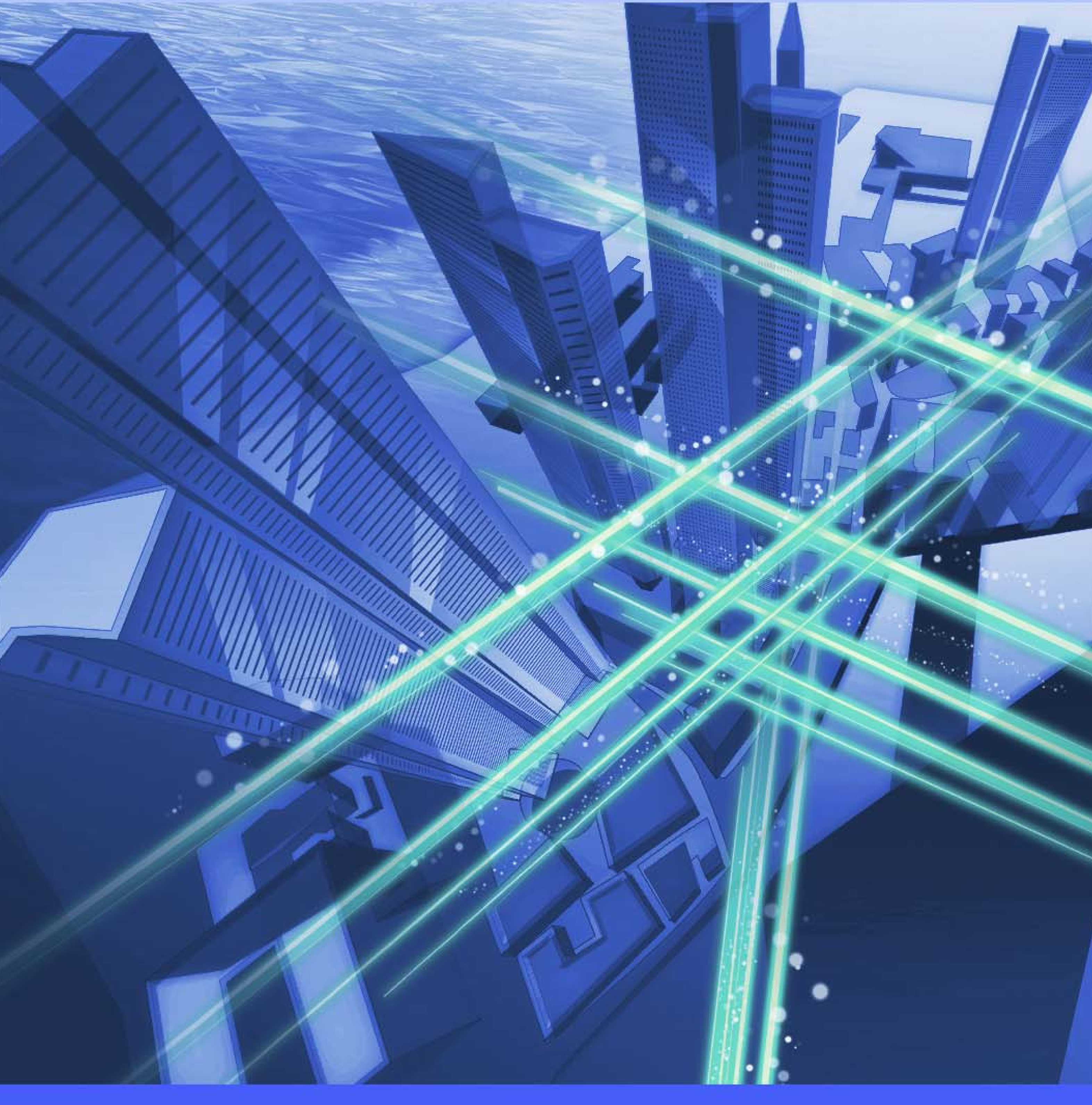
NTT Technical Review

6
2023



June 2023 Vol. 21 No. 6

NTT Technical Review

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Human Resources Is the Foundation of Our Business and Empathy Is the Driving Force That Creates New Value

Keigo Kajimura
Senior Executive Vice President,
NTT Communications

Abstract

In 2022, the new DOCOMO Group was formed after a reorganization of NTT DOCOMO, NTT Communications, and NTT COMWARE. Since then, the Group has integrated the three companies' business functions and clarified their respective roles to improve the value it provides to customers and boost growth. Under its brand slogan "Changing worlds with you," the new DOCOMO Group aims to reform the structure of society/industry and create new lifestyles. We interviewed Keigo Kajimura, senior executive vice president of NTT Communications, which is responsible for the enterprise business, about the initiatives he is focusing on and his beliefs as a top executive.

Keywords: digital transformation, customer experience, human resource

Contributing to digital transformation in society and industry through multiplication rather than addition

—It has been more than a year since the reorganization of NTT DOCOMO, NTT Communications, and NTT COMWARE, how do you feel looking back?

In accordance with the New DOCOMO Group Medium-Term Strategy announced in 2021, management policies of NTT DOCOMO, NTT Communications (NTT Com), and NTT COMWARE were merged in January 2022, and the three companies were reorganized, including transferring certain businesses among them, in July 2022. I was appointed senior executive vice president of NTT Com at the time of the reorganization. As head of the Platform Service Division, I am in charge of all services provided by NTT Com. I am also in charge of corporate affairs, technology and innovation, internal systems, information security, and promoting transformation in all areas, i.e., digital transformation (DX), customer experience (CX), green transformation, and employee experience.

Through this reorganization, NTT Com can now provide total solutions in a one-stop-shop manner to all customers nationwide by combining our core businesses, such as fixed networks, cloud computing, and datacenters, with NTT DOCOMO's fifth-generation mobile communications system (5G) and Internet of Things (IoT) and NTT COMWARE's software-development capabilities.

At the time of the reorganization, NTT Com offered about 100 services, to which NTT DOCOMO added about 200, thus increasing the total number of services to about 300. I see this increase as multiplication rather than addition, and I was very excited that the possibilities would expand infinitely if we further strengthened our sales capabilities.

During the past year, in addition to carrying out the Start Dash Program in which we focus on offering newly added services to existing NTT Com customers, we have also endeavored to create new value by combining technologies such as 5G, drones, robots, IoT, and XR (cross/extended reality) and provide it to our customers according to their needs.

These efforts at the first stage of our transformation have begun to bear fruit in various areas, and I feel that customers are expecting to be offered an even wider range of products from NTT Com. In 2023, which marks the next stage of our transformation, we aim to make even greater strides and provide concrete value to our customers in a timely manner to meet their expectations.

—Your attitude toward meeting customer expectations is encouraging. Can you give us specific examples of your efforts?

For large enterprises, IoT solutions for remote management and optimization (energy, automobiles, etc.) and solutions using 5G and docomo MEC™ (Multi-access Edge Computing) with low latency and high security are beginning to show results. For example, we jointly verified in an experiment that the AI (artificial intelligence) face-recognition mobile gate system developed by Kumahira Co. Ltd. combined with 5G and docomo MEC™ improves the efficiency of admission-control operations at large-scale events. The number of people passing through the gate per minute increased by 23% compared with that possible with the previous setup. We are also seeing the results of experiments on automated driving and autonomous drone flight, and we would like to turn these results into commercial products in the future.

