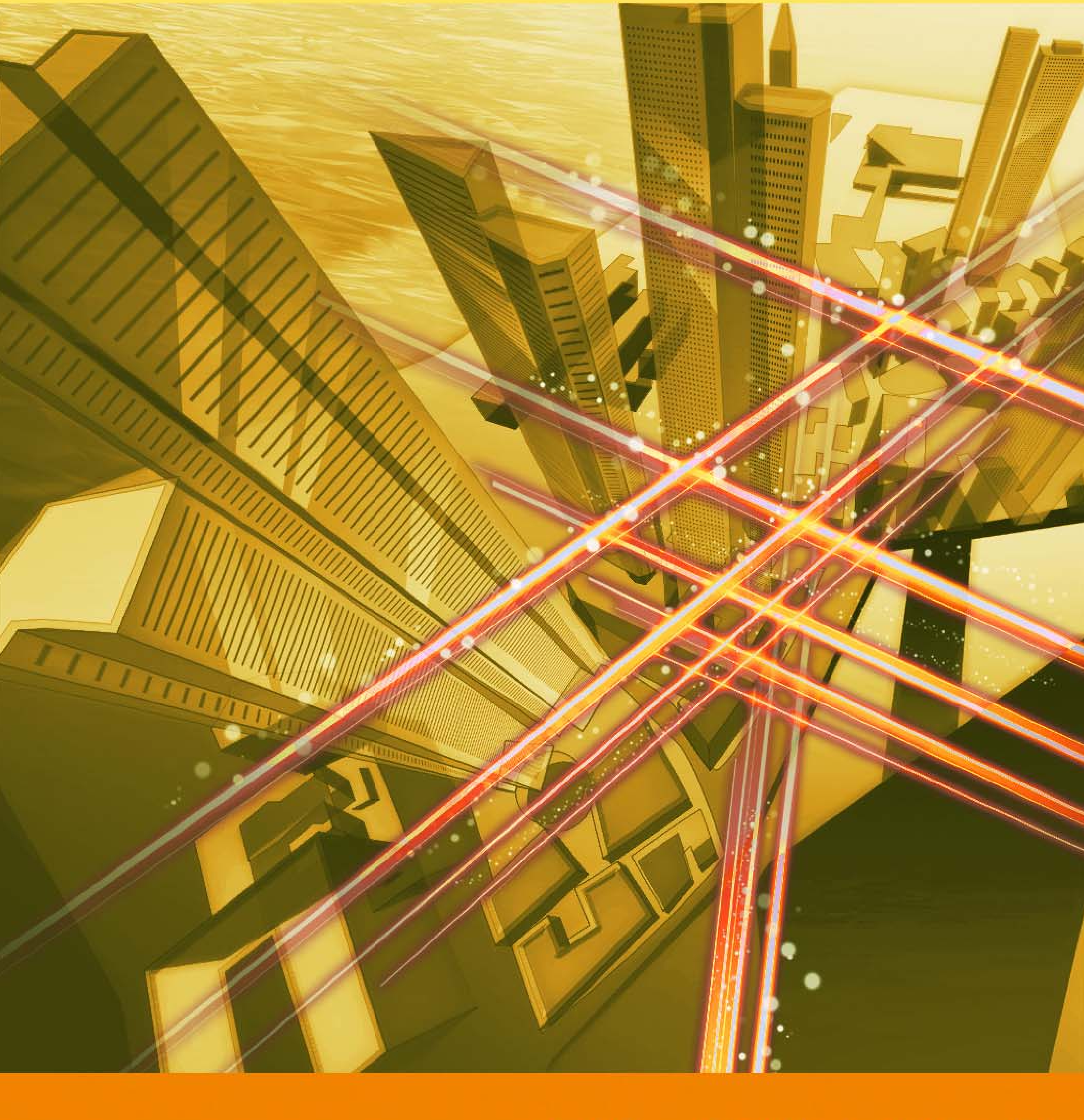
NTT Technical Review

10
2021



October 2021 Vol. 19 No. 10

NTT Technical Review

October 2021 Vol. 19 No. 10

View from the Top

- Tomoyoshi Oono, Senior Vice President, Head of NTT Service Innovation Laboratory Group

Front-line Researchers

- William John Munro, Senior Distinguished Researcher, NTT Basic Research Laboratories

Rising Researchers

- Takeru Inoue, Distinguished Researcher, NTT Network Innovation Laboratories

NTT Technology Report for Smart World

- Release of NTT Technology Report for Smart World 2021

Feature Articles: Network-service Technologies Enabled by the All-Photonics Network for IOWN

- Network-service Technology Enabled by the All-Photonics Network
- On-demand Photonic Multipoint Connection Technology Supporting High-presence Communications Services
- Wireless Technologies toward Extreme NaaS—Multi-radio Proactive Control Technologies (Cradio®)
- Wireless Technology for Extreme NaaS—Remote Beamforming Schemes for Analog Radio-over-fiber-based High-frequency-band Wireless Communication Systems
- Cooperative Infrastructure Platform for Delivering Mission-critical Services

Regular Articles

- Real-time Virtual-network-traffic-monitoring System with FPGA Accelerator

Global Standardization Activities

- Latest Trends in 400- and Beyond 400-Gbit/s Ethernet Standardization in IEEE 802.3

Practical Field Information about Telecommunication Technologies

- Investigation on Damage to Optical Fiber Cables Caused by Freezing and Thawing of Water in a Lifting Pipe

External Awards

Be Altruistic! What You Get in Return Will Come from the Results of Your Giving

Tomoyoshi Oono
Senior Vice President, Head of NTT Service Innovation Laboratory Group

Overview

The NTT Service Innovation Laboratory Group aims to create a world in which all people are happy and can live their lives safely, securely, and healthy. Its three laboratories (i.e., NTT Human Informatics Laboratories, NTT Social Informatics Laboratories, and NTT Computer and Data Science Laboratories) research and develop technologies for integrating cyber and physical spaces to create a world in which a harmonious relationship between the Earth, society, and individuals is built. We interviewed Tomoyoshi Oono, senior vice president, head of the NTT Service Innovation Laboratory Group, who is orchestrating the laboratory group's efforts to solve social issues and create new value by thinking outside the box, about his new mission and the qualities required of top management.

Keywords: well-being, cyber and physical, service development

We want to create a future in which all people can be happy

—You were appointed senior vice president, head of the NTT Service Innovation Laboratory Group in July 2021. First, could you tell us about the laboratory group?

In a future society, social problems will be more diversified and the integration of cyber and physical spaces will be increased. The major goal of the NTT Service Innovation Laboratory Group is to help all people live in a state of well-being that satisfies both their wellness and mindfulness in such a society.

Specifically, we are researching and developing technology to provide daily food advice and support behavioral changes for long-term management of physical health as well as technology to create "Another Me," which has the same personality as oneself in cyberspace that can have various experiences, gain knowledge, and feed the results back to oneself in the real space for that person to lead a spiritually fulfilling life. We are also researching next-generation artificial intelligence (AI) that can execute many tasks in a versatile manner with less learning processes, just like the human brain does. We are also researching platform technologies to support a society emphasizing well-being, such as a social system platform to enable the results of the above research and development (R&D) to be widely and ethically accepted in society as well as an AI computing platform to enable AI functions installed in various places in the real space to autonomously interact each other. We are working on these

challenging themes by thinking outside the box.

The NTT Service Innovation Laboratory Group consists of three laboratories. Taking a human-centric approach, NTT Human Informatics Laboratories conducts innovative R&D to create a new symbiosis between the real and cyberspaces as the development of cyberspace rapidly accelerates. NTT Social Informatics Laboratories carries out wide-ranging research on social values, information utilization, cybersecurity, privacy, ethics, law, regulations, and beyond, to further the transformation and development of social systems and human societies through information and communication technologies. NTT Computer and Data Science Laboratories conducts R&D on innovative computer science and data science that enable the processing of the data that have been difficult to handle due to their scale and complexity and create useful value from those data for people and society.

—Could you tell us how you feel about your new position?

Prior to assuming my current position, I worked at NTT DOCOMO, where I was mainly involved in the development of the next-personal handy-phone system (PHS) location-information system, promotion of the introduction of the Freedom Of Mobile multimedia Access (FOMA) service, and the development of technologies and services such as the "Otayori Photo Service" for photo/video sharing via mobile phones, "Shabette Concierge" voice-activated user interface, and "Photo Collection" cloud-based photo/video-storage service. When I took my current position in July this year, I was very surprised to find that the world I was aiming for when I was at NTT DOCOMO and the world the NTT Service Innovation Laboratory Group is aiming for is the same. That aim is to create a society in which all people are happy and can live their lives safely, securely, and healthy, which we term a "well-being society." However, although both NTT DOCOMO and the NTT Service Innovation Laboratory Group share the goal of creating such a society, the former focuses on how to solve the most recent problems, while the latter looks further ahead. This difference lies in their stance: NTT DOCOMO considers what they can do now to develop business, while the NTT Service Innovation Laboratory Group takes on challenges of what they cannot do now to change the world.

In the age of volatility, uncertainty, complexity, and ambiguity, go out into the field and repeat trial and error

—Do you feel that your experience at NTT DOCOMO has made a difference in your current work?

I try to communicate directly with staff and researchers, and I am sometimes asked, "How can I create a service?" At such times, my long experience in service development at NTT DOCOMO comes in handy.

Service development is composed of several phases. The first phase is called "customer-problem fit," a process in which a customer's real problem is identified. The second phase is called "problem-solution fit," a process in which a solution to the identified customer's problem is found. A minimum number of products are then developed through trial and error, and whether those products are actually useful is verified. Finally, the products and services that solve the customer's problem are provided. The last phase is called "product-market fit" in which the company's products and services fitting the market is achieved.

However, in this era of volatility, uncertainty, complexity, and ambiguity (VUCA), predicting the future is difficult. Markets, which used to be easy to predict to some extent, have become unpredictable. I therefore believe that we have no choice but to repeat the process of trial and error.

I also have always placed importance on going out into the field when creating services. I once visited the city of Unnan in Shimane Prefecture here in Japan to conduct interviews with the elderly. Although it is possible to use online tools or have elderly people come to Tokyo to talk with us, visiting the site ourselves to talk with them allowed us to experience their environment with all five senses, which is something that words and facial expressions alone cannot convey. I was surprised to hear that the elderly people participating in the interviews had no particular problems, despite the fact that Japan is facing the social problems of a very low birthrate and aging population. This experience made me realize that even in a super-aging society, which has been called a social problem, the perspective differs in accordance with the standpoint of ordinary citizens, local government, and the state, and that the things that need to be addressed also varies.

It is important to take a close look at the real world in this manner. As I support the activities of researchers, I intend to make them aware of seeing the reaction to their research results in the real world. In fact, some researchers told me of their desire to create a service, release it to the world, and see the reaction. I know this task is difficult during the COVID-19 pandemic, but I want to emphasize the importance of researchers being aware of the real world.

—What is important to you as a field-oriented manager?

I often hear people hesitate to try something because they are afraid of failure, but I think we should just try it anyway. As I mentioned earlier, I used to be involved in developing a service called "Otayori Photo Service" for emailing photos via mobile phones. NTT DOCOMO developed the first such service in the world, but while we were making internal procedures to complete the development, another Japanese company announced a similar service

to the press. That situation arose because our internal rules required us to finish an internal procedure for completing the development before announcing a new product. We took it as an opportunity to review and change our rules so that we could make press announcements in the pre-launch phase. It was our failure when the other company made a press announcement ahead of us; however, because we tried something new, we were able to uncover issues in the process and improve the situation. In other words, from a different perspective, this failure led to success. I think this example demonstrates the fact that although organizations have rules, researchers should not be too bound by those rules. My former boss used to say, humorously but genuinely, “Rules are there to be broken.” and “You can make your own rules.” Looking back, I welcome that attitude.

I also believe that the role of top management is to have their staff feel comfortable in their work. For example, if a rule prevents good work from being done, I, who has the authority to change the rule, should change it. It is my role to make comprehensive judgments, which include risk assessment, and take on the risk if it seems to be a positive move.

For the growth of my staff, what I value is to leave the details to the staff. In the past, we used to prepare materials for meetings to put our plans into action by creating a single A3 sheet of paper summarizing the plan from the introduction (background) in the upper left to the conclusion in the lower right. In many cases, the management designated only the introduction and the conclusion and left the creation of materials to their staff. The staff members are free to use their ideas to create a proposal to match the conclusion while taking into account the background, trends followed by other companies, and strengths of their company. I believe that staff members can grow if we give them clear goals and more freedom.

Create the future, rather than predict it

—I understand you trust your staff. What qualities and attitudes are required of researchers in the future?

In addition to challenging yourself and repeating trial and error as I mentioned, I think it is important to take a backcasting approach; that is, envision the ideal future and then think what should be done now. It is also important to have “intrapersonal diversity,” which is advocated by Professor Akie Iriyama of Waseda University, in other words, a wide range of diversity within one person. The key to innovation is human resources who can build an H-shaped collaboration by connecting their expertise (vertical axis) with other people's expertise (other vertical axis) using a horizontal axis.

I also want researchers to consider NTT's social mission, which is often referred to as "noblesse oblige" in Europe and the United States. I believe that NTT has the power to change Japan through our Innovative Optical and Wireless Network (IOWN) initiatives, and NTT researchers are in a position to change the world from Japan. I hope that you will fulfill this role.

Having passion for goals is what will lead our business to success. Alan Kay said, "The best way to predict the future is to invent it." In this VUCA era, I want you to approach your research activities with the attitude of creating your ideal future and achieving your goals.

Last but not least, the most important thing is to take care of yourself. Professor Satoshi Fukushima of the University of Tokyo, who has vision and hearing impairments says, "No one born in this world is unnecessary." Life is short, so I hope that you will take good care of yourself and live your life with no regrets. However, remember to be altruistic. Life is about "give and give," rather than "give and take." What you get in return will come from the results of your giving.

Interviewee profile

■ Career highlights

Tomoyoshi Oono joined Nippon Telegraph and Telephone Corporation (NTT) in 1989. In 1999, he moved to NTT DOCOMO, where he was responsible for the development of NTT DOCOMO's next-PHS location-information system and promoting the introduction of FOMA. He became a senior vice president and head of the R&D Strategy Department/Innovation Management Department of NTT DOCOMO in 2017. After concurrently serving as a member of the Board of Directors of NTT DOCOMO Ventures, Inc. from 2018 and as president of Mirai Translate, Inc. from 2020, he started his current position in July 2021.

Have an Open Mind and Don't Worry about Failure to Stay on the Cutting Edge of Science and Technology

William John Munro
Senior Distinguished Researcher,
NTT Basic Research Laboratories

Overview

Researchers at NTT Basic Research Laboratories are aiming to create new technologies harnessing the power of quantum mechanics. In November 2020, they proposed a method for compressing quantum circuits to enable high-speed quantum computation and the miniaturization of quantum computers in the US scientific journal Physical Review X. In February 2021, the British scientific journal Nature Communications published a paper on the demonstration of a high-speed quantum random-number generator that achieves the highest levels of security by using the world's first practical optical device. We interviewed William John Munro, a senior distinguished researcher at the laboratories and leading figure in the broad field of quantum technology, about his research activities and his attitude as a researcher.

Keywords: quantum computer, noisy intermediate-scale quantum processor, time crystals

Research activities spanning a broad field of quantum technology—from quantum computers to secure communications

—Please tell us about the research you are currently working on.

Quantum computers and quantum information processors are one of the research themes that we have been continuously focusing on. Noisy intermediate-scale quantum (NISQ) processors, which can be called medium-sized quantum computers, have been actualized and we are now focused on how we advance from these NISQ processors to future quantum supercomputers. Last year, for example, we proposed a method of compressing quantum circuits that significantly reduces both the time and resources required for a quantum computer to solve a problem (**Fig. 1**) [1].

We have also been investigating what applications can be run on these NISQ processors. This year, we were able to implement a *quantum walk** on a 62-qubit quantum processor (**Fig. 2**) [2]. This demonstration on the world's largest quantum computer of a quantum walk is a milestone research result that has attracted significant attention because it showed a

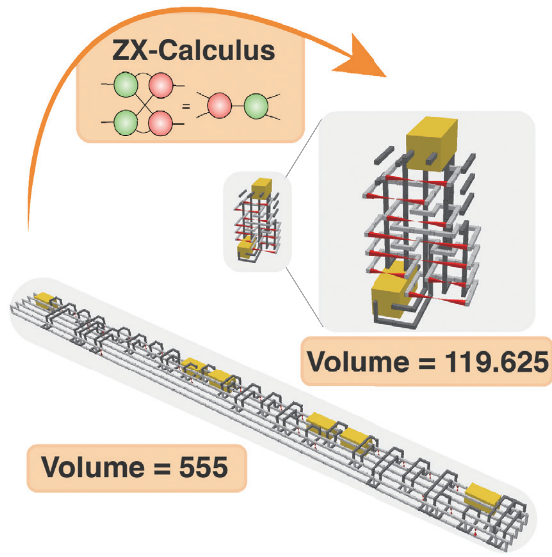


Fig. 1. Illustration of the compression of a quantum circuit.

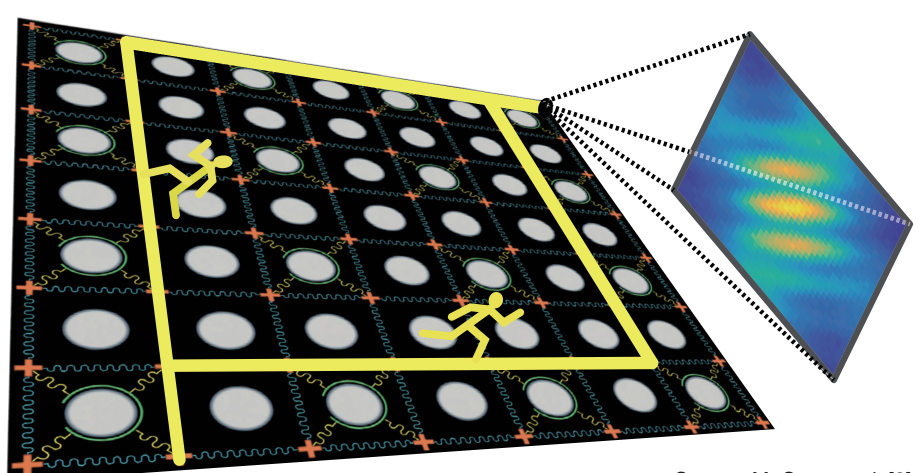


Fig. 2. A 62-qubit quantum computer executing a quantum walk.

different way to program these quantum processors.

I have also been researching the *quantum internet*—a quantum-enabled version of today's Internet. My focus is on how we design it and how it would work in practice. Quantum physics gives us new opportunities for how information can flow in such a quantum-enabled internet. We have introduced new concepts, such as quantum multiplexing, quantum routing, and quantum network aggregation, and studied their properties. We found that their unique properties can be exploited for quantum communication and allow us to overcome a number of weaknesses that were inherent in quantum computers. Although

* Quantum walk: A quantum version of a random walk, in which the position that a particle next steps to is determined randomly by rolling a die. It is one of the most-important quantum algorithms and is expected to be used to describe and analyze phenomena in a variety of fields, including diffusion and noise problems. Furthermore, quantum walks enable one to perform universal quantum computation.

the quantum internet has not received that much attention yet, it is an interesting research subject and one that will be very important in the future. Combining quantum computation and communication technologies is an area that must be investigated.

The study of *time crystals* is something a little different. You may have heard the word "time crystal" from Star Trek, but what we mean here is a little different. Salt and sugar are well-known examples of crystals—periodic arrays of atoms—, but time crystals are ones that are arranged periodically in time rather than space. The use of graph structures has proven to be an effective means to represent and visualize such time crystals. When a quantum system is used to generate a time crystal, it is possible to create an extremely large-scale network with more than one million nodes even if the number of qubits is as small as, say, 20. We found that when the time crystal melts, the network also changes and becomes scale-free [3]. This finding is important because scale-free networks are normally associated with today's Internet. We may have a means of exploring the properties of global-scale networks on a small quantum computer. This possibility is quite fascinating, and who knows where it could lead in the future; it could lead to a new approach to quantum simulation.

Another of our recent achievements is the development of a secure and high-speed quantum random-number generator [4]. Random numbers play an important role in a variety of information, computation, and communication technology tasks.

Quantum technology is expected to contribute to achieving communication networks with dramatically improved security. The concept of the Innovative Optical and Wireless Network (IOWN) calls for the construction of a new network and information-processing infrastructure using innovative technologies centered on photonics, and we believe that our research will enable a quantum-enabled IOWN, namely, qIOWN, which will allow us to construct a distributed quantum-information-processing system composed of quantum processors, sensor, and clocks all connected through a quantum network.

—Those research results are amazing. Quantum computers are being actively researched worldwide. What is required of researchers if they are to quickly produce research results that will benefit society as a whole?

The field of quantum computation is attracting a great deal of attention worldwide, and advanced efforts are being made in Europe, the United States, and China in particular. It's a shame that Japan is lagging a bit behind in this. At present, small-scale quantum processors with about 60 qubits have been fabricated, and they are available in some countries. These quantum processors are useful for exploring the possibilities offered by quantum mechanics and have been reported to execute tasks that would probably take thousands of years even on today's largest supercomputers. However, such processors generate noise during operation, so their use is limited to tasks that are not affected much by noise.

For quantum computers to develop, they will need to be scaled up to much larger-scale quantum processors, preferably consisting of millions of qubits. It is not clear yet how this will be done, but we know that it requires an approach that is fundamentally different from the way current NISQ processors are fabricated. I believe that it is essential for the scientific community to collaborate on a global scale. Keeping the research closed will only lead to delaying the actualization of large-scale quantum computers.

We do not yet fully understand the true potential of large-scale quantum computers, but we can expect them to have a profound impact on society. The impact could be as revolutionary as that of original computers on society in the 1940s and 50s. They will be able to solve complex problems that we can't even imagine today. I hope to see large-scale quantum computers before I retire.

A cup of coffee and a whiteboard can create a magical place

—What do you think a researcher is?

To be a researcher, you must have an inquisitive mind and want to solve problems, think outside the box, and find out how things work without being bound by existing ideas. I like the Cambridge dictionary definition which says a researcher is "someone who studies a subject, especially in order to discover new information or reach a new understanding." This is a very broad definition and obviously you are successful if you achieve that. How successful is however a different question!

I am not really sure I am a researcher in the sense you mean. I am more of a scientist/engineer, which is a little different. I want to understand how things work, be able to design and build interesting devices and technologies and more importantly have fun doing it. One of the differences between me and many other researchers is that I am more of a generalist than specialist. I cover many topics (optics & photonics, superconducting systems, computer science, chemistry, cryptography, system engineering, etc.) and can integrate them together. Other researchers typically have much more in-depth knowledge about a few specialist fields.

NTT allows us to choose large problems (grand challenges) that take an extended time to solve. At many universities, however, projects must be completed well before the end of the grant that lasts only a couple of years.

The research environment is very important for us researchers, and interaction with other researchers is critical. We can accomplish much more when we have researchers get together as a team. When researchers gather in the same place, a cup of coffee and a whiteboard is all that is needed to create a magical place. The research environment has changed as the amount of remote work has been increased as a measure to prevent the spread of the COVID-19. Although certain things can be done with electronic platforms, it is not the same. It is not spontaneous. The tools are just not there to achieve the same effect as face-to-face communication.

—How do you search for problems and themes during your ongoing research activities?

When looking for a research theme, I spend about 20% of my time checking out a wide range of research outside my field of expertise. This enables me to discover new and exciting trends coming through and investigate topics that I find to be interesting, some of which become new themes for me. International conferences also offer great opportunities to get in touch with the latest research. At large conferences, I try to attend sessions on topics outside my field of expertise. Invited talks and tutorials are especially useful because they accurately showcase what those fields have to offer and open problems in those fields.

In retrospect, most of my research has been focused on creating new trends, not following them. In other words, I always try to think ahead of the game. For example, in one of my previous research projects, which focused on quantum repeaters, it was thought that the performance of a quantum repeater would be limited by the time it takes for a signal to travel from one node to another. We tried for nearly five years to circumvent the limitation imposed by the signaling time; however, like most researchers in this field at that time, we concluded that it was impossible to remove this limitation. To overcome the limitation, we had to completely change the way we thought about quantum repeaters. In other words, we disregarded quantum memories, an element that was previously thought to be essential in quantum repeaters. Initially, that new way of thinking seemed too far-fetched and unlikely to work. However, a few simple calculations showed that it could work, and it has created a new subfield concerning quantum repeaters. What we showed would be extremely hard to physically achieve—but if we could do it, then the repeater's performance could be improved millions of times compared with previous approaches—a potential game changer.

A lot of potential is buried in unexplored fields

—Isn't it tough to take on challenges in unexplored fields? Do you ever feel pressured?

No, the opposite is true. A lot of potential is buried in unexplored fields, and anyone can be a pioneer. Stepping into those fields also means being on the cutting edge of science and technology. I think that is something every researcher wants to do. Uncharted territory is extremely rewarding no matter which angle you look at it from. However, naturally, there are risks, and you need to be prepared for the fact that there is no path before you.

Failure is part of research—especially if you are working at the cutting edge of it. You can't expect everything to work, and you will always face problems. Therefore, we should not criticize people for their failures, although we do need to be careful if there are repeated failures. In my case, about 20% of the projects I took on did not turn out the way I expected. However, I believe that we can learn valuable lessons from our failures and become better researchers.

I also believe that technology has the potential to change society for the better. Although natural evolution of technology can be expected, sometimes, a disruptive technology bursts onto the scene, causing profound changes. Quantum technology has such disruptive properties. If it is achieved, it will force a fundamental change in many aspects of e-commerce and how information is moved and stored. Quantum technology also provides new opportunities for the processing power of computers, such as using quantum laws as a means of privacy protection. We need to remember that technology is not one-sided; it can always be used in different applications beyond our imagination.

—What would you like to say to next-generation researchers?

Have an open mind and don't worry about failure. Choose a problem that you find interesting and enjoy trying to solve it. I also think it is important to broaden your knowledge by reading a wide variety of literature. This will help you explore new areas.

There is no single answer to the question of how to develop a new field. I have been developing themes at a pace of about one every five years. While focusing on my current research themes, I am simultaneously developing new ones. Over time, the new one would take over from the old one which would be retired. I recommend that you attend international conferences and read popular scientific magazines to determine areas you find fascinating. You will then see if you can find an interesting problem you want to try solving.

You might feel lost when jumping into a new field or facing a new challenge or you might have trouble organizing your thoughts or writing a paper. In such a case, it is useful to talk with the researchers around you. You may be able to receive advice on a new field or hints on how to construct your paper. However, it is up to you to start the conversation with them, then decide yourself what to do.

There are always highs and lows during research, and sometimes results will come easily, while at other times, it seems that nothing works out. Remember that this is natural. I always try to have several projects with different themes going at the same time. When there is an issue with one, I can focus on another. This allows me to take my mind off the issue and clear my head. I can then come back refreshed with new ideas.

Finally, I'd like you to keep in mind that there are many other researchers around you with whom you can talk and interact. As senior researchers, we are here to help you.

References

[1] M. R. Hanks, M. P. Estarellas, W. J. Munro, and K. Nemoto, "Effective Compression of Quantum Braided Circuits Aided by ZX-Calculus," Phys. Rev. X, Vol. 10, No. 4, 041030, Nov. 2020.

[2] M. Gong, S. Wang, C. Zha, M. Chen, H. Huang, Y. Wu, Q. Zhu, Y. Zhao, S. Li, S. Guo, H. Qian, Y. Ye, F. Chen, C. Ying, J. Yu, D. Fan, D. Wu, H. Su, H. Deng, H. Rong, K. Zhang, S. Cao, J. Lin, Y. Xu, L. Sun, C. Guo, N. Li, F. Liang, V. M. Bastidas, K. Nemoto, W. J. Munro, Y. Huo, C. Lu, C. Peng, X. Zhu, and J. Pan, "Quantum Walks on a Programmable Two-dimensional 62-qubit Superconducting Processor," Science, eabg7812, May 2021.

[3] M. P. Estarellas, T. Osada, V. M. Bastidas, B. Renoust, K. Sanaka, W. J. Munro, and K. Nemoto, "Simulating Complex Quantum Networks with Time Crystals," Sci. Adv., Vol. 6, No. 42, eaay8892, Oct. 2020.

[4] Y. Zhang, H. Lo, A. Mink, T. Ikuta, T. Honjo, H. Takesue, and W. J. Munro, "A Simple Low-latency Real-time Certifiable Quantum Random Number Generator," Nat. Commun., Vol. 12, 1056, Feb. 2021.

■ Interviewee profile
William John Munro

Senior Distinguished Researcher, Theoretical Quantum Physics Research Group, NTT Basic Research Laboratories.

He received a B.Sc in chemistry, M.Sc and D.Phil in physics from the University of Waikato, New Zealand, in 1989, 1991, and 1995. After several years in the computing industry, he returned to physics as a research fellow at the University of Queensland, Australia from 1997 to 2000 before becoming a permanent staff scientist at Hewlett Packard Laboratories in Bristol, UK (2000–2010). He joined NTT Basic Research Laboratories in 2010 and was promoted to senior distinguished researcher in 2016. His research interests range from foundational issues in quantum science through to the design and development of quantum technology. He is a fellow of the Institute of Physics (IOP), American Physical Society (APS), and the Optical Society (OSA).

A Glimpse of the Information Communication Networks of the Future: Research on Optical Path Design for Large-scale Computing Infrastructure

Takeru Inoue
Distinguished Researcher, NTT Network Innovation Laboratories

Overview

One of the current challenges with information and communication networks is their lack of flexibility. It takes a lot of work to set up a new optical path between sites. Moreover, it is very difficult to establish optical paths if each site uses different optical transmission devices. Distinguished Researcher Takeru Inoue aims to configure a flexible network that allows us to freely switch between paths. Here, he tells us more about his field: optical path design for large-scale computing infrastructure.

Keywords: optical path, optical cross-connect, network design

Technology development for networks five or ten years down the line

—What kind of research do you do at NTT Network Innovation Laboratories?

