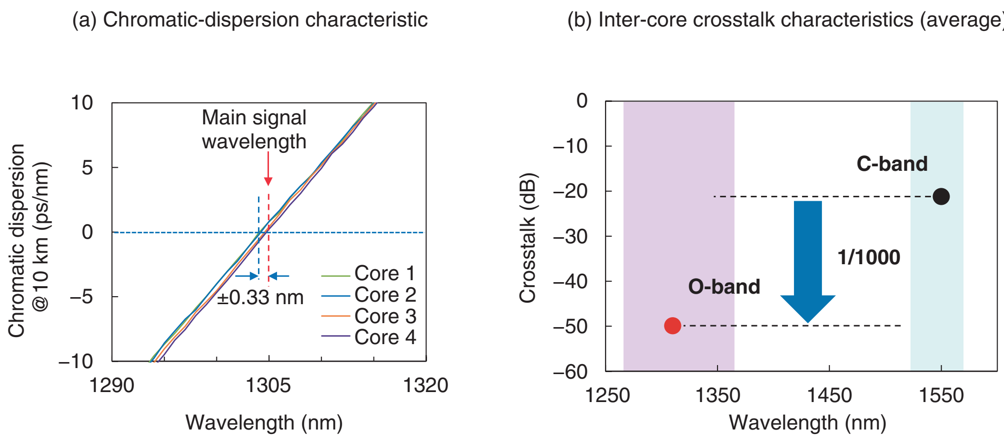


Fig. 6. Multi-core-fiber characterization results.

from the transmitter. Because all the parallelized signals were modulated by the same random symbol sequence, they were connected to fibers of different lengths before they were incident on each core of the multi-core fiber, and the symbol sequence was temporally shifted between each core and each lane, so that inter-lane crosstalk acted as a transmission-performance-degradation factor, as in an actual deployment environment.

The multi-core fiber used in this experiment simulates an actual 10-km cable installation environment by laying a 4-core fiber cable in an underground facility of 1-km round trip in an NTT laboratory and fusing it into 10 round trips [10] (Fig. 5). This 4-core fiber uses the same cladding outer diameter*11 (125 µm) as existing fiber, and each core has the same simple step-index-type refractive index structure as existing fiber. Therefore, crosstalk between cores is an issue in the 1.5-µm wavelength band (C-band), which is generally used for long-distance transmission, but the structure is suitable for mass production. The optical characteristics of each core are equivalent to those of the current international standards for optical fibers, and the dispersion of the characteristics of each core is reduced compared with the PSM system using individual fibers. Therefore, the zero-dispersion wavelength of each core is within ±0.33 nm, light-source wavelength of the transmitter can be the same, and light source can be reduced to 1 in 4-parallel configurations (**Fig. 6(a)**). The crosstalk (amount of light leakage from adjacent cores) between cores during 10-km transmission is about 1/1000 in the 1.3-µm wavelength band (O-band) of the Ethernet standard using the IM-DD system compared with the 1.5-µm wavelength band (C-band), which reduces the optical signal transmission to a level that does not affect it (**Fig. 6(b)**). Therefore, the configuration of this experiment, which involved a multi-core fiber of standard cladding outer diameter and step-index profile to transmit O-band optical signals in one lane per core, could directly solve the problems of chromatic dispersion, nonlinear optical effects, and crosstalk between cores introduced thus far, and can be achieved economically. Therefore, it is highly compatible with a datacenter network with a very large number of installations.

We successfully conducted a field-ambient optical-transmission experiment over 10 km of an ultrafast IM-DD signal exceeding 1.6 Tbit/s per fiber by executing 4-parallel SDM transmission at 400 Gbit/s per lane using a field-installed multi-core fiber and reducing the bit error rate by applying NL-MLSE to the PAM-8 system (**Fig. 7**).

5. Summary

The technologies presented in this article are expected to achieve a large capacity, more than 4 times the conventional practical level, and reliably transmit Ethernet signals exceeding 1.6 Tbit/s per fiber, which will be used in future large-scale datacenter networks.

*11 Cladding outer diameter: The optical fiber used in current optical communications is internationally standardized at 125±0.7 µm in diameter (cladding outer diameter) and 235 to 265 µm in diameter, including the cladding layer that protects the optical fiber, to ensure superior mass production and interconnectivity.

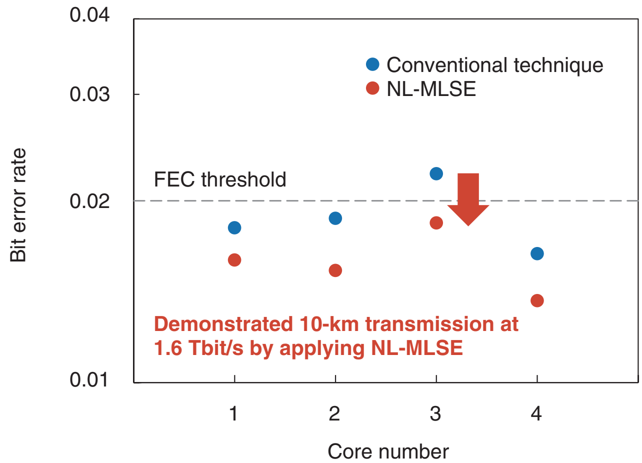


Fig. 7. 10-km transmission results of an ultrafast IM-DD signal at 1.6 Tbit/s per fiber.

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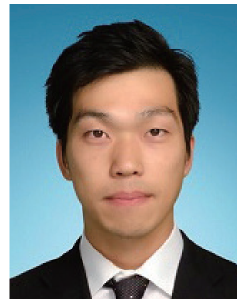

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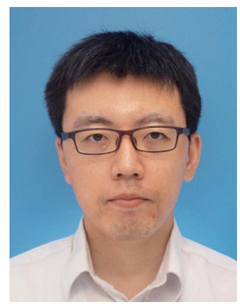

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Mistimed Motor Signals from the Brain Affect Force Precision

Atsushi Takagi

Abstract

Even a seasoned baseball pitcher has difficulty throwing a ball to the same location repeatedly. Such movement variability is assumed to come from neural noise, which causes the muscle activity's amplitude to fluctuate between movements. We explored an alternative source of noise, namely the variability in the muscle activity's timing. We constructed a computational model of a shoulder controlled by two muscles then varied the muscle activity's amplitude and timing independently to predict their effect on the shoulder's force. These predictions were then tested by recording the muscle activity from human participants who used their shoulder to produce periodic forces. The force's variability was explained more accurately by timing noise, suggesting that variable motor timing could play an important role in determining movement precision.

Keywords: force precision, signal-dependent noise, motor timing

1. Introduction

An ideal baseball pitcher can throw a ball to the same location repeatedly. A hallmark of motor skill lies in the ability to carry out actions with both accuracy and precision. While the learning of accurate actions has been revealed by decades of studies, comparatively less is known about how the brain learns to improve movement precision.

Movements are made possible by muscles. The brain sends electrical signals to contract the muscles, which leads to joint motion. Since muscles can only contract, at least two muscles are needed to control a joint. A motion such as moving an elbow from one position to another is composed of a burst in flexor-muscle activity, which accelerates the limb, followed by a burst in extensor activity that slows the elbow down (**Fig. 1(a)**). In a landmark paper, Harris and Wolpert showed that noise in the muscle's activity scales with its activation amplitude. Thus, force variability tends to increase with the magnitude of the applied force [1] (**Fig. 1(b)**). This signal-dependent noise is believed to be a major source of force variability in humans. Another studied showed that sensory noise in vision when localizing the target or final position augments force variability [2]. Others have noticed that noise in planning the duration of the movement can lead to force and movement variability as well [3, 4]. While previous studies have described several sources of noise that contribute to force variability, to the best of our knowledge, no study has investigated how noise in the timing of a burst in muscle activity could lead to force variability. To fill this gap, we explored whether and how volatility in the timing of muscle activity could contribute to force variability.