In addition to addressing a growing demand for mobile services from customers who are operating their businesses globally, we also plan to strengthen our lineup of fixed-mobile convergence services by creating services for small- and medium-sized businesses. We will continue to contribute to the DX of society and industry by providing advanced solutions with the mobile and cloud-first approach.

It is important to create and sell services that are used by people

—It's exciting to think about the new value you can offer and the impact you can have on society. So, could you introduce NTT Com's unique technology as well as your service strategy?

During my time as the general manager of the Solution Services Department, I launched and completed various system integration (SI) projects to meet individual customer requirements; however, SI tailored to individual customers inevitably requires a lot of work, has long lead times, and does not scale well. Accordingly, we have been working on company-wide innovation to address this issue by creating repeatable models of solutions based on the value we provide to our customers.

The service that supports these solution models is the Smart Data Platform (SDPF), a platform that connects data and value to enable data-driven DX. More than 80 components, including network, cloud, storage, security, AI engine, and data-utilization functions, can be freely combined to meet the needs of customer businesses. As I mentioned earlier, the reorganization has strengthened our capabilities regarding mobile services, terminals, and software, so the added value provided by us thus far has become much higher and wider by combining those capabilities with the SDPF.

Technologies that support this *composable* service strategy include the VxF (Virtual Everything Function) infrastructure, which virtualizes network-added functions, and Qmonus, which is a DevOps (development and operations) platform for integrating components. We have contributed to the speedy development and provision of various services by customers, including the Flexible Mobile Connect, which was the first integrated service of the three companies. Qmonus has begun to be used by other NTT Group companies and scheduled to be incorporated into the multi-orchestrator part of the Cognitive Foundation, which is one of the pillars of NTT's Innovative Optical and Wireless Network (IOWN). Although we are only halfway, I believe that there is no other example of telecommunications carriers working on this type of technology in-house.

We are currently using the SDPF in a wide range of projects involving market-oriented service development, including for the expansion of zero-trust network services that use the strengths of telecommunications carriers. In the promotion of a smart world that addresses social issues, the SDPF is used as the platform for data utilization in smart cities and for supporting the Manabi Pocket, which has five million user identifications in smart education.

—You provide services underpinned by solid technology, right?

I believe that it is important to create and sell services that are used by people and especially important to enable people to use them safely and comfortably. Since improving CX is crucial to provide services that customers continue to choose, we are making company-wide efforts to anticipate customer needs and improve the value of CX throughout the entire customer journey—from the proposal and introduction of services to post-introduction operations and response to problems that arise.

To this end, it is necessary to analyze the gap between service expectations and the current situation on the basis of the voice of customer (VoC), and to implement a cycle of improvement from the customer's perspective. For example, we provide a customer portal for customers who are using our services; unfortunately, the 2021 VoC survey showed very low Net Promoter Scores (NPS; an indicator of recommendation) and satisfaction levels. In response to these results, we established a cross-organizational project structure and spent a year establishing "personas" (profiles of typical customers), organizing the customer journey for each persona, and redefining the value provided by the portal to improve those scores. Therefore, we were able to significantly improve both NPS and satisfaction levels in the 2022 VoC survey. We thus intend to promote such initiatives across the organization at each touch point with our customers.

If you don't listen to others, you will stop growing as a person

—How do you view this era in which new technologies are being created one after another?

It may seem off the subject, but you've probably heard of a science-fiction television series and movie called "Star Trek," right? I love science fiction, particularly Star Trek. It was one of the reasons I joined NTT. I joined NTT in 1989 and was involved in designing telephone services such as toll-free telephone numbers. At that time, there were already signs that the era of exchanging data over networks was coming, but I had no idea that it would develop so rapidly.

Exactly as depicted in Star Trek, innovation has advanced and a world that was unthinkable in the telephone age has become a reality. In 2000, people doubted the new era of space development, but it is now a business trend. The future beyond that era is also becoming a reality through the development of IOWN.

Bringing about such innovations that transform society is the best part of my job, and to make that happen, I believe that top management must look ahead to the world five or ten years from now and show the company the way it should be and the direction it should take.

I think few people would dare to review a business with stable earnings or want to start something new that spans the whole organization. However, in such a stable environment, innovation is unlikely to occur. For that reason, we focus on taking a broad view of the business in general. Our ongoing efforts embody this attitude.

I also feel the need to look at things from multiple angles. People tend to stop listening to others as we move up the corporate ladder or get older. Such a way of being may stop people from growing, not only those at the top management. Therefore, I try to communicate with our employees without fail.

—How did you come to realize the importance of communication?

The trigger was so-called "failures" at work. I experienced several failures, and each time I experienced a failure, many people helped me and I was able to find a breakthrough by listening to them carefully.

I believe that the foundation of our business is human resources. I'd like to nurture human resources by improving their skills in the ability to create services, assemble services, and empathize (activation of communication that transforms human connections into power), which is the driving force behind new innovations.

An "encounter" between a company and its customers and between employees creates a connection, and the empathy that arises from this connection is the driving force that creates new value. I want to create an "empathetic organization" in which people cooperate autonomously and inspire one another so that innovation can continue to take place.

I also think we must hold the core of our company firmly in place and not let its axis waver. However, today is not the era of a planned economy, and innovation is accelerating. We can no longer take things with the sense of speed that we have in the past, so I try to make sure that the core that cannot be compromised remains, and the rest can be changed according to the situation.

—Please say a few words to our engineers, employees, and customers.

To our engineers. Hearing from professionals about technologies that I don't know much about is not only educational but also fun and exciting. Innovation occurs when people with various expertise and knowledge connect, so I think it is important to have technological exchanges between different industries and competitors. Technology is truly a common language. I also expect you to become customer-oriented engineers who connect technologies with the market.

To our employees. There is no end to our transformation, so let's work together toward the next stage.

Finally, we cannot solve social issues alone. NTT Com has established OPEN HUB Park at Otemachi Place in Tokyo as a place for demonstration and co-creation of various technologies, including IOWN. We have also established the IOWN Promotion Office to accelerate efforts to create software-based networks, the application of the All-Photonics Network to datacenter interconnection, and field demonstrations using the IOWN testbed. We would like to work with our customers to co-create solutions to social issues while refining various technologies toward the future. We look forward to working with you.

Interviewee profile

■ Career highlights

Keigo Kajimura joined NTT in 1989. In his career at NTT Communications, he became general manager of the Systems Department in 2012, member of the Board and general manager of the Solution Services Department in 2017. He became president and representative member of the Board of NTT Com Engineering in 2020. He assumed his current position in June 2022.

Turning an Innovative Idea into Common Sense and Making It Useful to Society

Yutaka Miyamoto
NTT Fellow, NTT Network Innovation Laboratories

Abstract

With the increase in video-data distribution, the development of cloud technology, and spread of new information and communication services, such as 5th-generation mobile communications and remote work, information and communication traffic has been increasing and will continue to increase. Implementation of the All-Photonics Network of IOWN (the Innovative Optical and Wireless Network) to meet the demand for diverse services and exponential growth of data traffic will require a huge increase in transmission capacity as well as drastic reductions in power consumption and latency. NTT Fellow Yutaka Miyamoto at NTT Network Innovation Laboratories is pioneering new optical network technology to overcome the capacity crunch. We interviewed him about the progress of his research and what is the best part of being a researcher.