The intercity relay transmission paths that NTT has constructed, managed, and operated up to now consist of optical cables and transmission devices with the capacity to accommodate the predicted traffic. In the past, when looking at the traffic in terms of each intercity transmission path, it was possible to predict this traffic to some extent. For example, traffic would gradually increase in the morning, peak at night before bedtime, and then be quite low in the small hours of the night. Another trend was that there would be a lot of communications with major search engines, popular video streaming websites, and so on. However, in recent years, user behavior has diversified, systems and devices have become faster and more sophisticated, and traffic is rapidly increasing at a rate of some tens of percent every year. Fluctuations in traffic are becoming more varied, making traffic difficult to predict, and there is growing concern that traffic will exceed the capacity of existing relay transmission paths.

Until now, these concerns have been addressed through building new relay transmission paths or

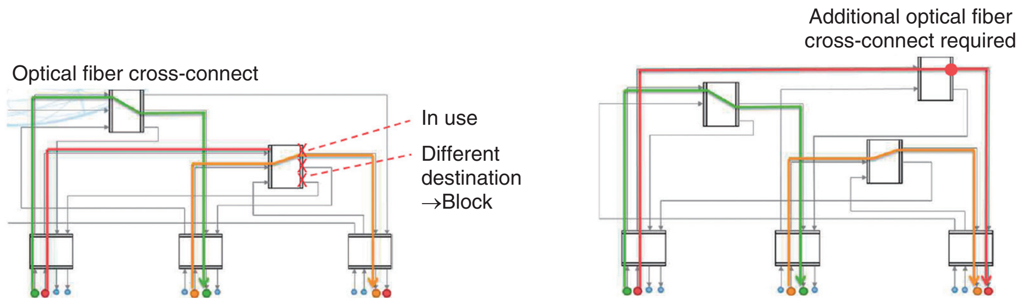


Fig. 1. A block occurring when laying a new transmission path.

adding to existing ones. However, this not only takes months, but is also dependent on how accurate traffic predictions are, meaning that the same capacity shortages will occur sooner or later. This led us to the idea that, by flexibly configuring relay transmission paths to cope with these traffic fluctuations, it might be possible to further expand the possibilities of communication through things like new applications.

In order to make this flexible network configuration a reality, NTT Network Innovation Laboratories is researching configuration technologies. The Transport Innovation Laboratory, which gathers experts in optical technology, is conducting research on broadband optical signal transmission by increasing the amount of light passing through a single optical fiber and increasing the number of optical pathways (cores) in an optical fiber.

I'm part of the Frontier Communication Laboratory, which is researching and developing technologies for optimally switching optical signals from one optical fiber to another, and technologies for optimally switching between optical routes within a relay transmission network. Today, I will briefly introduce two of these technologies: efficient network design using optical fiber cross-connects for communication buildings, and automatic optical path provisioning.

—What is "efficient network design using optical fiber cross-connects"?

Consider a situation where you want to run a new optical path from a communication building to another building or company. For example, on the left-hand diagram in **Fig. 1**, say you want to connect the red optical fiber coming in from the bottom left to the optical fiber in the bottom right. However, the fiber cross-connect in between those points cannot be connected to the bottom right, as indicated by the three crosses. This is referred to as a "block." The conventional approach would be to open up the network by adding another cross-connect, as shown in the right-hand diagram. However, this approach requires installing lots of expensive optical fiber cross-connects, which is not desirable from a business point of view.

We have therefore developed technology to mathematically determine the optimum number of cross-connects and their configuration. Specifically, this is a redesign of the existing standard hierarchical network structure. It allows lower-level optical signals to loop back without going via higher levels, and rather than preventing blocks altogether, we are looking for an efficient network structure where we permit them at such a low level—say, one in a million—that they will almost never occur. We made particular use of mathematics from fields such as puzzle-solving. You may have heard of things like "discrete mathematics" and "graph theory." This technology has demonstrated that in a hypothetical network with 20,000 optical fibers and several thousand connections required every year, a five-hour calculation can reduce the number of cross-connects by 42%.

—What is "automatic optical path provisioning technology"?

Even if the network configuration technology for fiber-optic switching equipment guarantees that one or more destination ports are always free, it is not always possible to open an optical transmission path immediately. When the vendors of the transmission devices that transmit and receive optical signals are different, it is a prerequisite that the sending and receiving transmission devices operate as a pair. However, since specifications for anything non-standardized differ between vendors, ordinarily they will

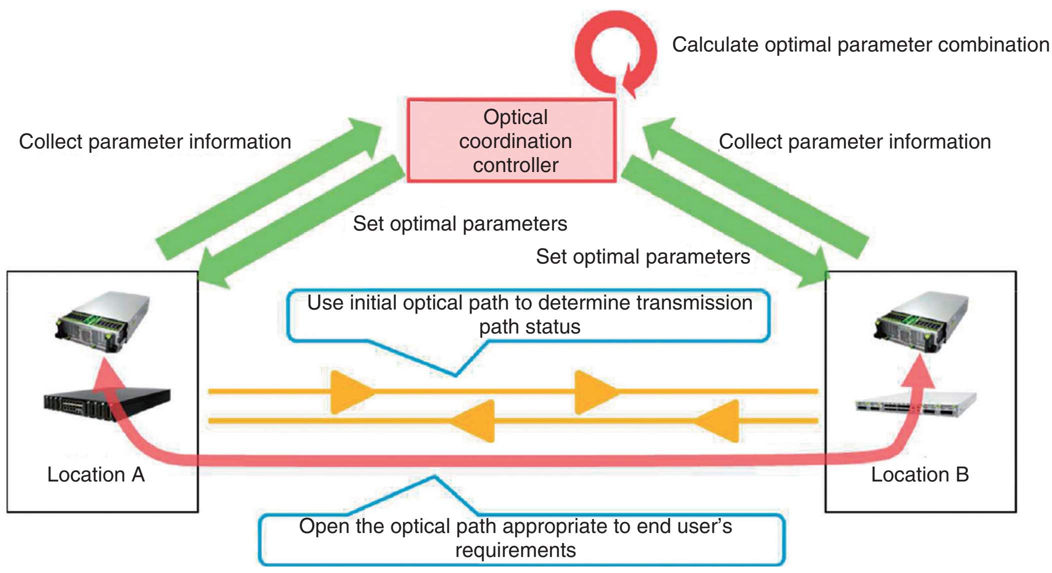


Fig. 2. Overview of automatic optical path provisioning technology.

not be able to communicate. However, given the need to switch destinations, we need to be able to use a standard interface to control equipment, even from different vendors. We also need to optimize communication according to the required speed, the distance, and the quality. For example, firing a powerful laser at short distances can break the receiver. We also need to prevent interference from adjacent signals.

To do this, we have developed technology that can automatically optimize the transmission mode used for communication using only standard interfaces. Specifically, we need to first understand the condition of the transmission path using the initial optical path, which is a weak signal, as shown in **Fig. 2**. The process is then to collect information about the parameters of communication from Location A and Location B to the optical coordination controller, calculate the optimal combination of parameters, then open the optical path according to the end user's requirements.

These things are controlled using software. In addition to the rise of software-defined networks, there is a trend toward open source in all fields, and the current need for these technologies is increasing. While the technology for efficient network design using optical fiber cross-connects involves a mathematical approach, this one involves a software approach.

Working on yet more practical technologies

—What kinds of possibilities will these two technologies unlock?

These technologies will make it possible to configure the network optimally at all times in response to ever-changing network conditions. I believe that the All-Photonics Network (APN), one of the three main fields of technology of the Innovative Optical and Wireless Network (IOWN), are also based on this concept. For example, although the image quality of teleconferencing systems has improved significantly over time, they are still very different from actual meetings. I personally believe that these slight delays in conversations and overlaps in speech mean there is still this sense of separation. The APN is capable of sending and receiving all the information that a human can process, so I hope that the era of just being able to manage remotely will shift to an era of not even noticing that things are remote. I also think it will be possible to use the network for applications that are still difficult at this time—things that are very sensitive to communication delays such as remote surgery.

—What do you think about the future direction of your field?

We talked about two technologies here, but neither

of them has been put into practical use yet. It would probably be more accurate to say that we are finally reaching the start line. For example, efficient network design using optical fiber cross-connects is useful when there is a fixed number of optical fibers—but networks are constantly growing. As the network gets bigger you need to add or rearrange cross-connects, but optical signals are already traveling through them. Optical communication is more difficult to stop and migrate than packet communication, so I believe we need to find methods to expand networks while keeping them running. It's a tricky problem.

There are also challenges with automatic optical path provisioning technology. These examples I gave were limited to the setup of the two endpoints of the transmission line, the transmitter and receiver, but in reality it takes more than those to achieve optical communication. For example, above a distance of 12 to 19 miles, the optical signal becomes weaker and must be boosted with an amplifier. Additionally, to achieve optimal communication, all devices along the route generally need to be controlled together using devices such as filters. When you think, too, about the daily maintenance and operation processes, you can see this is a complex problem with a large number of considerations. Everyone working on these things has probably felt this at some point.

—What would you say to anyone hoping to become involved in information communication network research?

NTT's research environment is extremely well-equipped. It's fair to say we have almost all the necessary equipment when it comes to information communication networks in particular. Optical transmission equipment and optical signal transmission equipment may be much cheaper than in the past, but it's still difficult to assemble them all in a single university laboratory. At NTT, we are able to conduct research and testing using actual equipment. This is one of the major strengths of the NTT Group.

When you think of information communication networks, you may picture electronic engineering, which deals with electrical signals. However, as you can see from my research, which mixes mathematics, information science, and other fields, it is an incredibly broad discipline. Of course, electronic engineering is an important area, but today's information communication networks are more than just a means to transmit signals, so we need a variety of expertise, including the software and programming technology to manage the networks, the mathematics to back up the concepts, and occasionally, other perspectives such as economics. If you are interested in making the most of your expertise to support the social infrastructure, I encourage you to take on the challenge.

■ Interviewee profile

Takeru Inoue

Distinguished Researcher, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in engineering science and a Ph.D. in information science from Kyoto University in 1998, 2000, and 2006. He joined NTT in 2000. He was an ERATO (Exploratory Research for Advanced Technology) researcher involved in the Minato Discrete Structure Manipulation System Project, Japan Science and Technology Agency, from June 2011 to June 2013. He has been with NTT Network Innovation Laboratories since July 2013. He has been a visiting lecturer at Waseda University School of Fundamental Science and Engineering since September 2016. He has also belonged to NTT Communication Science Laboratories since March 2020.

Release of NTT Technology Report for Smart World 2021

Tomoyuki Kanekiyo, Takayuki Onishi, and Atsuyuki Muramoto

Abstract

NTT Research and Development Planning Department annually releases the NTT Technology Report for Smart World, which summarizes its vision for the Innovative Optical and Wireless Network (IOWN) launched in 2019 and technologies intended to make the world a better place for everyone. It has now published the 2021 edition. This article provides an overview and main updates of the new edition.

Keywords: technology, social trend, smart world

1. Innovations and technologies that overcome limitations in transforming society

Our world is undergoing dramatic changes (the COVID-19 pandemic, environmental destruction, and climate change). It has become evident that, if humanity does not change course, even sustainable development will no longer be possible. As artificial intelligence (AI) processes big data and use of virtual currency expands, the volume of data requiring information processing has exploded, consuming ever-growing amounts of electricity. In the face of these new changes, the technologies we are researching and developing are intended to form the foundation for a world in which people can live bountiful lives. This article describes integrated technologies essential for transcending current limitations and building a better world and explains how these technologies are related to each other while focusing on the Innovative Optical and Wireless Network (IOWN) vision, which is at the center of our activities.

2. Three pillars, three platforms, and five kinds of value for the IOWN vision

IOWN consists of three pillars: the All-Photonics Network (APN), which uses photonics-based technology in everything from networks to terminals; Cognitive Foundation, which connects and controls everything; and Digital Twin Computing, which combines the real and digital worlds to predict the future.

The IOWN vision originated with the announcement in April 2019 of the invention of optical transistors. Alongside the development of these devices based on photonic technology, three common platforms are part of the IOWN vision: photonic direct communication, extreme network as a service (NaaS), and data-centric computing infrastructure. From these platforms, five kinds of value that aim at solving social issues and making the world a better place can be generated: fourth-dimensional (4D) digital platform™, the Remote World, well-being, zero environmental impact, and a value chain that will build new trust. These three common platforms and five kinds of value are described below.

3. Three common platforms

3.1 Data-centric computing infrastructure

It is imperative to create a data-centric society capable of creating new value from a wide variety of data. On the data-centric computing infrastructure, a platform to be built through IOWN, new value will be created for data owners and middle service providers, helping to create a sustainable society. This platform will be built atop three core functions: data hub service, AI service platform, and photonic disaggregated computing.

3.2 Extreme NaaS

As the reach of the fifth-generation mobile communication system (5G) services expands and the deployment of 6G technology comes into sight, even faster networks are needed. In addition to high capacity, it is vital to have networks that can reliably maintain connectivity. We believe that implementing extreme NaaS requires innovation in three areas: network service provision, the concept of control information, and access networks.

3.3 Photonic direct communication

We believe that if we are to fully utilize the APN of IOWN, we need multi-point connection technology that can promptly handle a wide range of bandwidths coupled with a stress-free user experience, along with ultra-reality communication technology. Thus, one of our objectives is to provide a photonic direct communication service. Two technologies are important for this: network information acquisition and provision and provision of multi-point connectivity. When this service becomes available, people in different locations will be able to communicate with each other as if they were in the same place, and new ways of engaging in sports and entertainment may be found.

4. Five kinds of value

4.1 4D digital platform™

The 4D digital platform™ provided through IOWN is a digital platform that integrates 4D information (accurate 3D location information plus time information) into high-precision geospatial information. It provides four kinds of value: efficient management of road traffic, utilizing urban assets, cooperative maintenance of social infrastructure, and understanding the Earth's environment and natural disasters. It can conduct cross-industry analysis of the prevailing situation and make predictions regarding the future for a range of social activities and feed the resulting data into various industrial infrastructures, thereby making it possible to balance people's comfort with overall optimization in traffic and smart city management, reduce the cost of operating and maintaining social infrastructure, and contribute to achieving harmony between society and the natural environment.

4.2 Remote World

In the wake of the COVID-19 pandemic, many industries have clearly shifted towards remote activities. Consequently, there is a need for mechanisms, such as remote work and online education that can provide value similar to the real world without having to be physically present. Through IOWN, we aim to achieve the Remote World by integration and unification of environmental conditions between remote sites, conveying people's thoughts and intentions and synthesizing abilities, transcending barriers of culture and values, and integration with activities carried out in close proximity.

4.3 Well-being

The concept of well-being that has recently garnered attention encompasses not only physical but also mental and social well-being and has spurred initiatives that seek to understand human well-being from medical, pleasure-seeking, sustainable, and other perspectives. In line with this, we will build the foundations that allow each individual to achieve a state of well-being. Key points in this effort will be visualization of well-being factors, presentation of options tailored to each individual, promoting autonomous behavioral change and choice, and complementary ecosystems that transcend industries.

4.4 Zero environmental impact

It is urgent to create a society that can cope with global environmental changes, such as climate change, major disasters, and pandemics. The key points in providing zero environmental impact will be achieving a society that accepts environmental change, next-generation energy distribution networks, optimal operation of nuclear fusion reactors, and ultra-high accuracy weather prediction. A new communications platform such as IOWN will be essential to utilizing next-generation energy technology and optimal energy distribution.

4.5 Value chain to build new trust

The digitalization of society has made it possible for people to enjoy more convenient services, but at the same time, the risk of cybercrime is increasing. As information processing becomes an integral part of human society, damage in the cyber world has a direct impact on people. That is why we want to create a platform that can support a safe and secure society. Key points in creating such a platform will be establishing more robust and simple security, practicing glocalism by working with trustworthy organizations, connecting value chains that span industries, and accelerating data-driven value creation.

5. Conclusion

NTT Research and Development Planning Department will continue to release a summary of technology trends and the activities of NTT R&D. You can download NTT Technology Report for Smart World 2021 from NTT R&D's website [1].

Reference

[1] NTT Technology Report for Smart World 2021, https://www.rd.ntt/e/techreport/

Tomoyuki Kanekiyo
Vice President, Research and Development Planning Department, NTT.

He received a B.E. in applied physics engineering from Osaka University in 1992. Since joining NTT the same year, he has been researching video distribution systems and ultra-realistic communication systems and developed a commercial Internet protocol television system. He assumed his current position in 2021.

Atsuyuki Muramoto
Manager, Research and Development Planning Department, NTT.

He received an M.E. in information science and computing engineering from the University of Tokyo in 2004. He joined NTT EAST the same year and has been engaged in corporate sales, network planning, and research and development in digital signage. He assumed his current position in 2018.

Takayuki Onishi
Senior Manager, Research and Development Planning Department, NTT.

He received a B.E. and M.E. in information and communication engineering and a Ph.D. in engineering from the University of Tokyo in 1997, 1999, and 2019. In 1999, he joined NTT Cyber Space Laboratories and has been engaged in research and development on high-quality image coding and transmission. He assumed his current position in 2019.

Network-service Technology Enabled by the All-Photonics Network

Akio Kawabata and Yuji Aoyagi

Abstract

To implement the Innovative Optical and Wireless Network (IOWN), an advanced network that can efficiently process a large amount of data incomparable with the conventional Internet is required. To satisfy this requirement, NTT is researching and developing the epoch-making All-Photonics Network (APN), which will make maximum use of photonics-electronics convergence technology. This article describes activities related to function-dedicated network (FDN) architecture and the network-service technology that can be implemented on an FDN to provide various services via the APN.

Keywords: IOWN, APN, network architecture

1. All-Photonics Network

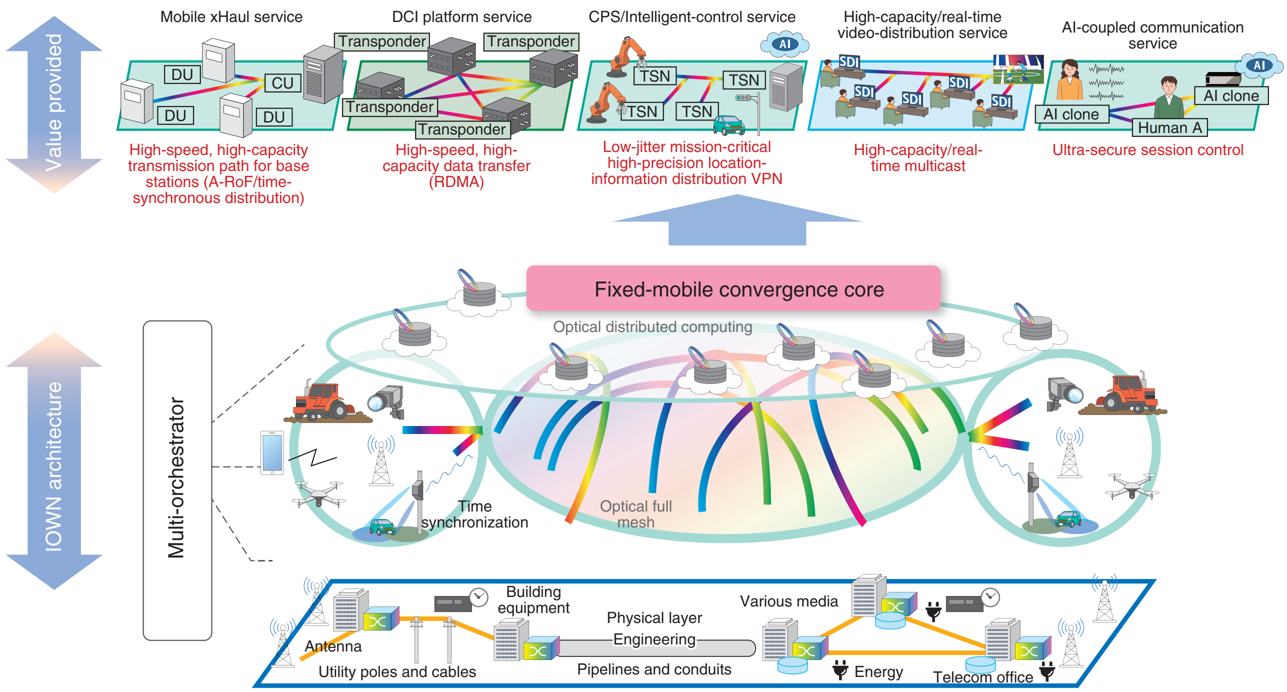
The goal with the All-Photonics Network (APN) [1], which is one element of the Innovative Optical and Wireless Network (IOWN) [2], is to have it become the *infrastructure of infrastructure* of various information and communication technology (ICT) platforms in the digital-transformation and digital-distribution era. To meet this goal, we aim to build a network that enables anyone to (i) use ultra-high-speed optical transmission and wireless transmission by connecting not only communication buildings but also user facilities (factories, hospitals, etc.) and datacenters with wideband optical networks and wireless access in an end-to-end (E2E) manner and (ii) share such a network (as an infrastructure of infrastructure) with services provided as an ICT infrastructure for various industries. Various services that will be possible with the APN are illustrated in **Fig. 1**.

As shown in Fig. 1, the APN will be an infrastructure that (i) provides a large-capacity, low-delay optical multicast path on demand on an arbitrary ground-to-ground basis to provide video distributors and users with high-presence video-distribution services such as 4K and 8K; (ii) provides a closed feedback path that guarantees mission-critical remote-control message forwarding from multi-access edge computing located near the user to terminals via wireless access; and (iii) supports mission-critical remote-monitoring-and-control services in various usage scenarios such as autonomous vehicles and factory-control systems. Serving as an infrastructure platform for various ICT and networks, the APN will also provide optical transmission services between large-scale datacenters and among base stations, wireless control systems, and the mobile core for fifth-generation mobile communication systems (5G) and 6G.

2. Function-dedicated networks

To provide services with various network requirements and enable them to coexist in the same network (i.e., the APN), a function-dedicated network (FDN) architecture [3] is adopted. FDN types and examples of use cases are shown in **Table 1**.

An FDN provides three types of transmission services: (1) digital signal transmission (Straight Digital), which maps digital signals directly to the optical path; (2) analog signal transmission (Natural), which maps analog signals directly to the optical path; and (3) packet frame transmission (Framed Digital), which frames data into packets and transfers the framed data to the optical path. Types (1) and (2) are the characteristic services that will be provided via the APN. An example of (1) is a service that transmits high-definition-media-interface and other signals for



A-RoF: analog radio-over-fiber
CPS: cyber-physical system
CU: central unit
AI: artificial intelligence
DU: distributed unit
DCI: data-centric infrastructure
RDMA: remote direct memory access
SDI: serial digital interface
TSN: time-sensitive networking
VPN: virtual private network

Fig. 1. Illustration of the APN and possible services.

Table 1. FDN types and examples of use cases.

FDN concept	Use cases
(1) Straight Digital	Real-time high-presence video distribution (HDMI transmission)
	Terminal/device input/output interface/internal bus transmission
	D-RoF (CPRI)
	Leased line (wavelength rental) service
(2) Natural	Quantum cryptography
	Optical power supply
	Fiber sensing
	Optical frequency synchronization
	A-RoF
(3) Framed Digital	Datacenter connection
	Datacenter access
	Mobile/D-RoF (eCPRI)
	IoT
	CPS/intelligence control (smart factory, etc.)
	AI-coupled communication service
	End-to-end fixed-cycle guarantee

CPRI: Common Public Radio Interface
D-RoF: digitized radio-over-fiber
eCPRI: enhanced CPRI
HDMI: high-definition multimedia interface
IoT: Internet of things

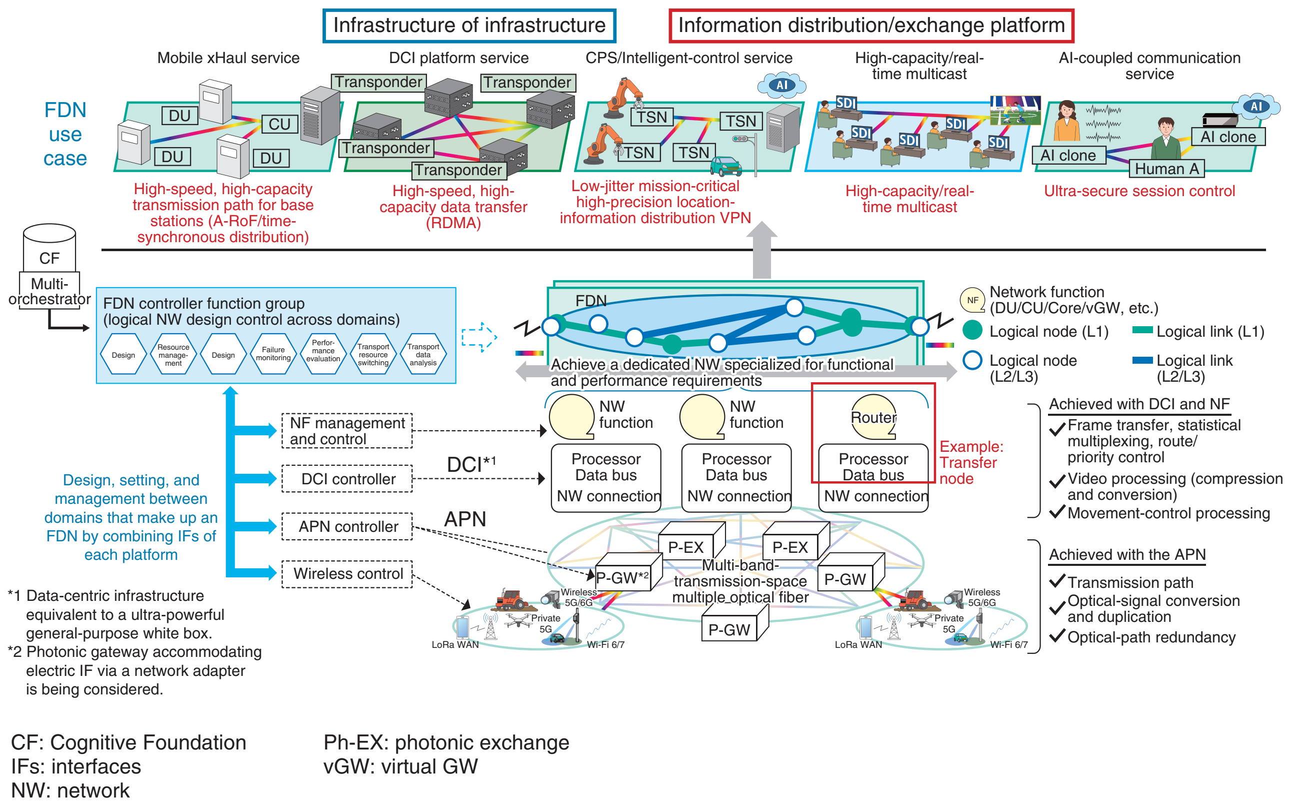


Fig. 2. Model of FDN architecture.

low-latency video transmission over an optical path. An example of (2) is a cryptographic-key transmission service using quantum cryptography for ultra-secure communication. For (3), an FDN is characterized by its ability to provide E2E defined-period-guaranteed services for frequency-synchronized transmission of control messages in an E2E manner using the ultra-high capacity of optical fiber.

A model of the architecture to create such an FDN is shown in **Fig. 2**. The FDN combines APN transmission and a wireless infrastructure, a data-centric infrastructure (DCI), namely, the compute infrastructure, and network functions for controlling connections between terminals and data distribution. As shown in Fig. 2, following the instructions of the multi-orchestrator, the FDN controller provides dedicated E2E forwarding functions to meet various service requirements by controlling the configuration and allocating respective resources to coordinate between domains, namely, the APN, wireless infrastructure, DCI, and network functions.

3. On-demand photonic multipoint connection technology to support high-presence communication services

Meetings and events that used to be commonplace where many people would gather in one place and share the space are now being held remotely from a variety of locations, and while people find this state of affairs convenient, they expect more-realistic communication and high-definition visuals. These drawbacks are due to the limitations of the network technology that supports the services that can be used by a large number of people. Such services will be transformed into high-presence communication services through the creation and popularization of new network technology.

To develop this new network technology, we are actively researching on-demand photonic multipoint connection technology (Photonics On-demand) as one element of an FDN [4]. To actualize Photonics On-demand, the APN must create a much larger number of optical communication connections in the same network than possible with current technologies.

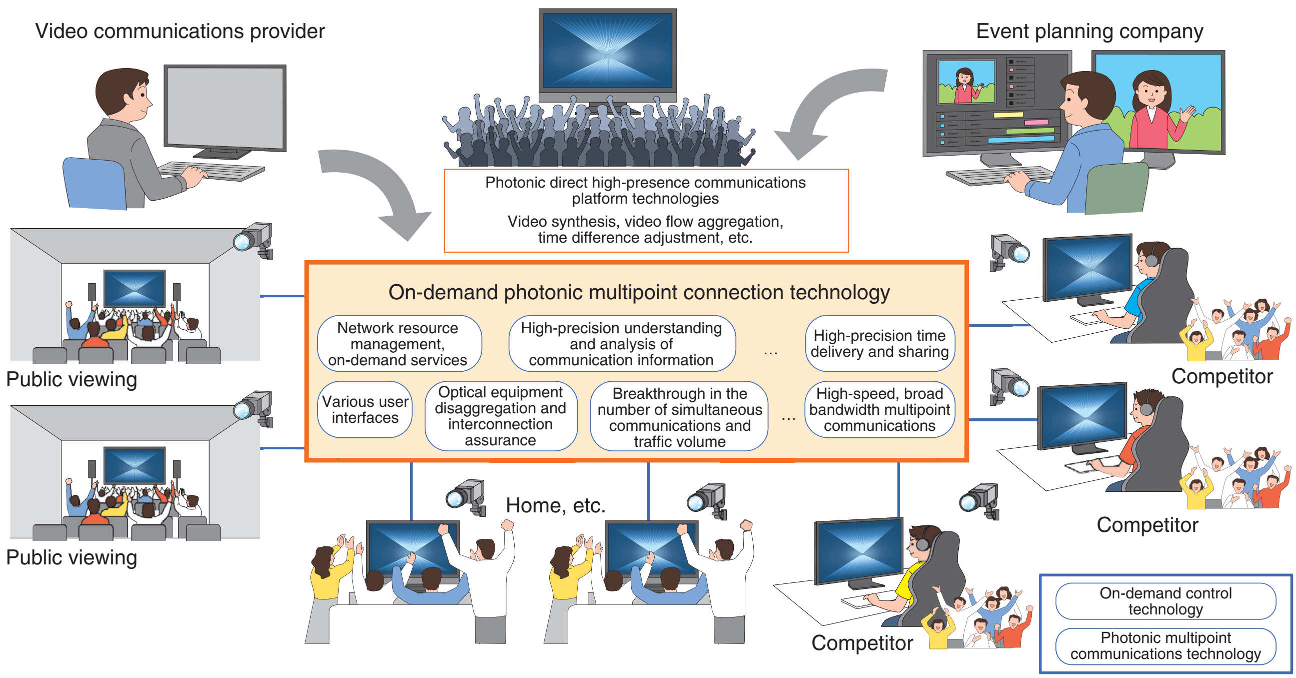


Fig. 3. On-demand photonic multipoint connection technology for high-presence communication services.