2. Motor timing as a source of force variability

Day et al. showed that the entire muscle-activity pattern from a single muscle can shift in time when the brain is blasted by an electromagnetic pulse given just before the muscle is activated [5]. The muscle activity's shape remained unchanged, and only its timing was affected. If the brain has a mechanism that controls the timing of muscle activity independently of its amplitude, then neural noise could cause the muscle to activate earlier or later than the intended time. A crude simulation of the resultant force from mistimed flexor and extensor activity revealed substantial force variability when the timing of each burst fluctuated (**Fig. 1(c)**). Mistimed muscle activity

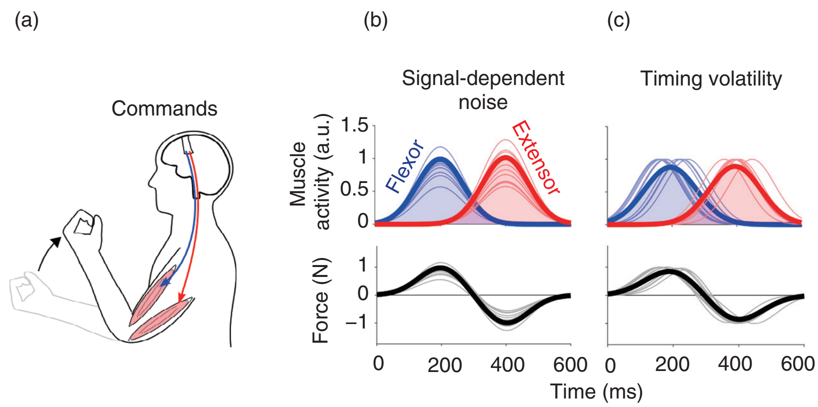

Fig. 1. Force variability during movements as predicted from signal-dependent noise and noise in motor timing.

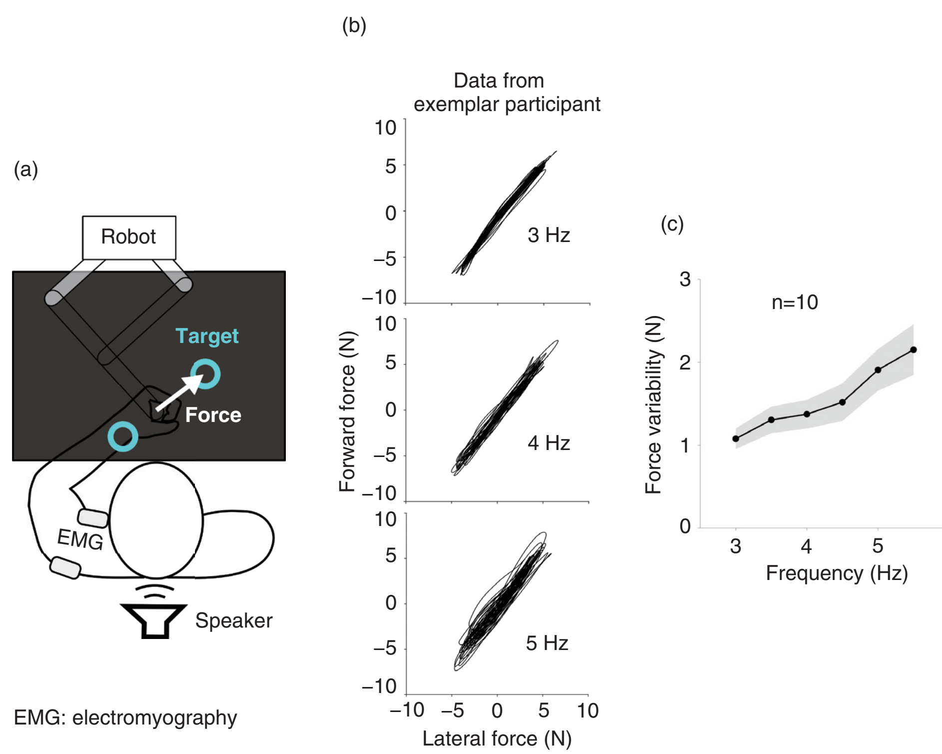

Fig. 2. Experiment to measure the arm's force variability during rhythmic force production. Force variability increased with frequency.

also shifted the timing of the peak force unlike with signal-dependent noise and baseline noise where only its amplitude was affected. When the brain controls the arm's force, how much of its variability can be explained by timing volatility?

3. An experiment to observe the arm's force variability

We asked ten right-handed participants to use their left shoulder to push and pull a robotic handle, the position of which was fixed to prevent motion (**Fig. 2(a)**). A speaker produced periodic beeps at a

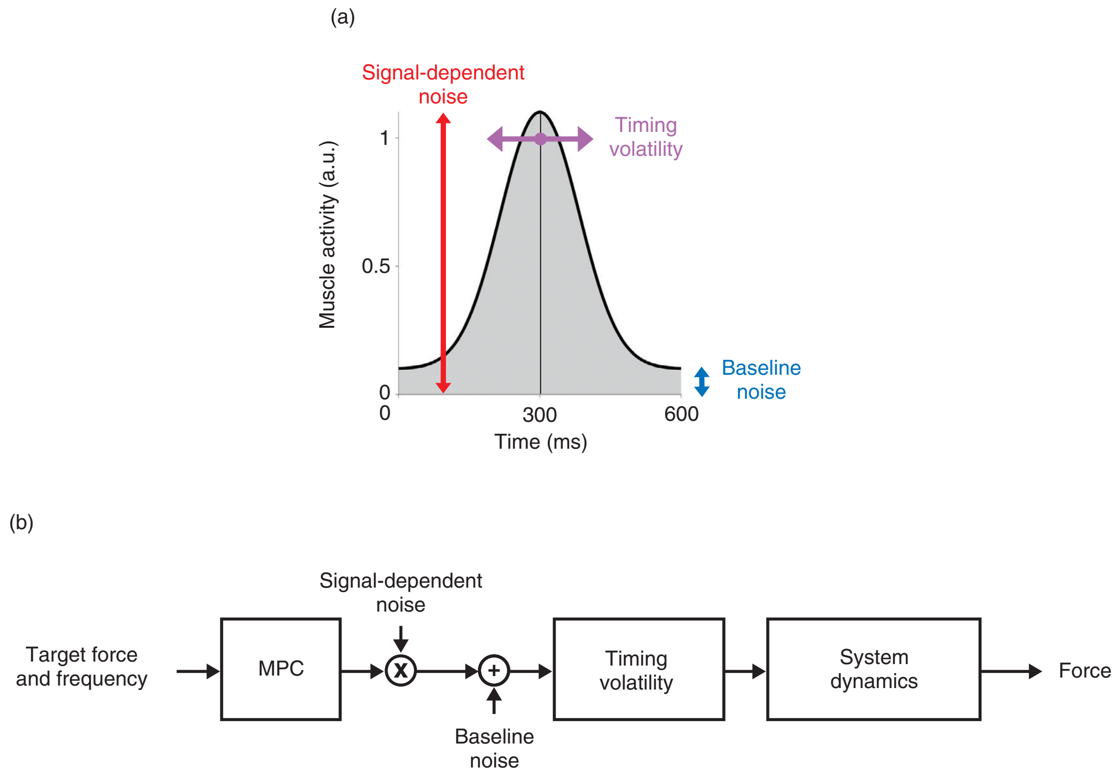

Fig. 3. Computer model of the shoulder to test the source of noise that could explain the empirically observed force variability.

frequency of either 3, 3.5, 4, 4.5, 5, or 5.5 Hz. Participants had to use their shoulder to push and pull the handle to hit two targets displayed on a monitor at the designated frequency. During this task, the shoulder's force and the muscle activity from its flexor and extensor muscles were recorded. The force trajectory from an exemplar participant showed that the force variability grew as the speaker's frequency increased (**Fig. 2(b)**). To quantify this relationship, we calculated the force magnitude from each trial and examined how its variability changed as a function of the frequency. Data from all participants revealed that the force variability positively correlated with its frequency (**Fig. 2(c)**). What source of noise in the muscle activity contributed to this increase in force variability?