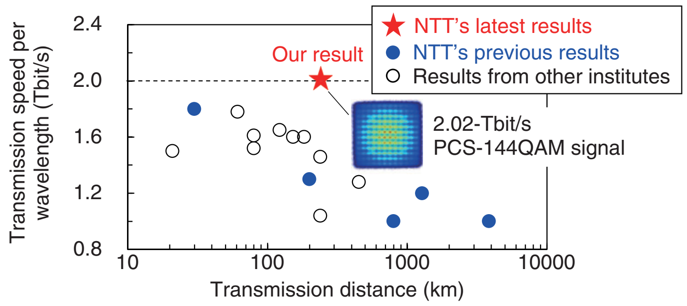
Keywords: scalable optical transport network, optical-amplification repeater, space-division multiplexing

Developing fundamental technologies for high-capacity scalable optical transport networks

—Could you give us an overview of the research you are currently conducting?

To implement a scalable optical transport network with petabit per second (Pbit/s)-class link capacity that can accommodate communication traffic that will increase due to the expansion of cloud services and spread of smartphones, I'm conducting research on four fundamental technologies: (i) large-scale digital-signal-processing technology for optical communications; (ii) photonics-electronics convergence integrated circuit (IC) technology; (iii) ultra-low-noise optical-amplification technology for signal-to-noise-ratio improvement; and (iv) space-division multiplexing (SDM) optical-transmission-system technology.

NTT has been a world leader in research and development (R&D) of optical communication technology. Since the practical application of time-division multiplexing systems in 1981, NTT has continued to drive three paradigm shifts concerning optical transmission systems: optical-amplification repeater systems, wavelength-division multiplexing (WDM) systems, and digital-coherent systems. As a result of these shifts, transmission capacity has increased



PCS: probabilistic constellation shaping
QAM: quadrature amplitude modulation

Fig. 1. Extending transmission distance of multi-terabit-class optical signals by increasing modulation rate.

approximately one million times in the past 40 years.

Data traffic has continued to increase at a rate of about 1.4 times per year, and as 5th-generation mobile communications (5G) and the Internet of Things services begin to be rolled out widely and 6G services are also in sight, communication traffic is expected to continue to grow exponentially. In fact, it is predicted that long-distance transmission with Pbit/s-class capacity will be necessary in the 2030s. To meet such future communication demands, the Innovative Optical and Wireless Network (IOWN) aims to economically provide higher capacity through the All-Photonics Network (APN).

However, recent research has shown that the physical limit on transmission capacity (namely, the capacity crunch) of long-distance transmission using optical fibers currently in use becomes apparent around 100 terabits per second (Tbit/s). To overcome the technical challenges posed by the capacity crunch and implement a Pbit/s-class optical communication infrastructure that can accommodate more than 100 times the current data traffic in a low-power consumption and economical manner, my research colleagues and I are conducting R&D on scalable optical transport technologies. We are driving the fourth paradigm shift through technological innovation that combines the advancement of optical transmission technology that we have been developing with new optical transmission medium (optical fiber) technology.

—Since our last interview two years ago, you have continuously tackled the technical issues concerning the capacity crunch.

In the previous interview, I talked about the results of our R&D at that time, including (i) SDM optical communication technology that can increase transmission capacity per link to more than 1 Pbit/s, which was more than 125 times the capacity of practical WDM systems using current optical fiber (100 Gbit/s/wavelength), and (ii) the demonstration of long-distance WDM transmission exceeding 1 Tbit/s per wavelength, both of which were the world's first at the time.

These achievements were the result of timely collaboration with the transmission medium and device research departments within NTT laboratories as well as external research institutes. We have continued to develop these technologies through close collaboration among our research departments, especially those among young researchers, and were able to produce world-first and world-leading research results in FY 2022.

For example, in 2022, we experimentally demonstrated the world's first optical amplified transmission using digital-coherent optical signals exceeding 2.02 Tbit/s per wavelength over 240 km (**Fig. 1**).

To expand transmission capacity per wavelength by overcoming the speed limit of silicon complementary metal oxide semiconductor circuits, we had to both broaden bandwidth and increase output power of the driver amplifier for driving the optical modulator as well as achieve extremely accurate compensation for differences in tributary-signal-path lengths and variations in tributary-signal-path loss in the optical transmitter and receiver circuits. We addressed this issue by integrating an ultra-broadband baseband-amplifier IC module and digital-signal-processing technology that enables ultra-high-precision compensation of loss variation and distortion in the optical transmitter and receiver circuits, both of which were developed by NTT, and achieved optical amplified transmission

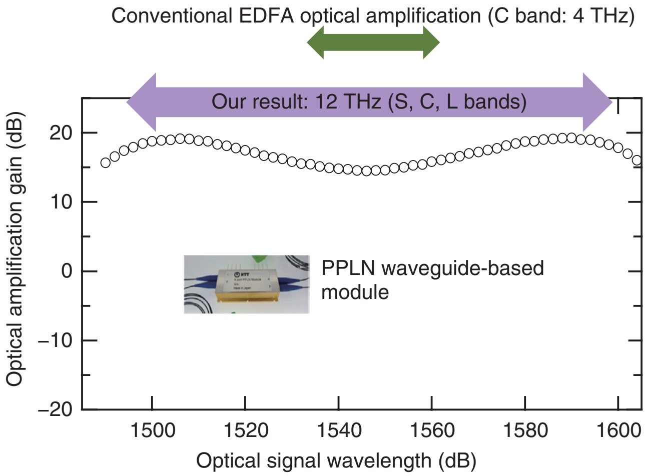


Fig. 2. Broadening the amplification bandwidth and expanding wavelength resources by applying optical-parametric amplification repeater system using PPLN waveguide modules.

over a distance of 240 km at 2.02 Tbit/s. This result indicates the potential for further scalability of digital-coherent optical-transmission technology that can achieve both high capacity and long-distance transmission. A paper reporting this achievement was accepted as a postdeadline paper—a paper presented at the most-challenging session—at the European Conference on Optical Communication (ECOC 2022).

Conducting experiments in historic facilities at NTT Yokosuka R&D Center

—You are developing core technology for the IOWN APN, right?

We also made significant progress in terms of broadband optical-amplification repeater technology using NTT's proprietary periodically poled lithium-niobate (PPLN) waveguide modules.

In close cooperation with the device research department, we proposed an optical-amplification repeater system that combines an optical parametric inline amplifier that handles polarization-division-multiplexed digital-coherent optical modulation and demodulation signals, which are currently the mainstream. We conducted the world's first ultra-wideband WDM optical amplified transmission experiment over 240 km by applying an optical parametric amplifier to multiplex optical signals at 1 Tbit/s per wavelength within the amplification bandwidth of 12 THz (**Fig. 2**).

While the WDM signal bandwidth of the widely used optical amplifier (erbium-doped fiber amplifier (EDFA) in the C band) is approximately 4 THz, our newly developed optical-parametric amplifier can amplify a bandwidth of 12 THz or greater, which is approximately three times that of an EDFA, and can cover the wavelength regions (S, C, and L bands) in which optical fiber has low loss. It is thus possible to expand wavelength resources by broadening bandwidth. This broadband optical-amplification repeater technology, with its wide bandwidth and low distortion, is expected to provide further high-capacity optical amplification enabling implementation of the APN, which dynamically uses abundant wavelength resources in accordance with the IOWN concept proposed by NTT. This accomplishment was also accepted as postdeadline papers at the Optical Fiber Communication Conference (OFC) in 2021 and 2022.

—You are also working closely with the transmission medium research department on SDM optical communication technology.