Therefore, two problems arise: (i) a conventional leased-line service incurs a large cost burden on the user because the optical path is left unattended and (ii) it takes time to start using the service because it requires time to design and set up the optical path. Accordingly, automatic-configuration control software is introduced to the FDN as a control mechanism to mediate between the user and APN; as a result, the user will be provided with an optical-communication path with the desired quality when they want it. This mechanism makes it possible to provide an inexpensive, low-latency, broadband optical path for video events in the Remote World. Moreover, the optical connections for each event (with different requirements) can be provided without interfering with each other; therefore, many events can be provided simultaneously in a manner that reduces service costs. Although this technology is in the realm of optical networks, it can also contribute to the provision of high-presence services to wireless users by combining and coordinating with the next-generation wireless control technology described below (**Fig. 3**).

4. Extreme network as a service

To cover a variety of use cases involving an FDN, it is necessary to provide services including wireless access. To extend the scope of an FDN to wireless access, we are researching and developing a network service called extreme network as a service (NaaS), which can continuously satisfy extreme requirements (such as ultra-low latency, ultra-reliability, and ultra-high capacity) in an E2E manner by using various access methods (**Fig. 4**).

Three types of innovation are pursued with extreme NaaS. The first innovation is to change from providing user-specified access to providing an access environment that enables users to do what they want. It would thus become possible for users to use the services they want without being aware of the various access methods. The second innovation is to expand control information. By using various types of information (such as sensor information from cameras and human behavior) as control signals, we aim to create highly accurate predictions and new added value. The third innovation is expanding access itself. That means expanding access to *extreme* service areas such as outer space and undersea and maximizing the

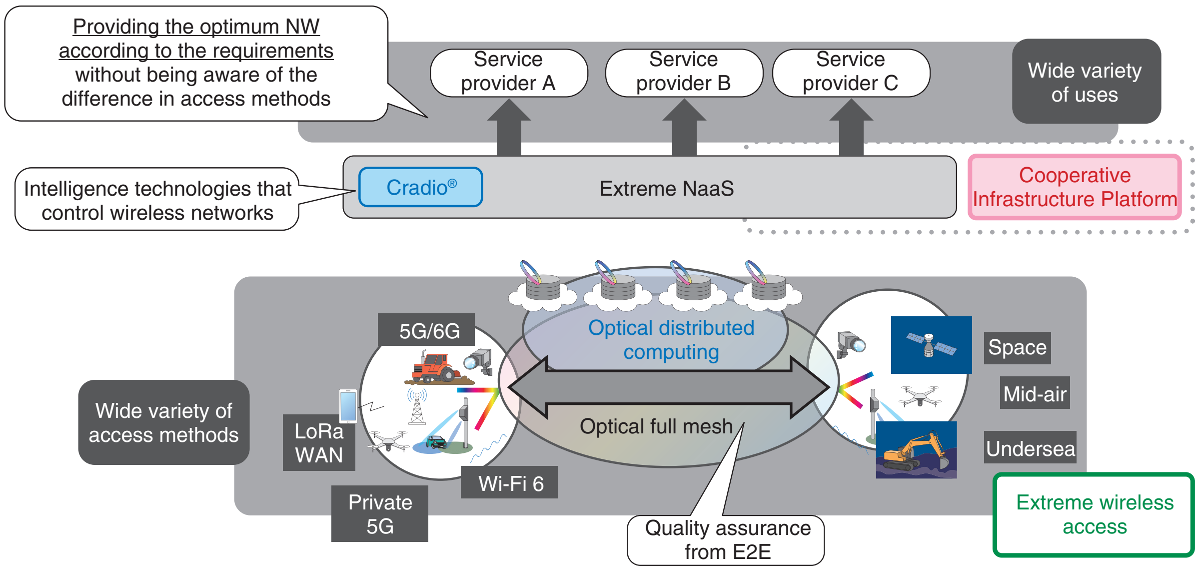


Fig. 4. Concept of extreme NaaS.

potential of wireless space.

To make extreme NaaS a reality, various wireless technologies and their peripheral technologies must be upgraded and combined. Two technologies that play an important role in meeting this need are Multi-radio Proactive Control Technologies (Cradio®) [5] and beamforming technology using analog radio-over-fiber (RoF) [6].

Cradio combines various wireless technologies (such as wireless sensing and visualization, wireless-quality prediction and estimation, and wireless-network dynamic design and control) in multiple wireless networks, including private and public networks, to meet ever-changing user requirements and radio-wave conditions. By cooperating with various social systems and applications, Cradio also makes it possible to create a natural communication environment in which people do not need to be aware of the wireless networks.

Regarding beamforming technology using analog RoF, a wireless analog signal is transmitted directly on a fiber without digital conversion in a manner that makes it possible to reduce the size and cost of antennas that are deployed in many areas. Remote beamforming also enables efficient area deployment of antennas.

5. Services provided by the Cooperative Infrastructure Platform

To provide services, such as agricultural ICT and mobility as a service (MaaS), by using the APN, it is necessary to satisfy service requirements in an E2E manner by linking terminals, cloud infrastructure, and networks. The architecture of the Cooperative Infrastructure Platform [7], which is an important elemental technology of an FDN and is being researched and developed to enable this cooperation, is explained below.

An example of the cooperative operation on the Cooperative Infrastructure Platform in the agricultural ICT field is shown in **Fig. 5**. In this example, farm work is automated by implementing remote monitoring and control for operating farm machinery within and between fields. When a tractor moves from field A to field B, the mobile network is switched from private 5G to carrier 5G, and the tractor and Cooperative Infrastructure Platform proactively predict the tractor's movement and position and communication quality for the field in question and switch to the optimal mobile network before the communication quality deteriorates.

In this example, the remote-control and monitoring functions on the cloud infrastructure use Global Navigation Satellite System (GNSS) positioning to determine the current position and predict the future route and wireless quality. When the quality of

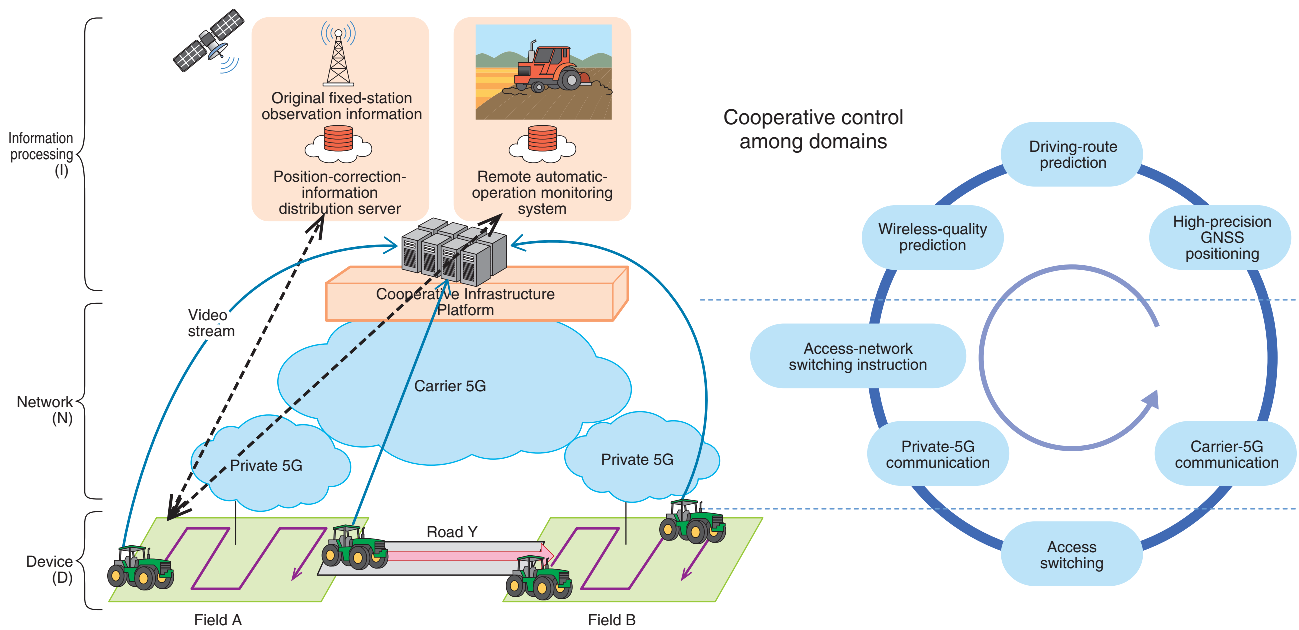


Fig. 5. Cooperative Infrastructure Platform and coordinated operation of information processing, network, and devices.

private 5G is predicted to degrade, an instruction is executed to switch to a carrier-5G network before such degradation occurs. Such a mechanism enables switching in an E2E manner without communication breakdown from the application layer. It will thus enable remote monitoring and control of mission-critical services such as level-3 automated driving of agricultural machinery, i.e., monitoring and controlling the machinery from locations far from the field such as monitoring centers.

6. Future developments

Typical network services enabled by the APN and an FDN were described, and examples of their implementation were presented. To promote system implementation and social implementation of the APN, we will continue to study architectures that enable these network services as well as conducting proofs of concept for each use case.

References

[1] APN, https://www.rd.ntt/e/iown/0008.html
[2] IOWN, https://www.rd.ntt/e/iown/
[3] IOWN Global Forum, "IOWN GF System and Technology Outlook," https://www.ietf.org/lib/dt/documents/LIAISON/liaison-2021-05-28-iown-global-forum-iesg-iab-iown-global-forum-to-ietf-attachment-1.pdf
[4] H. Yoshioka, T. Narumi, M. Nakagawa, and K. Matsumoto, "On-demand Photonic Multipoint Connection Technology Supporting High-presence Communications Services," NTT Technical Review, Vol. 19, No. 10, pp. 25–30, Oct. 2021. https://ntt-review.jp/archive/ntttechnical.php?contents=ntr202110fa2.html
[5] K. Kawamura, T. Moriyama, T. Ogawa, Y. Asai, and Y. Takatori, "Wireless Technologies toward Extreme NaaS—Multi-radio Proactive Control Technologies (Cradio®)," NTT Technical Review, Vol. 19, No. 10, pp. 31–37, Oct. 2021. https://ntt-review.jp/archive/ntttechnical.php?contents=ntr202110fa3.html
[6] M. Suga, K. Ito, T. Arai, Y. Shirato, N. Kita, and T. Onizawa, "Wireless Technology for Extreme NaaS—Remote Beamforming Schemes for Analog Radio-over-fiber-based High-frequency-band Wireless Communication Systems," NTT Technical Review, Vol. 19, No. 10, pp. 38–43, Oct. 2021. https://ntt-review.jp/archive/ntttechnical.php?contents=ntr202110fa4.html
[7] T. Kuwahara, R. Ishibashi, K. Kawakami, H. Masutani, H. Yamamoto, and S. Yasukawa, "Cooperative Infrastructure Platform for Delivering Mission-critical Services," NTT Technical Review, Vol. 19, No. 10, pp. 44–50, Oct. 2021. https://ntt-review.jp/archive/ntttechnical.php?contents=ntr202110fa5.html

Akio Kawabata
Vice President, Head of NTT Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. from the University of Electro-Communications, Tokyo, in 1991, 1993, and 2016. In 1993, he joined NTT Communication Switching Laboratories, where he has been engaging in the development of switching systems and researching network design and switching system architecture. He served as a senior manager of R&D Department at NTT EAST from 2011 to 2014.

Yuji Aoyagi
Vice President, Head of NTT Access Network Service Systems Laboratories.

He joined NTT in 1992 and has been engaged in developmental research on optical access network systems. He has been at his current position since July 2019.

On-demand Photonic Multipoint Connection Technology Supporting High-presence Communications Services

Hirotaka Yoshioka, Takamitsu Narumi, Masahiro Nakagawa, and Kenichiro Matsumoto

Abstract

Aiming for the next generation of high-presence communications services, this article presents a multipoint connection technology to provide a user-specific photonic communications network on demand for specific applications and requirements by constantly monitoring and linking/controlling various technical elements of the All-Photonics Network, such as the user interface, communication bandwidth, low latency, and local high-precision time keeping.

Keywords: high-presence communication, on-demand, photonic multipoint connection

1. Achieving a world of high-reality experiences for many people

The world where people used to meet each other, gather in large groups, and enjoy on-the-spot conversations and events is changing to one where people gather remotely from various locations to participate in meetings and events. People who are far away can easily meet each other via a display, and events that used to be difficult to experience due to capacity limitations are now easier to participate in, offering new ways to have fun. However, people may still feel a lack of realism. This is probably because many people feel uncomfortable due to unstable and highly variable communications quality, e.g., communications slowing down when talking to a friend or cheering for their favorite entertainer.

High-quality communications are also very expensive, takes several months for services to become available, and is a privilege only for a limited number of people. This is due to the limitations of current communications network technologies (**Fig. 1**). To achieve both *high-speed and broad bandwidth* as well as *low cost and immediate use*, NTT is collaborating with many partners and using All-Photonics Network (APN) technology to research and develop on-demand photonic multipoint connection technology called Photonics On-demand. We will add service technologies, such as the advanced next-generation video service platform called Photonic Direct Multipoint Connection Service Platform, to this communications technology to deliver high-presence communications to many of customers even in remote environments and making the Remote World a reality.

2. Service overview: A remote communications network that connects the world on demand

The key to solving the current network issues with remote communications, which will be achieved with Photonics On-demand, is how to make the smallest unit (one optical wavelength, commonly known as λ) of an optical communications path, which is high-speed but expensive and has limited applications,

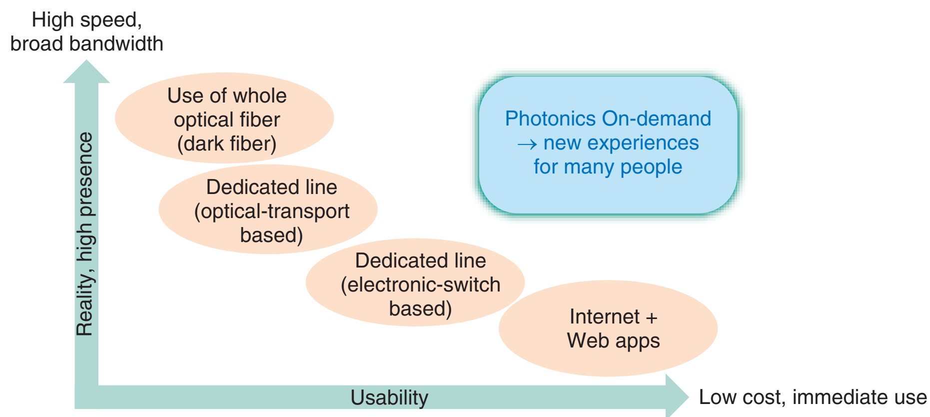


Fig. 1. Relationship among current services and target area for new technologies.

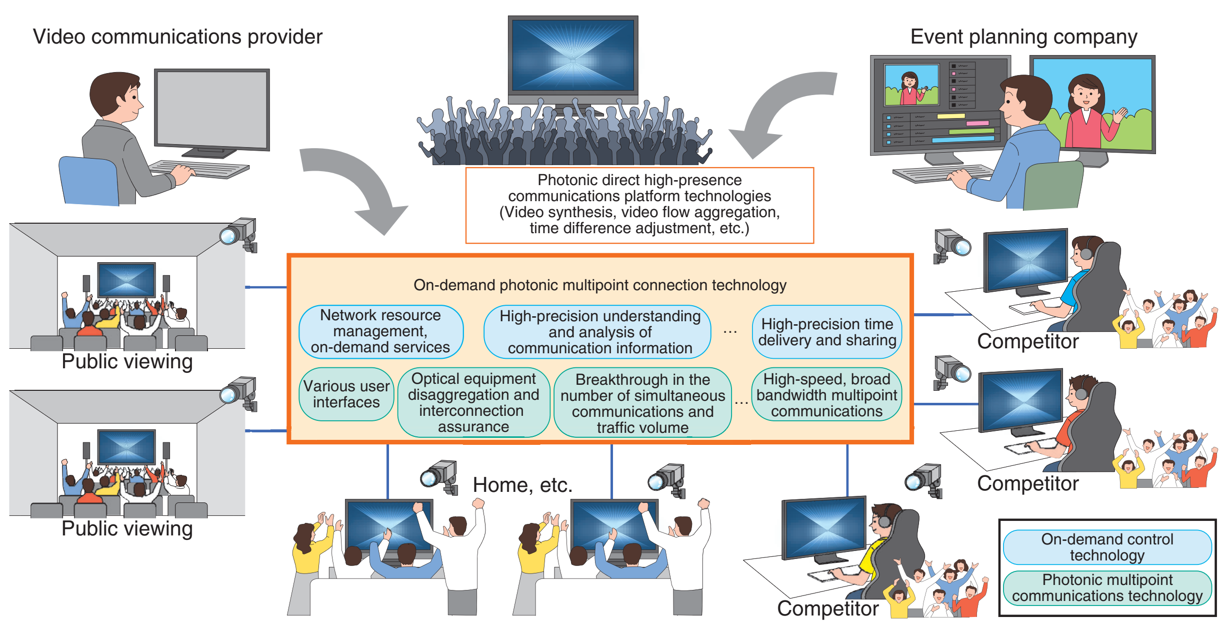


Fig. 2. A service provided by a remote communications network that connects the world on demand and key technologies.

available to a large number of people at low cost. To achieve this, the key is to increase the number of λs that can be used with a single optical fiber and achieve on-demand using the optical resources only when necessary and minimize use to only the amount of time needed.

It is also important to greatly expand service menus, which currently have little variety, to meet a wide range of user needs on the same network, and superimpose networks that can be provided to each user. This service is illustrated in **Fig. 2**.

3. Key technologies supporting services: Innovative technologies and total coordination

In this section, we introduce the key technologies that support Photonics On-demand.

3.1 Various interface types: Varied protocol support and flexible bandwidth selection

To enable users to use their own assets and the network freely, it is important to have a variety of interfaces to connect devices. We aim for various types of communications such as uncompressed video transmission (e.g., via serial digital interfaces) and analog optical signals essentially without the need for conventional protocols such as Ethernet or TCP/IP (Transmission Control Protocol/Internet Protocol). We will also use technology that divides a λ into time-domain elements and/or treats multiple λs as a group to provide communications with optimal quality and speed at all times.

3.2 Vendor-agnostic photonic device connection: Disaggregation and multi-vendor interconnection

To enable users to use a variety of interfaces, it will be necessary to expand the choice of connectible user devices and guarantee a variety of network combinations. However, since optical transmission equipment is conventionally provided by a single vendor in an end-to-end (E2E) manner, it will be necessary to disaggregate such equipment by function and freely interconnect different vendors. This type of disaggregation between hardware functions is called *horizontal disaggregation*. NTT is promoting this through global communities such as Metro Ethernet Forum, Open Networking Foundation, Telecom Infra Project (TIP) [1], and OpenROADM. The Innovative Optical and Wireless Network (IOWN) will further accelerate these interconnections.

3.3 Improving network utilization efficiency: Expanding network capacity and number of available wavelengths

The key to providing highly realistic services at low cost is a dramatic increase in the number of users using the network. To achieve this, we aim for a 125-fold increase in transmission capacity. This will be achieved by expanding the number of wavelength bands (introducing multiband transmission technology for stable, long-distance transmission [2]), by increasing the capacity per λ and exploiting the spatial dimension (e.g., space division multiplexing transmission). To meet diverse user needs, we will also establish technology that divides a single λ into the time-domain elements while guaranteeing long-distance transmission to provide services to even more users [3].

3.4 High-speed distribution of large-volume content to multiple locations: Multipoint simultaneous connection and photonics multicast

E2E communications leveraging optical transport technology alone are generally point-to-point (P2P), one-to-one connections. By grouping these and providing frame multiplexing and other features required by users, simultaneous connection of multipoint users can be achieved as function dedicated networks (FDNs). An FDN is a dedicated logical network that is independent for each user. These networks enable a large number of separate service levels that do not interfere with each other. It could be said that this is the network slice in which optical layer is the core, in contrast to the slicing technology currently accelerating around 5G (fifth-generation mobile communications systems). P2P connections alone also require servers to provide services and large numbers of optical λs to be handled at all times. However, APN optical components can copy and branch the same data to deliver them to multiple locations at high speed while maintaining quality.

Next, we introduce the core technologies to provide services on demand according to user requirements.

3.5 On-demand connection: FDN controllers

The most important technology in Photonics On-demand—and in all FDN services—is the FDN controller. With facility planning based on network design technology and usage forecasting based on macro information, which had been mainly adopted by telecommunications carriers, it is assumed that optical paths will be used on a fixed basis, but construction requires a long time and network resources are occupied even during periods of non-use, resulting in the inefficient use of these resources. Photonics On-demand enables high-efficiency usage of network resources by precisely allocating physical and logical network resources only when users need them, contributing to the provision of cost-effective, high-presence services. The key points are the management of network resources, creation and release of logical networks optimized for the required service level, and provision and maintenance of service levels. NTT laboratories are working with the above-mentioned global communities to demonstrate and promote the use of existing and new transport equipment.

By coordinating the innovative technologies provided by IOWN, we are working on the demonstration and establishment of workflows and the practical application of FDN controllers to shorten the time of providing optical communications paths from several months of construction to tens of minutes, and a few minutes shorter in the future, in line with the development of APN technology. By securely and reliably managing network resources on a per-user basis, an enormous number of services can be provided on a single network (hundreds to tens of thousands of connection points per service, provision of tens of thousands of simultaneous services, etc.).

3.6 Real-time and detailed understanding and adjustment of networks: Network monitoring, latency adjustment

With on-demand resource utilization, it is important to accurately determine the state of the vast amount of disaggregated network resources in real time. Specifically, it is important not only to monitor equipment-failure states but also guarantee the various network conditions and their strict service levels when each resource is linked. To achieve this, high-precision E2E service monitoring and network control are required. Although NTT has been working on monitoring technology at the transport layer, we are also working on the basic technologies to manage optical resources, measure communication speeds, and adjust latency according to service requirements.

3.7 Network-wide high-precision time synchronization

The low-latency network brought about by IOWN/APN will come into its own with more accurate time management and synchronization between devices. For example, for stock trading and professional remote e-sports, where fairness is key, we are working on high-precision time-synchronization technology to deliver more accurate clock time across the country without compromising accuracy and precisely adjust the timing between devices. Embedding highly accurate timestamps of communication locations in communication data enables services to conduct highly accurate and fair data timing correction. Increasing the accuracy of frequency sources will also make it possible to provide even more accurate clock time in the future.

3.8 Usability improvements: Photonic direct high-presence communications platform

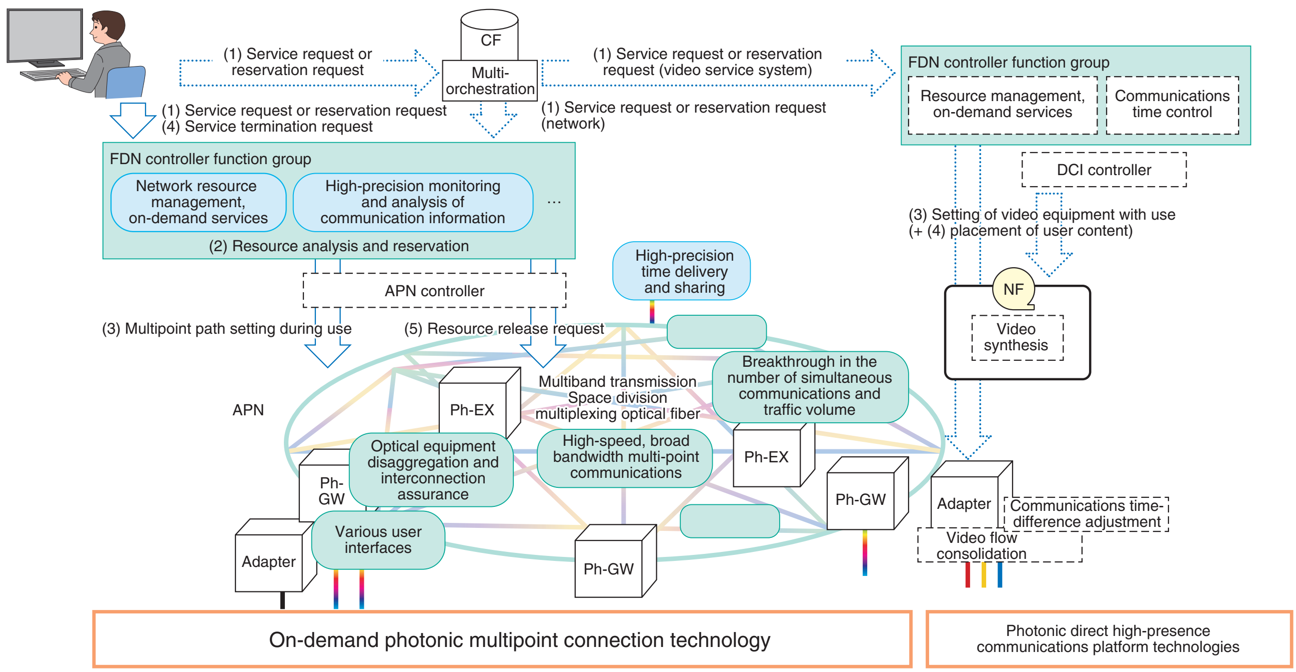
To make Photonics On-demand available to as many service providers as possible, we have started to study a photonic direct high-presence communications platform—a video platform to provide more convenient user interfaces. Video communications include functions such as rendering, video composition, video-flow aggregation, compression/decompression, and time-difference adjustment. These technologies are provided as a platform through batch control by the controller. Users can combine these functions in the order in which they actually want to carry out processing and add content such as captured video and audio that they want to use with each function. Inter-site communications of services and video functions can be combined with a Photonics On-demand FDN, while connecting to a minimum of video equipment makes it possible to provide high-presence video communications, connecting to any point freely at any time.

Figure 3 shows the workflow for the current service provision. Many technologies can be used on-demand with advanced management control by using the Cognitive Foundation (CF) and FDN controllers.

4. Prospects for the future: Deployment of usable technologies to the market and sustainable development of services

Although APN innovative technologies are needed to complete the establishment of on-demand photonic multipoint connection technology (its culmination is targeted for 2030), the key on-demand connection technologies can be used on existing optical networks. In the early stages, we will work on using the high-level control and network monitoring functions to provide a more cost-effective optical path.

To show the latest technology at Expo 2025 Osaka, Kansai, we will work together with partners to research and develop fundamental technologies to achieve the Remote World. Going forward, we will improve the real-time functionality of service delivery and scale of concurrent usage to bring more affordable services to more people. This technology, when used in conjunction with IOWN's new radio technology, will also contribute to increasing the effectiveness of extreme NaaS (network as a service).



DCI: data-centric infrastructure
NF: network function
Ph-EX: photonic exchange
Ph-GW: photonic gateway

Fig. 3. On-demand photonic multipoint connection technology workflow.

References

[1] TIP News, "TIP OOPT Project Group Completes Successful Proof of Concept for Open Optical Networks," June 3, 2021. https://telecominfraproject.com/tip-oopt-project-group-completes-successful-proof-of-concept-open-optical-networks/

[2] M. Nakagawa, H. Kawahara, T. Seki, and T. Miyamura, "Adaptive Link-by-link Band Allocation: A Novel Adaptation Scheme in Multi-band Optical Networks," Proc. of the International Conference on Optical Network Design and Modeling (ONDM) 2021, Gothenburg, Sweden, June/July 2021.

[3] M. Nakagawa, K. Masumoto, H. Onda, and K. Matsumura, "Experimental Demonstration of a PON Technology-based Optical Transport Solution over Field Installed DSF," Proc. of the 45th European Conference on Optical Communication (ECOC 2019), Dublin, Ireland, Sept. 2019.

Hirotaka Yoshioka

Senior Research Engineer, Supervisor, Vice President of Transport Network System Project, NTT Network Innovation Center.

He received an M.E. in physics in 1995 from Tokyo Metropolitan University. He joined NTT Network Service Systems Laboratories in 1995 and engaged in research and development (R&D) and supported NTT's commercial network and the software of legacy exchange systems, IP servers, IP edge router, and transport technologies. He is now leading R&D of disaggregation and integration of IP transport and driving open projects such as Multi-Service Fabric and Beluganos. He is also leading R&D of optical systems. As a co-lead, he is leading the sub-group of OOPT (Open Optical Packet Transport Project) in TIP, i.e., CANDI (Converged Architectures for Network Disaggregation and Integration), and collaborating with other operators toward use-case driven IP/Optical converged technology.

Takamitsu Narumi

Senior Research Engineer, Core Network Technology Research Project, NTT Network Service Systems Laboratories.

He received an M.E. in pure and applied sciences from Tsukuba University, Ibaraki, in 2009 and joined NTT the same year. He is currently with NTT Network Service Systems Laboratories, where he has been involved in R&D of transport service control systems. He is researching and developing network slicing, with the goal of commercialization.

Masahiro Nakagawa

Senior Research Engineer, Core Network Technology Research Project, NTT Network Service Systems Laboratories.

He received a B.E. and M.E. in electrical engineering and computer science from Nagoya University, Aichi, in 2008 and 2010. In 2010, he joined NTT, where he is currently with NTT Network Service Systems Laboratories. He has been involved in the R&D of transport network systems. His research interests include photonic network systems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Kenichiro Matsumoto

Executive Research Engineer, Vice President of Core Network Technology Research Project, NTT Network Service Systems Laboratories.

He received a B.E. and M.E. in electronics and communication engineering from Waseda University, Tokyo, in 1992 and 1994. Since he joined NTT Network Service Systems Laboratories in 1994, he engaged in the R&D of several network node system software such as SIP server for the Next Generation Network of the NTT Group. In his current position, he is responsible for the core research on network technology such as optical transport and network service platform. He also joined Core Network Development Department of NTT DOCOMO from 2017 to 2019 and engaged in the study on 5G core network architecture. He is a member of IEICE.