4. A model of shoulder-force control

The shoulder's force variability could come from several different sources. To understand their contributions to the final force variability, we constructed a computer model of the shoulder controlled by flexor and extensor muscles that pushed and pulled against a rigid constraint similar as in the experiment. In this model, we considered how the muscle activity was corrupted by three sources of noise. First, a baseline noise changes the entire amplitude of the muscle activity (blue in **Fig. 3(a)**). Second, signal-dependent noise modulates the amplitude of the muscle activity, effectively scaling its size (red in Fig. 3(a)). Third, the timing of the muscle activity changes from one burst to the next (magenta in Fig. 3(a)). When simulating each burst in muscle activity, these three sources of noise were controlled independently. Noise was resampled for every burst. We used model predictive control (MPC) to optimize the flexor and extensor muscle activity to generate the correct amount of force at the intended frequency [6] (**Fig. 3(b)**). After this optimization process, noise was added to the muscle activity.

We first determined whether our model could generate muscle activity that resembled those recorded during the experiment. **Figure 4(a)** shows the filtered muscle activity and force of an exemplar participant producing a force at 5 Hz. When the model was set to

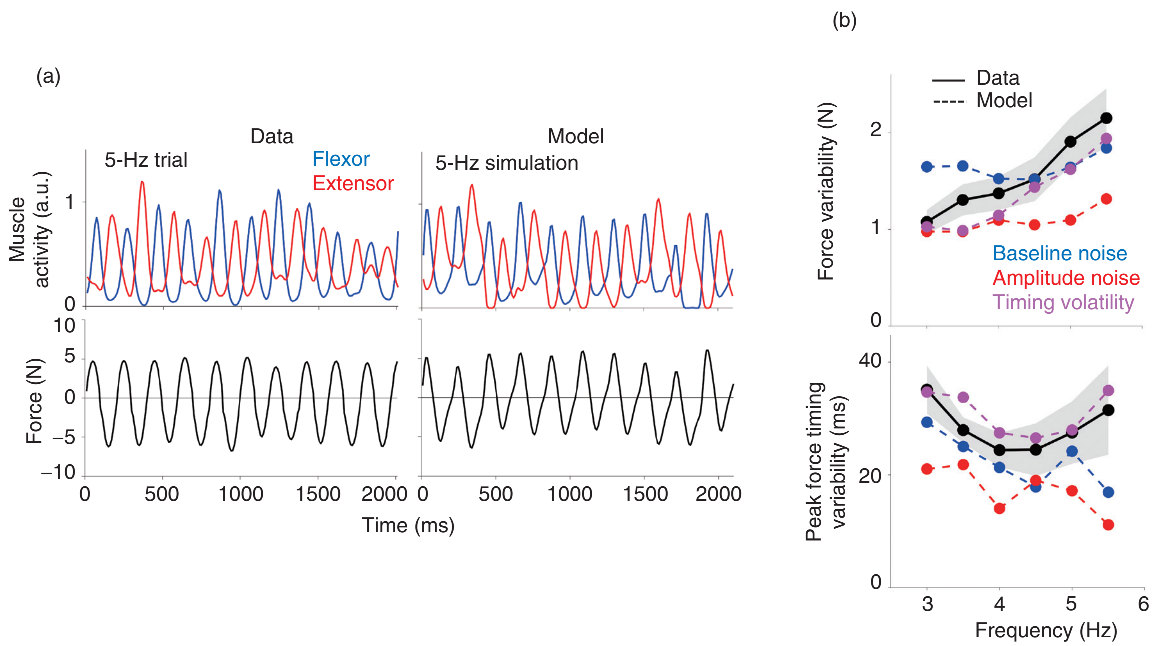

Fig. 4. Computer model of the shoulder produced simulated muscle activity and force that resembled those recorded during the experiment.

produce a force at 5 Hz, the simulated muscle activity and force resembled the empirical data (right of Fig. 4(a)). Using this human-like model, we manipulated the baseline noise, signal-dependent noise, and timing volatility independently to best fit the data from the experiment. Importantly, the amount of baseline noise and timing volatility was kept the same for all frequencies, but signal-dependent noise was increased linearly from 3 to 5.5 Hz since such noise increases with speed [1]. However, the size of the signal-dependent noise was kept below 5% within the empirically observed range [7, 8]. When the noise from one source was manipulated, the other two noise sources were fixed. This enabled us to study the effects of each source of noise independently and assess their ability to explain the data.

Baseline noise only increased the force variability evenly for all frequencies (top of **Fig. 4(b)**). While signal-dependent noise caused the force variability to increase as a function of the frequency, the predicted force variability underestimated the observed value. Furthermore, signal-dependent noise could not accurately predict the variability in the peak force's timing (bottom of Fig. 4(b)). When timing volatility was injected into the model, the simulated force's variability gradually increased with frequency as in the data, and timing volatility predicted the variability in the peak force's timing more accurately than baseline noise and signal-dependent noise. Thus, while baseline and signal-dependent noise in the muscles affects the amount of force variability and can explain its dependence on frequency, only timing volatility could accurately predict both the force variability and variability in the peak force's timing.

Next, we calculated the variability in the timing of the peak force in both the data and model (bottom of Fig. 4(b)). Again, the model with timing volatility was most accurate at explaining the variability in the peak force's timing. These results suggest that fluctuations in the timing of muscle activity play an important role in determining the variability of the arm's force.

5. Conclusion

We conducted an experiment and simulation to understand how different sources of noise in muscle activity could affect the variability in the arm's force. While both baseline and signal-dependent noise play an important role in movement variability, they could not explain how force variability increases as a function of its frequency. The results suggest that timing volatility could be an important factor that sways the variance of the arm's force. Future research will delve into how timing volatility affects the variability of movements and determine whether the source of variable timing is in the periphery or is more centrally located in the brain.

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ITU World Radiocommunication Conference 2023 (WRC-23)

Shinya Otsuki, Nobuki Sakamoto, Saiko Kameda, and Junichi Iwatani

Abstract

Since radio waves used in radio communications travel across national borders, international rules are required. Therefore, the International Telecommunication Union (ITU), the United Nations' organization specialized in telecommunications, set forth the Radio Regulations (RR), which provides international rules for radio waves in each frequency and in each region of the world. The RR is reviewed and revised about every four years, and the international conference held for this purpose is the ITU World Radiocommunication Conference (WRC). Since the revised RR will be reflected in the regulations of Japan, the WRC is an extremely important meeting for the NTT Group, which provides mobile phones and other wireless services. This article reports on the ITU WRC 2023 (WRC-23) held in Dubai, United Arab Emirates, from November 20 to December 15, 2023.

Keywords: ITU-R, World Radiocommunication Conference, Radio Regulations

1. ITU World Radiocommunication Conference 2023 (WRC-23)

The World Radiocommunication Conference (WRC) is the largest conference in the International Telecommunication Union (ITU) to discuss updating the Radio Regulations (RR), which provides international rules and regulations for allocation of the spectrum to radio services, use of satellite orbits, and administrative and operational procedures for radio stations. The WRC is usually held every three to four years [1] and the last WRC, the ITU WRC 2023 (WRC-23), was held in Dubai, United Arab Emirates, from November 20 to December 15 (**Fig. 1**). Approximately 3900 participants from 163 Member States attended the WRC-23 and discussed agenda items for revision of the RR, as shown in **Table 1**. About 130 delegates from Japan, including the Ministry of Internal Affairs and Communications, other government agencies, and private companies attended the WRC-23, as well as NTT and NTT DOCOMO from the NTT Group.

In the RR, the world is divided into three regions, as shown in **Fig. 2**, and frequencies are allocated to services all over the world or in each region. In some cases, frequencies are allocated to services only for specific countries. As also shown in Fig. 2, there are four regional telecommunication organizations in Region 1, one in Region 2, and one in Region 3. Each

Fig. 1. WRC-23 meeting session.

Table 1. Agenda items of WRC-23.