In addition to broadening the bandwidth of conventional single-mode optical fibers (SMFs), we are promoting R&D on optical fibers for SDM optical communication technology with the aim of fundamentally overcoming the capacity crunch. Working closely with the transmission medium research department, we are developing prototypes of various types of SDM optical fibers, including multicore optical fibers (MCF) having multiple cores (which are pathways for light) in a single fiber and multimode optical fibers having multiple propagation states (spatial modes) in a single core, and are assessing the feasibility of these optical fibers as new transmission media for future optical communications. To maximize the performance of the above-mentioned new transmission media, we are also studying high-capacity SDM optical communication systems.

Since SDM optical fiber with a standard cladding diameter of 125 µm (which is the same diameter as that of current SMF) is suited for mass production of optical-fiber cables, we are investigating SDM optical communication technology that can increase the capacity of such fiber more than ten times that of current SMF while maintaining a standard cladding diameter. We have been focusing our research on mode-multiplexed transmission technology that uses and controls multiple spatial modes to overcome the limitation on transmission distance imposed by interference (crosstalk) between different spatially multiplexed optical signals, which is an issue regarding SDM optical communication systems. Mode-multiplexed transmission technology consists of the following three technologies: (i) mode-multiplexing optical-fiber cabling technology, which can control spatial modes; (ii) mode-multiplexed multiple-input multiple-output (MIMO) digital-signal-processing configuration technology, which can multiplex and demultiplex multiple different optical signals at the same wavelength in accordance with dynamic optical characteristics attributed to the cable-installation properties; and (iii) fundamental transport technology that unifies the spatial-mode-multiplexing optical-amplification repeater technology with (i) and (ii).

Regarding mode-multiplexed MIMO digital-signal-processing configuration technology, NTT successfully demonstrated in a proof-of-principle experiment long-distance transmission over 6000 km of mode-multiplexed optical communications using six independent spatial modes. For this experiment, we developed a MIMO signal-processing system and optical-amplification repeater system that have strong compensation characteristics against transmission loss and propagation-delay differences that occur between different spatial modes. In March 2023, we also reported in our highly scored OFC 2023 paper the demonstration of long-distance mode-multiplexed optical-amplified transmission with ten spatial modes.

Research on the above three technologies has partly been supported by National Institute of Information and Communications Technology under the “R&D of basic technologies of spatial mode control type optical transmission for the Beyond 5G era” program (started in 2021). We are collaborating with four domestic research institutes and NTT Access Network Service Systems Laboratories to establish an SDM optical transmission system that will enable us to build a high-capacity, long-distance backbone optical network in the Beyond 5G era. Specifically, we are investigating the following technologies: (i) design, installation, and connection technologies for coupling-type MCF cable that has a standard cladding diameter and can control spatial modes; (ii) optical-amplification repeater technology that is compatible with MCF cabling technologies (i); and (iii) a new low-complexity MIMO signal-processing technology that can follow dynamic changes in the transmission link. By investigating these three technologies, we aim to establish a basic technology for spatial-mode-control optical transmission that enables long-distance transmission of spatially multiplexed signals of ten or more.

Over the last few years, our research has advanced to the stage of installing various types of SDM optical-fiber cables in underground facilities at the NTT Yokosuka R&D Center and testing their transmission characteristics under conditions similar to those in the field. The NTT Yokosuka R&D Center, which celebrated its 50th anniversary in 2022, has an underground facility (conduit) built in the 1970s to verify wired communication system technology. Optical-fiber cables developed at the dawn of optical-fiber-communication systems in the mid-1970s were laid, and tests on the characteristics of those cables in terms of practical use were conducted. We are taking on the challenge of conducting new demonstration experiments at this historical site, where our predecessors have been testing technology and putting it to practical use for more than 40 years.

Collaborating with others like the tale of the “three arrows” to accumulate achievements

—Can you tell us what is key in your research activities?

Optical communication systems cannot be put into practical use by using only a single technology. The process of achieving target performance in a timely manner by combining several of our technologies with those of various companies and institutes as necessary is important. Given the rapid pace of change in the world today, it is essential to promote collaboration within other research institutes and other laboratories within NTT in a timely manner to take the lead in standardization activities and keep ahead of global competition. We need to combine multiple advanced technologies as in the tale of the "three arrows" (which conveys that one arrow can be easily broken, but three bundled arrows cannot) to achieve results and build a track record.

I believe that one of my roles as an NTT Fellow is to create opportunities for young researchers to test their ideas and collaborate effectively with other leading researchers. To fulfil that role, it is of course important to have advanced technologies of our own, but it is also important to share the goal to be reached with other researchers and research institutes that have advanced technologies and build a relationship of trust with them. I try to find partners who share our goals through joint experiments and at academic conferences and collaborate with them in a timely manner. I believe that if our ultimate goal is in line with our collaborative partners, we can get back to the basics and move forward without wavering, even if difficulties arise. If we are working with overseas research institutes, we may face differences in cultures, business practices, and mentalities, so we may need to take subtle tactics; even so, when taking up a challenge concerning a new technology, I want to keep a positive mindset and say, "It looks interesting and challenging, so let's give it a try."

As I mentioned in the previous interview, I believe it is important to be prepared on a daily basis so as not to miss any critical "This is it!" moments. For this reason, it is also important to identify the areas in which we produce technology that surpasses others and has value. We also need to pay attention to what value we can provide to our collaborative partners. Since this perspective can be lost when focusing on cutting-edge technologies only, we are working on both R&D and practical applications in conjunction with our colleagues in the practical application department.

—What is important to be a good researcher?

I said before that an important perspective for system researchers is to "turn an innovative idea into common sense and make it useful to society." I want to tell young researchers that everything starts from an innovative idea. For example, when we first presented a research result at a conference, the reaction was not so great; however, at the next conference, many people presented something similar, creating a technological trend.

I urge all researchers to pursue what you find interesting without fear of failure. However, it may be difficult to determine how long you need to pursue it. There were many cases in which a technology that had remained obscure became widespread when combined with another technology 20 years later. It is also important to investigate things over a long time span without being too concerned about the results in front of you and obtain rights to your ideas in preparation for the day that they are put to practical use.

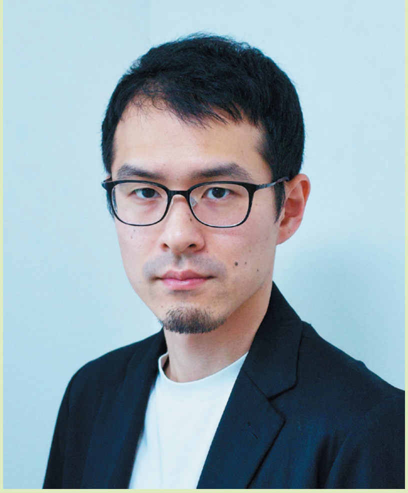
As a final point, in the spring of 2021, on behalf of all my colleagues, I was honored with receiving the Medal with Purple Ribbon for the development of a high-capacity optical transmission scheme using coherent-multicarrier multilevel modulation. The subject of this award is related to the R&D on long-haul high-capacity optical-fiber communication systems, with which I was involved from 1995 to 2010. In 2007, the technology that won this award was put to practical use for the first time in NTT Group's 1.6-Tbit/s WDM optical communication system with a channel capacity of 40 Gbit/s per wavelength. Our major contributions include the practical application and international standardization of (i) digital-signal multiplexing/framing—called the optical transport network (OTN)—equipped with strong error-correcting codes to flexibly accommodate data traffic in WDM optical networks and (ii) multilevel differential phase shift keying for replacing the intensity-modulation direct-detection technology. The above technologies we have developed facilitated the spread of the Internet and global broadband services via optical access networks and smartphones (4G) and continue to support the communication infrastructure that is deeply involved in the transformation of people's businesses and lifestyles. It is most gratifying to me that the contribution of the research field that we have been pursuing, including those of our predecessors who have guided us and the many people that we have worked hard with to advance R&D and practical applications, have been recognized. Being able to engage in R&D that will produce results that will be used around the world and contribute to society as a whole is the best part of being a researcher.