Wireless Technologies toward Extreme NaaS—Multi-radio Proactive Control Technologies (Cradio®)

Kenichi Kawamura, Takatsune Moriyama, Tomoaki Ogawa, Yusuke Asai, and Yasushi Takatori

Abstract

Services accommodated by wireless communications require not only improvements in basic performance such as extreme high capacity, extreme low latency, and extreme mass connectivity but also the means of satisfying requirements that combine these features in sophisticated ways. The provision of services that can deliver wireless access applicable to extreme service requirements in a flexible manner whenever and wherever needed is called "extreme network as a service (NaaS)." The technologies needed for extreme NaaS are currently under development, and as elemental technologies, NTT is promoting the research and development of Multi-radio Proactive Control Technologies (Cradio®) for assessing diverse wireless conditions and proactively controlling wireless access. This article introduces an image of the world that extreme NaaS will make possible and describes Cradio.

Keywords: wireless communications, Cradio®, extreme NaaS

1. Achieving extreme NaaS by combining diverse wireless access systems

Wireless communications are essential to delivering ultra-high speed and ultra-low latency communication services achieved by NTT's Innovative Optical and Wireless Network (IOWN) to the user's terminal in an end-to-end manner. The remarkable progress made by wireless communications has made it possible to enjoy high-speed and high-capacity communications at a variety of locations. The use of wireless communications for wide-area, power-efficient communications by sensors and other devices is also progressing. Going forward, we can expect the requirements of wireless communications to expand even further through the appearance of new services driven by the expansion of communications by people and things and the fusion of the cyber and physical worlds. In the field of mobile communications, research and development has begun toward the sixth-generation mobile communications system (6G). The targets that have been established for 6G include performance improvements such as high data rates greater than 100 Gbit/s, high capacities 100 times greater than the previous generation, extreme low latency, and extreme massive connectivity as well as expanded coverage to areas heretofore unreachable such as inside aircraft, under the ocean, and space [1]. At the same time, we can expect next-generation wireless standards to accommodate wireless local area networks (LAN) and wide-area, power-efficient wireless access called low power wide area (LPWA) that can be used in a flexible manner through autonomous deployment by users using unlicensed spectrum. It is important that diverse wireless standards with different characteristics be used

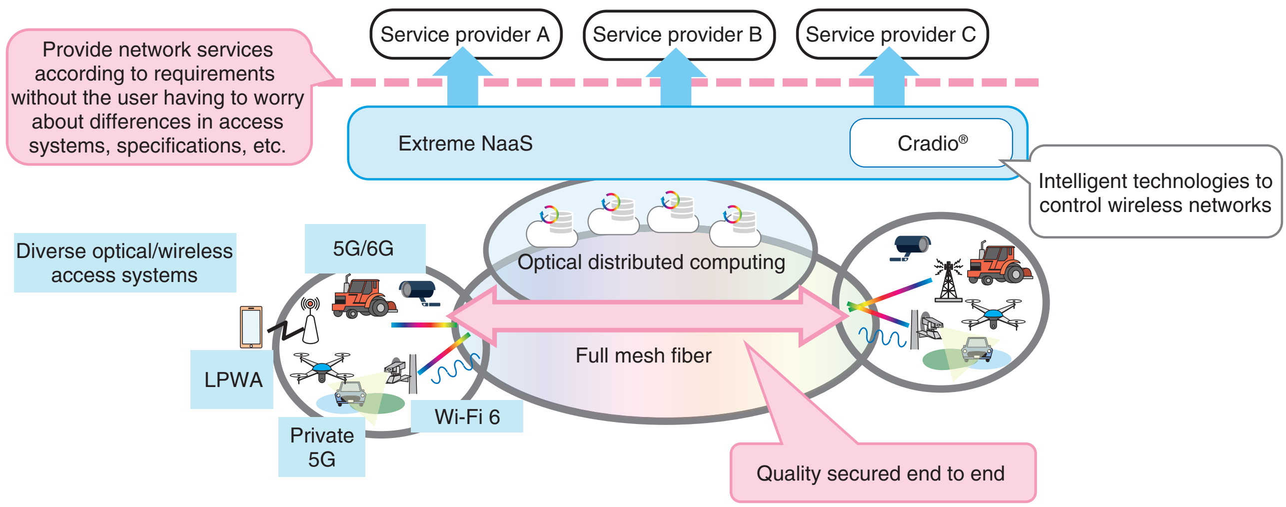


Fig. 1. Concept of extreme NaaS.

appropriately depending on the requirements.

Individual wireless access systems each have a set of available features such as throughput, communication distance, power consumption, and stability of quality, so a network operator selects the system it needs to construct a network and provide services. In contrast, the objective in the IOWN world is to interconnect these wireless access systems naturally without the user being aware of their differences so that the performance needed in wireless communications can be obtained. This service concept has been given the name of "extreme network as a service (NaaS)" (**Fig. 1**). Research and development of a platform to provide extreme NaaS is now moving forward. Extreme NaaS is made possible by combining diverse optical and wireless access systems based on the full-mesh-fiber network and optical distributed computing of IOWN.

2. Achieving natural wireless access by Cradio®

To achieve extreme NaaS, research and development is progressing on Multi-radio Proactive Control Technologies (Cradio®) [2] that targets and combines multiple wireless access systems as needed to achieve network connections that feel natural to the user.

In mobile communications, characteristics, such as data rate, latency, reliability, coverage, and terminal power consumption, differ in accordance with the radio frequencies and communication system used. In addition, wireless systems can be highly diverse depending on the legal system governing radio waves. These can range from wireless systems operated by telecommunications carriers owning a license to those that can be set up as desired by users with no license requirement and those that share frequencies with other systems. Given that the quality of wireless communications can change from moment to moment depending on the environment due to the effects of surrounding structures and moving objects, peripheral interference, etc., it is not easy to ensure stability in communication quality. There is therefore a need to master the use of frequencies and systems with such different features, track a dynamically changing radio environment, and meet unprecedented diverse and extreme requirements such as extreme high capacity, extreme reliability, extreme mass connectivity, and extreme power efficiency. The issue is how to obtain thorough knowledge of radio-wave physical characteristics and the characteristics of each wireless access system, how to select these characteristics in an optimal manner, and how to then design and operate the network desired. Using multiple wireless access systems that require such complex and specialized knowledge in a more advanced and automatic manner can be achieved using Cradio.

The concept of Cradio is illustrated in **Fig. 2**. The Cradio group of technologies can be broadly classified into the three areas of "assessment," "prediction," and "control." Cradio achieves and interlinks these three areas of technologies in an advanced manner and cooperates with various applications to create wireless access networks applicable to diverse application requirements amid ever-changing wireless

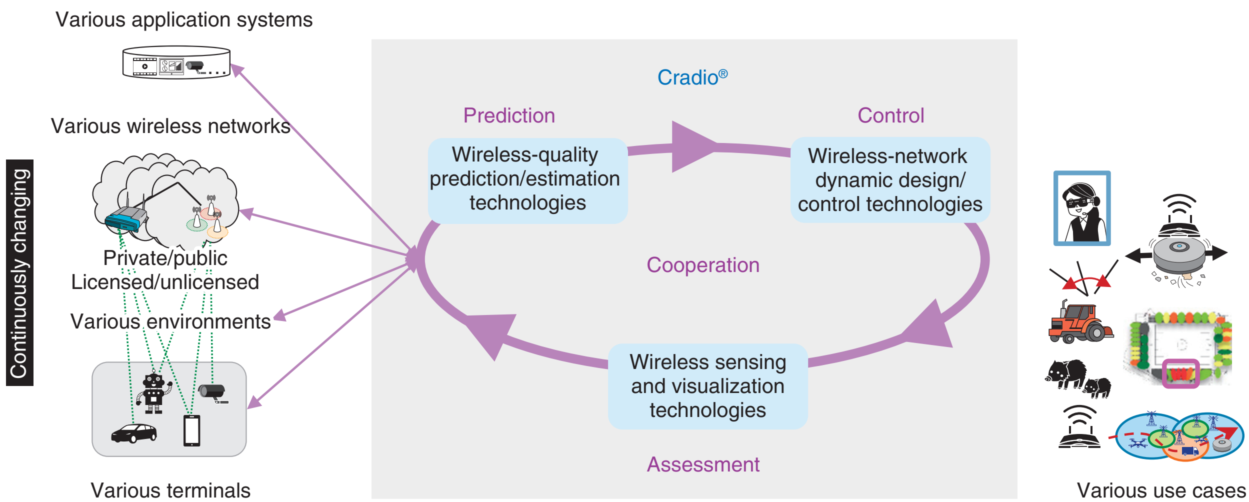


Fig. 2. Multi-radio Proactive Control Technologies (Cradio®).

quality.

The next section summarizes key technologies now under development in each of these Cradio areas toward practical implementation.

3. Cradio elemental technologies

3.1 Assessment: wireless sensing and visualization technologies

The “assessment” area enables sensing and analysis with respect to various types of wireless information and visualizes the quality of radio signals and communications, level of congestion, usage conditions of each terminal, interference conditions, etc. (**Fig. 3**). It is also possible to estimate with high accuracy the level of quality that can be obtained through technologies that assess changes in structures that affect the wireless environment and that execute highly accurate positioning of terminals [3].

To give an example, a Cradio technology under development will estimate and visualize available radio-signal quality to a high degree on the basis of highly accurate three-dimensional data of buildings and other structures combined with various types of radio-wave propagation models, ray tracing, etc. that take into account various types of wireless access and frequency bands. In the past, it was common to design wireless networks using radio-zone design tools specialized for each system, but the design of multi-radio networks that organically integrate wireless networks will require visualization of integrated quality across multiple systems. Such visualization and assessment technologies being developed will enable a wireless network designer handling multiple types of wireless access to simulate communication quality in virtual space with a feeling of uniform control and assess quality that optimally takes into account frequency and system characteristics.

3.2 Prediction: wireless-quality prediction/estimation technologies

The “prediction” area predicts and estimates the future in terms of how the communication quality of each terminal might change in the future based on wireless information that assesses and clarifies the radio-wave environment and on terminal position, peripheral environment, and other types of information. Therefore, quality degradation in unstable wireless communications can be detected beforehand so that proactive application control can be carried out such as by switching to a network with better quality or adjusting the transmission rate of a video stream.

Wireless-quality prediction/estimation technologies [4] using past quality information are examples of such technologies under development. An overview of these technologies is illustrated in **Fig. 4**. These technologies predict and estimate communication quality such as signal intensity or throughput at a certain base station using artificial intelligence (AI) techniques based on quality data collected from past records. They learn quality information such as signal intensity or throughput measured using a variety of terminals in combination with position information, wireless-environment scan information, time-period

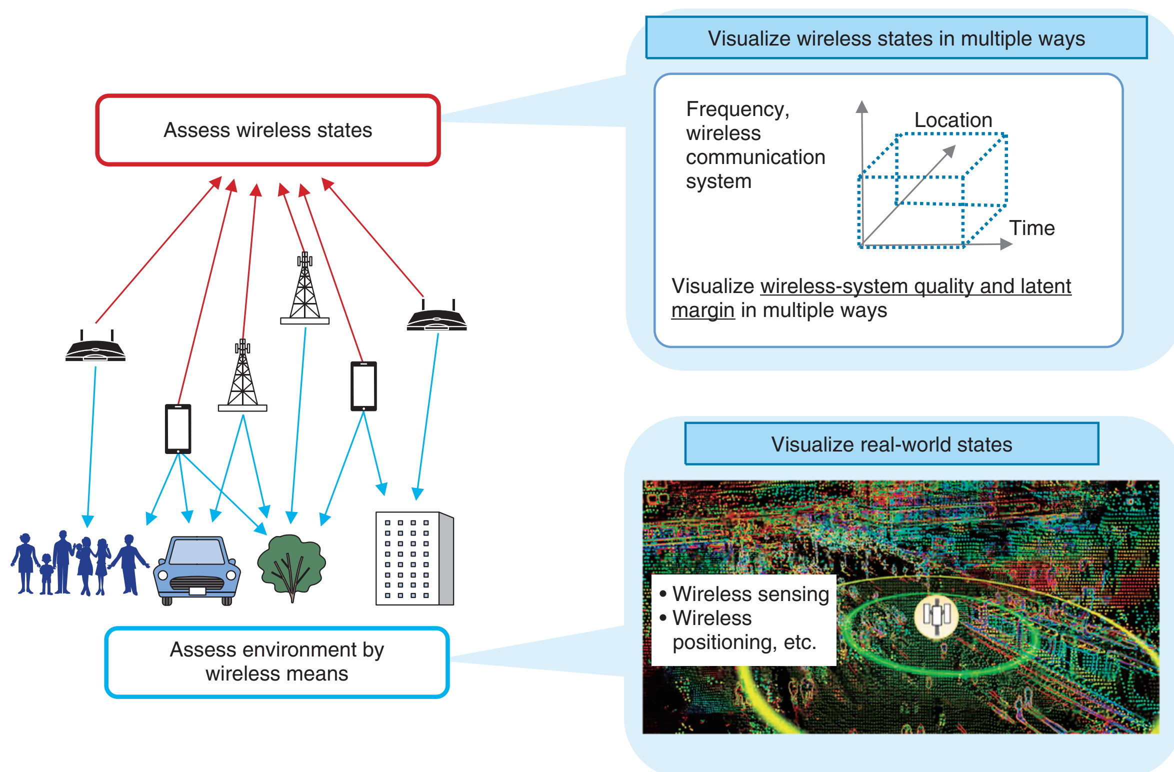


Fig. 3. Wireless sensing and visualization technologies.

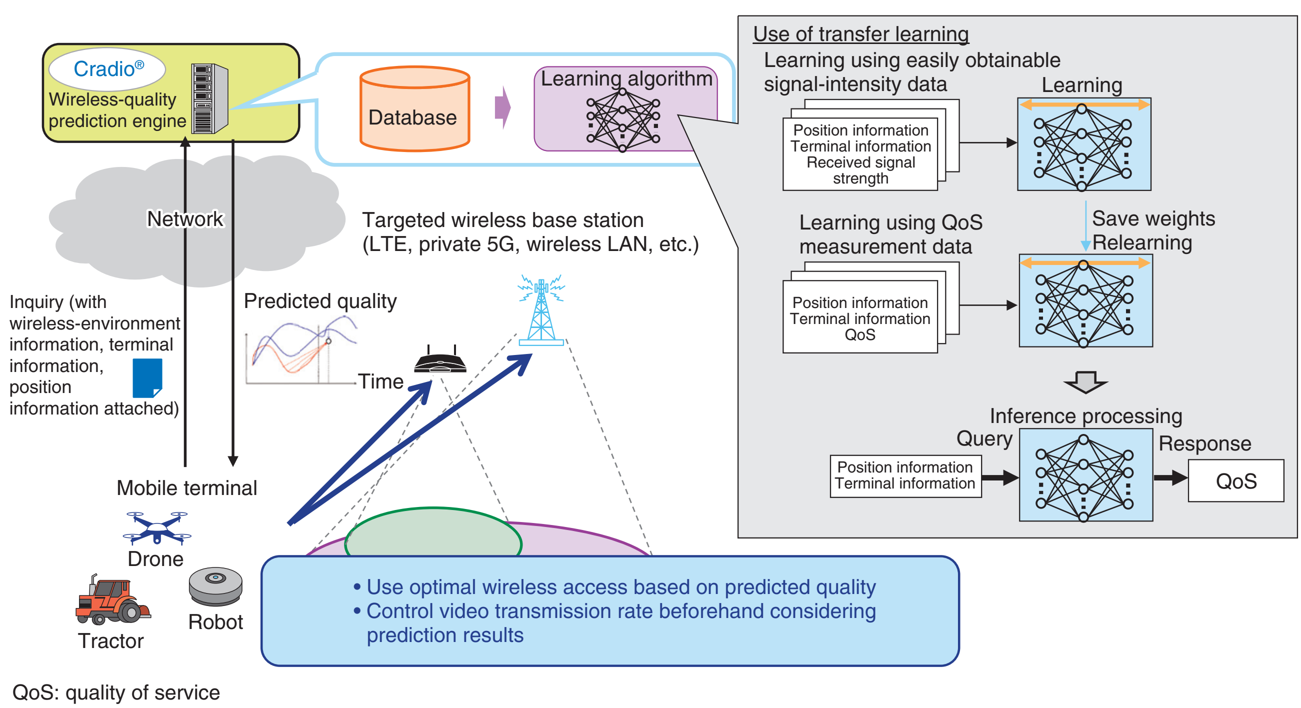


Fig. 4. Wireless-quality prediction/estimation technologies.

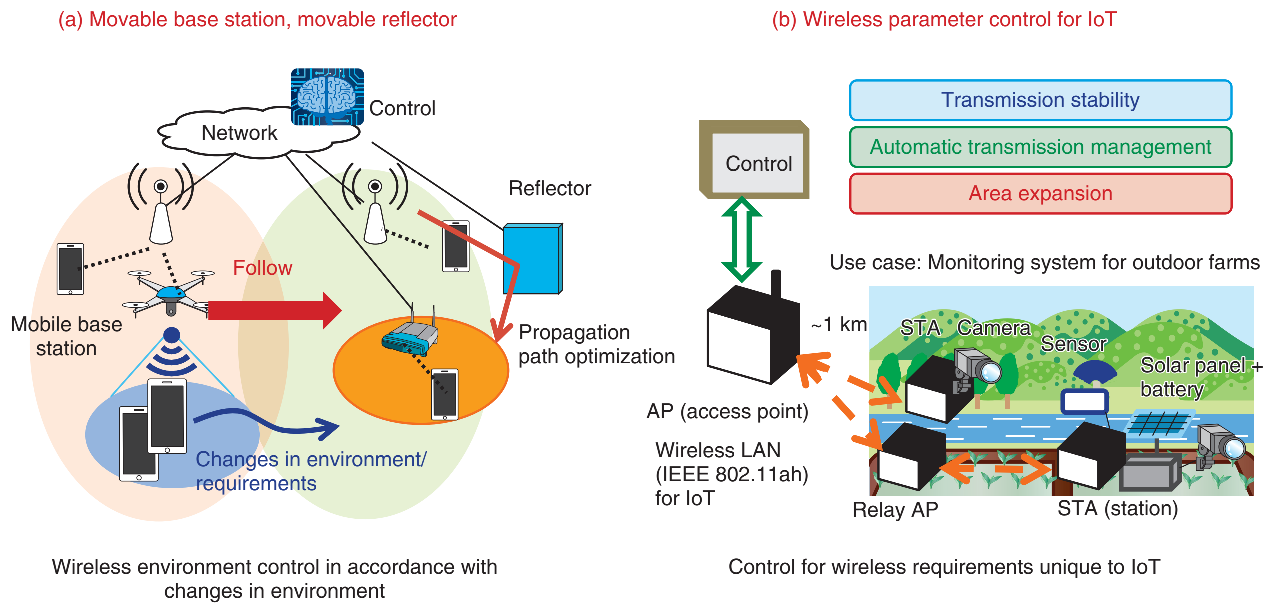


Fig. 5. Wireless-network dynamic design/control technologies.

information, etc. This makes it possible to calculate estimated values according to place and time and predict the quality of a wireless base station targeted for use. Prediction technology using AI also uses transfer learning technology based on neural networks. In this process, learning results based on signal-intensity data, which is relatively easy to collect for learning purposes, are passed on to learning based on throughput and other types of data that are not abundantly available, thereby increasing the accuracy of estimations. In the smart agriculture field, for example, field trials of this technology have been conducted [5]. In one such trial involving a self-driving tractor, stable switching among multiple wireless access systems was achieved on the basis of predicted quality. It has been shown that switching to a better wireless access system before quality degrades in this way is effective, for example, in achieving stable transmission of video for monitoring purposes.

3.3 Control: wireless-network dynamic design/control technologies

The "control" area uses the results of assessment and prediction to control the parameters of a wireless access network and link and coordinate various wireless networks. Examples of two key technologies under development in this area are illustrated in **Fig. 5**. The first is movable-base-station and movable-reflector technology for automatically moving wireless base stations that have generally been fixed to optimize wireless coverage in accordance with changes in the environment. With this technology, a base station mounted on a drone or automatic transport vehicle is made to automatically move to a location where traffic is concentrated, inducing terminals to move to that location and avoid locally generated congestion [6]. A key feature of this technology is the use of clustering technology to analyze the positional relationship between wireless base stations and terminals and automatically infer an optimal arrangement. In this regard, research is being conducted on dynamic area formation technology using movable reflectors. the second technology is wireless parameter control, which is being developed to stabilize transmissions and expand the coverage area for wireless access having wide-area and low-power-consumption requirements suitable for Internet of Things (IoT) [7]. This technology controls parameters with respect to the IEEE (Institute of Electrical and Electronics Engineers) 802.11ah wireless system to achieve area expansion and transmission stability as required in particular by IoT wireless networks.

A variety of control technologies in addition to the ones described above are also being researched and developed. The aim is to use these control technologies as a foundation for technology that can automatically construct and operate optimal wireless networks as needed.

4. Future outlook

NTT aims to satisfy application requirements that will be expanding into diverse and extreme areas and enable users to seamlessly make connections without having to be aware of the type of wireless access being used. To this end, NTT is promoting the development of Cradio with the goal of providing them in time with the deployment of IOWN around 2030. The first step in this process is the development of a platform for implementing the various technologies making up Cradio.

References

[1] NTT DOCOMO, "White Paper on 5G Evolution and 6G," Version 3.0, Feb. 2021.
https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_6g/DOCOMO_6G_White_PaperEN_v3.0.pdf

[2] M. Sasaki, T. Nakahira, T. Moriyama, T. Ogawa, Y. Asai, and Y. Takatori, "Multi-radio Proactive Control Technology (Cradio®): A Natural Communication Environment where Users Do Not Need to Be Aware of the Wireless Network," NTT Technical Review, Vol. 19, No. 8, pp. 37–45, Aug. 2021.
https://ntt-review.jp/archive/ntttechnical.php?contents=ntr202108ra1.html

[3] NTT Access Network Service Systems Laboratories, "Technology for Visualizing Radio Environments," ANSL R&D Times, Vol. 108, Mar. 2019 (in Japanese), https://www.rd.ntt/as/times/108/02/top.html

[4] K. Wakao, K. Kawamura, and T. Moriyama, "Quality-prediction Technology for Optimal Use of Multiple Wireless Access Networks," NTT Technical Review, Vol. 18, No. 6, pp. 17–20, June 2020.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr202006fa2.html

[5] Joint press release issued by Hokkaido University, Iwamizawa City, NTT, NTT EAST, and NTT DOCOMO, Nov. 16, 2020 (in Japanese).
https://group.ntt/jp/newsrelease/2020/11/16/201116b.html

[6] T. Nakahira, M. Sasaki, T. Moriyama, and Y. Takatori, "Dynamic Radio Control Using Movable Base Stations in Multi-Radio Proactive Control Technologies (Cradio)," IEICE Technical Report, Vol. 120, No. 314, CQ2020-62, pp. 11–16, Jan. 2021 (in Japanese).

[7] S. Shinohara, Y. Inoue, Y. Asai, and Y. Takatori, "Channel Selection Technique of Wide Area Wireless LAN IEEE 802.11ah for Internet of Things," IEICE Technical Report, Vol. 121, No. 43, RCS2021-23, pp. 41–46, May 2021 (in Japanese).

Kenichi Kawamura

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received a B.E. in electrical and electronic engineering and M.S. in informatics from Kyoto University in 1999 and 2001. Since joining NTT in 2001, he has been engaged in the research and development of wireless LAN systems, mobile routers, and network architecture for wireless access systems. His current research interests include wireless network technologies for IOWN. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Takatsune Moriyama

Senior Research Engineer, Supervisor, NTT Access Network Service Systems Laboratories.

He received a B.E. in electrical engineering and M.E. in electrical and electronic engineering from Muroran Institute of Technology, Hokkaido, in 1991 and 1993. He joined NTT in 1993. From 1999 to June 2019, he worked at NTT Communications, where he was in charge of network service development and operation for corporate customers. He has been in his current position since July 2019.

Tomoaki Ogawa

Senior Research Engineer, Supervisor, NTT Access Network Service Systems Laboratories.

He received a B.A. in environmental information and an M.A. in media and governance from Keio University, Kanagawa, in 1996 and 1998. He joined NTT Wireless Systems Laboratories in 1998, where he was engaged in the research and development of indoor location systems. His most recent interest is on the development of 6G wireless network technologies. He is a member of IEICE.

Yusuke Asai

Senior Research Engineer, Supervisor, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. in electronical engineering from Nagoya University, Aichi, in 1997, 1999, and 2017. He joined NTT Network Innovation Laboratories in 1999, where he has been engaged in the research and development of signal processing and resource-management techniques for broadband wireless LAN systems. He received the Young Researcher's Award from IEICE in 2004 and the Certification of Appreciation for outstanding contributions to the development of IEEE 802.11ac-2013 from the IEEE Standards Association in 2014. He is a member of IEICE and IEEE.

Yasushi Takatori

Executive Manager, Senior Distinguished Researcher, NTT Access Network Service Systems Laboratories.

He received a B.E. and M.E. in electrical and communication engineering from Tohoku University, Miyagi, in 1993 and 1995. He received a Ph.D. in wireless communication engineering from Aalborg University, Aalborg, Denmark, in 2005. He joined NTT in 1995 and has served as a secretary of IEEE Japan Council Awards Committee and a vice chairman of the Wireless LAN system development project in the Association of Radio Industries and Businesses (ARIB). He was a visiting researcher at the Center for TeleInFrastructure (CTIF), Aalborg University from 2004 to 2005. He served as a co-chair of COEX Adhoc in IEEE 802.11ac from 2009 to 2010. His current research interests include future wireless access systems for IOWN. He received the Best Paper Awards from IEICE in 2011, 2016, and 2020. He was honored with the IEICE KIYASU Award in 2016. He received Radio Achievement Award from ARIB in 2020 and the IEEE Standards Association's Outstanding Contribution Appreciation Award for the development of IEEE 802.11ac-2013 in 2014. He is a senior member of IEICE and a member of IEEE.

Wireless Technology for Extreme NaaS—Remote Beamforming Schemes for Analog Radio-over-fiber-based High-frequency-band Wireless Communication Systems

Mizuki Suga, Kota Ito, Takuto Arai, Yushi Shirato, Naoki Kita, and Takeshi Onizawa

Abstract

As one of the wireless communication technologies for extreme NaaS (network as a service), NTT Access Network Service Systems Laboratories previously proposed a system configuration to effectively expand the coverage area of high-frequency-band wireless systems. This configuration can separate the functions of a wireless base station and simplify remote radio units by using the analog radio-over-fiber technique. High-frequency-band wireless systems require beamforming to improve receiving sensitivity. This article describes remote beamforming schemes to enable beamforming with simplified remote radio units.

Keywords: radio-over-fiber, beamforming, high-frequency-band wireless communication

1. Introduction

One key component of extreme NaaS (network as a service) is wireless communication systems that use high-frequency bands such as millimeter-wave band. High-frequency-band wireless systems can enable larger transmission capacity through their wider bandwidths. However, many wireless base stations must be densely deployed because the propagation loss becomes large as the frequency increases. Therefore, we previously proposed a system configuration that uses the analog radio-over-fiber (RoF) technique to separate the functions of wireless base stations into a central station (signal processing unit) and remote radio unit (antenna unit) [1]. Signal-processing functions, including analog-to-digital (A/D) and digital-to-analog (D/A) conversions, are executed in the central station, and simple remote radio units are connected via analog RoF links. Since our configuration drastically simplifies the remote radio units, coverage-area expansion can be efficiently achieved. Our configuration is expected to be a promising area-expansion technology for sixth-generation mobile communication (6G) systems [2].

Beamforming to improve receiving sensitivity is necessary in high-frequency-band wireless systems since their propagation loss is significant. To enable beamforming with simplified remote radio units that have no signal processing unit, it is necessary to remotely control beamforming by the central station. Therefore, we also previously proposed two remote beamforming schemes that enable the central station to remotely control beamforming by remote radio units [3, 4].

Since these remote beamforming schemes have both advantages and disadvantages, it is important to

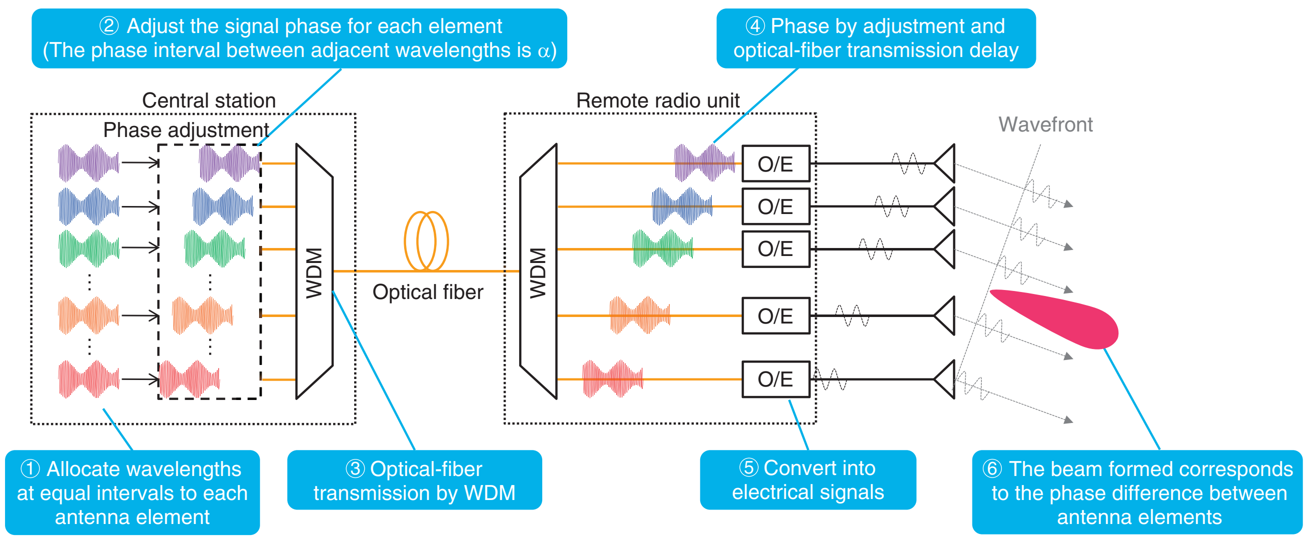


Fig. 1. Remote beamforming scheme with fixed wavelength allocation.

apply the appropriate remote beamforming scheme for each use case. This article details these remote beamforming schemes and describes suitable use cases.