No.	Agemda item
1.1	Possible measures to address, in the frequency band 4800–4990 MHz, protection of stations of the AMS and MSS located in international airspace and waters from other stations located within national territories and to review the pfd criteria in No. 5.441B.
1.2	Study of IMT identification including primary distribution to mobile operations in the 3300–3400 MHz, 3600–3800 MHz, 6425–7025 MHz, 7025–7125 MHz and 10.0–10.5 GHz bands
1.3	Studies to consider possible allocation of the frequency band 3600–3800 MHz to the mobile, except aeronautical mobile, service on a primary basis within Region 1
1.4	Facilitating mobile connectivity in certain frequency bands below 2.7 GHz using high-altitude platform stations as International Mobile Telecommunications base stations
1.5	Review of the spectrum use of the frequency band 470–960 MHz in Region 1
1.6	Consideration of regulatory provisions to facilitate the introduction of sub-orbital vehicles
1.7	Studies on a possible new allocation to the aeronautical mobile-satellite (R) service within the frequency band 117.975–137 MHz in order to support aeronautical VHF communications in the Earth-to-space and space-to-Earth directions
1.8	Review and possible revision of Resolution 155 (Rev.WRC-19) and No. 5.484B in the frequency bands to which they apply
1.9	Consideration of regulatory provisions for updating Appendix 27 of the Radio Regulations in support of aeronautical HF modernization
1.10	Studies on frequency-related matters, including possible additional allocations, for the possible introduction of new non-safety aeronautical mobile applications
1.11	Consideration of possible regulatory actions to support modernization of the Global Maritime Distress and Safety System and the implementation of e-navigation
1.12	Possible secondary allocation to the Earth exploration-satellite service (active) for spaceborne radar sounders in the range of frequencies around 45 MHz
1.13	Examination of a possible upgrade to primary status of the secondary allocation to the space research service in the frequency band 14.8–15.35 GHz
1.14	Review of existing distributions and review of new distributions for earth exploration satellite services (passive) in the 231.5–252 GHz band in accordance with the requirements of modern remote sensing observations
1.15	Operation of earth stations on aircraft and vessels communicating with geostationary space stations in the fixed-satellite service in the frequency band 12.75–13.25 GHz (Earth-to-space)
1.16	Use of the frequency bands 17.7–18.6 GHz, 18.8–19.3 GHz and 19.7–20.2 GHz (space-to-Earth) and 27.5–29.1 GHz and 29.5–30 GHz (Earth-to-space) by earth stations in motion communicating with non-geostationary space stations in the fixed-satellite service
1.17	Study of technical and operational issues and regulatory provisions for satellite-to-satellite links in the frequency bands 11.7–12.7 GHz, 18.1–18.6 GHz, 18.8–20.2 GHz and 27.5–30 GHz
1.18	Studies relating to spectrum needs and potential new allocations to the mobile satellite service in the frequency bands 1695–1710 MHz, 2010–2025 MHz, 3300–3315 MHz and 3385–3400 MHz for future development of narrowband mobile-satellite systems
1.19	Primary allocation to the fixed-satellite service in the space-to-Earth direction in the frequency band 17.3–17.7 GHz in Region 2
2	Use of incorporation by reference in the Radio Regulations
4	General review of the Resolutions and Recommendations of world administrative radio conferences and world radiocommunication conferences
7	Implementation of Resolution 86 (Rev. Marrakesh, 2002) of the Plenipotentiary Conference
8	Footnotes to the Table of Frequency Allocations in Article 5 of the Radio Regulations
9	Report of the Director of the Radiocommunication Bureau
9.1	Activities of the ITU Radiocommunication Sector since WRC-19
Issue a)	Protection of radio spectrum-reliant space weather sensors used for global prediction and warnings
Issue b)	Studies on technical and operational measures to be applied in the frequency band 1240–1300 MHz to ensure the protection of the radionavigation-satellite service (space-to-Earth)
Issue c)	Use of International Mobile Telecommunications systems for fixed wireless broadband in the frequency bands allocated to the fixed service on a primary basis
Issue d)	Protection of EESS in the frequency band 36–37 G
9.2	Report of the Director on any difficulties or inconsistencies encountered in the application of the RR and comments from administrioons
9.3	Action in response to Resolution 80 (Rev. WRC-07)
10	Preliminary agenda for the 2027 World Radiocommunication Conference

AMS: aeronautical mobile service
EESS: Earth exploration-satellite service
HF: high frequency
MSS: mobile-satellite service
VHF: very high frequency

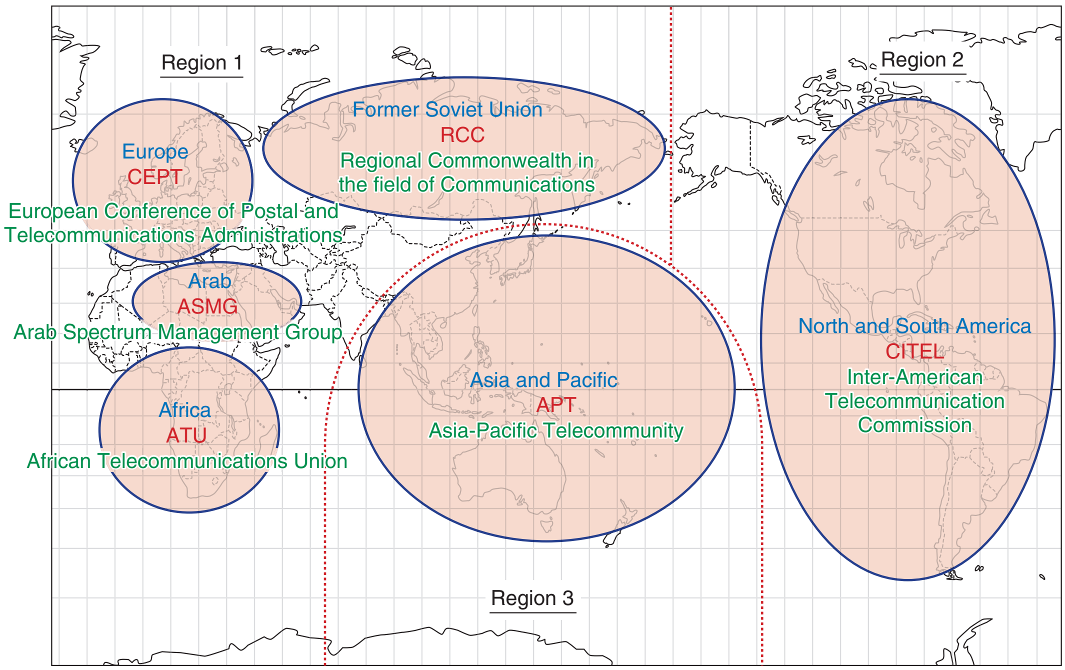

Fig. 2. Regions in the RR and regional telecommunication organizations.

regional telecommunication organization conducts activities for preparation work on WRC. Japan is a member of the Asia-Pacific Telecommunity (APT) in Region 3 and is also active in the APT Conference Preparatory Group for WRC (APG), which develops common proposals for WRC from APT.

Figure 3 shows the structure of WRC-23. There are seven committees (COMs 1–7) under the Plenary. Discussions to revise the RR were mainly made in COM 4 for terrestrial/maritime/aeronautical issues, COM 5 for satellite issues, and COM 6 for general issues and agenda items for future WRCs. Dr. Hiroyuki Atarashi (NTT DOCOMO) from Japan was appointed as the chair of COM 4, which addresses terrestrial issues, including identifications of frequencies for International Mobile Telecommunication (IMT)*1 such as fifth-generation mobile communication systems (5G) and Beyond 5G (agenda item 1.2) and considerations on the use of high-altitude platform stations (HAPS)*2 as IMT base stations (HIBS) for the implementation of non-terrestrial networks (NTN) (agenda item 1.4).

1.1 Identification of frequencies for IMT (agenda item 1.2)

Regarding the additional identification of frequencies for IMT such as 5G and Beyond 5G, discussions were held on the frequency range of 6425–7025 MHz (Although the scope of this agenda item is only for Region 1, this agenda item relates to Japan in Region 3 and the details are described later in this article) and the frequency range of 7025–7125 MHz (worldwide). Japan supported the identification of the frequency range of 7025–7125 MHz for IMT based on the studies conducted by the ITU Radiocommunication Sector (ITU-R) and supported the identification of the frequency range of 6425–7025 MHz for IMT in Region 1 because of the benefit of economies of scale. Although identification of the frequency range of 6425–7025 MHz for IMT in Region 3 is out of the scope of this agenda item, proposals were made for identification of this frequency range for IMT in 6 countries in Region 3, including China, and countries in Region 2. From the view of the harmful interference to existing radio systems, such as satellite systems, that are operated in the same frequency band, discussions were held with respect to the limit on

*1 IMT: Includes 3rd-generation mobile communication systems and beyond, such as IMT-2000, IMT-Advanced, IMT-2020, and IMT-2030.