■ Interviewee profile

Yutaka Miyamoto received a B.E. and M.E. in electrical engineering from Waseda University, Tokyo, in 1986 and 1988 and Dr.Eng. in electrical engineering from the University of Tokyo in 2016. He joined NTT Transmission Systems Laboratories in 1988, where he engaged in R&D on high-speed optical communications systems including the 10-Gbit/s first terrestrial optical transmission system (FA-10G) using EDFA inline repeaters. He was with NTT Electronics Technology Corporation between 1995 and 1997, where he engaged in the planning and product development of a high-speed optical module at the data rate of 10 Gbit/s and beyond. Since 1997, he has been with NTT Network Innovation Labs, where he has researched and developed optical transport technologies based on 40/100/400-Gbit/s channel and beyond. He is currently investigating and promoting a future scalable optical transport network with Pbit/s-class capacity. He is a member of the Institute of Electrical and Electronics Engineers (IEEE) and a fellow of the Institute of Electronics, Information and Communication Engineers (IEICE).

Fast Sparse Modeling Technology Opening Up the Future with Ultra-high-dimensional Data

Yasutoshi Ida
Distinguished Researcher,
NTT Computer and Data Science Laboratories



Abstract

As one pillar of NTT's IOWN (Innovative Optical and Wireless Network) vision, Digital Twin Computing aims to construct the world in a digital space. To this end, it is essential that data be obtained from people and things by sensors. However, advances in sensing technologies have created a new issue in which an increase in the number of data dimensions makes processing time longer, which makes it difficult to analyze and use collected data within a realistic period of time. We asked NTT Distinguished Researcher Yasutoshi Ida to tell us about "fast sparse modeling technology" as a means of solving this problem.

Keywords: sparse modeling, deep learning, high-dimensional data

Creation of a new technique for overcoming increased processing time of ultra-high-dimensional data

—Dr. Ida, what exactly is "sparse modeling" that you are now researching?

Sparse modeling is a technology that applies sparsity to data usage in the sense that "the amount of information needed is only a small part of all information obtained—most of the remaining information is unnecessary." Here, "sparse" has the meaning of "thin" or "scattered" based on the idea that "we should not make more assumptions than necessary to explain a certain matter" (Occam's razor) put forth by William of Ockham, a 14th-century English theologian.

To give an example of sparse modeling, let's consider the case of predicting tomorrow's temperature in Tokyo from weather data consisting of temperature, wind direction, pressure, etc. throughout Japan. In this case, the hypothesis that "data related to Tokyo temperature prediction is only that from some of the neighboring prefectures" can be postulated taking geographical relationships into account. This hypothesis is a basic precondition for using sparse modeling expressed as "important data is only a small part of the entire amount of data—all other data is unnecessary." Incorporating this prior knowledge called sparsity into our analysis enables us to specify those prefectures related to the prediction of tomorrow's temperature in Tokyo.

Example of high-dimensional data

In a global observation system consisting of ships, buoys, airplanes, weather satellites, etc., the number of dimensions in weather data collected by a sensing network can reach from several tens of thousands to several hundreds of millions or more.

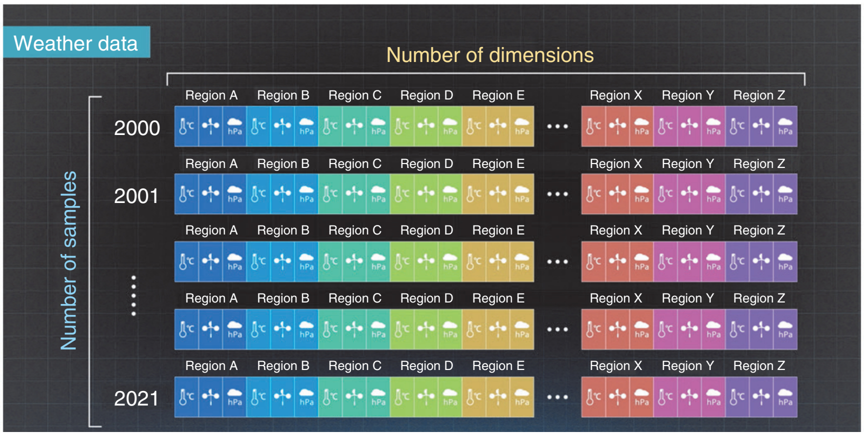


Fig. 1. Number of dimensions and number of samples in weather data.

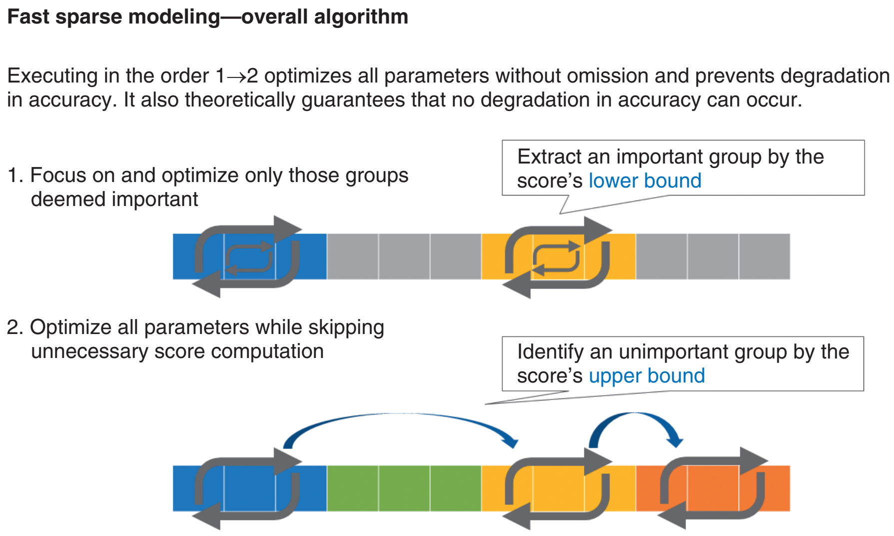
The background to the need for this technique lies in the increase in the number of data dimensions that can be obtained due to recent advances in sensing technologies. In recent weather analysis, for example, the number of items of weather information (number of dimensions) that can be observed in regions throughout the world can reach several tens of thousands to several hundreds of millions with respect to the number of years (number of samples) on the vertical axis (**Fig. 1**). However, machine learning in recent years has widely adopted the approach that using a massive number of samples in training improves accuracy, but handling data in which the number of samples is relatively smaller than the number of dimensions is difficult. The aim of sparse modeling is to therefore solve this problem at least in part by using sparsity to select only those dimensions needed for analysis.