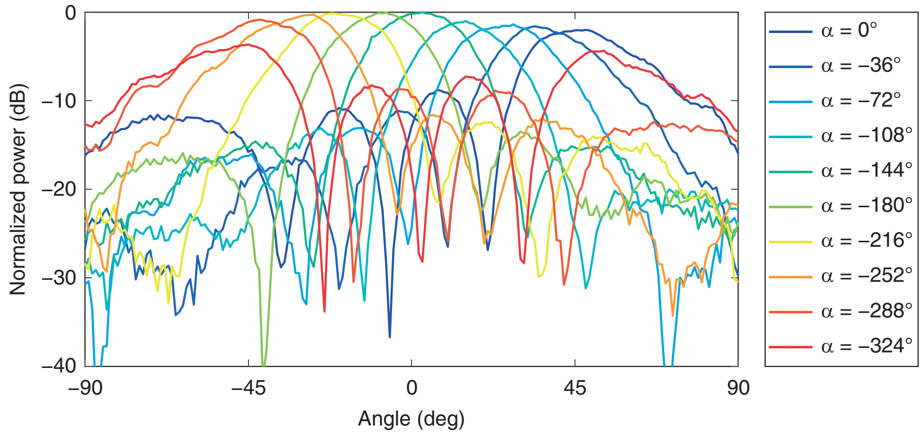
2. Problems with existing remote beamforming schemes

Existing remote beamforming schemes control the beam direction by changing the wavelength assigned to each antenna element and using the chromatic dispersion of the optical fiber link [5, 6]. However, these schemes have the following limitations; (1) optical fiber length information is required, (2) optical filter control in remote radio units is required, and (3) wireless signal form is restricted if high-frequency bands or long optical fibers are used. Therefore, it is difficult to apply these schemes for function separation of high-frequency-band wireless systems.

3. Scheme (1): Remote beamforming scheme with fixed wavelength allocation

Scheme (1) is a remote beamforming scheme with fixed wavelength allocation. This scheme is explained using the example of a transmitter (**Fig. 1**). The central station assigns a fixed wavelength to each antenna element; wavelength division multiplexing (WDM) combines the signals and transmits one optical signal to the remote radio unit. Due to the chromatic dispersion of the optical fiber link, signals input to each antenna element have different time delays depending on the wavelength and optical fiber length. However, if the wavelengths corresponding to each antenna element are allocated at narrow and equal intervals, the time delays due to chromatic dispersion will also be equal. Therefore, the antenna elements receive input signals that have equal phase differences. When signals with equal phase differences are transmitted from each antenna element, signals to be transmitted are synthesized in-phase to yield a certain beam direction. The beam direction is determined by the phase difference between antenna elements. Therefore, beam direction control is possible by adjusting the phases corresponding to each antenna element beforehand to have equal phase differences, while arbitrary equal phase differences are achieved by adjusting the phases and adding phase rotation by optical fiber transmission.

We investigated the applicable conditions and the effectiveness of scheme (1) through simulations and experiments [7]. We conducted a verification experiment using 10-GHz signal frequency, a 4-antenna element linear array in the remote radio unit, 10-km single mode fiber, and 1500-nm band wavelengths. The beam direction can be controlled by changing the phase interval (α) between adjacent wavelengths at the central station. **Figure 2** shows the results of this experiment in which the beam direction was scanned by changing α at the central station; the wavelength interval was set to 50 GHz. The results confirmed that changing α changes the beam direction. We also



Experimental confirmation that the beam direction can be controlled by phase adjustment in central station

Fig. 2. Validation of remote beamforming scheme with fixed wavelength allocation.

confirmed that the obtained beam patterns in the experiment was almost equal the ideal beam pattern for a 4-antenna element array antenna. The wavelength interval of 50 GHz is one of the intervals specified in the dense WDM standard. This experiment confirmed that scheme (1) can enable almost ideal beamforming even when using off-the-shelf devices that comply with industrial standards and that continuous beam scanning is possible by phase adjustment in the central station.

In scheme (1), there are restrictions on wavelength allocation because it is necessary to allocate wavelengths at narrow and equal intervals. Since the number of wavelengths must equal that of antenna elements used, the number of antenna elements is limited, and it is difficult to apply for massive antenna arrays. Since the remote radio unit requires only optical-to-electrical (O/E) conversion, each remote radio unit can be greatly simplified. Scheme (1) can form beams in arbitrary directions. Therefore, it is suitable for cases in which the area covered by one remote radio unit is relatively small, and a massive antenna array is not required, for example, room-based remote radio units in an office building that are connected to the same central station.

4. Scheme (2): Remote beamforming scheme using passive beamformer

Scheme (2) is a remote beamforming scheme that uses a passive beamformer (**Fig. 3**). The remote radio unit has the passive beamformer, and different wavelengths are assigned to its input ports. The central station selects and uses the wavelength assigned to the input port corresponding to the desired beam during electrical-to-optical (E/O) conversion. The signal transmitted from the central station is then passed to only the input port corresponding to the desired beam after passive WDM filtering and O/E conversion by the remote radio unit. Therefore, the input port of the passive beamformer can be switched by selecting the wavelength at the central station, and the beam can be switched remotely.

We tested scheme (2) using prototype devices [8]. This test was conducted with 28-GHz band wireless signals, 20-km single mode fiber, and 1500-nm band wavelength. A reflector array was also used as the passive beamformer in the remote radio unit. The reflector array consists of feeding antennas that radiate radio waves and a reflecting surface made of metamaterial. The metamaterial reflector is designed so that the reflecting directions of waves radiate from the feeding antennas depending on the positions of the feeding antennas. Since the radiated waves are reflected strongly in specific directions, beams can be formed. The beam direction can be changed by changing the feeding antennas. In the test, the reflector array had nine feeding antennas, thus formed nine beams, as shown in **Fig. 4** left side. The beam direction can be switched by switching the feeding antenna to which the signal is input. The input ports of each feeding antenna are assigned wavelengths in the 1500-nm band with 100-GHz intervals, and beam patterns are measured while switching wavelengths

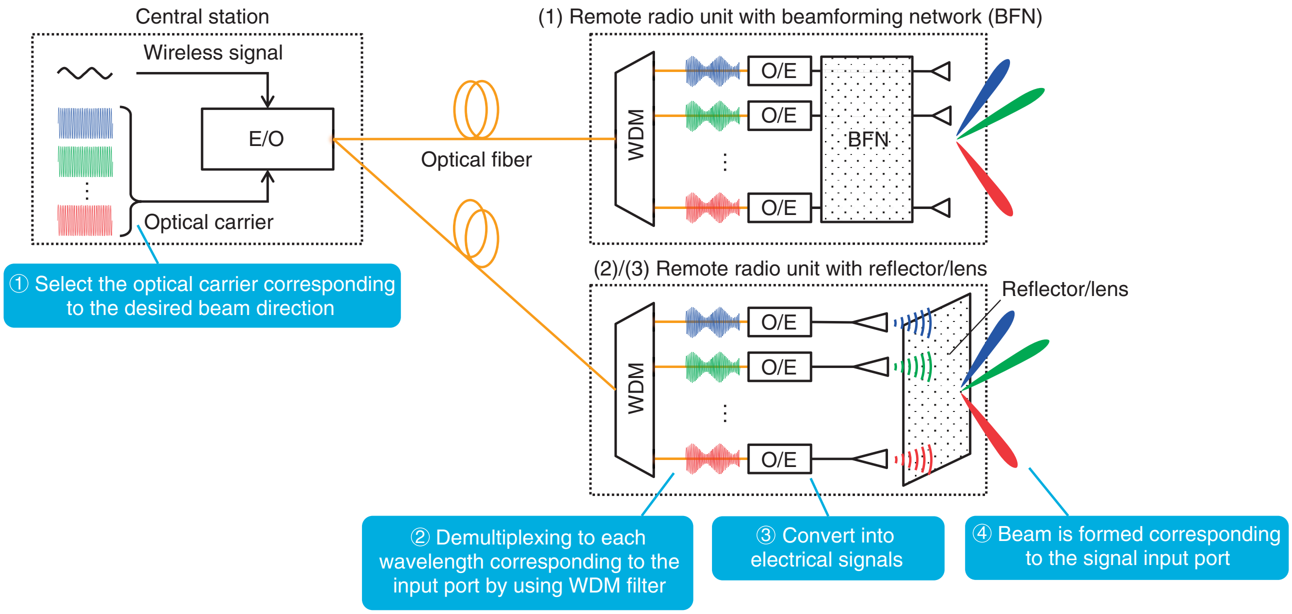
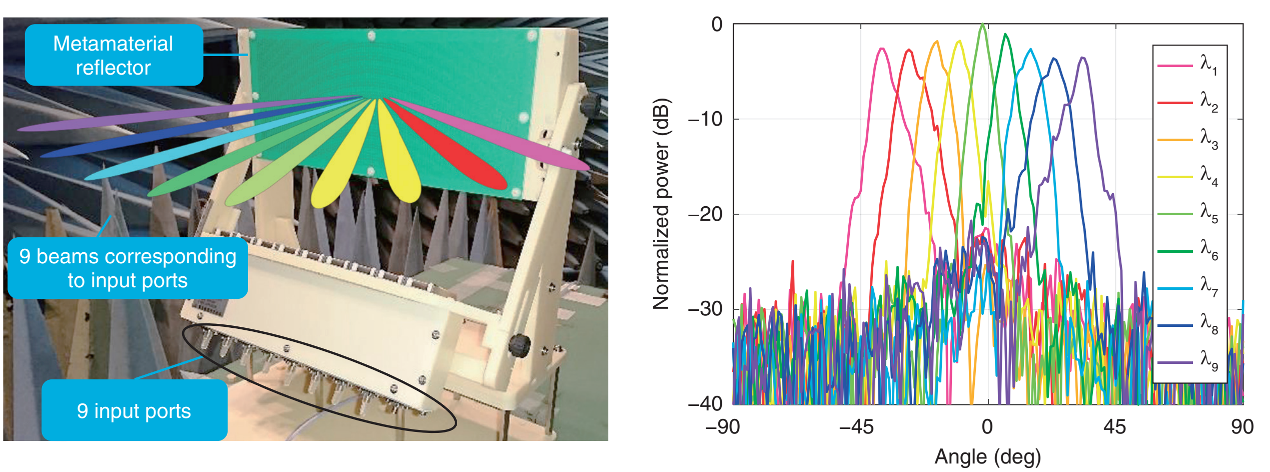


Fig. 3. Remote beamforming scheme using passive beamformer.



9-port reflector array used in the test

Confirmation that the beam direction can be controlled by switching wavelength in accordance with the input port of the reflector array

Fig. 4. Validation of remote beamforming scheme using passive beamformer.

used for E/O conversion at the central station. The results shown in Fig. 4 right side confirm that the beam direction changes with the wavelength, which is selected at the central station. The reason the beam gain decreases as the beam direction diverges from the front is due to the reflection characteristics of the reflector array.

It is necessary to set a beamformer at the remote radio unit so that the functionality of the remote radio unit will increase and installation sizes will be larger than with scheme (1). Since beam direction is determined by the design of the beamformer, there is a problem that only discrete beam directions are possible. However, when high beamforming gain is required, fewer wavelengths are needed compared with scheme (1) because the number of beams is expected to be lower than that of antenna elements when using massive antenna arrays. It is also possible to form multiple beams simply by inputting signals to multiple input ports. Since only one wavelength is used for one beam, there are no restrictions on wavelength allocation. Therefore, scheme (2) is suitable when one remote radio unit covers a wide area and high beamforming gain is needed, for example, wide service areas outdoors.

5. Future outlook

We will continue to improve remote beamforming characteristics to reduce the number of wavelengths required, increase beamforming gain, and enable arbitrary beam directions. We will also consider integration with distributed antenna systems and try to support 6G toward high-frequency-band wireless systems using analog RoF.

References

[1] K. Ito, M. Suga, Y. Shirato, N. Kita, and T. Onizawa, "Efficiently Accommodating High-frequency-band Wireless Systems by Using Analog Radio-over-fiber," NTT Technical Review, Vol. 18, No. 5, pp. 19–23, May 2020.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr202005fa3.html

[2] NTT DOCOMO, "White Paper on 5G Evolution and 6G," Version 3.0, Feb. 2021.
https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_6g/DOCOMO_6G_White_PaperEN_v3.0.pdf

[3] K. Ito, M. Suga, Y. Shirato, N. Kita, and T. Onizawa, "A Novel Centralized Beamforming Scheme for Radio-over-fiber Systems with Fixed Wavelength Allocation," IEICE Communications Express, Vol. 8, No. 12, pp. 584–589, 2019.

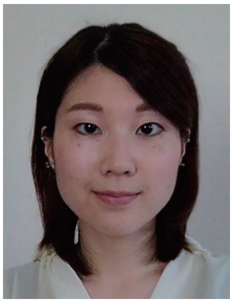
[4] K. Ito, M. Suga, T. Arai, Y. Shirato, and N. Kita, "Remote Beamforming Scheme for Higher Frequency Bands Radio-over-Fiber Systems," The 2021 IEICE General Conference, CI-7-5, Mar. 2021.

[5] S. Akiba, M. Oishi, Y. Nishikawa, K. Minoguchi, J. Hirokawa, and M. Ando, "Photonic Architecture for Beam Forming of RF Phased Array Antenna," 37th Optical Fiber Communication Conference and Exposition (OFC 2014), San Francisco, CA, USA, Mar. 2014.

[6] M. Tadokoro, T. Taniguchi, and N. Sakurai, "Optically-controlled Beam Forming Technique for 60 GHz-ROF System Using Dispersion of Optical Fiber and DFWM," OFC/National Fiber Optic Engineers Conference (NFOEC) 2007, Anaheim, CA, USA, Mar. 2007.

[7] K. Ito, M. Suga, Y. Shirato, N. Kita, and T. Onizawa, "Experimental Evaluation of Remote Beamforming Scheme with Fixed Wavelength Allocation for Radio-over-fiber Systems," Proc. of 44th European Conference on Optical Communication (ECOC 2020), Brussels, Belgium, Dec. 2020.

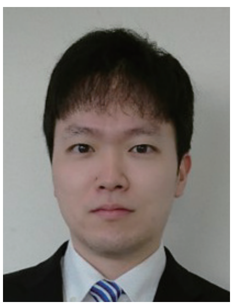
[8] K. Ito, M. Suga, T. Arai, Y. Shirato, N. Kita, Y. Kishiyama, S. Suyama, S. Nagata, and T. Asai, "Remote Beamforming Scheme Using Passive Beamformer for Higher Frequency Bands RoF Systems," The 2021 IEICE General Conference, B-5-8, Mar. 2021.



Mizuki Suga

Engineer, NTT Access Network Service Systems Laboratories.

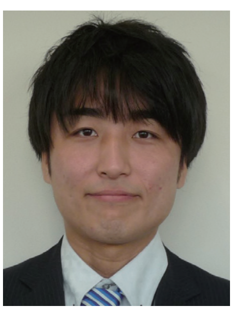
She received a B.E. and M.E. in engineering from Chiba University in 2012 and 2014. In 2014, she joined NTT Access Network Service Systems Laboratories and is currently researching high-frequency-band systems for wireless communications. She received the Young Researcher's Award in 2017 from the Institute of Electronics, Information and Communication Engineers (IEICE). She is a member of IEICE.



Kota Ito

Engineer, NTT Access Network Service Systems Laboratories.

He received a B.S. and M.S. from Tokyo Institute of Technology in 2013 and 2015. He joined NTT EAST in 2015 and has been with NTT Access Network Service Systems Laboratories since 2017. He is currently engaged in researching RoF systems. He received the Young Researcher's Award in 2019 from IEICE. He is a member of IEICE.



Takuto Arai

Research Engineer, NTT Access Network Service Systems Laboratories.

He received a B.S. and M.S. in computer science and engineering from Waseda University, Tokyo, in 2010 and 2012. Since joining NTT Access Network Service Systems Laboratories in 2012, he has been engaged in the research and development (R&D) of Massive MIMO techniques for wireless access systems. He is currently researching and developing future wireless systems for 5G Evolution and 6G mobile communications systems. He received the Best Paper Award in 2018 from IEICE. He is a member of the IEICE.

Yushi Shirato

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and D.E. in electrical engineering from Tokyo University of Science in 1990, 1992, and 2018. Since joining NTT Wireless Systems Laboratories in 1992, he has been engaged in R&D of adaptive equalizers, modems for fixed wireless access systems, and software-defined radio systems. He is currently engaged in R&D of millimeter-wave-band very high throughput fixed wireless backhaul systems. He received the Best Paper Award in 2018 and the Young Engineer's Award in 2000 from IEICE, and the 18th Telecom System Technology Award from the Telecommunications Advancement Foundation in 2003. He is a senior member of IEICE.

Naoki Kita

Senior Research Engineer, Supervisor, Group Leader, NTT Access Network Service Systems Laboratories.

He received a B.E. from Tokyo Metropolitan Institute of Technology in 1994 and M.E. and Ph.D. from Tokyo Institute of Technology in 1996 and 2007. Since joining NTT in 1996, he has been researching the propagation characteristics of wireless access systems and developing future satellite communication systems. From 2009 to 2010, he was a visiting scholar at Stanford University, CA, USA. From 2013 to 2014, he was a visiting research scholar at Waseda University, Tokyo. He is currently researching and developing future wireless access networks. He received the Young Researcher's Award, the Communications Society Best Paper Award, and Best Paper Award from IEICE in 2002, 2011, and 2014, respectively. He also received the Best Paper Award at the International Symposium on Antennas and Propagation 2016 (ISAP2016) in 2016. He is a senior member of IEICE and a member of the Institute of Electrical and Electronics Engineers (IEEE).

Takeshi Onizawa

Executive Research Engineer, Supervisor, Executive Manager - Wireless Entrance Systems Project, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. from Saitama University in 1993, 1995 and 2003. Since joining NTT in 1995, he has been engaged in the R&D of personal communication systems, high data rate wireless LAN systems, future wireless access systems, and radio propagation. He is in charge of management strategies of wireless communication systems. He received the Best Paper Award, Young Investigators Award, and Achievement Award from IEICE in 2000, 2002 and 2006, respectively. He received the Maejima Hisoka Award in 2008 and the Best Paper Award at ISAP in 2016. He is a senior member of IEICE and a member of IEEE.

Cooperative Infrastructure Platform for Delivering Mission-critical Services

Takeshi Kuwahara, Ryota Ishibashi, Kenta Kawakami, Hitoshi Masutani, Hiroshi Yamamoto, and Seisho Yasukawa

Abstract

To solve various social problems, we are researching the integration of network and computing technologies as social infrastructure. The Cooperative Infrastructure Platform being researched and developed at NTT Network Service Systems Laboratories is introduced in this article. To meet service requirements in an end-to-end manner and provide mission-critical services, this platform uses coordinated control among three domains—information processing, network, and device—in fields such as remote monitoring and control of autonomous agricultural machinery, advanced autonomous vehicles, and smart cities.

Keywords: IOWN, All-Photonics Network, Cooperative Infrastructure Platform

1. Background

Under the concept of cyber-physical systems (CPS), efforts are underway to collect various types of sensor information in the real world (the physical system) via networks, analyze the information collected in cyberspace constructed on an information-processing platform, and use the analysis results for controlling systems in the real world and distributing data between systems. As use cases of CPS [1] under the Innovative Optical and Wireless Network (IOWN), area management (such as surveillance cameras in smart cities), mobility management (such as autonomous vehicles), and industry management have been studied to enhance their functionality and develop new social infrastructures.

Unlike the conventional Internet and cloud computing, a CPS must collect a large amount of information from a huge number of devices, such as cameras and sensors, and requires a mechanism to efficiently collect a huge amount of upstream traffic through the network. In use cases of self-driving buses and automated guided vehicles, feedback control (actuation) of the physical system is executed from cyberspace by using sensing information such as video streams and positional information of the physical system in a real-time manner. In such cases, not only the network but also the computing infrastructure that constitutes the cyberspace and system on the device side (i.e., the physical system) must satisfy the requirements for low latency and stable data processing on an end-to-end (E2E) basis. We give an overview on the technology of the Cooperative Infrastructure Platform we are developing—to provide mission-critical services (such as CPS) under IOWN—and describe a field demonstration of the platform in smart agriculture.

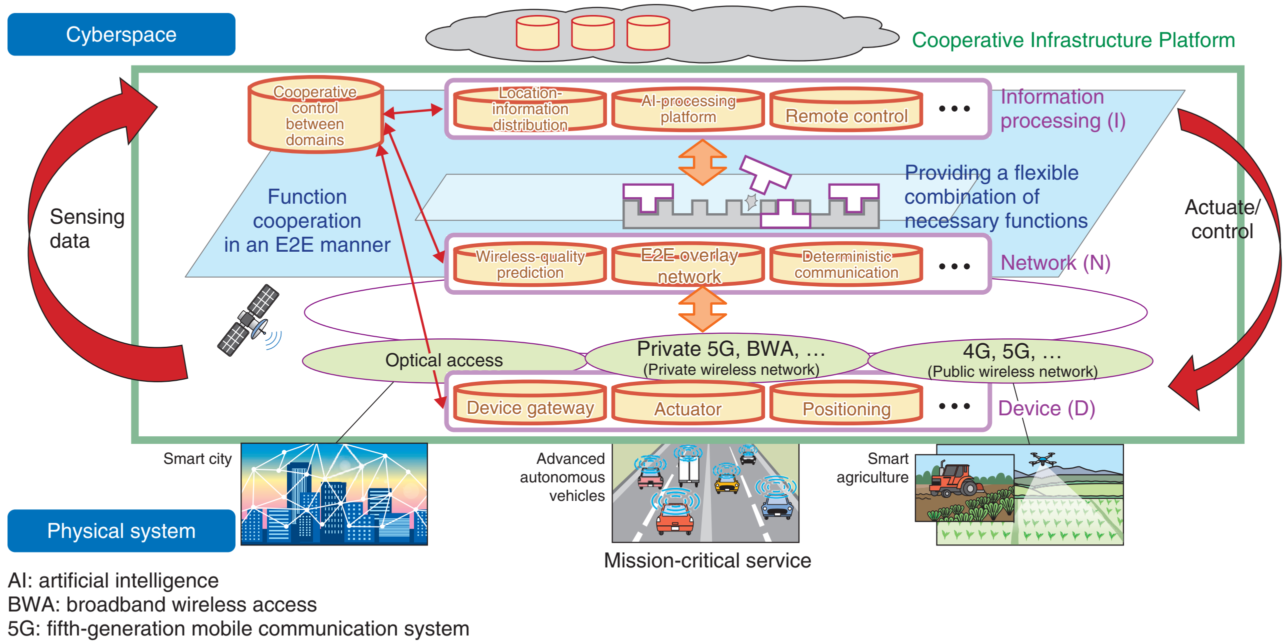


Fig. 1. Overview of Cooperative Infrastructure Platform.

2. Overview of the Cooperative Infrastructure Platform

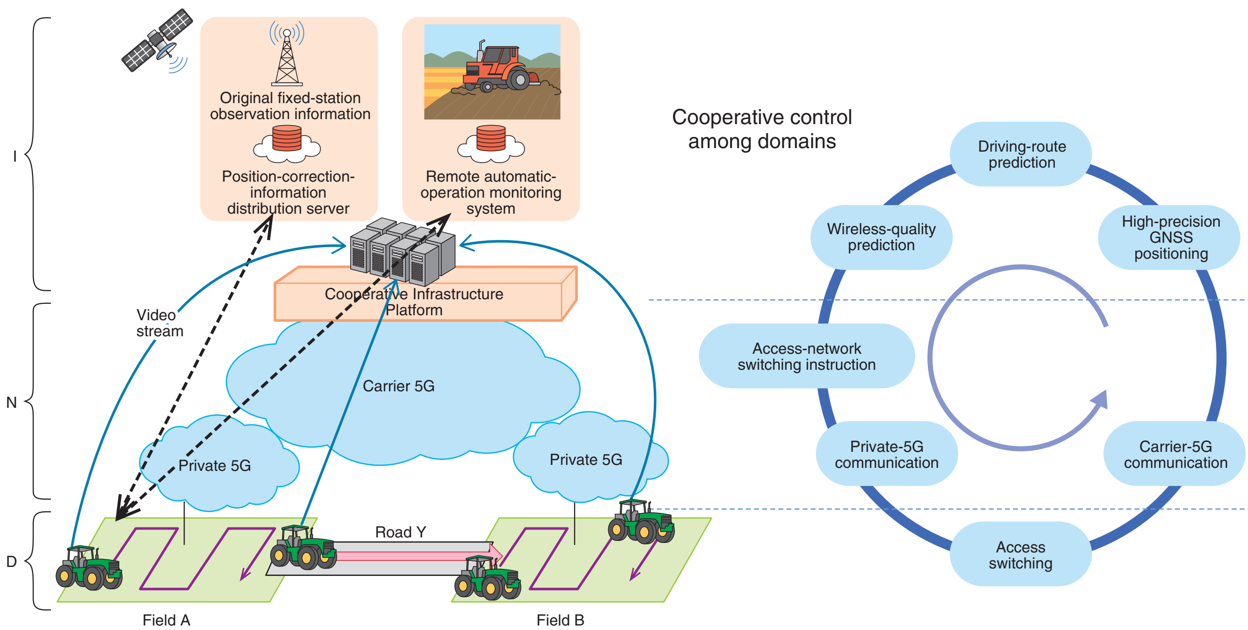
2.1 Concept and basic architecture

The Cooperative Infrastructure Platform is an infrastructure technology for providing advanced services that cannot be provided by the conventional Internet or cloud computing by using the All-Photonics Network and various wireless networks and linking their functions with an information-processing infrastructure and device functions. The basic architecture of this platform is shown in **Fig. 1**. The platform consists of elemental and control functions in the information processing (I), network (N), and device (D) domains, which are cooperatively controlled to satisfy mission-critical service requirements in an E2E manner. The elemental functions of each domain are intended to be configurable by combining functions in accordance with the services to be provided. This will enable flexible disposition of functions as a foundation for multi-access edge computing and edge datacenters.

2.2 Cooperative control among domains

We explain inter-domain cooperative control through the Cooperative Infrastructure Platform on the basis of specific use cases. A use case of automated driving of farm tractors and of the cooperative control of the tractor are outlined in **Fig. 2**. When an automated tractor moves from field A to field B, it must send a video stream for remote monitoring to the monitoring center via multiple wireless accesses via a private fifth-generation mobile communication system (5G) and carrier 5G, and in the event of an emergency, the system must be shut down remotely. The operator must therefore monitor and control the tractor remotely at all times, and the monitoring images and control signals must be transmitted without being affected by switching from one wireless network to another.

The procedure of the Cooperative Infrastructure Platform is outlined as follows. First, the position of the tractor is measured using a high-precision Global Navigation Satellite System installed on the tractor. Next, the driving route is predicted on the basis of the obtained positioning information, and the quality of the wireless network at the future location is predicted. If the network quality is predicted to degrade to the extent that the transmission of monitoring images or control signals is affected, the wireless network is switched from private 5G to carrier 5G, for example, before the quality actually degrades. Cooperative operation of the I, N, and D domains in this manner enables seamless switching between multiple wireless



GNSS: Global Navigation Satellite System

Fig. 2. Cooperative control among domains.

networks.

3. Initiatives for applying the Cooperative Infrastructure Platform to smart agriculture

NTT Network Service Systems Laboratories is working on applying the Cooperative Infrastructure Platform to agriculture, which is facing labor shortages due to declining birthrate and aging population. Under an industry-academia-government collaboration agreement between Hokkaido University, the city of Iwamizawa, Hokkaido, NTT, NTT EAST, and NTT DOCOMO, we have been researching and developing technology for achieving world-class smart agriculture by using cutting-edge robotics and IOWN information and communication technology. In November 2020, we conducted a demonstration experiment [2] in Iwamizawa. The benefits provided by our platform are discussed below with a focus on the experiment.

3.1 Challenges concerning level-3 autonomous driving of agricultural machinery

One of the issues attracting attention in the agricultural field is level-3 automated driving of agricultural machinery, i.e., monitoring and controlling the machinery from locations far from the field such as monitoring centers. As in the case of cars, automation of agricultural machinery is categorized as different levels, and level-2 agricultural machinery that can operate automatically in an unattended state (but under the user's visual supervision) has been commercialized. The user monitors the target agricultural machinery and carries out emergency operations, such as stopping the machinery in case of danger, either by direct visual observation from around the field or using a tablet via a local communication network such as a wireless local area network. Note that such commercially available automated agricultural machinery is equipped with cameras and distance sensors to autonomously detect hazards and automatically stop the machinery.