*2 HAPS: Airborne platform expected to operate at high altitude such as stratospheric environment using solar plane type aircraft and airships. The frequencies used for communications between HAPS and the ground base station (gateway station) (feeder link) was added at WRC-19.

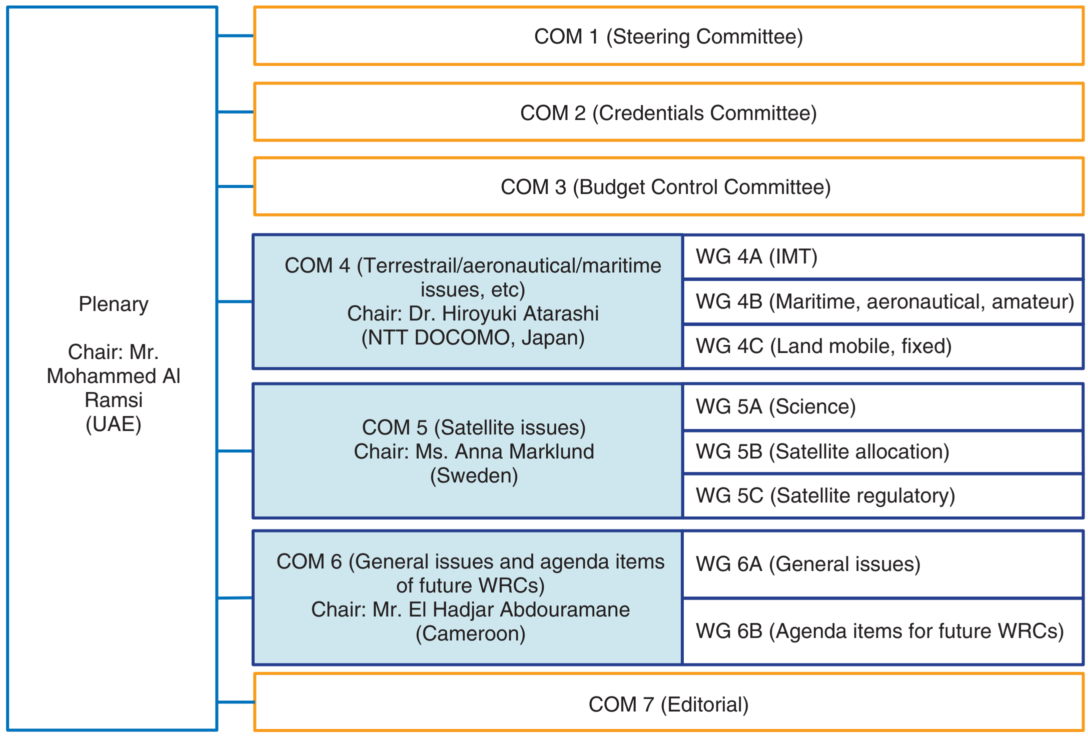

Fig. 3. Structure of WRC-23.

equivalent isotropic radiated power applied to IMT base stations. After discussion, consensus was finally reached, and the identification of the frequency range of 7025–7125 MHz for IMT was agreed to in all of Region 1, some countries in Region 2 (Brazil and Mexico), and all of Region 3. Regarding the proposal of identifying the frequency range of 6425–7025 MHz for IMT in some counties of Region 3, considering the interference to neighbouring countries, identification of this frequency range to only a few countries (Cambodia, Laos, and Maldives), excluding China, was agreed. Identification of the frequency range of 6425–7025 MHz for IMT was also agreed in all of Region 1 and in some countries in Region 2 (Brazil and Mexico).

1.2 Consideration of the use of HIBS (agenda item 1.4)

In Beyond 5G, a space radio access network (RAN) and NTN are expected to be implemented, which will enable the expansion of coverage in mountainous areas and at sea and the quick restoration of communication networks in the event of a large-scale disaster. HIBS is one candidate to implement a space RAN and NTN [2]. At the previous WRC (WRC-19), Japan proposed and led discussions to include the consideration of HIBS in the WRC-23 agenda item, and at WRC-23, discussions were held on the addition of new frequency bands (694–960, 1710–1885, 2500–2690 MHz) and a review to relax conditions for the use of existing available frequency bands (1885–1980, 2010–2025, 2110–2170 MHz) for use of communications between HIBS and terminals. As a result of the discussions, the addition of new frequency bands other than 694–960 MHz and the relaxation of conditions in the existing available frequency bands were agreed. Regarding the 694–960-MHz band, there were many discussions with China, Russia, Vietnam, and Iran, who were concerned about interference to existing systems. Finally, it was agreed to use this frequency band for HIBS in Regions 1 and 2. In Region 3, it was also agreed to use the entire frequency band or portions of this frequency band for HIBS in 14 countries, including Japan and countries where HIBS is expected to be deployed[*3].

*3 HIBS (694–960 MHz): The entire band or portions of this band is now available in Australia, Maldives, Micronesia, Papua New Guinea, Tonga, Vanuatu, China, India, Indonesia, Japan, Korea, Malaysia, Philippines, and Thailand.

1.3 Other agenda items (agenda items relating to science and satellite issues)

Other topics relating to science and satellites issues were also discussed. In agenda item 1.13, consideration was made to upgrade the status of space research (satellite-to-satellite, satellite-to-Earth station) in the frequency range of 14.8–15.35 GHz from secondary service to primary service[*4], and it was agreed to upgrade the status to primary service in principle. However, it was also agreed to apply a power flux density (pfd) limit at the surface of the Earth to radio waves transmitted from a satellite for satellite-to-satellite link and to keep a secondary basis between a satellite and an Earth station with respect to the protection of terrestrial services in several countries including Japan.

Agenda item 1.16 relates to non-geostationary orbit satellites, which have been increasingly used. In this agenda item, it was discussed to enable communications with the Earth stations on ships and aircraft in the frequency ranges of 17.7–18.6, 18.8–19.3, 19.7–20.2, 27.5–29.1, and 29.5–30 GHz. Finally, it was agreed to make the communications available in those frequency bands and to establish conditions so that such communications would not adversely affect terrestrial radio systems, including 5G and private 5G systems in the 28-GHz-frequency band.

1.4 Agenda items for WRC-27

During the WRC-23, the agenda items for future WRCs were also discussed, and the agenda items shown in **Table 2** were decided as the agenda items for the WRC-27.

Regarding additional identification of frequencies for IMT, discussions were held mainly on the frequency range so-called Frequency Range 3 (FR3) or mid-band, particularly the frequency range of 7–15 GHz. After discussion, the frequency ranges of 7125–8400-MHz and 14.8–15.35-GHz bands were agreed as candidates. The frequency range of 4400–4800 MHz was also decided as a candidate, a certain range of which is already used for IMT in Japan.

To implement NTN, direct-to-handset satellite communications are very attractive, which provide direct communications between mobile terminals such as smartphones and low-Earth orbit satellites. For the agenda item for WRC-27, frequency bands for this type of communications were discussed on the basis of proposals from Japan and other countries, and it was decided that the frequency range of 694 MHz–2.7 GHz would be a candidate for discussion at WRC-27.

2. ITU Radiocommunication Assembly 2023 (RA-23)

Preceding WRC-23, the ITU Radiocommunication Assembly 2023 (RA-23) was held from November 13 to 17, 2023 at the same venue as the WRC-23. The RA is the general meeting of the ITU-R and approves ITU-R Recommendations, ITU-R Questions, and ITU-R Resolutions, which provide the working method of ITU-R and appoints the chairs and vice-chairs of ITU-R Study Groups (SGs).

The RA-23 approved Resolution ITU-R 56-3, which defines the name of the so-called “6G” as IMT-2030 [3]. The RA-23 also approved Recommendation ITU-R M.2160, which provides a framework and overall objectives of the future development of IMT for 2030 and beyond [4]. With these documents, it is expected to accelerate studies relating to 6G in ITU-R.