Model compression in deep learning is another example of how sparse modeling can be used. In deep learning, which can be called a fundamental technology of modern-day artificial intelligence (AI), accuracy has continuously improved by increasing the number of model parameters. However, a massive number of parameters increase memory consumption and processing time, so applying AI to edge-side hardware having limited memory capacity, for example, can be difficult. Under these conditions, incorporating sparsity in deep learning in the sense that "important parameters are only a small part of all parameters—all other parameters are unnecessary" decreases the number of AI parameters and the amount of memory consumed.

—What are the strengths of "fast sparse modeling technology" compared with existing technology?

Fast sparse modeling that I'm researching is achieving speeds up to 35 times faster than existing sparse modeling technology, which requires much processing time to compute a score expressing the importance of each dimension. Fast sparse modeling, on the other hand, replaces this score with the score's upper and lower bounds that can be computed at high speeds. In this way, fast sparse modeling has been successful in greatly shortening processing time while preventing degradation in accuracy. This approach is influenced by the high-speed technique used in database research by NTT Distinguished Researcher Yasuhiro Fujiwara, who was my research mentor when I entered NTT. By combining sparse modeling with databases, which are seemingly unrelated, I was able to achieve high speeds with an original technique not found in the existing research field of sparse modeling (**Fig. 2**).

Armed with this approach, I have my sights on the processing of ultra-high-dimensional data of several hundreds of millions of dimensions or more of which there are not many examples in existing sparse modeling technology. In 2019, the fast algorithm I just



Fast sparse modeling—overall algorithm

Executing in the order 1→2 optimizes all parameters without omission and prevents degradation in accuracy. It also theoretically guarantees that no degradation in accuracy can occur.

1. Focus on and optimize only those groups deemed important

Extract an important group by the score's lower bound

2. Optimize all parameters while skipping unnecessary score computation

Identify an unimportant group by the score's upper bound

Fig. 2. Computational algorithm of fast sparse modeling.

mentioned increased processing speed by as much as 35 times, and the paper describing this achievement was accepted at Neural Information Processing Systems (NeurIPS), a leading conference in this field. This technology was subjected to tests under a variety of environments over a period of about one year so that it could be provided to NTT Group companies, and it was found that the algorithm could increase speeds in many analysis examples.

Yet, it was also found that high speeds could not be attained for a very small number of use cases. On conducting a detailed analysis as to why this occurred, we found that there were cases in which the overhead (pre-computation) for computing the score's upper bound in the fast algorithm was too large depending on the properties of the target data. We are now developing an algorithm with the aim of reducing this overhead as far as possible, and if successful, we expect a twofold increase in speed, which means that we should be able to improve processing speed by 35×2, or in other words, by a maximum of 70 times.

In parallel with these activities, we are studying an approach that combines sparse modeling with deep learning that achieves high accuracy with large-scale data. Basically speaking, deep learning requires a large number of samples, so we are researching how deep learning could be applied to use cases with a small number of samples. Combining the knowledge gained from this research with sparse modeling, we are studying technology that can achieve high accuracy even for high-dimensional data in which the number of samples is small. This is research with a long-term view, and my aim here is to improve the accuracy of sparse modeling by 10%.

—What kind of world can we expect to see through fast sparse modeling?

Fast sparse modeling can be applied mainly to tasks that perform analyses and predictions from ultra-high-dimensional data. In the Industrial Internet of Things targeting factories, for example, applying fast sparse modeling to the preprocessing of analysis for identifying time slots affecting an increase/decrease in production can speed up the PDCA (Plan–Do–Check–Act) cycle in data analysis and shorten the lead time to decision-making. This increase in speed also allows for the handling of time-series data spanning even longer periods thereby enabling high-speed analyses that have so far not been possible. Similarly, in genome-wide association studies, fast sparse modeling can be applied to the preprocessing of analysis for identifying genetic factors, or single nucleotide polymorphisms (SNPs), related to cancer and other diseases. Increasing processing speed in this way will enable the analysis of SNP data on an even larger scale. Moreover, in a nuclear fusion reactor, fast sparse modeling can be applied to the preprocessing of analysis for identifying control operations and sensors related to plasma disruption and maintenance. This capability should contribute to the explanation of phenomena related to the stable operation of nuclear fusion reactors.

In addition, Digital Twin Computing in NTT's IOWN (Innovative Optical and Wireless Network) vision aims to create digital twins using large amounts of sensor data collected from sensors attached to people and things. Amid this initiative toward the future, sensing technologies are progressing and sensor data is becoming increasingly high dimensional, so I think that the opportunities for using sparse modeling that is especially adept at high-dimensional data analysis are increasing. Moreover, since the processing time devoted to sparse modeling will be increasing as data becomes increasingly high dimensional, I think that establishing technology for making sparse modeling even faster will become all the more important.

—How do you think fast sparse modeling will evolve going forward?

From here on, a key issue will be spatial complexity, that is, "To what extent can the amount of memory consumption be minimized?" The speed-up factor of fast sparse modeling is top class even from a global perspective, and in terms of shortening processing time, it's reaching milestones. It must be kept in mind, though, that memory consumption naturally increases as data takes on more dimensions. For example, when performing technical testing of fast sparse modeling to support the implementation of developed technologies in services, it may happen that memory consumption becomes too large. As a result, the number of dimensions at which processing can be performed can hit a ceiling even if no problems are occurring in the speed-up factor. Of course, bolstering the amount of memory through additional facility investment can solve this problem, but depending on the type of service being targeted, this method may prevent a profit from being made thereby creating a new problem. To resolve these issues, we are searching for a new method of fast sparse modeling that can hold down memory consumption while maintaining the speed-up factor.

Another direction that I can envision for fast sparse modeling is a "quantum leap in speed." As data becomes increasingly high dimensional together with advances in sensing technologies and limits to increasing speed are reached whatever the algorithm, I believe that we will have to consider new integrated approaches to achieving higher speeds that include distributed processing platforms and the use of advanced hardware. To tackle this research issue, collaborating with experts in other fields is essential—we must carefully search out a solution taking a long-term perspective. At NTT Computer and Data Science Laboratories, the research and development of advanced computers is also underway, so we are now investigating whether even faster sparse modeling could be achieved by making good use of such computers.

Determined to create practical technology after experiencing a "valley of death"

—What do you think is an important attitude to adopt in the work of research and development?

Based on what I learned from participating in a venture company during my university days, I place much importance on research and development focused on practical use. It was in 2010 during my third year of undergraduate studies that I first encountered machine learning. At that time, I was researching "topic modeling" technology that can visualize what kinds of topics occur in a document, and I felt strongly that I would like to incorporate this technology into an actual service. As a result, I participated in a venture company on the invitation from a friend. Once there, however, I was confronted with a number of problems not present at the research stage, such as "the mixing of data I had not expected with training data," "the model consequently behaving in unexpected ways," "output results that could not be interpreted by humans," and "a scale of data that was so large overall that training could not be completed." As a result, we never got to the point of implementing the technology in an actual service. The barrier between research and services is sometimes called the "valley of death." This was my first experience with this "valley of death" in which I was not able to implement machine learning into some kind of a service. From this experience, my idea of wanting to create machine-learning technology that could solve problems in real-world settings took root. Today, I am committed to “developing practical algorithms that can be applied to actual services” and am researching such algorithms on a day-to-day basis while exchanging information with people at actual work sites.