For level-3 automated driving, monitoring images and control information must be transmitted between remote locations and the agricultural machinery via communication networks such as 5G/Long-Term Evolution (LTE). In addition to covering agricultural work in fields, level-3 includes driving in sheds and on roads connecting fields. Enabling remote monitoring control of multiple agricultural machinery from a remote monitoring center should result in further labor saving regarding all agricultural work using agricultural machinery and development of new businesses based on the sharing model. However, to

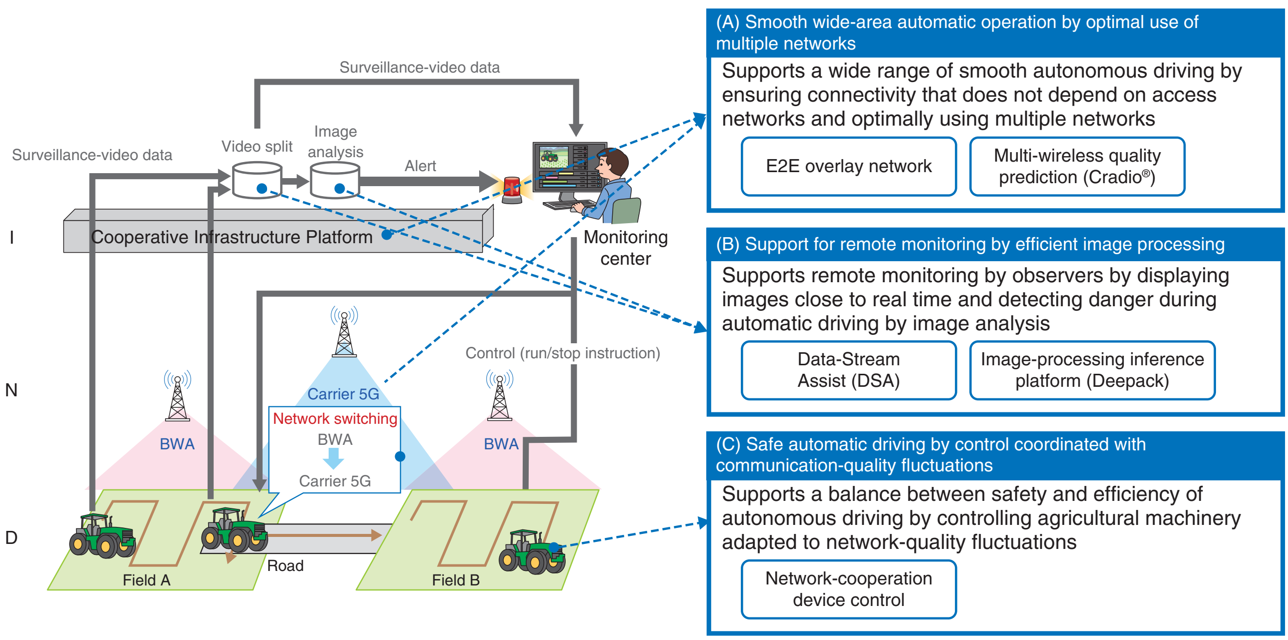


Fig. 3. Overview of field demonstration involving automated driving of agricultural machinery.

conduct surveillance control remotely, in addition to transferring the video from machinery with high quality, it is necessary for the remote operator to carry out an emergency stop if the surveillance video indicates an impending emergency, and achieving stable remote monitoring with low latency across the entire system (including the network) is a technical challenge.

3.2 Field demonstration of automated driving of agricultural machinery using the Cooperative Infrastructure Platform

As mentioned above, the Cooperative Infrastructure Platform aims to provide the added value necessary for networks as social infrastructure by cooperatively operating multiple elemental technologies. The overall structure of the content demonstrated in Iwamizawa and an overview of the operation in each scenario are shown in **Figs. 3** and **4**.

In scenario A, as a component of cooperative-infrastructure-platform technology, an uninterrupted network is implemented, and stable remote monitoring and control of autonomous driving is achieved. In particular, E2E overlay network technology and multi-wireless-quality-prediction technology (Cradio®) [3] are used to enable agricultural machinery to run automatically across multiple networks. This automatic running is enabled by automatically switching to an appropriate network before communication quality fluctuates or deteriorates, as predicted using artificial intelligence. The results of a demonstration in which a farm tractor was driven automatically on a farm road in Iwamizawa are shown in **Fig. 5**. In this demonstration, the network was successfully switched automatically—without interrupting communication—by using the above-mentioned technologies.

In scenario B, the processing of the video stream for remote monitoring is streamlined using a stream-merge function that efficiently processes multiple video streams, and utilization efficiency of server capacity for image analysis of such obstacle detection is improved using an inference-processing platform technology that optimizes various resources such as central processing units and graphics processing units. In addition, Data-Stream-Assist technology [4] enables simultaneous use of real-time video for multiple purposes (such as remote monitoring and image analysis) while reducing network load by replicating video streams at the packet level with low delay for such multiple applications.

In scenario C, network-cooperation device-control technology is used to support the control of agricultural machinery in response to changes in network quality. The effectiveness of this technology in terms of automatically stopping a tractor safely when the

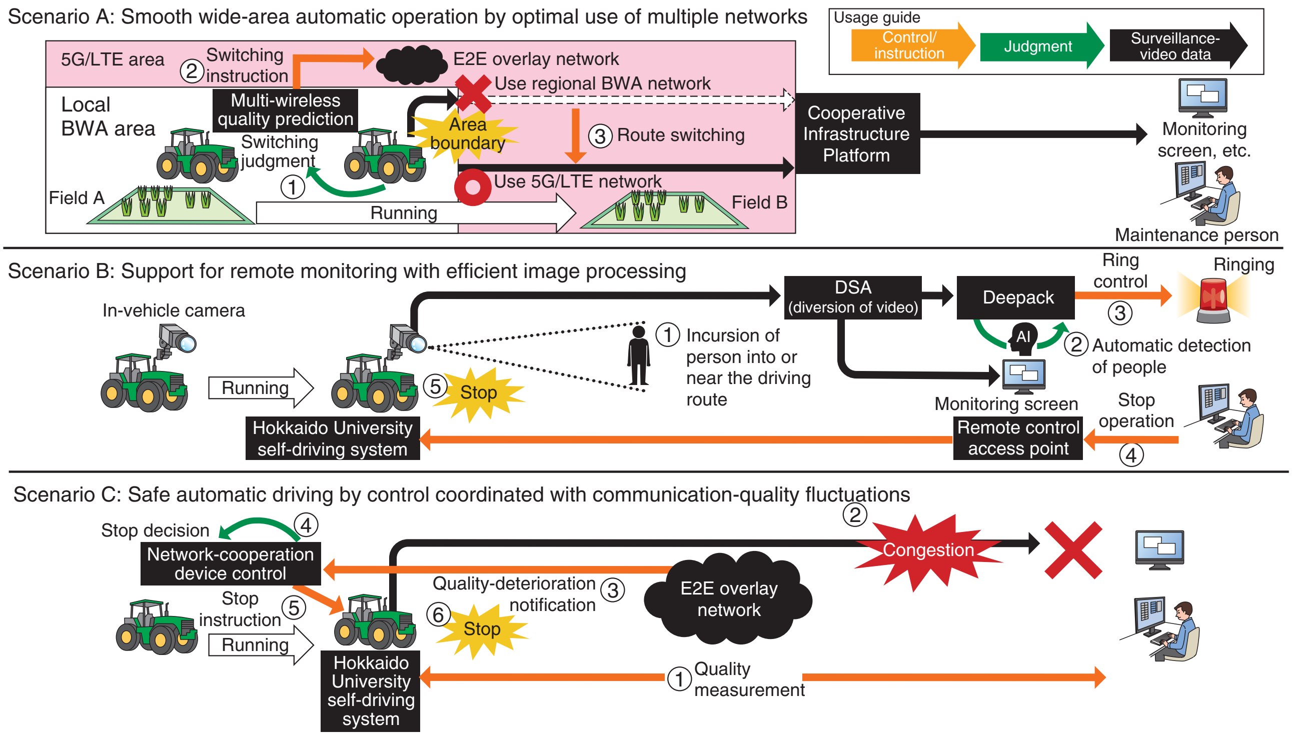


Fig. 4. Overview of operation in demonstration scenario.

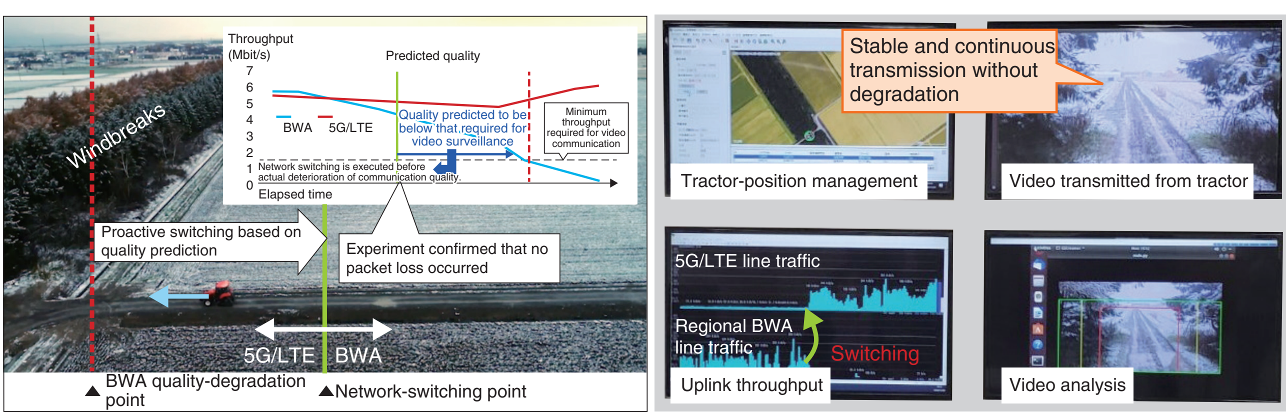


Fig. 5. Results of demonstration of seamless switching across multiple networks.

network quality deteriorated to the level at which the surveillance video could not be transmitted was confirmed.

4. Future developments

The Cooperative Infrastructure Platform we are developing to provide mission-critical services under IOWN was discussed, and a field demonstration of remote monitoring and control of automated tractor driving conducted in the city of Iwamizawa, Hokkaido was described. In the future, we will expand the applicability of the Cooperative Infrastructure Platform and establish an integrated architecture and elemental technologies through studying use cases of high-speed moving vehicles (such as advanced autonomous vehicles) in addition to smart agriculture.

References

[1] IOWN Global Forum, "Cyber-Physical System Use Case Interim Report," https://iowngf.org/wp-content/uploads/formidable/21/IOWN-GF-RD-CPS_Use_Case_Interim_Report__2.0-1.pdf
[2] Joint press release issued by Hokkaido University, Iwamizawa City, NTT, NTT EAST, and NTT DOCOMO, Nov. 16, 2020 (in Japanese). https://www.ntt.co.jp/news2020/2011/pdf/201116b.pdf
[3] K. Wakao, K. Kawamura, and T. Moriyama, "Quality-prediction Technology for Optimal Use of Multiple Wireless Access Networks," NTT Technical Review, Vo. 18, No. 6, pp. 17–20, 2020. https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr202006fa2.html
[4] N. Higo, T. Tsubaki, K. Koshiji, T. Tsubaki, and T. Kuwahara, "Data Stream Assist Technology Supporting IoT Services," NTT Technical Review, Vo. 16, No. 9, pp. 19–27, 2018. https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201809fa4.html

Takeshi Kuwahara

Senior Research Engineer, Supervisor, and Group Leader of the Network Service Platform Research Group, NTT Network Service Systems Laboratories.

He received a B.E. and M.E. from Waseda University, Tokyo, in 1995 and 1997. Since joining NTT in 1997, he has been engaged in research and development (R&D) of asynchronous transfer mode networks, Internet protocol (IP) virtual private networks, cloud systems, network security, and edge computing technologies. He was in charge of telecom carrier relations regarding network R&D while based in Washington, D.C., USA, and led the establishment of the APAC Telecom Innovation Initiative (ATII) while in his current position. He has been working on the fusion of networking and computing in the IOWN architecture. He is a member of the Technical Advisory Council of LF Edge.

Ryota Ishibashi

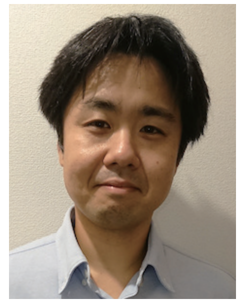
Senior Research Engineer, NTT Network Service Systems Laboratories.

He received a B.E. and M.E. in engineering from Tokyo Institute of Technology in 2005 and 2007. In 2007, he joined NTT Service Integration Laboratories, where he studied the design of telecom network architecture and signaling protocols for next-generation multimedia communication such as the next-generation network (NGN). He was with DOCOMO Communications Laboratories GmbH in Munich, Germany, from 2011 to 2012 then NTT DOCOMO from 2013 to 2016, where he was engaged in the development of mobile application service systems. He is currently studying the architecture and innovative network technologies of IOWN.

Kenta Kawakami

Senior Research Engineer, Network Service Platform Research Group, Core Network Technology Research Project, NTT Network Service Systems Laboratories.

He received a B.S. in information science from Kyushu University, Fukuoka, in 2004 and an M.E. in engineering from Tokyo Institute of Technology in 2006. He joined NTT Service Integration Laboratories in 2006, where he was involved in researching and standardizing NGN architecture, in particular, IP television and quality of service architecture. He has been involved with several standards developing organizations, including the European Telecommunications Standards Institute (ETSI), the 3rd Generation Partnership Project (3GPP), the Telecommunication Standardization Sector of International Telecommunication Union (ITU-T), and Broadband Forum. In ETSI, he was a rapporteur of the standards specification of the DIAMETER protocol. He transferred to NTT EAST R&D Center in 2010 and developed the domain name system for NGN and contributed to starting new IPv6 services. He is currently researching network edge architecture.



Hitoshi Masutani

Senior Research Engineer, Network Service Platform Research Group, Core Network Technology Research Project, NTT Network Service Systems Laboratories.

He received a B.E. in communication engineering and M.E. in electrical, electronic and information engineering from Osaka University in 1999 and 2001. After joining NTT Network Innovation Laboratories in 2001, he studied multicast networking and Session-Initiation-Protocol-based home networking. In 2005, He moved to the Visual Communication Division of NTT-Bizlink, where he was responsible for developing and introducing visual communication services, including an IP-based high-quality large-scale video conferencing system and real-time content delivery system on IPv6 multicast. He also worked on developing their service order management system and network management system for video conference services. Since returning to NTT Network Innovation Laboratories in 2012, he has been engaged in the R&D of programmable network nodes, including software-defined networking and network function virtualization, e.g., high-performance software openflow switch Lagopus. He is currently engaged in R&D of deterministic communication services' technologies.

Hiroshi Yamamoto

Senior Research Engineer, Supervisor, NTT Network Service Systems Laboratories.

He received a B.S. and M.S. in information and computer science from Waseda University, Tokyo, in 1999 and 2001. In 2001, he joined NTT Service Integration Laboratories (now NTT Network Technology Laboratories), where he was engaged in the performance evaluation of IP networks, web applications, and video delivery. In 2006, he joined NTT Communications, where he engaged in the development of voice over IP systems. In 2010, He joined NTT Network Technology Laboratories, where he engaged in R&D of a quality-of-experience control video-delivery mechanism. In 2015, he was assigned as the primary USA liaison based in Washington D.C. and engaged in enhancing collaborations with US academia and industry. He is currently engaged in the R&D of future network architecture.

Seisho Yasukawa

Project Manager, Network Architecture Project, NTT Network Service Systems Laboratories.

He received a B.E. and M.E. in applied physics from the University of Tokyo in 1993 and 1995. Since joining NTT in 1995, he has conducted R&D of asynchronous transfer-mode-based multimedia switching and NGN architecture. He has also been involved in standardization efforts for point-to-multipoint multiprotocol label switching. His current research includes IOWN architecture.

Real-time Virtual-network-traffic-monitoring System with FPGA Accelerator

Yuta Ukon, Shuhei Yoshida, Shoko Ohteru, and Namiko Ikeda

Abstract

There is a growing demand for a virtual-network-traffic-monitoring system for managing and controlling network services. Such a system must be able to handle high-load processing such as analyzing encapsulated packets and network-traffic classification using many header fields. To visualize network traffic for a virtual machine in real time, we propose a real-time virtual-network-traffic-monitoring system with a field-programmable gate array (FPGA) accelerator. Our system consists of a resource-saving hash-based network-traffic classifier (NTC) that classifies virtual network traffic at high speed using many search conditions. The hash-based NTC reduces memory resources by using a two-step hash search. Our system with this hash-based NTC provides a real-time visualization of multiple statistics such as the number of packets, bytes, microbursts, and histograms of jitter and latency for each virtual machine. To verify the performance of the hash-based NTC, we evaluated the number of searches per input packet. As a result of classifying virtual extensible local area network (VXLAN) packets into 10,000 categories using 17 header fields, the average number of searches executed with the hash-based NTC was about one-fourth that of a search-tree-based NTC. In addition, memory and logic-resource usage of the hash-based NTC were on average about 40 and 80%, respectively, which were less than those of several FPGA-based ternary content addressable memories with the same rules. Finally, we demonstrated that our system with the hash-based NTC visualizes VXLAN traffic for each virtual machine in real time.

Keywords: traffic monitoring, virtual network, FPGA, hash-based search

1. Introduction

Real-time network-traffic monitoring is important for managing network services in a datacenter. Datacenter traffic has been diversifying as a result of advances in network virtualization technology such as software-defined networking [1] and network function virtualization [2]. Therefore, network operators require a real-time network-traffic-monitoring system to detect problems in the virtual network.

A virtual-network-traffic-monitoring system constructed within a server enables the monitoring of communication with external machines and between virtual machines (VMs) in the server. However, in-server monitoring degrades the performance of VMs because the virtual-network-traffic-monitoring system uses the server's computing resources. To avoid this problem, such a system should be constructed on the virtual network. In this case, it must monitor virtual-network traffic to multiple servers. Traffic-monitoring software is not suitable for monitoring a high volume of virtual-network traffic because it cannot handle high-load processing such as analyzing encapsulated packets and classifying network traffic using many header fields at high speed. We propose a real-time virtual-network-traffic-monitoring system with

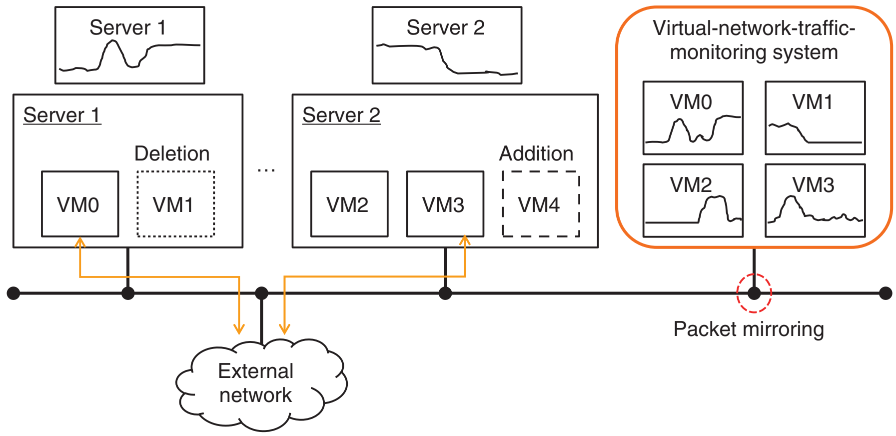


Fig. 1. Network-traffic monitoring using virtual-network-traffic-monitoring system.

a field-programmable gate array (FPGA) accelerator that processes encapsulated packets at high speed.

Our system visualizes virtual-network traffic at the VM, server, and network level to identify the cause of failure in network service. To provide this function, the system must have a network-traffic classifier (NTC) to classify virtual-network traffic. NTCs using a search tree [3, 4], which are often used in traffic-monitoring software, do not operate at high speed on the FPGA because it takes many processing cycles to search for a rule consisting of multiple conditions. A ternary content addressable memory (TCAM) [5–8], on the other hand, enables high-speed processing by searching for rules in parallel. However, virtual-network-traffic classification requires a large amount of memory resources when using many search conditions. Therefore, it may not be possible to implement a TCAM with sufficient rules in the FPGA. To classify virtual-network traffic using more rules, our system consists of a resource-saving NTC based on a hash method. This hash-based NTC uses a two-step hash search to reduce the memory resources needed.

The rest of the article is organized as follows. In Section 2, we introduce our real-time virtual-network-traffic-monitoring system with an FPGA accelerator. Section 3 discusses the shortcomings of conventional NTCs and describes our hash-based NTC. Section 4 discusses the experimental results from evaluating our hash-based NTC's processing performance and circuit area. Finally, Section 5 concludes the article.

2. Our virtual-network-traffic-monitoring system with FPGA accelerator

The systems described in this article are for monitoring virtual-network traffic on a network. **Figure 1** shows an example of monitoring for four VMs implemented on two servers. A network-traffic-monitoring system visualizes network traffic for each VM by analyzing packets copied with a router and network test access point. Such a system must process many encapsulated packets at high speed. High-speed packet processing can be achieved using an FPGA accelerator. An FPGA accelerator can change its configuration when the target network changes. Therefore, an FPGA-based network-traffic-monitoring system is suitable for monitoring a virtual network that continues to evolve rapidly.

2.1 System architecture

Our virtual-network-traffic-monitoring system uses an FPGA accelerator to analyze and classify encapsulated packets at high speed and calculate multiple statistics such as the number of packets, bytes, microbursts, and histograms of jitter and latency. These statistics are visualized using open-source software such as Kibana [9] and Zabbix [10]. The system also captures packets received before and after detecting microburst traffic. This function helps reduce the cost analyzing network failures.

Figure 2 shows a block diagram of our system. The FPGA accelerator contains a packet receiver, packet-header analyzer, NTC, statistics aggregator, and microburst detector [11, 12]. The packet receiver supports 10-Gigabit Ethernet. The packet-header analyzer

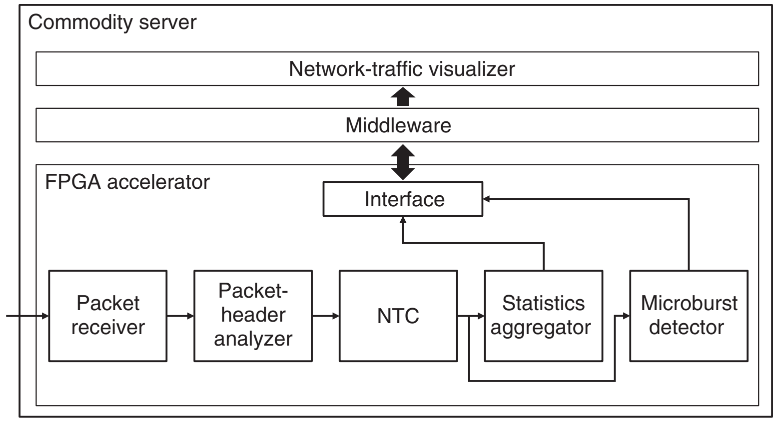


Fig. 2. Block diagram of our virtual-network-traffic-monitoring system with FPGA accelerator.

Table 1. Header fields used for virtual-network-traffic classification.

No.	Header	Field	# of bits
1	Outer Ethernet	Source MAC address	48
2		Destination MAC address	48
3		VLAN ID	12
4	Outer IP	Source IP address (v4 and v6)	32 or 128
5		Destination IP address (v4 and v6)	32 or 128
6		IP protocol number	8
7	Outer UDP	Source port	16
8		Destination port	16
9	VXLAN	VXLAN network ID (VNI)	24
10	Inner Ethernet	Source MAC address	48
11		Destination MAC address	48
12		VLAN ID	12
13	Inner IP	Source IP address (v4 and v6)	32 or 128
14		Destination IP address (v4 and v6)	32 or 128
15		IP protocol number	8
16	Inner TCP/UDP	Source port	16
17		Destination port	16

ID: identifier
IP: Internet Protocol
MAC: media access control
TCP: Transmission Control Protocol
UDP: User Datagram Protocol

analyzes a virtual extensible local area network (VXLAN) and virtual LAN (VLAN) packet and extracts several header fields from the packets. This analyzer also supports packets encapsulated in both VXLAN and VLAN. Although analyzing an encapsulated packet requires more calculation than analyzing an un-encapsulated packet, the packet-header analyzer achieves high throughput by pipeline processing. The NTC uses inner header fields as well as outer header fields to classify the packets in accordance with the VM, server, and network. **Table 1** shows the 17 header fields used in the NTC. Since classification using multiple header fields increases the amount of calculation, the system requires a high-performing NTC to process many packets at high speed. The statistics aggregator aggregates the number of packets, bytes, and histograms of jitter and latency for each VM, server, and network. These

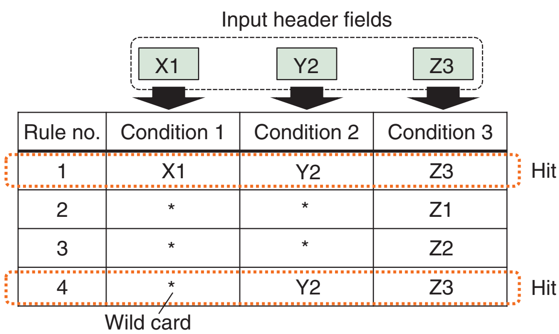


Fig. 3. Concept of NTC using partial match search.

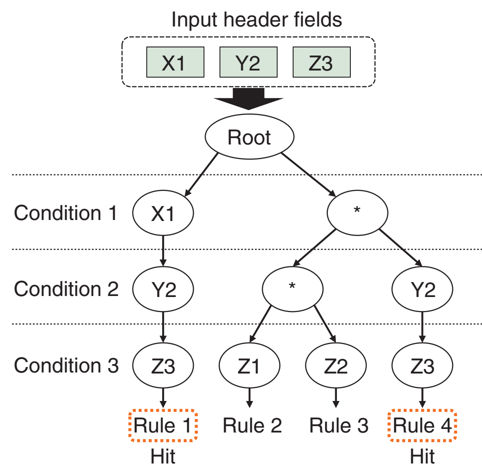


Fig. 4. Network-traffic classification using search tree.

statistics are then sent to the middleware via a PCI (Peripheral Component Interconnect) Express bus, and the microburst detector detects network traffic that increases rapidly within 100 microseconds and counts the number of microbursts. The microburst detector captures packets in the ring buffer until a microburst is detected. This method enables only packets received before and after the microburst to be captured. As mentioned above, our system enables real-time virtual-network-traffic monitoring by offloading high-load processes to the FPGA accelerator.

3. NTC

To classify network traffic by using a VM, server, and network, the NTC searches for rules that have different conditions. For example, outer and inner Internet Protocol (IP) addresses and VXLAN network interfaces (VNIs) are necessary for VM classification, whereas only a VNI is used for network classification. To enable flexible traffic classification, our system uses an NTC with a partial match search algorithm. The algorithm can potentially reduce FPGA memory resources because it requires minimal rules for flexible classification. **Figure 3** shows the concept of this NTC using the partial match search. Three input header fields (X1, Y2, and Z3) are compared with four rules consisting of three conditions. Comparing the input header fields with Conditions 1, 2, and 3, X1 matches the first rule, Y2 matches the first and fourth rules, and Z3 matches the first and fourth rules. These input header fields also match wild cards. Hence, X1 and Y2 also match the second, third, and fourth rules and the second and third rules, respectively. From the above, it is determined that the first and fourth rules match for all the input header fields. Therefore, the partial match search algorithm enables flexible searching with a small rule table since unnecessary conditions can be compressed using wild cards. In implementing this algorithm, it is important to suppress the amount of computation for achieving high-speed operation. It is also important to suppress the volume of memories and logic resources because our system has to implement it on an FPGA.

3.1 Conventional implementation approach

A search tree with wild card nodes can potentially conserve memory resources by reducing the number of nodes. However, it may be computationally expensive because all follower nodes of the wild card node must be checked. **Figure 4** shows an example of network-traffic classification using the search tree under the same conditions when using the NTC illustrated in Fig. 3. In this case, Rule 1 is found as a matching rule by searching the X1 node of Condition 1, Y2 node of Condition 2, and Z3 node of Condition 3 in this order. Rule 4 is also found by searching all nodes on the right side of the root node. As this example shows, almost all nodes must be checked to find multiple matching rules. The search tree compares input header fields with nodes sequentially; hence, the processing speed is slow on the FPGA when using a low clock frequency.

A TCAM enables high-speed classification by searching rules in parallel. It also classifies network traffic flexibly using rules consisting of 0s, 1s, and wild cards. **Figure 5** illustrates the TCAM architecture consisting of AND circuits and one-bit comparators

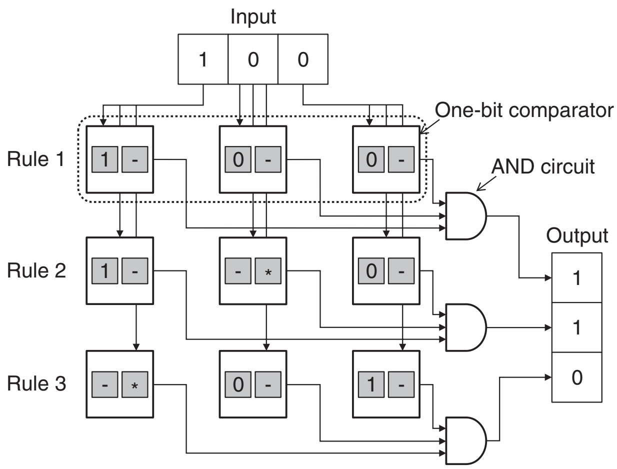


Fig. 5. TCAM architecture.

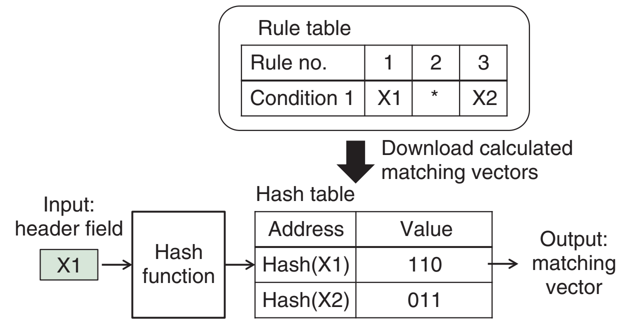


Fig. 6. Operation of hash-based NTC, which obtains a matching vector from the hash table. The matching vector is calculated in advance and downloaded to the hash table.

containing two memories: condition and wild card. The condition memory holds a one-bit rule, and the wild card memory holds a valid flag. The one-bit comparator outputs a high-level signal if the condition memory matches the input or the wild card memory is valid; otherwise, it outputs a low-level signal. The AND circuit collects outputs of one-bit comparators and determines whether the rule matches the input data. For example, if the TCAM shown in Fig. 5 receives input data "100," all one-bit comparators in Rules 1 and 2 output the high-level signal. The AND gates collect these signals and output the matching vector "110," which means the input data match Rules 1 and 2. These one-bit comparators work in parallel, so the TCAM operates at high speed. However, the TCAM uses a large volume of memory and logic resources since it requires two memories and a comparator for each one-bit comparator. Therefore, this approach is unsuitable for our system implementation.

3.2 Implementation approach for our system (hash-based NTC)

For the above-mentioned reason, we devised a hash-based NTC for high-speed virtual-network-traffic classification. **Figure 6** shows the operation of the hash-based NTC. When receiving the input header field, the hash-based NTC converts it into a hash value using the hash function and obtains the matching vector from the hash table by using that value as the search key. In this example, Rules 1 and 2 are matched to the input header field X1, and the matching vector "110" is output with a single access to the hash table. Therefore, the hash-based NTC operates at high speed since it can obtain the matching vector with a small number of memory accesses. The hash-based NTC can also reduce memory and logic resources because it does not compare the input and conditions bit-by-bit. Although this NTC does not allow bitwise wild cards, flexible virtual-network-traffic classification is still feasible by using wild cards per condition.