As shown in **Fig. 4**, the chairs and vice-chairs of each SG were appointed, and all three candidates nominated by Japan were approved as candidates for vice-chairs of SG 4, SG 5, and SG 6. Regarding the structure and scope of the SGs, inter-satellite service is explicitly included in the scope of SG 4 [5].

During the RA-23, the maximum number of terms for Working Party (WP) chairs was discussed. It was agreed that the maximum number of terms is 2 (1 term corresponds to approximately 4 years), extendable to 3 if circumstances necessitate.

Other ITU-R Resolutions, Recommendations, and Questions were also approved and will serve as guidelines for future ITU-R activities.

3. Future plans

Towards WRC-27, the NTT Group will continue to actively participate in and contribute to ITU-R meetings, preparatory meetings in the Asia-Pacific region such as APG, and relevant meetings in Japan.

*4 Primary and secondary services: Radiocommunication services are classified into primary basis or secondary basis. Radiocommunication stations for services on secondary basis shall not cause harmful interference to stations for services on primary basis and shall not claim protection against interference from radio stations for services on primary basis.

Table 2. Agenda items of WRC-27.

No.	Agenda item
1.1	Studies on the use of the frequency bands 47.2–50.2 GHz (Earth-to-space) and 50.4–51.4 GHz (Earth-to-space), or parts thereof, by aeronautical and maritime earth stations in motion in the fixed-satellite service
1.2	Studies on possible revisions of sharing conditions in the frequency band 13.75–14 GHz to allow the use of uplink fixed-satellite service earth stations with smaller antenna size
1.3	Studies relating to the use of the frequency band 51.4–52.4 GHz to enable its use by gateway earth stations transmitting to non-geostationary-satellite orbit systems in the fixed-satellite service (Earth-to-space)
1.4	Possible new primary allocation to the fixed-satellite service (space-to-Earth) in the frequency band 17.3–17.7 GHz and possible new primary allocation to the broadcasting-satellite service (space-to-Earth) in the frequency band 17.3–17.8 GHz in Region 3, and consideration of equivalent power flux-density limits to be applied in Regions 1 and 3 to non-geostationary-satellite systems in the fixed-satellite service (space-to-Earth) in the frequency band 17.3–17.7 GHz
1.5	Studies on development of regulatory measures, and implementability thereof, to limit the unauthorized operations of non-geostationary-satellite orbit (non-GSO) earth stations in the fixed-satellite service (FSS) and mobile-satellite service (MSS) and associated issues related to the service area of non-GSO FSS and MSS satellite systems
1.6	Consideration of technical and regulatory measures for fixed-satellite service satellite networks/systems in the frequency bands 37.5–42.5 GHz (space-to-Earth), 42.5–43.5 GHz (Earth-to-space), 47.2–50.2 GHz (Earth-to-space) and 50.4–51.4 GHz (Earth-to-space) for equitable access to these frequency bands
1.7	Sharing and compatibility studies and development of technical conditions for the use of International Mobile Telecommunications (IMT) in the frequency bands 4400–4800 MHz, 7125–8400 MHz (or parts thereof), and 14.8–15.35 GHz for the terrestrial component of IMT
1.8	Studies on possible new additional allocations to the radiolocation service on a primary basis in the frequency range 231.5–275 GHz, and possible new identifications for radiolocation service applications in frequency bands within the frequency range 275–700 GHz
1.9	Consideration of appropriate regulatory actions to update Appendix 26 in support of modernization of high-frequency spectrum use in the aeronautical mobile (OR) service
1.10	Power flux-density and equivalent isotropically radiated power limits for inclusion in Article 21 for the fixed-satellite, mobile-satellite and broadcasting-satellite services to protect the fixed and mobile services in the frequency bands 71–76 GHz and 81–86 GHz
1.11	Study of technical and operational issues and regulatory provisions for space-to-space transmissions in the frequency bands 1518–1544 MHz, 1545–1559 MHz, 1610–1645.5 MHz, 1646.5–1660 MHz, 1670–1675 MHz and 2483.5–2500 MHz
1.12	Studies on potential new allocations to, and regulatory actions for, the mobile-satellite service in the frequency bands 1427–1432 MHz (space-to-Earth), 1645.5–1646.5 MHz (space-to-Earth) (Earth-to-space), 1880–1920 MHz (space-to-Earth) (Earth-to-space) and 2010–2025 MHz (space-to-Earth) (Earth-to-space) required for the future development of low-data-rate non-geostationary mobile-satellite systems
1.13	Studies on possible new allocations to the mobile-satellite service for direct connectivity between space stations and International Mobile Telecommunications (IMT) user equipment to complement terrestrial IMT network coverage
1.14	Studies on possible new frequency allocations to the mobile-satellite service in the frequency bands 2010–2025 MHz (Earth-to-space) and 2160–2170 MHz (space-to-Earth) in Regions 1 and 3 and 2 120–2160 MHz (space-to-Earth) in all Regions
1.15	Studies on frequency-related matters, including possible new or modified space research service (space-to-space) allocations, for future development of communications on the lunar surface and between lunar orbit and the lunar surface
1.16	Studies of technical and regulatory provisions necessary to protect radio astronomy operating in specific Radio Quiet Zones and, in radio astronomy service primary allocated frequency bands globally, from aggregate radio-frequency interference caused by systems in the non-geostationary-satellite orbit
1.17	Consideration of regulatory provisions and potential primary allocations to the meteorological aids service (space weather) to accommodate receive-only space weather sensor applications in the Radio Regulations
1.18	Studies on compatibility between the Earth exploration-satellite service (passive), the radio astronomy service in certain bands above 76 GHz, and active services in adjacent and nearby frequency bands
1.19	Studies on possible allocations to the Earth exploration-satellite service (passive) in the bands 4200–4400 MHz and 8400–8500 MHz
2	Use of incorporation by reference in the Radio Regulations
4	General review of the Resolutions and Recommendations of world administrative radio conferences and world radiocommunication conferences
7	Implementation of Resolution 86 (Rev. Marrakesh, 2002) of the Plenipotentiary Conference
8	Footnotes to the Table of Frequency Allocations in Article 5 of the Radio Regulations
9	Report of the Director of the Radiocommunication Bureau
9.1	Activities of the ITU Radiocommunication Sector since WRC-23
9.2	Report of the Director on any difficulties or inconsistencies encountered in the application of the RR and comments from administrioons
9.3	Action in response to Resolution 80 (Rev. WRC-07)
10	Preliminary agenda for the 2027 World Radiocommunication Conference

SG 1 (Spectrum management)
Chair: Mr. W. Sayed (Egypt)
Vice-chairs: 15 persons

SG 3 (Radiowave propagation)
Chair: Ms. C. Allen (United Kingdom)
Vice-chairs: 12 persons

SG 4 (Satellite services)
Chair: Mr. V. Strelets (Russia)
Vice-chairs: Mr. Kono (Sky Perfect JSAT, Japan) and 17 other persons

SG 5 (Terrestrial services)
Chair: Dr. K.-J. Wee, (Korea)
Vice-chairs: Mr. Imada (KDDI, Japan) and 19 other persons

SG 6 (Broadcasting service)
Chair: Mr. T. Aguiar Soares (Brazil)
Vice-chairs: Dr. Oode (NHK, Japan) and 11 other persons

SG 7 (Science services)
Chair: Mr. M. Dreis (EUMETSAT)
Vice-chairs: 10 persons

Fig. 4. ITU-R Study Group structure, and chairs and vice-chairs for 2024–2027.