Of course, there’s more to research than simply adopting a practical approach. If a researcher is to produce research results that are truly groundbreaking and original, I believe it’s also necessary to take up long-term research that is somewhat removed from practical considerations. A researcher who pursues both short-term and long-term research may find that the knowledge gained from practical research can also be useful in long-term research, and conversely, that some of the ideas being pondered in long-term research can be useful in practical research. In short, a researcher can take on real-world problems in practical research and feed back the knowledge gained there to long-term research, and vice versa, can share ideas nurtured in long-term research with practical research to solve problems in the real world. Long-term research may also lead to technologies or papers that can produce groundbreaking results. These two types of research with different properties can mutually interact with each other or create a feedback loop, which I think is an ideal form of research.

—Dr. Ida, could you leave us with a message for other researchers, students, and business partners?

Yes, of course. I feel that research and development at NTT spans a wide range of fields and has a portfolio of unique research fields even on a global basis. This is especially advantageous in problem solving. For example, to speed up deep learning, severe targets can be imposed on the speed-up factor. NTT, however, has a lineup of experts across many areas from algorithms to hardware and interconnects, so by simply talking to a colleague sitting right next to you, it may be possible to discover an integrated solution in no more than ten minutes. I believe that this ability of coming up with an approach to a difficult problem in a short period of time is something that only the NTT environment can provide thanks to its original portfolio and diverse lineup of research personnel.

In addition, I think that NTT Computer and Data Science Laboratories that I belong to is an organization that researches a broad layer of technology related to data science in terms of both the breath of fields and short-term/long-term perspectives. For example, data analysis technology developed with a focus on real-world problems is researched on the premise that it will be introduced into business relatively soon, which I think contributes to added value in NTT services. On the other hand, I think that the research and development of advanced computers and searching out applications for them play an important role in the long-term development of data science.

Finally, if working as a corporate researcher, surrounding conditions can suddenly change due, for example, to an organizational restructuring. At this time, if you significantly change your direction of research in an attempt to adapt to changes in the environment, you will not be able to use the technical abilities that you have so far developed and results will not be forthcoming, all of which can lead to stress and a loss of confidence. In my experience, however, if you have a universal, unshakeable core character and refuse to compromise, I think that you will be able to adapt to your environment more often than not without sacrificing your good qualities. This way of thinking can be expressed as “gentle in appearance but tough in spirit,” or in other words, “my core research philosophy is uncompromising, but apart from that, I will adapt in a flexible manner to my environment.” To students reading this who are looking to become a corporate researcher, I would like them to enjoy research while discovering and treasuring one’s core character.

■ Interviewee profile

Yasutoshi Ida received his M.E. from Waseda University in 2014 and entered NTT in the same year. He received his Ph.D. in informatics from Kyoto University in 2021. He has been a distinguished researcher at NTT Computer and Data Science Laboratories since 2022. He is engaged in the research of fast-and-accurate sparse modeling and supports the implementation of developed technologies in services. He administers a liaison meeting that brings together AI-related engineers in the NTT Group for information exchange (NTT Deep Learning Liaison Meeting). His papers on developed technologies in this field have been accepted at many leading conferences (NeurIPS/ICML/AAAI/IJCAI/AISTATS).

Expectations and Prospects for Innovation in Quantum Technology

Tetsuomi Sogawa

Abstract

NTT laboratories have been engaged in basic research on various quantum-related technologies, including quantum information, since the mid-1980s before research on quantum computers took off. The Feature Articles in this issue present the latest global trends in quantum technology and NTT's research portfolio regarding quantum technology. In addition to quantum computing, quantum sensing and quantum networks are also extensively discussed from both experimental and theoretical perspectives.

Keywords: quantum computer, quantum sensing, quantum internet

1. Trends in quantum technology

The first "quantum-computer boom" was triggered by the development of Shor's algorithm in 1994, which drew attention to the potential threat to the security of the information technology (IT) society in which public-key cryptography is widely used. Numerous important advances, particularly in academia, have been made including the demonstration of qubit operation in various physical systems and the development of theory of quantum error correction. Around 2010, the technical difficulties in implementing those advances as a quantum computer became widely recognized and excessive expectations began to subside.

However, in 2011, the sudden announcement by D-Wave Systems of their development of a dedicated machine for solving combinatorial optimization problems (called a *quantum annealer*) by using a completely different technology called *quantum annealing* came as a surprise to all concerned. The significant improvement in performance of superconducting qubits around 2014 prompted IT companies such as Google, IBM, and Microsoft to enter into full-scale research and development of quantum computers and triggered a second quantum-computer boom, which has since continued as venture capital investments continue to increase.

Facing the added perspective of security, research and development of quantum technologies, such as quantum computers, quantum security, and quantum sensing, is in the midst of fierce global competition. Around 2015, Europe, the U.S., and China began to significantly expand government support under their quantum technology strategies. Although a few years behind them, Japan formulated the "Quantum Technology and Innovation Strategy" in 2020 [1] and the "Vision of Quantum Future Society" in 2022 [2], which aims to create new industries and business opportunities and address social issues on the basis of quantum technology. In response to this action, the Quantum STrategic industry Alliance for Revolution (Q-STAR) [3] was established in 2021 with the aim of making Japan a "quantum technology innovation-oriented nation," and Q-STAR is accelerating efforts to implement quantum technology in society.

2. Fundamental characteristics of quantum nature and application areas

As shown on the left side of **Fig. 1**, the world we live in is described by classical mechanics represented by Newtonian mechanics, i.e., a world that can be actually observed and touched. In contrast, as shown on the right side, the quantum world represented by the behavior of atoms and electrons is defined by

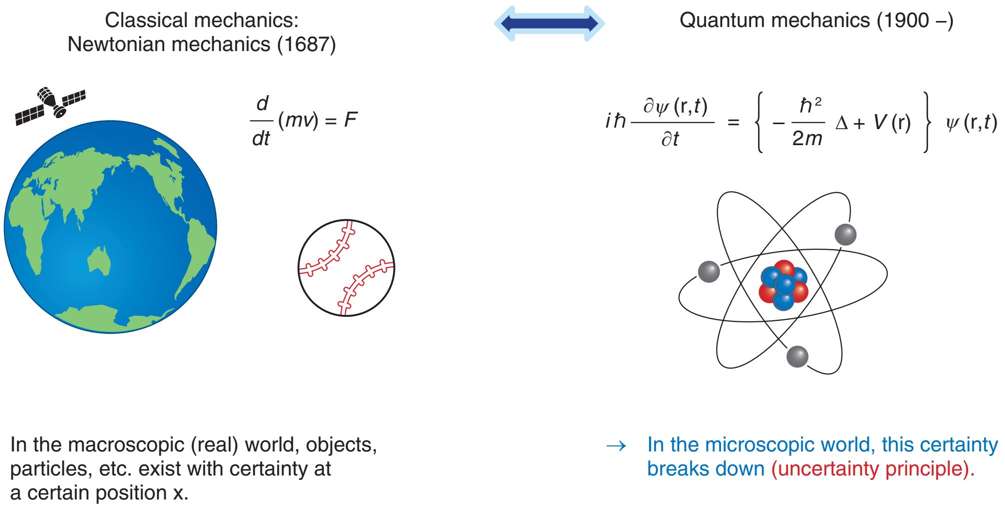


Fig. 1. Contrast between the real (classical) world and quantum world.