Figure 7(a) shows the overall architecture of the hash-based NTC. The architecture consists of hash functions, condition comparators, and an aggregator. The condition comparator evaluates an input header field using a rule table for one condition. The aggregator collects the evaluation results of the condition comparators and calculates the matching vector. This hash-based NTC works at high speed even if the number of conditions increases because the condition comparators operate in parallel, making it suitable for classifying network traffic using many header fields.

A typical hash table uses a large memory space to avoid memory-address conflict; however, this results in inefficient memory usage. Our condition comparator solves this problem by searching tables in two steps. **Figure 7(b)** shows a detailed diagram of the condition comparator. It includes the address table (hash table), multiple candidate memories (CMs), and a selector. The search mechanism is as follows. When receiving the hash value, the condition comparator divides the hash value into two values: a search key and reference value. The search key is used in the address table to extract an address for the CMs. When a small search key is used, the address table may output the same CM address for different inputs due to a memory-address conflict. This problem

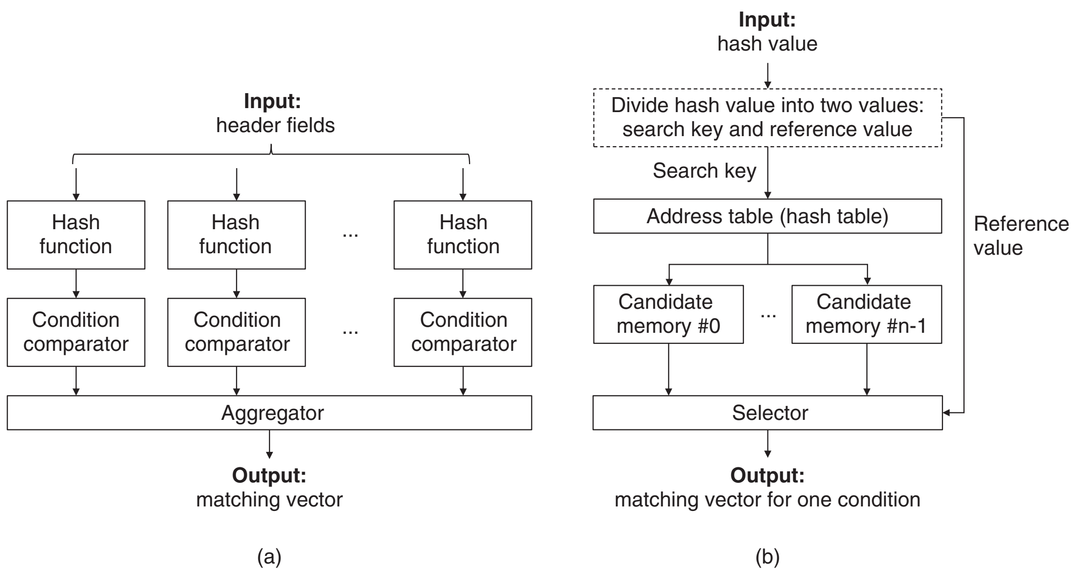


Fig. 7. Block diagrams of hash-based NTC: (a) overall architecture and (b) detailed condition comparator.

can be avoided using multiple CMs and the selector. The CMs receive the CM address from the address table and output candidate values and comparative values stored at the address. The selector selects one of the candidate values by comparing the comparative values with the reference value and outputs it as a matching vector for one condition. If the bit widths of the reference value and comparative value are sufficient, the selector can select the appropriate candidate value. Although this architecture has overhead, which holds the comparative values in the CMs, the memory-resource usage becomes highly efficient as the total usage is reduced by storing candidate values in the CMs.

The memory-resource usage of the address table and the CMs can be estimated using the following equations. Note that MRU_{AT} and MRU_{CM} are memory-resource usages of the address table and CMs, respectively.

$$MRU_{\mathrm{AT}} = 2^N \times \lceil \log_2 R \rceil \quad (1)$$
$$MRU_{\mathrm{CM}} = C \times R \times M + C \times R \times R, \quad (2)$$

where N is the bit width of the search key, R is the number of rules, C is the number of CMs, and M is the bit width of the reference value. The first and second terms on the right side in Eq. 2 are the memory-resource usage required to store the comparative values and candidate values, respectively. The MRU_{AT} increases exponentially for N because the search key is used as addresses in the table. In contrast, as N increases, MRU_{CM} decreases because fewer CMs are used to store candidate values. Due to the trade-off between Eqs. 1 and 2, the condition comparator should be designed with the appropriate parameters.

4. Experiment

To verify the advantages of the hash-based NTC, we evaluated its processing performance and circuit area.

4.1 Implementation

We designed our hash-based NTC that classifies VXLAN traffic using rules consisting of 17 conditions. MurmurHash3 [13] was used in the hash function because it is relatively unlikely to have output collisions between different inputs. To determine the optimal parameters for our implementation, we evaluated the maximum number of output collisions of the hash function. **Figure 8** shows the maximum number of output collisions when 500 random hash keys were input and the memory-resource usage of the hash-based NTC was estimated from Eqs. 1 and 2. Note that the maximum numbers of output collisions were the highest values in several simulations. The bit width of the hash function output was set to 32-bit. This figure shows that the maximum number of collisions decreases as the bit width of the search key increases. However, the memory-resource usage

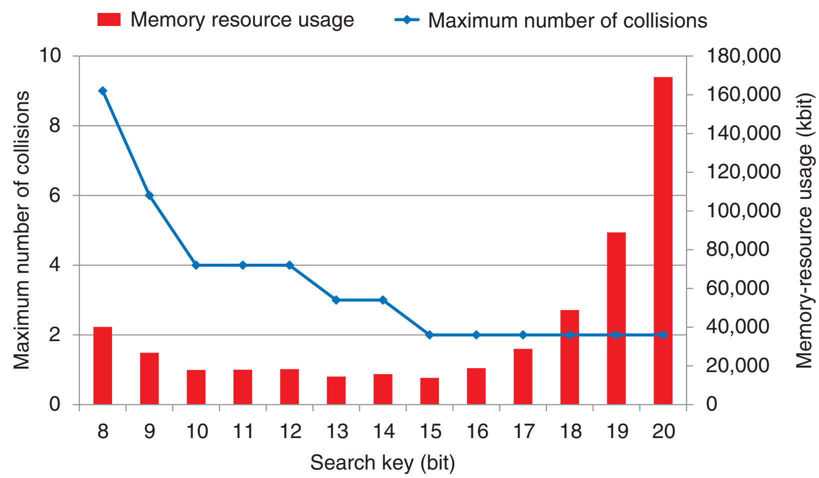


Fig. 8. Maximum number of output collisions when 500 random hash keys are input to the hash function using MurmurHash3 and memory-resource usage of the hash-based NTC.

Table 2. Implementation parameters.

Parameter	Variable	Value
Search key (bit)	N	16
Maximum # of address collisions	R	4
# of rules	C	500
Reference value (bit)	M	16

of the hash-based NTC increases when using 16-bit or higher search keys because the memory-resource usage of the address table increases rapidly. The figure also shows that the memory-resource usage of the hash-based NTC is minimized using the 15-bit search key and two CMs for each condition comparator. Given these results, we used the parameters shown in **Table 2** for the hash-based NTC and implemented it with an Arria 10 GX1150 FPGA [14].

4.2 Evaluation

Figures 9(a) and **(b)** show the average number of searches for 100,000 inputs for a search-tree-based NTC and the hash-based NTC. Note that these results were evaluated through simulation. We used the search-tree-based NTC with a Patricia tree [3], which can efficiently store long strings, for comparison. Figure 9(a) shows that on average the search-tree-based NTC executed more searches than the hash-based NTC when there were more than ten rules due to the increase in nodes to be searched. The average number of searches of the hash-based NTC was also constant regardless of the number of rules. These results indicate that each condition comparator accessed the internal memories only once for each input. Figure 9(b) shows that the average number of searches using 17 conditions in the hash-based NTC is about one-fourth that of the search-tree-based NTC. The difference in the throughput of these NTCs is even greater since the hash-based NTC executes the search for each condition in parallel.

We implemented these NTCs, which classify virtual-network traffic using 17 conditions, on an FPGA operating at 100 MHz. The search-tree-based NTC processed 1.3 million packets per second, meaning that it is capable of wire-speed processing for an input rate of about 0.9 Gbit/s. The hash-based NTC processed one hundred million packets per second and executed wire-speed processing for a higher input rate of about 67 Gbit/s.

Table 3 shows the logic- and memory-resource usages of the hash-based NTC and several FPGA-based TCAMs. The resource usage of the hash-based NTC was calculated using the Intel Quartus Prime version 17.1.1. The amount of memory and logic resources per unit was calculated by dividing the logic- and memory-resource usage by the product of the number of rules and total bits of the conditions. In other words, these indicators are the amount of resources required to store a one-bit rule.

Comparing the indicators of each circuit, the memory- and logic-resource usage of the hash-based NTC was on average about 40 and 80% less than that of several FPGA-based TCAMs, respectively. This

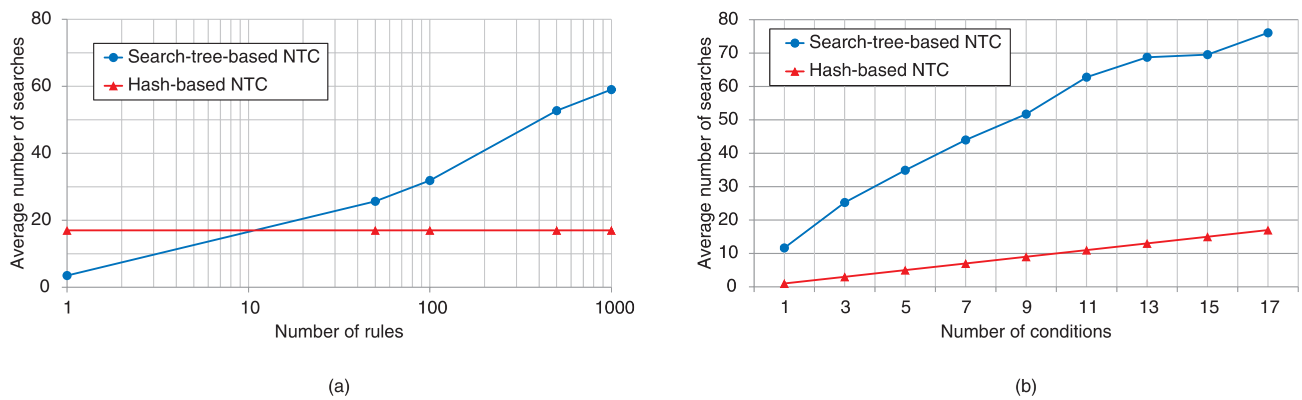


Fig. 9. Average number of searches per input for (a) number of rules and (b) number of conditions. The number of rules in the experiment was 500.

Table 3. FPGA-resource usage of the hash-based NTC and FPGA-based TCAMs.

Design	Size	Speed (MHz)	LUTs	Memory (kbit)	LUTs/Size	Memory/Size
Xilinx Locke [6]	256 × 32	130	4576	1152	0.56	140.63
UE-CAM [7]	512 × 36	202	3652	1152	0.2	62.5
RAM-based TCAM [8]	1024 × 150	150	48,552	9792	0.32	63.75
Hash-based NTC	500 × 832	100	26,480	19,040	0.06	44.7

LUT: look-up table
RAM: random access memory

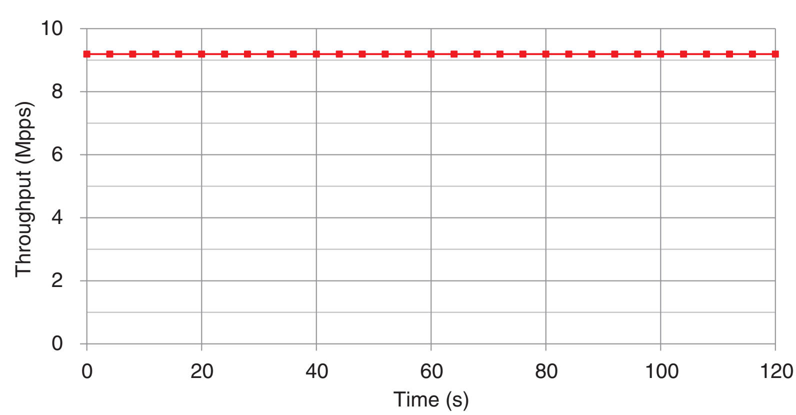


Fig. 10. Throughput for VXLAN packets with the shortest length.

indicates that the hash-based NTC can have more rules than FPGA-based TCAMs while using the same amount of FPGA resources.

Finally, we evaluated the performance of our system with the hash-based NTC. **Figure 10** shows the throughput for VXLAN short packets with a length of 116 bytes. The results indicate that the system achieved a theoretical performance of 9.19 mega-packets per second (Mpps) throughput at an input rate of 10 Gbit/s. The figure also shows that the system processed the packets without packet loss under a high workload. **Figure 11** shows the results of

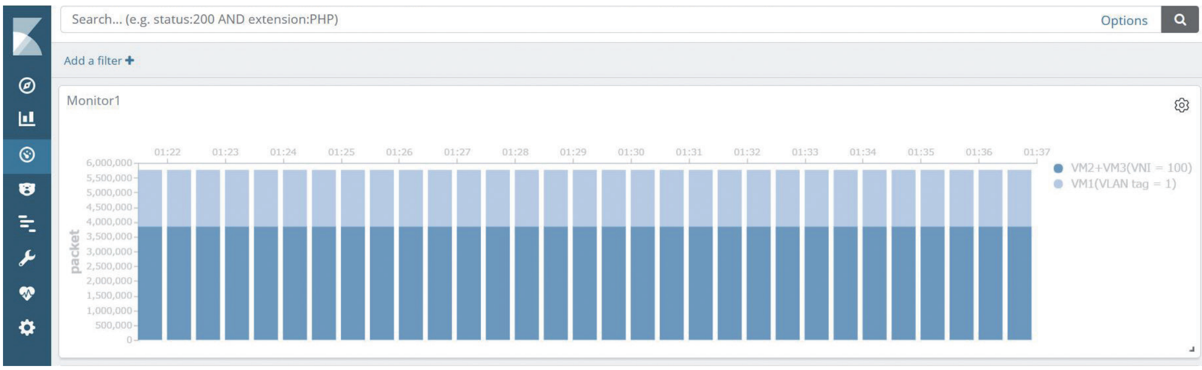


Fig. 11. Network-traffic visualization by VM and VXLAN network.

visualizing the number of packets in units of VM and VNI using Kibana. The system classified VXLAN traffic flexibly with the hash-based NTC and visualized communication volumes of different groups at short intervals.

5. Conclusion

We proposed a real-time virtual-network-traffic-monitoring system with an FPGA accelerator to monitor VXLAN and VLAN traffic. The key module in the system, the hash-based NTC, attained high-speed, flexible virtual-network-traffic classification with fewer FPGA resources by using a two-step hash search. The experimental results indicate that the hash-based NTC used fewer logic and memory resources compared with several FPGA-based TCAMs. Finally, we determined that our system with the hash-based NTC was able to visualize the amount of VXLAN traffic in real time for a 10-Gbit/s input rate.

References

[1] D. Kreutz, F. M. V. Ramos, P. E. Veríssimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined Networking: A Comprehensive Survey," Proc. IEEE, Vol. 103, No. 1, pp. 14–76, Jan. 2015.

[2] R. Mijumbi, J. Serrat, J. L. Gorricho, N. Bouten, F. D. Turck, and R. Boutaba, "Network Function Virtualization: State-of-the-art and Research Challenges," IEEE Commun. Surv. Tutor., Vol. 18, No. 1, pp. 236–262, 1st quarter 2016.

[3] K. Sklower, "A Tree-based Packet Routing Table for Berkeley UNIX," USENIX Winter, pp. 93–104, Dallas, TX, USA, Jan. 1991.

[4] P. Gupta and N. McKeown, "Algorithms for Packet Classification," IEEE Netw., Vol. 15, No. 2, pp. 24–32, Mar. 2001.

[5] K. Pagiamtzis and A. Sheikholeslami, "Content-addressable Memory (CAM) Circuits and Architectures: A Tutorial and Survey," IEEE J. Solid-State Circuits, Vol. 41, No. 3, pp. 712–727, Feb. 2016.

[6] K. Locke, "Parameterizable Content-addressable Memory," Application Note: Xilinx FPGAs, XAPP1151 (v1.0), Mar. 2011.

[7] Z. Ullah, M. K. Jaiswal, R. C. C. Cheung, and H. K. H. So, "UE-TCAM: An Ultra Efficient SRAM-based TCAM," Proc. of TENCON 2015 – 2015 IEEE Region 10 Conference, Macao, China, Nov. 2015.

[8] W. Jiang, "Scalable Ternary Content Addressable Memory Implementation Using FPGAs," Proc. of the ninth ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS), pp. 71–82, San Jose, CA, USA, Oct. 2013.

[9] Y. Gupta, "Kibana Essential," Packt Publishing Ltd, 2015.

[10] R. Olups, "Zabbix 1.8 Network Monitoring," Packt Publishing Ltd, 2010.

[11] S. Yoshida, Y. Ukon, S. Ohteru, H. Uzawa, N. Ikeda, and K. Nitta, "FPGA-based Network Microburst Analysis System with Flow Specification and Efficient Packet Capturing," Proc. of 2020 IEEE 31st International Conference on Application-specific Systems, Architectures and Processors (ASAP), pp. 29–32, July 2020.

[12] S. Yoshida, Y. Ukon, S. Ohteru, H. Uzawa, N. Ikeda, and K. Nitta, "FPGA-based Network Microburst Analysis System with Efficient Packet Capturing," J. Opt. Commun. Netw., Vol. 13, No. 10, pp. E72–E80, Oct. 2021.

[13] A. Appleby, "MurmurHash," 2008, https://sites.google.com/site/murmurhash/

[14] "Intel®Arria®10 Device Overview," A10-OVERVIEW, Nov. 2018.

Yuta Ukon

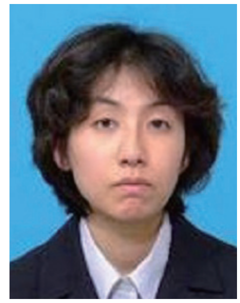
Deputy Senior Engineer, NTT Advanced Technology Corporation.

He received a B.E. and M.E. in engineering from Osaka University in 2010 and 2012. In 2012 he joined NTT Microsystem Integration Laboratories and has been engaged in research and development on a packet processing accelerator and packet processing circuit. He moved from NTT Device Innovation Center to NTT Advanced Technology in July 2021. His research interests include hardware accelerators for software-defined networking and network function virtualization, hardware and software co-design technologies, and packet processing circuit. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Shuhei Yoshida

Engineer, NTT Device Innovation Center.

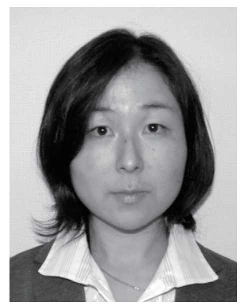
He received a B.E. and M.E. in computer science and systems engineering from Kobe University, Hyogo, in 2014 and 2016. In 2016, he joined NTT Device Innovation Center and has been engaged in research and development on hardware design methodology and FPGA-accelerated systems. He is a member of IEICE.



Shoko Ohteru

Research Engineer, NTT Device Innovation Center.

She received a B.S. in physics from Ochanomizu University, Tokyo, M.S. in physics from the University of Tokyo, and Ph.D. in engineering from Nihon University, Tokyo, in 1992, 1994, and 2011. She joined NTT Telecommunication Networks Laboratories in 1994. She is currently with the NTT Device Innovation Center. She is a member of IEICE.



Namiko Ikeda

Senior Research Engineer, NTT Device Innovation Center.

She received a B.E. and M.E. in inorganic materials from Tokyo Institute of Technology in 1996 and 1998. In 1998, she joined NTT, where she engaged in research and development of an image-enhancement algorithm for single-chip fingerprint sensor/identifier large-scale integrated circuits. She is currently with the NTT Device Innovation Center and engaged in research and development of a virtual-network-traffic-monitoring system with an FPGA accelerator. She is a member of IEICE.

Latest Trends in 400- and Beyond 400-Gbit/s Ethernet Standardization in IEEE 802.3

Yoshiaki Sone and Shuto Yamamoto

Abstract

The IEEE (Institute of Electrical and Electronics Engineers) 802.3 Working Group has been proceeding with high-speed point-to-point Ethernet standardization to address increasing communication bandwidth demand in datacenter and telecom networks. Discussion has begun on beyond 400-Gbit/s Ethernet as a next-generation rate of Ethernet. This article explains the trends in the standardization of 400-Gbit/s and beyond 400-Gbit/s Ethernet.

Keywords: IEEE 802.3, Ethernet, optical interface

1. Standardization of high-speed Ethernet in IEEE 802.3

Ethernet is a standard defined in the IEEE 802 LAN/MAN standardization committee, which develops standards related to local area networks (LANs) and metropolitan area networks (MANs) in the Institute of Electrical and Electronics Engineers (IEEE), and has been used broadly in telecom networks from access to core, as well as datacenter, enterprise, and automobile networks. In the committee, the specifications for the link and physical layers (PHY)*1 have been defined in the 802.3 Working Group (WG) while expanding the application coverage (**Fig. 1**). The highest standardized interface speed is 400-Gbit/s Ethernet (GbE). The discussions on 400GbE standardization started in May 2014 in the 802.3bs Task Force (TF), and the standardization of the first-generation specification was completed in December 2017. New specifications were then added to increase the area of applications and achieve further cost reductions. Discussions on a higher rate of Ethernet started as the IEEE 802.3 Beyond 400 Gb/s Ethernet Study Group (SG) in January 2021. The SG is responsible for defining the objectives of the beyond 400GbE standardization, such as rates and reaches, before defining the technical specifications in the TF. Therefore, the standardization on beyond 400GbE is in an important initial phase to determine future standardization directions.

2. Applications of high-speed Ethernet

Datacenter and telecom networks are important application areas of point-to-point (P2P) high-speed Ethernet. In datacenter applications, transmission specifications are defined in accordance with the floor layout and networking hierarchy. **Figure 2** shows typical use cases in a datacenter. The transmission reach between servers and top-of-rack switches is less than 30 m. For such connections, twinax cables or multimode fibers are used as the transmission media. From top-of-rack switches to a higher-level switch, the reach is up to 500 m and multi-mode fibers (MMFs) or parallel single mode fibers (PSMs) are used as the media. For longer reach up to 10 km, single mode fibers (SMFs) are used. There are two typical SMF use cases in telecom network applications. One is usage inside buildings as a client interface of a long-haul transmission system. The other is usage of a non-wavelength division multiplexing

*1 PHY: The 1st layer of the Open Systems Interconnection (OSI) reference model.

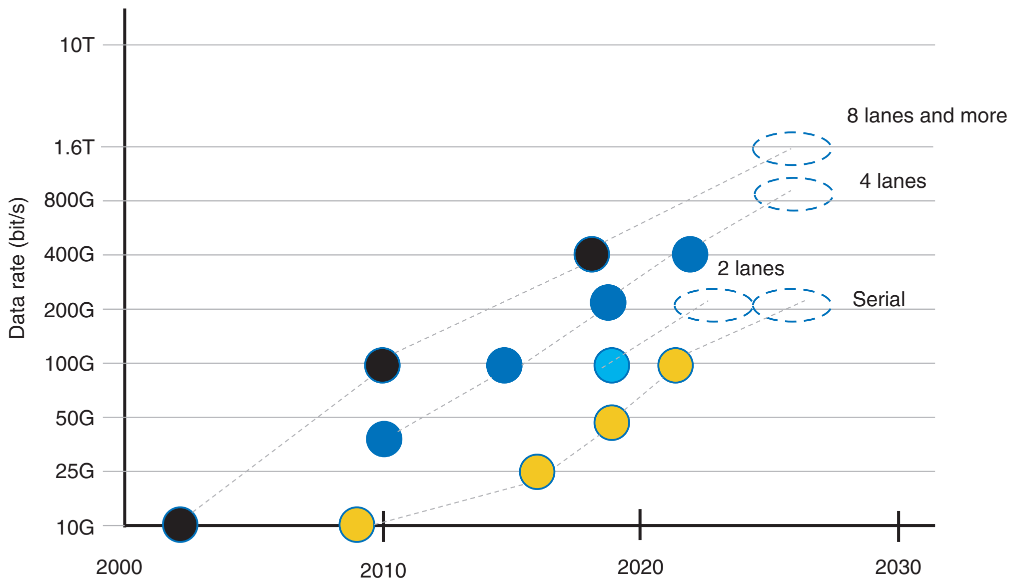


Fig. 1. History of high-speed Ethernet standardizations.

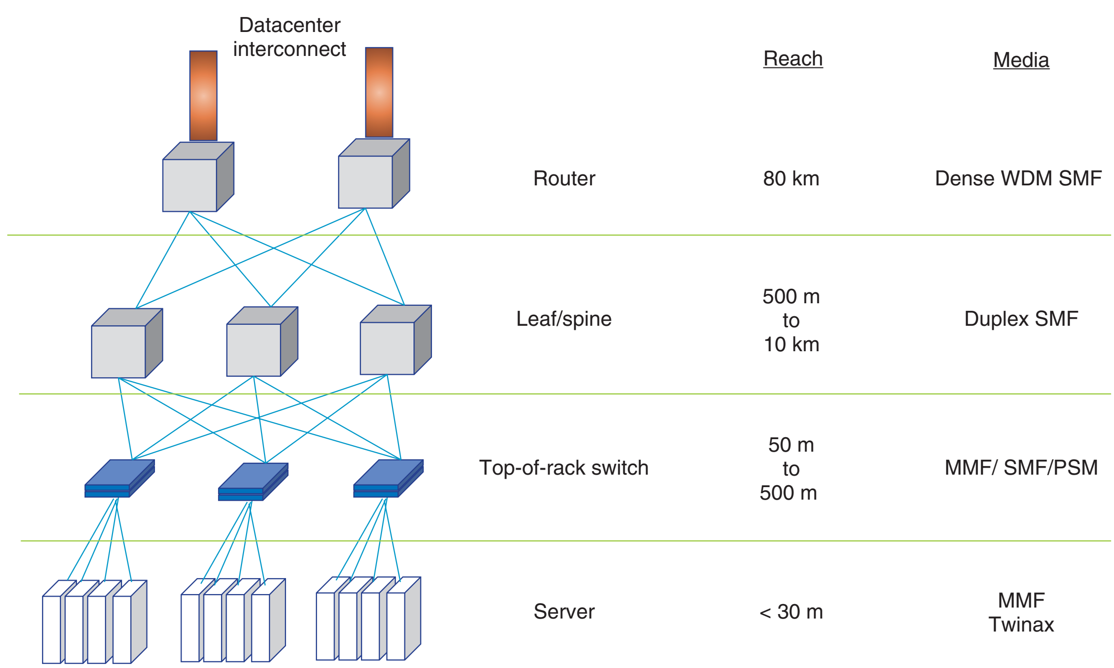


Fig. 2. Applications of P2P Ethernet interfaces (datacenter).

(WDM) optical interface for inter-building connections. For intra-building applications, an optical interface of less than a 10-km reach is used. For inter-building applications, a 40-km interface is used as well as a 10-km interface (**Fig. 3**).

3. History of high-speed Ethernet interfaces

The Ethernet interface has been evolving to higher speed through multiple means, such as parallelization of fibers and lanes, WDM, increase in modulation

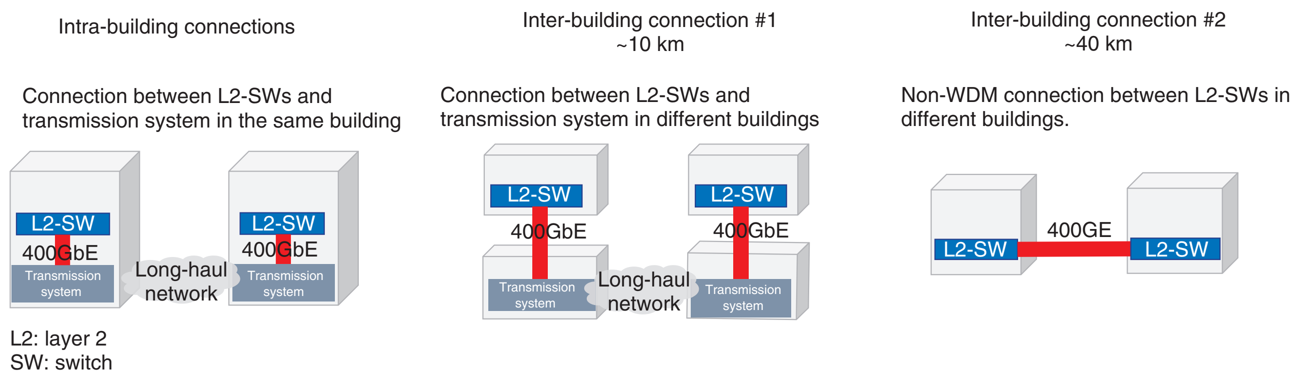


Fig. 3. Application of P2P Ethernet interfaces (telecom networks).

Table 1. 200GbE and 400GbE optical interface specifications (red: work in progress).

	< 100-m MMF	500-m PSM	2-km SMF	10-km SMF	40-km SMF	80-Km SMF
200GbE	SR4 (cd) SR2 (db)	DR4 (bs)	FR4 (bs)	LR4 (bs)	ER4 (cn)	
400GbE	SR16 (bs) SR8 (cm) SR4.2 (cm) VR4 (db) SR4 (db)	DR4 (bs)	FR8 (bs) FR4 (cu)	LR8 (bs) LR4-6 (cu)	ER8 (cn)	ZR (cw)

speed, and adoption of higher-order modulations. In the 10GbE market, a serial interface has been the mainstream implementation, but multi-lane was adopted for 40GbE and 100GbE by using 10-Gbit/s/lane and 25-Gbit/s/lane modulation speeds, respectively. For 400GbE, 4-level pulse amplitude modulation (PAM4) was adopted for the first time. PAM4 can achieve a two times higher data rate using the same modulation speed compared with the conventional non-return-to-zero transmission scheme.