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[5] Resolution ITU-R 4-9, https://www.itu.int/pub/R-RES-R.4-9-2023

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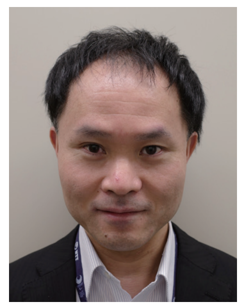

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Latest Trends in Open Optical Transmission Equipment in TIP OOPT

Kazuya Anazawa, Xiaocheng Zhang, Shigenari Suzuki, and Hideki Nishizawa

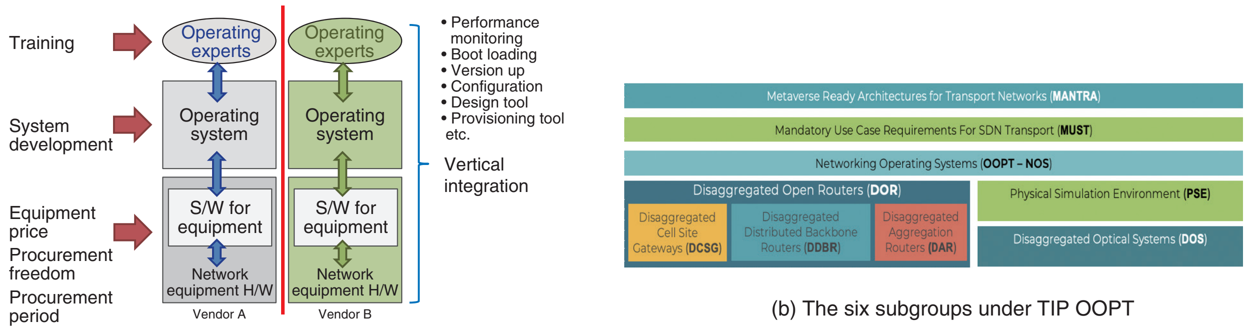
Abstract

The Telecom Infra Project Open Optical & Packet Transport (TIP OOPT) carries out activities aimed at decoupling hardware and software and accelerating innovation in optical and IP networks. This article focuses on the TIP Phoenix Project, in which operators are working together to present common use cases and specifications to encourage the entry of new vendors and reduce costs. The background of the project, efforts to date, and contribution of the NTT Group are explained.

Keywords: TIP OOPT, network operating system (NOS), optical transmission equipment

1. Background to the establishment of TIP OOPT

New technologies to separate hardware and software are being implemented in datacenters to efficiently handle the rapidly increasing traffic for social network services and image distribution services. In particular, server virtualization technology, in which a single piece of high-performance hardware is partitioned and used efficiently by virtualization, and storage virtualization technology, in which multiple pieces of server hardware are treated as a single computer to improve capacity and fault tolerance, have emerged. These virtualization technologies enable datacenter operators to not only reduce costs through efficiency but also build systems in a short period (speed and agility) and expand system reliably (redundancy) and flexibly. In 2011, the Open Compute Project (OCP) was established to verify and openly share system specifications of datacenter facility elements (servers, air conditioning, power, etc.) that enable high efficiency. Hyperscalers, such as Facebook (now Meta) and Microsoft, and white-box vendors are entering and expanding the market for these elements. In 2016, the Telecom Infra Project (TIP) was established with the aim of enabling companies to cooperate and create new technologies for constructing and developing telecommunication network infrastructures in emerging and developed countries. While OCP covers the inside of the datacenter, TIP targets the outside of the datacenter. The latter has established project groups, such as Open RAN, which develop and build radio access network (RAN) solutions from second-generation mobile communications system (2G) to 5G based on general-purpose, vendor-neutral hardware, open interfaces, and software, and Open Optical & Packet Transport (OOPT), which aims to decouple hardware and software and accelerate innovation in optical and Internet protocol (IP) networks. The challenges faced by OOPT operators in the vertical integration market are illustrated in **Fig. 1(a)**. When an operator procures and installs optical transmission equipment from Vendor A and Vendor B, since each vendor has different equipment interfaces and operations (performance monitor, file update, version upgrade, etc.), the operator must separately conduct operating-system development and engineer training for equipment A and equipment B. When the business model is based on vertical integration, there is less flexibility



(a) The challenges of the vertical integration market

(b) The six subgroups under TIP OOPT

Fig. 1. The challenges of the vertical integration market and the six subgroups under TIP OOPT.

in procurement, prices tend to remain high, and the time from ordering to delivery is long (about a year in the case of optical transmission equipment). To solve this problem, OOPT carries out activities in the six subgroups shown in **Fig. 1(b)**; Metaverse Ready Architectures for Transport Networks (MANTRA), Mandatory Use Case Requirements For SDN Transport (MUST), Networking Operating Systems (OOPT-NOS), Disaggregated Open Routers (DOR), Physical Simulation Environment (PSE), and Disaggregated Optical Systems (DOS). This article introduces OOPT-NOS and DOS, which are most closely related to the disaggregated 400G transponder "Phoenix."

2. OOPT-NOS

The mission of this group is to (1) define the specifications, architecture, and reference implementation of Goldstone, an open and disaggregated network operating system (NOS) for optical transmission equipment, and (2) promote openness and bring Goldstone to the market through commercial implementation by equipment vendors. Goldstone implements various functions on a device as containers, making it easy for vendors and operators to add or modify functions.

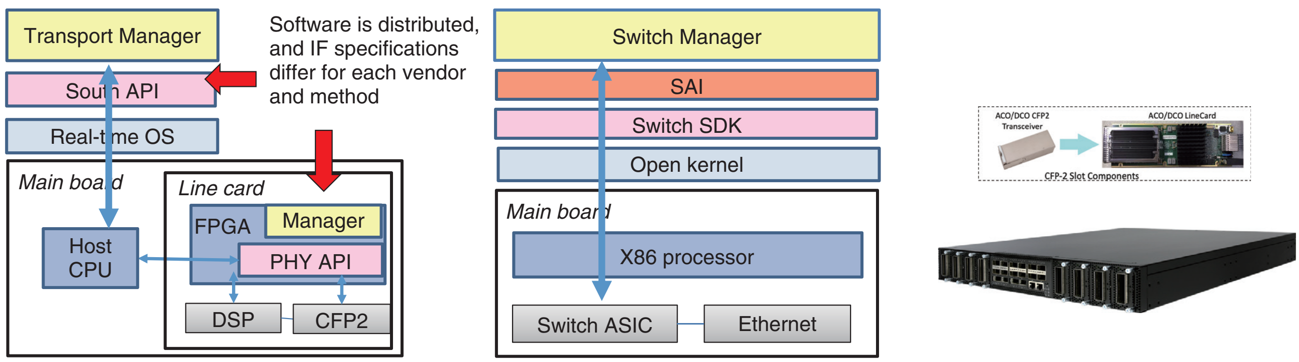
Thus far, NTT R&D laboratories have developed: (1) a function to enable device control using standard control interfaces, such as OpenROADM [1] and OpenConfig [2], for specification development, (2) a function to enable control by standard communication protocols, such as gNMI [3] as well as NETCONF, and (3) a streaming telemetry function to collect various information on a device, for Phoenix, a piece of open optical transmission equipment. NTT developed these functions in collaboration with partners including NEC and Fujitsu and contributed to the uptake of Phoenix in collaboration with worldwide operators [4, 5]. NTT also worked with IP Infusion (IPI) to implement functions to support CSR320, a disaggregated cell site gateway (DCSG), and the aggregation router AGR400 as well as contributed to their content.

NTT's partner, NEC, commercialized NEC NOS on the basis of Goldstone NOS together with Phoenix, which is described later, and in October 2023, received a Silver Badge [6] from TIP, which proves that it has passed verification of more than 100 items by network operators.

The group will continue to study and promote openness of platforms for switchponders that can use optical transmission functions by inserting pluggable coherent modules into router switches, such as DCSG and AGR400.

3. DOS

The mission of this group is to define specifications for open and disaggregated optical transmission equipment and bring such equipment to market. Separating hardware and software makes it easier to adapt to changing service requirements by enabling quick, individual application of the latest technologies and continuous improvement of performance. This article introduces the Cassini open packet/optical transponder, which is a representative DOS achievement, and the Transponder Abstraction Interface (TAI), an open interface for optical transmission that hides the differences among different devices



(a) Conventional transmission equipment

(b) Whitebox switch

(c) Cassini integrates a coherent interface in whitebox switch

API: application programming interface
ASIC: application-specific integrated circuit
CFP: C form-factor pluggable
CPU: central processing unit
DSP: digital signal processor
FPGA: field-programmable gate array
IF: interface
PHY: physical layer
SAI: software abstraction interface
SDK: software development kit

Fig. 2. A whitebox switch architecture for optical transmission equipment.

and vendors and complex register access.

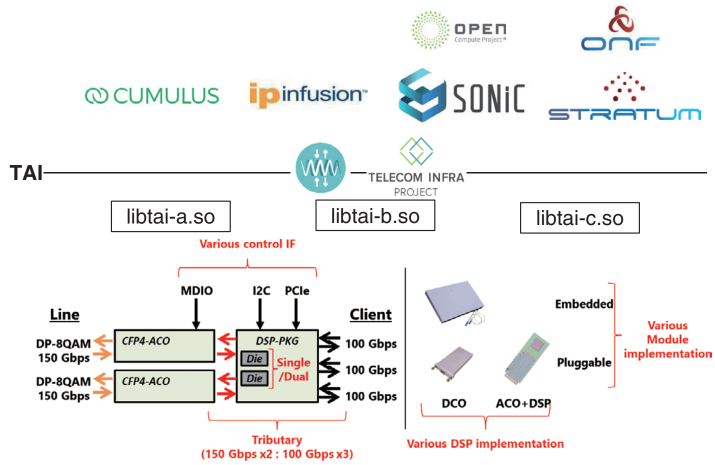
The conventional transmission-equipment market has formed a vertically integrated business model in which system vendors that manufacture mainboards and implement line cards of their own specifications work closely with transceiver vendors that manufacture and supply line cards to these systems to pursue high transmission performance (**Fig. 2(a)**). However, the software to be implemented on the device is distributed on the mainboard and on the line cards, and the interfaces are different for each vendor and method, making it unsuitable for separating hardware and software. DOS, in cooperation with Edgecore, the world's top market shareholder in the whitebox switch market, applied a whitebox switch architecture that separates hardware and software (**Fig. 2(b)**) to optical transmission equipment to create Cassini, which integrates 100GbE switching and Layer 1 optical transport functions into a single enclosure as a line card module compatible with multi-vendor, multi-generation coherent transceivers (**Fig. 2(c)**). Since this required an open interface to hide the differences among devices and vendors and complex register access, the NTT Group and Cumulus Networks (now NVIDIA) took the lead and cooperated with hyperscalers and major component suppliers such as NTT Electronics (now NTT Innovative Devices) and Acacia to develop the TAI [7]. **Figure 3(a)** is a photo during the TIP Summit held in 2018, and **Figure 3(b)** shows an image of how the TAI conceals differences among devices and vendors and complex register access to enable control and management from various NOSs using common source code. IPI has implemented the TAI on OcNOS, its commercial OS, applied it to Cassini, and commercially introduced it in Burkina Faso in Africa, Chile, Pakistan, and other countries [8].

4. Disaggregated 400G transponder "Phoenix"

At the TIP Summit in 2018, Telefonica announced plans for a disaggregated 400G transponder. In anticipation of the uptake of 400-Gbit/s pluggable coherent transceivers, the company announced its goal to develop equipment that separate hardware and software, not only for switchponders such as Cassini, but also for transponders and muxponders, which are Layer 1 devices widely used by carriers to convert optical and electrical signals. It also aims to reduce costs through carrier collaborations to present common use cases and specifications to encourage new entrants to the market. The project, later named Phoenix, published its technical specifications in December 2019, and in April 2020, a joint request for information (RFI) by Vodafone, Telefonica, Telia Company, NTT Communications, DT, and MTN was issued (**Fig. 4(a)**).

After the RFI was issued, operators participating in DOS received a total of ten proposals for hardware, software, and total solutions. For each proposal,

(a) TIP Summit 2018 in London



(b) TAI conceals differences among different devices and vendors

Fig. 3. Development of TAI.

product explanations from the vendor, operator team discussions from a technical perspective, and discussions between the operator and vendor were conducted. Verification using actual equipment was carried out, and in June 2022, recommended requirements were established for the community and released as a detailed technical requirement document (dTRD). The dTRD consolidates about 200 detailed technical specifications for Phoenix in terms of physical requirements, optical transmission standards, control, monitoring operation, openness, etc. In regard to openness, the dTRD included the TAI's interface support mechanism for hardware and software separation, which is a distinct feature of Phoenix.

After the release of the dTRD, applications for Phoenix Badge certification (whether the dTRD specifications are met) were solicited. Galileo FlexT and NEC NOS obtained Silver Badge certification (whether specifications are met on prototype verification) in October 2023. NEC NOS, based on the aforementioned Goldstone NOS, became the first in the world to obtain Phoenix Silver Badge certification (**Fig. 4(b)**). Gold Badge certification (whether specifications are met on commercial-level environment) will also be conducted in the future.

The NTT Group worked with operators such as Telia, Vodafone, DT, and Telefonica to prepare the RFI, dTRD, test plans, and other documents, carried out discussions and verifications with vendors, and conducted badge certification evaluations. In the preparation of the dTRD, NTT was in charge of 40 out of about 200 items and contributed to the review and prioritization of all the items. In the Silver Badge certification process for NEC NOS in 2023, MTN and NTT Communications divided more than 100 operator tests and conducted tests with respective vendors in validation environments in South Africa and Japan, respectively. On the basis of the test results, badge certification was obtained as a community.

In the TIP community, granting a badge to a vendor product is an acknowledgment that the product meets the specified functionality and quality level of the relevant badge. The badge system allows vendors to promote their products in the community by being certified, thus increasing the market value of their products. Operators can refer to the badge specification when selecting products, partially simplifying the conventional RFP formulation and response evaluation processes and making it possible to omit the contents included in the badge for product introduction tests. Edgecore and Pegatron have newly joined the Phoenix hardware market as suppliers, further expanding the market for open optical transmission equipment.

5. Future prospects

The IOWN Global Forum has developed the

(a) Image of Phoenix and the operators participating in its specification development

(b) Phoenix commercial version certified with the Silver Badge

Fig. 4. Phoenix.

Innovative Optical and Wireless Network (IOWN) All-Photonics Network (APN) architecture that enables the optical wavelength path, which has thus far been used mainly between facilities of telecommunication carriers, to reach user sites, such as datacenters and medical facilities, as endpoints [9]. We will continue to promote the spread of open optical transmission equipment through the activities of TIP OOPT. By incorporating such optical transmission equipment in the Open APN*1 and Cognitive Foundation*2 architectures defined by the IOWN Global Forum, we will aim to provide new services that enable system construction in a short period and highly reliable and flexible system expansion.

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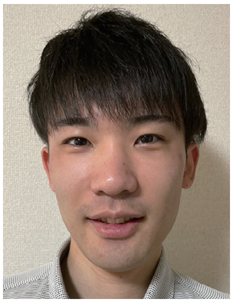
*1 Open APN: An innovative network based on photonics technology that is being developed with an open architecture at the IOWN Global Forum. https://www.rd.ntt/e/iown/0002.html

*2 Cognitive Foundation: A mechanism that centralizes management, operation, deployment, setting, and interlinking of information and communication technology resources in different layers such as edge computers, network services, and user equipment, all from the cloud. https://www.rd.ntt/e/iown/0004.html



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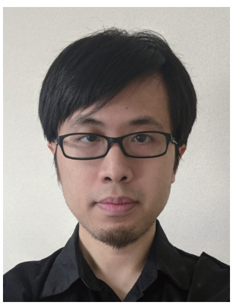

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External Awards

Electronics Society Activity Testimonial

Winner: Hidetaka Nishi, NTT Device Technology Laboratories
Date: March 5, 2024
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Electronics Society

For his contribution to the Technical Committee on Photonics Integration Circuit and Silicon Photonics as a secretary.

Best Young Professional Paper Award

Winner: Koji Takeda, NTT Device Technology Laboratories
Date: April 16, 2024
Organization: The Institute of Electrical and Electronics Engineers (IEEE)

For "III-V-on-Si Membrane Distributed Reflector Lasers with Intermixed MQW DBRs."
Published as: K. Takeda, T. Fujii, Y. Maeda, T. Segawa, and S. Matsuo, "III-V-on-Si Membrane Distributed Reflector Lasers with Intermixed MQW DBRs," IEEE Silicon Photonics Conference, paper ThB4, Tokyo, Japan, Apr. 2024.