4. 400GbE specification

4.1 400GbE defined in 802.3bs TF

The first 400GbE specification was standardized in the 802.3bs TF (May 2014 to December 2013) on the basis of the objectives defined in the 400GbE SG, which started in May 2013. In this TF, 200GbE was standardized as well as 400GbE to satisfy demand from the datacenter market [1]. **Table 1** shows the specifications of 200GbE and 400GbE, including works in progress.

In the 802.3bs TF, 500-m PSM (400GBASE-DR4, 200GBASE-DR4), 2-km SMF (400GBASE-FR8, 200GBASE-FR4), and 10-km SMF (400GBASE-LR8, 200GBASE-LR4) were defined for both 200GbE and 400GbE. In 500-m PSM, breakout connections, such as 4x100 and 4x50 Gbit/s, where the lanes are separated and used independently, are used for connections from top-of-rack switches to a higher-level switch (**Fig. 4**). This is a connection that uses the speed per lane, which is 100 or 50 Gbit/s, in PSM transmissions. For 400GBASE-DR4 with a 500-m reach, in addition to adoption of PAM4 modulation, higher modulation speed (about 50 GBaud) was adopted for the first time, and 400 Gbit/s was achieved by four lanes of 100 Gbit/s/lane. Regarding the 2- and 10-km optical interface specifications, where the reach is required to be longer than 500 m, the same modulation speed with 100GbE (25 GBaud) is used, and 400GbE is achieved by 8x50 Gbit/s/lane with PAM4. The connections to the area router in datacenter buildings uses 2-km SMF specifications while used for connections between client equipment to long-haul transmission equipment in telecom buildings. Regarding 10-km specifications, 400GBASE-LR8 and 200GBASE-LR4 were originally targeted for inter-building connection usage in

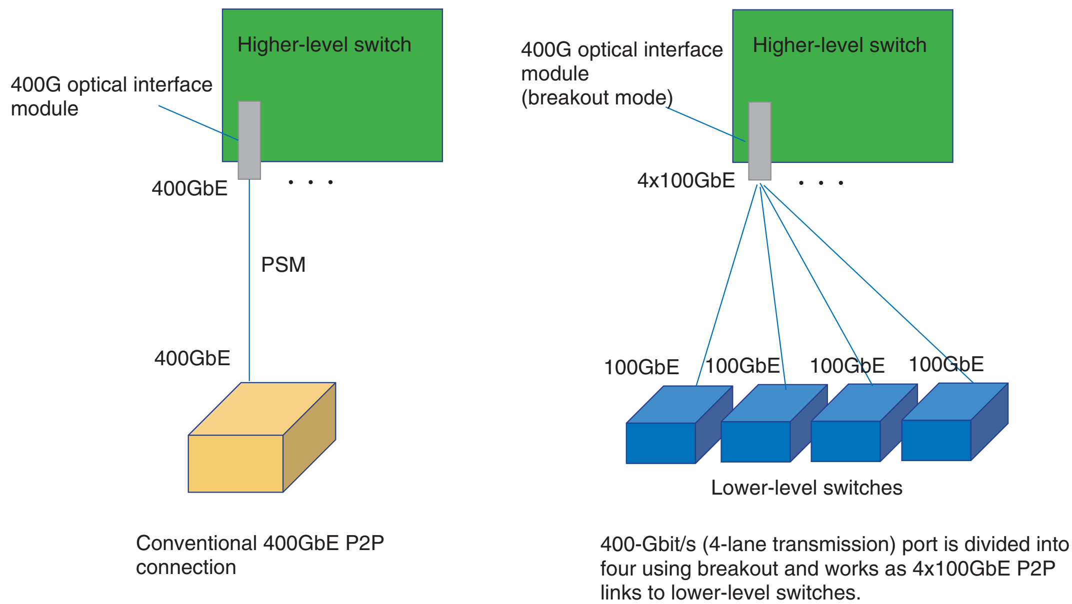


Fig. 4. Conventional P2P connection and breakout connection.

telecom networks. However, because of the advantages of a larger loss budget compared with 2-km specifications, these interfaces are also being used by datacenter operators for high loss link.

4.2 400GbE specification improvement

After the 802.3bs TF is completed, there were two activities to expand and improve 200GbE and 400GbE specifications, i.e., beyond 10 km and 100 Gbit/s/lambda. The Beyond 10 km SG was an activity to define interface specifications that can cover more than 10-km transmission for 25GbE, 50GbE, 200GbE, as well as 400GbE. This standardization activity was initiated to cover inter-building connection usage in telecom mobile backhaul networks. However, the scope was expanded to include cable systems and datacenter applications at the SG phase. At the TF formation phase, 400GbE standardization work in the Beyond 10 km SG were split into two TFs, 802.3cn and 802.3cw. In 802.3cn, 400GBASE-ER8, which is a specification that supports up to 40-km reach over SMF, was standardized. The implementation of a 40-km reach interface can be achieved by improving the performance of the existing 50-Gbit/s/lane transmission scheme used in 400GBASE-LR8 by additionally applying a high-sensitivity component called an avalanche photo diode at the receiver side [2]. The 802.3cw TF is still in progress and is defining a specification to achieve 80-km transmission over a P2P dense WDM (DWDM) system with 75-GHz channel spacing. This TF is reusing the Optical Internetworking Forum (OIF)*2 400G-ZR specification [3], which is an interface specification for 100-GHz-spaced DWDM defined prior to IEEE 802.3cw in OIF. IEEE 802.3 is introducing support for a 75-GHz grid on the basis of IEEE 802.3 standardization criteria.

The second activity to expand 400GbE specification, 100 Gbit/s/lambda, is targeting cost and power-consumption reduction by reducing the number of lanes in the optical interface by using 100 Gbit/s/lane instead of 50 Gbit/s/lane. This standardization activity progressed as 802.3cu by a strong request from datacenter operators who plan a large-volume deployment in hyper-scale datacenters. Regarding the 400GbE specification in 802.3cu, 400GBASE-FR4 was defined for 2-km reach using 100-Git/s PAM4, and 400GBASE-LR4-6 was defined to cover 6-km reach. The activity originally targeted 10-km-reach standardization. However, considering the worst-case condition based on IEEE 802.3 criteria for interoperability and backward compatibility, the reach limit was considered as 6 km. As a result, 400GBASE-LR4-6 standardization was completed as a 6-km reach specification over SMF.

*2 OIF: A standardization organization to define implementation agreement for optical transmission and networking protocols.

Table 2. IEEE 802.3 Beyond 400G SG standardization objectives (as of June 2021).

	50-m MMF	100-m MMF	500-m PSM	2-km PSM	2-km SMF	10-km SMF	40-km SMF
800GbE	8-pair MMF	8-pair MMF	8-pair SMF 4-pair SMF	8-pair SMF 4-pair SMF	Duplex SMF	Duplex SMF	Duplex SMF
1.6TbE			8-pair SMF	8-pair SMF			

5. Beyond 400GbE standardization

The Beyond 400GbE SG started in January 2020. Discussions on target rate and reach are currently underway in this SG. Currently, 800 Gbit/s and 1.6 Tbit/s have been adopted by motion as new Ethernet Media Access Control (MAC)[*3] rates. There are also many reach targets for Ethernet PHY mainly targeting datacenter applications.

5.1 Current status of beyond 400GbE discussion

To move standardization to the next-generation Ethernet rate, the Beyond 400G SG [4] was started on the basis of the consensus built by the IEEE 802.3 ad-hoc group. From the investigation of the ad-hoc group, a higher rate of Ethernet will be required around 2025 to address continuously increasing communication traffic including new needs of data communication such as fifth-generation mobile communications, artificial intelligence, and virtual reality as well as existing applications.

Applications and the necessary reaches of interfaces will be mostly the same as 400GbE standards. However, one difference is that the use case of breakout connection is clearer and becoming more important compared with the time of 400GbE standardization. Therefore, the maximum speed achievable per lane and number of lanes are important in determining the standardization directions.

On the basis of the assumptions that maximum lane speed achievable in the project timeframe is 200 Gbit/s/lane, 800-Gbit/s MAC has been adopted as project objectives because it enables 4x200- and 8x100-Gbit/s breakout connections. In addition to 800-Gbit/s MAC, 1.6-Tbit/s MAC has been included into the objectives to flexibly and promptly address potential user requirements for higher speed, as it can support 8x200 Gbit/s. **Table 2** shows the currently adopted objectives in the Beyond 400G SG. Because the usage of breakout connections is explicitly assumed, there are multiple interface specifications with the same distance but different number of lanes.

5.2 Beyond 400GbE discussion perspective

Optical interfaces discussed in the Beyond 400G SG are planned to be used with next-generation 51.2- and 104.8-Tbit/s capacity Ethernet switches based on datacenter user requirements. In these next-generation switch implementations, the switch application-specific integration circuit (ASIC) and Ethernet PHY can be integrated to reduce power consumption in the electrical path inside a switch. Conventional Ethernet had an explicit interface definition between the switch ASIC and Ethernet PHY to achieve a pluggable transceiver module. Therefore, it would be a new discussion point to consider integrated implementation of the switch ASIC and Ethernet PHY in the standardization. Another discussion point is transmission technologies used for beyond 400GbE optical interfaces. The current SG is responsible for investigating the market demands and technical feasibility to define the objective of the standardization; therefore, a detailed transmission scheme will be discussed in the following TF phase. However, technical hurdles will be higher to achieve reach as the modulation rate becomes higher. Therefore, PAM4 transmission is thought not to be enough to achieve all the objectives. The SG may have to consider coherent transmission to show that the technical feasibility and coherent transmission usage will be increased in the next-generation Ethernet specifications.

References

[1] IEEE 802.3bs-2017 – IEEE Standard for Ethernet Amendment 10: Media Access Control Parameters, Physical Layers, and Management Parameters for 200 Gb/s and 400 Gb/s Operation.

[2] Y. Muramoto, T. Yoshimatsu, M. Nada, and T. Ishibashi, “High-speed Photodetector Technologies,” NTT Technical Review, Vol. 10, No. 12, 2012.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201212fa8.html

[3] OIF-400ZR-01.0 – Implementation Agreement 400ZR, 2020.

[4] IEEE 802.3 Beyond 400 Gb/s Ethernet Study Group, https://www.ieee802.org/3/B400G/index.html

*3 MAC: A functionality corresponding to the datalink layer, which is the 2nd layer of the OSI reference model.

Yoshiaki Sone

Field Application Engineering Manager, NTT Electronics America, Inc.

He received a B.E. and M.E. in electronics engineering from Tohoku University, Miyagi, in 2001 and 2003. In 2003, he joined NTT Network Innovation Laboratories and engaged in research on network engineering technology for optical transport networks and related standardizations. He is currently with NTT Electronics America and responsible for field application engineering of coherent component products in North America. He is also actively participating in optical networking standardizations.

Shuto Yamamoto

Senior Research Engineer, NTT Network Innovation Laboratories.

He received a B.S. and M.S. in physics and a Ph.D. in electronic engineering from Tokyo Institute of Technology in 2003, 2005, and 2018. His research interest includes photonic transport network systems. He received the Best Paper Award at the 16th OptoElectoronics and Communications Conference (OECC) in 2011, the Young Researcher's Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 2012, and the Achievement Award from IEICE, in 2016. He also received the NTT Presidential Award in 2014 and the TELECOM System Technology Award from the Telecommunications Advancement Foundation in 2019.

Investigation on Damage to Optical Fiber Cables Caused by Freezing and Thawing of Water in a Lifting Pipe

Technical Assistance and Support Center, NTT EAST

Abstract

This article introduces an investigation into the mechanism of damage to optical fiber cables and polyethylene pipes in lifting pipes installed in cold regions. We carried out examinations using a physical simulation model in a large thermostatic room. This is the sixty-sixth article in a series on telecommunication technologies.

Keywords: optical fiber cable, lifting pipe, freezing and thawing

1. Introduction

A lifting pipe attached to a utility pole is used where an underground optical fiber cable goes up to ground level. In cold regions, an optical fiber cable in the pipe sometimes becomes damaged due to the accumulated water freezing in the lifting pipe. To prevent such damage, two measures are taken: (i) installing waterproof caps to the top-end part of the lifting pipe and (ii) installing polyethylene (PE) pipes together with the cable as cushioning. However, it is not known how the freezing and thawing of the accumulated water occurs in an actual environment and how it damages the optical fiber cable laid inside the pipe. Therefore, we investigated the impact of the freezing and thawing of the water accumulated in a lifting pipe on optical fiber cables.

2. Observation of damaged cable

A lifting pipe is used where an optical fiber cable goes up from underground to the aerial area (**Fig. 1**). In the field, the cable was inserted into a PE pipe, which were both installed in the lifting pipe. First, we inspected the damaged part of the optical fiber cable damaged within a 60 cm from the upper end of the lifting pipe. The sheath of the optical fiber cable was torn in the longitudinal direction in a manner that exposed the inner-core wire (**Figs. 2(a)**, **(c)**, and **(d)**), and the upper section of the exposed part was in a state in which the cable sheath was compressed, torn, and expanded (**Fig. 2(b)**).

We also found that the PE pipe was torn due to being crushed and bursting under pressure (**Fig. 2(e)**). The tip of the waterproof cap covering the top end of the lifting pipe was also damaged. During a field survey, we also found lumps of ice at the top-end of the lifting pipe (**Fig. 2(f)**).

3. Verification of the impact of freezing and thawing

Considering that ice lumps were confirmed near the top-end of the lifting pipe, we verified the impact of freezing and thawing of accumulated water on the optical cable and PE pipe.

(1) Freezing and thawing of accumulated water

To verify this impact, we constructed an experimental apparatus that simulates a lifting pipe in a

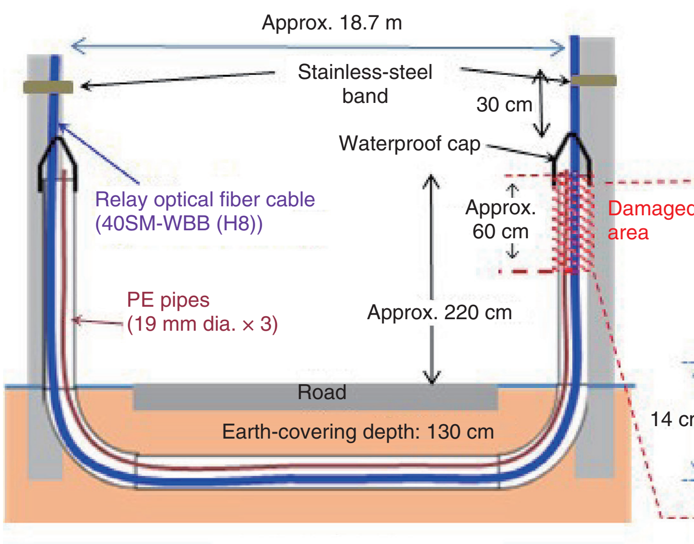


Fig. 1. Overview of equipment.

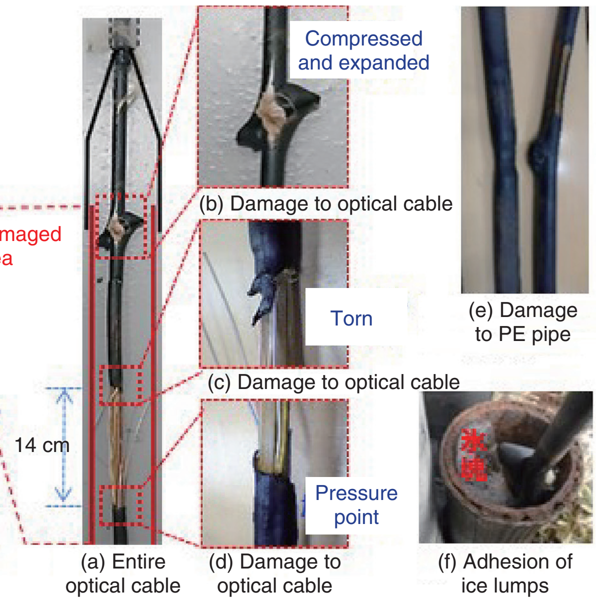


Fig. 2. Observed damage.

large thermostatic room. As shown in **Fig. 3**, a steel pipe, which is made of the same material as an actual lifting pipe, was installed in a thermostatic room, and an optical cable, PE pipe, and water were inserted into the steel pipe to simulate the field condition.

The temperature of the thermostatic room was repeatedly set between −15 and +10°C in accordance with the climatic environment at the field. We assumed that the lowest part of the lifting pipe would not freeze because it is in the underground section. Thus, we used a pipeline heater[*1] to reproduce this condition. A load cell was attached to the top of the optical fiber cable to measure the stress applied in the vertical direction by the freezing and expansion of the accumulated water.

The optical fiber cable and PE pipe rose by 1.7 cm when the water in most of the steel pipe (except for the heater section) froze and thawed. The measurements on the load cell showed that the tip of the optical fiber cable was pushed by an upward force of up to about 780 N during the thawing of the accumulated water. Note that the strong upward force was not recorded at the lowest temperature of −15°C, that is, it was always recorded during the subsequent temperature increase.

These results indicate that the freezing and thawing of the accumulated water in the lifting pipe generated an upward force on the optical fiber cable and PE pipe. Since the optical fiber cable outside the lifting pipe was pushed upward, we assumed that the compressed and expanded damage (Fig. 2(d)) to the sheath of the upper part of the optical fiber cable was caused by the repeated upward force exerted toward the fixture point (stainless-steel band) on the utility pole.

(2) Observation of phenomena inside a lifting pipe

Considering the results described in verification (1), we observed the changes in the water and their impact on the cable and PE pipe. The results are as follows. We inserted a plastic flexible (PF) pipe (which simulates an optical fiber cable) into a transparent polyvinyl chloride (PVC) tube (which simulates the lifting pipe). The experimental apparatus was filled with water and placed in a thermostatic room. We observed the phenomena inside the pipe, when temperature in the surrounding area repeatedly changed between −15 to 10°C, that is, water in the lifting pipe froze and thawed, repeatedly (**Fig. 4**).

The set temperature in the thermostatic room was assumed to be in the range of −15 to +10°C, as in verification (1). To simulate the unfrozen part (underground section) of the lifting pipe, a pipeline heater was installed at the bottom of the transparent PVC tube. The upper end of the PF pipe was fixed with a

*1 Pipeline heater: A strip heater used to prevent water pipes from freezing.

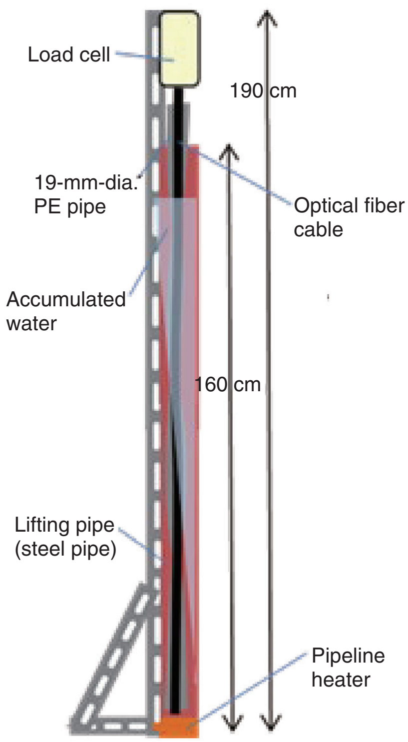


Fig. 3. Apparatus for reproducing lifting pipe.

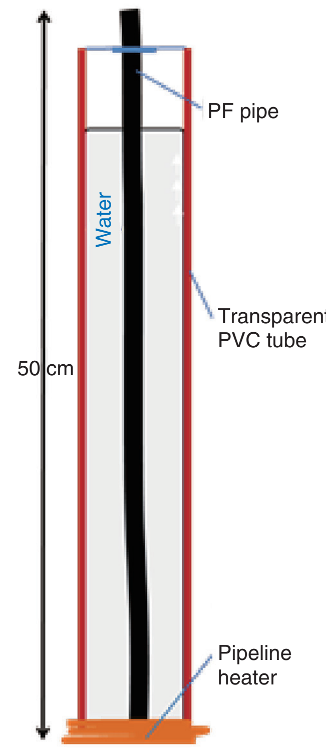


Fig. 4. Lifting pipe simulated with transparent PVC tube.

stainless-steel band at the opening of the PVC tube in the same manner as the optical fiber cable is fixed to the utility pole with a stainless-steel band. The results of repeated freezing and thawing are shown in **Figs. 5(a)** to **(h)** and summarized as follows.

Result 1: Freezing progressed from the top of the PVC tube to the sides, bottom, and center, and most of the tube froze except for the area near the heater. The water surface (Fig. 5(a)) also rose by about 2.5 cm (Fig. 5(b)).

Result 2: When the temperature was gradually increased from the frozen state, thawing progressed from the outside of the PF pipe, but ice remained from the center to the upper part of the pipe, wrapping around it (Fig. 5(d)).

Result 3: When the water was re-frozen from the state described in Result 2*2, new ice was formed in addition to the remaining ice from the center to the top of the PF pipe, and the water surface rose again (Figs. 5(e) and (f)). In the unfrozen area between the remaining ice and newly formed ice, the PF pipe was deformed as if it had been crushed under pressure (Fig. 5(f) and **Fig. 6**).

4. Discussion

From the results of the two verifications described above, it is conceivable that the optical fiber cable installed in a lifting pipe is pushed up during the process by which rainwater infiltrates the pipe and the accumulated water repeats freezing and thawing for the following three reasons: (i) the ice remaining near the top and center of the pipe solidifies when surrounding the cable; (ii) the internal pressure of the unfrozen part increases due to the expansion pressure caused by the subsequent new freezing from the periphery (Figs. 5(d) to (f)); and (iii) as the temperature increases, the surrounding ice begins to melt, and the optical fiber cable is pushed up from the pressure point when its internal pressure is released while being held by the ice (Fig. 5(g)).

We thus conclude that due to the repetition of freezing and thawing, the optical fiber cable inside the lifting pipe pushes upward and exerts a crushing force

*2 In consideration of the cold-climate environment, we assumed that not all the ice melts during the day but freezing progresses as the temperature drops again.

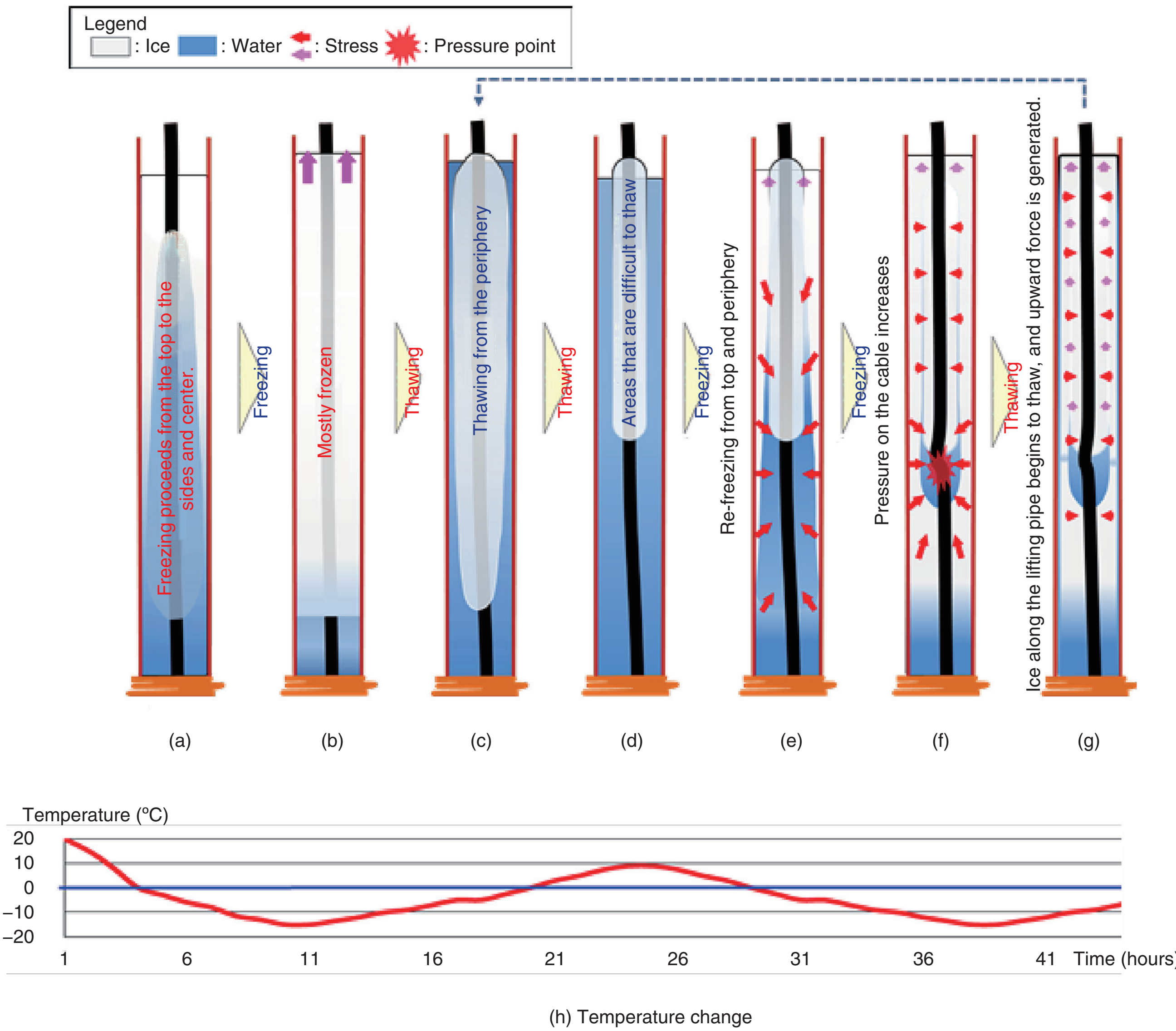


Fig. 5. Results of verification (2).

on the cable section outside the lifting pipe toward the point at which it is fixed to the utility pole.

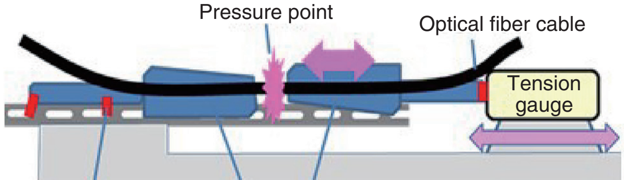
The strong upward force mentioned in verification (1) did not occur at the lowest temperature but during temperature increase. The reason is that the pressure applied to the inside of the lifting pipe was released by partial thawing and pushed upward to the top of the pipe, namely, along its escape route.

5. Reproduction of damage to cable sheath

As mentioned in verification (1), the optical fiber cable was pushed up with a force of about 780 N during thawing after the water in the steel pipe froze. To verify whether the tensile force due to repeated freezing and thawing during winter would damage the outer sheath of the optical fiber cable, we conducted a test in which one end of the cable was fixed and the other end was pulled with a force of 780 N (**Fig. 7(a)**).

The test was carried out by repeatedly applying then releasing the tension under the environment in which freezing and thawing are repeated. Applying and releasing tension, the outer sheath was damaged on the 35th repetition, and gradually torn off by further repetition (**Fig. 7(b)**).

Fig. 6. Part of the PF pipe deformed due to concentrated stress.



(a) Tensile-test system for cable sheath

(b) Torn-off cable sheath

Fig. 7. Tensile test on cable sheath.

6. Conclusion

We investigated the damage to an optical fiber cable and PE pipe in a lifting pipe installed in cold regions. The experimental results indicate that repeated freezing and thawing of accumulated water, which somehow enters the lifting pipe, causes pressure to build up inside the pipe as the water transforms (and expands) to ice, which in turn exerts a force that pushes up the optical fiber cable and deforms it during thawing. They also indicate that the repeated freezing and thawing tears the outer sheath of the optical fiber cable and PE pipe, eventually leading to failure of the optical fiber cable.

External Awards

Distinguished Achievement and Contributions Award

Winner: Masaya Notomi, NTT Basic Research Laboratories
Date: June 3, 2021
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE)

He has long been engaged in research into integrated nanophotonics that exploits nanofabrication technology, shedding light on new optical phenomena in nanostructures, and applying the results to dramatically reduce the size and energy consumption of optical communication devices.

Best Video Presentation Award Honorable Mention

Winners: Yuki Ban, The University of Tokyo; Yusuke Ujitoko, NTT Communication Science Laboratories
Date: July 9, 2021
Organization: IEEE World Haptics Conference 2021

For "Hit-Stop in VR: Combination of Pseudo-haptics and Vibration Enhances Impact Sensation."
Published as: Y. Ban and Y. Ujitoko, "Hit-Stop in VR: Combination of Pseudo-haptics and Vibration Enhances Impact Sensation," IEEE World Haptics Conference, July 2021.

Annual Conference Award

Winners: Soichiro Kaku, Kyosuke Nishida, and Sen Yoshida, NTT Media Intelligence Laboratories (currently, NTT Human Informatics Laboratories)
Date: July 26, 2021
Organization: The Japanese Society of Artificial Intelligence (JSAI)

For "Weight and Activation Ternarization in BERT."
Published as: S. Kaku, K. Nishida, and S. Yoshida, "Weight and Activation Ternarization in BERT," Proc. of the 35th Annual Conference of JSAI, June 2021.

IPSJ Yamashita SIG Research Award

Winner: Toshinori Usui, NTT Social Informatics Laboratories/Institute of Industrial Science, The University of Tokyo (NTT Secure Platform Laboratories/Institute of Industrial Science, The University of Tokyo when the paper was published)
Date: July 29, 2021
Organization: Information Processing Society of Japan (IPSJ)

For "Automatically Armoring Script Engine with Taint Analysis Capability."
Published as: T. Usui, T. Ikuse, Y. Kawakoya, M. Iwamura, J. Miyoshi, and K. Matsuura, "Automatically Armoring Script Engine with Taint Analysis Capability," Proc. of Computer Security Symposium 2020, pp. 932–939, Kobe, Japan, Oct. 2020.

IPSJ Yamashita SIG Research Award

Winner: Hiroyuki Uekawa, NTT TechnoCross Corporation (NTT Secure Platform Laboratories when the paper was published)
Date: July 29, 2021
Organization: IPSJ

For "Validation Method for Network Structure Information Using Passive and Incomplete Security Logs."
Published as: H. Uekawa, T. Ogami, E. Shioji, T. Shibahara, and M. Akiyama, "Validation Method for Network Structure Information Using Passive and Incomplete Security Logs," Proc. of Computer Security Symposium 2020, pp. 456–463, Kobe, Japan, Oct. 2020.