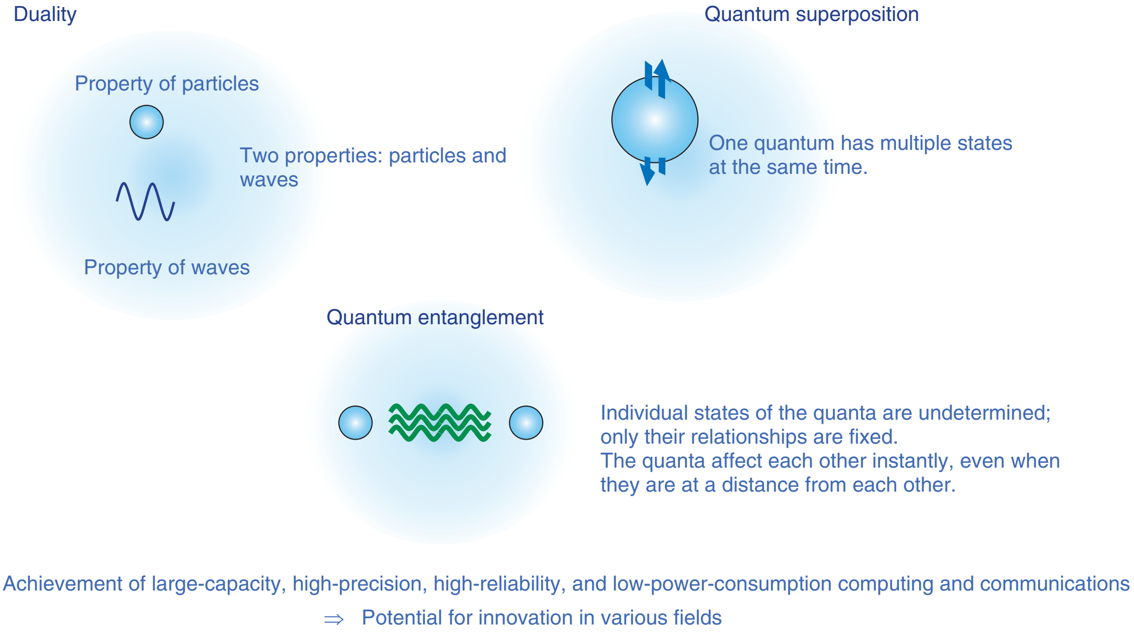


Fig. 2. Three characteristics of quantum behavior.

mathematical expressions that represent waves with existence probability under the laws of quantum mechanics, therefore far from our common sense and experience. There are various types of quanta, including extremely small ones, such as atoms and electrons, as well as light and relatively large superconducting quantum circuits; however, as shown in **Fig. 2**, regardless of the type, they all share the same characteristics of *duality*, *quantum superposition*, and *quantum entanglement*. Duality is the simultaneous possession of two properties: property of particles and property of waves. Quantum superposition enables two values, “0” and “1,” to be held in a single state, as illustrated in the figure with the upward arrow (corresponding to “0”) and downward arrow (corresponding to “1”) side by side. Quantum

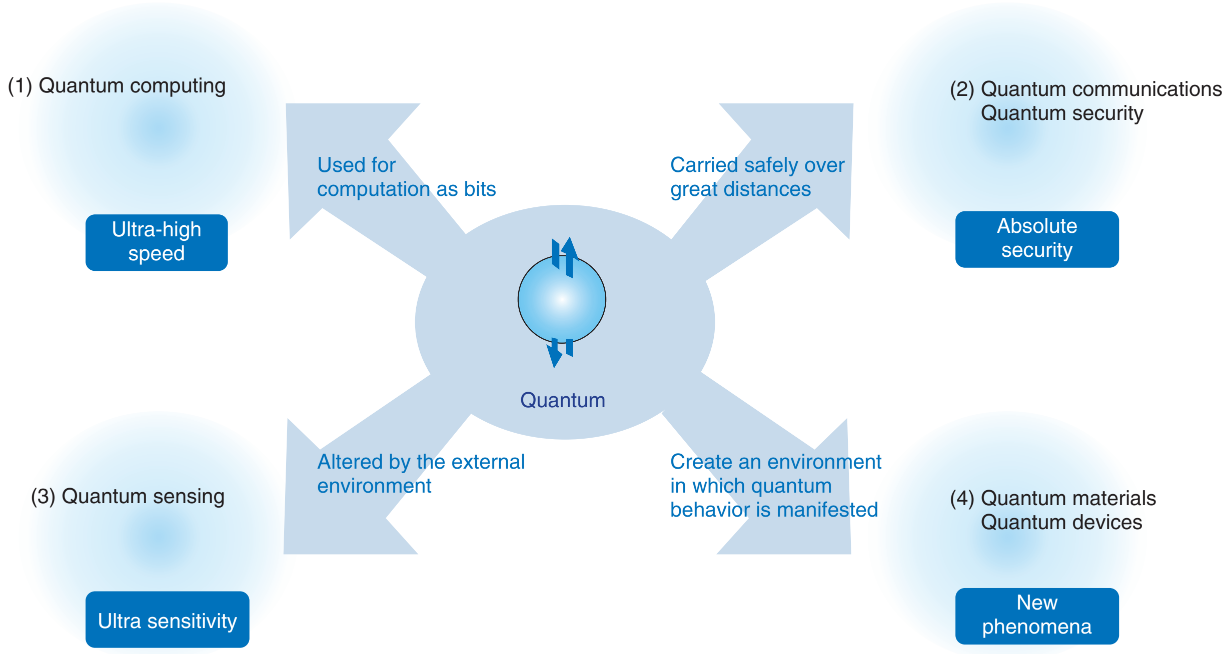


Fig. 3. Four application areas of quantum technology.

entanglement is a phenomenon in which the individual states of two quanta are undetermined, but the relationship between them is fixed in a way that even if the quanta are far apart, they can instantly affect each other when one is measured, even if they are at the other ends of Earth or even at opposites sides of the universe. In 1935, Einstein and other researchers published a paper arguing that the spooky behavior of quantum entanglement could not be sufficiently explained; therefore, quantum mechanics is incomplete. After 80 years of debate among many theorists and experimentalists, in 2015, it was finally concluded that quantum entanglement is real. Note that the 2022 Nobel Prize in Physics was awarded for significant work concerning this quantum entanglement controversy. The hope that harnessing these three quantum wonders will lead to technologies that achieve high-capacity, high-precision, high-reliability, and low-power-consumption computing and communications is drawing attention to the potential for innovation in a wide variety of fields.

The four main application areas of quantum technology—as shown in **Fig. 3**—are (i) quantum computing, which uses quanta as bits for high-speed computation; (ii) quantum communications and quantum security, which guarantee safety by using the property that quanta cannot be duplicated; (iii) quantum sensing, which uses the quantum sensitivity to the external environment to execute highly sensitive detection; and (iv) quantum materials, which create environments in which quantum behavior is manifested, and quantum devices, which use functions unique to quanta.

3. Recent progress in application of quantum technology

3.1 Quantum computers

Quantum computers can be broadly classified as two types: gate-based quantum computers, which can run a variety of algorithms and be used as general-purpose computers, and Ising machines, which are dedicated solvers for solving combinatorial optimization problems. Several companies have announced commercial gate-based quantum computers that are based on superconducting and ion-trap systems, but they can currently solve only small-scale problems. Various other approaches, such as using neutral atoms, photons, and semiconductor quantum dots, are also being researched and developed. In contrast, Ising machines have reached the practical application level of solving real problems of a certain scale. NTT reported that its coherent Ising machine called LASOLV™ can solve combinatorial optimization

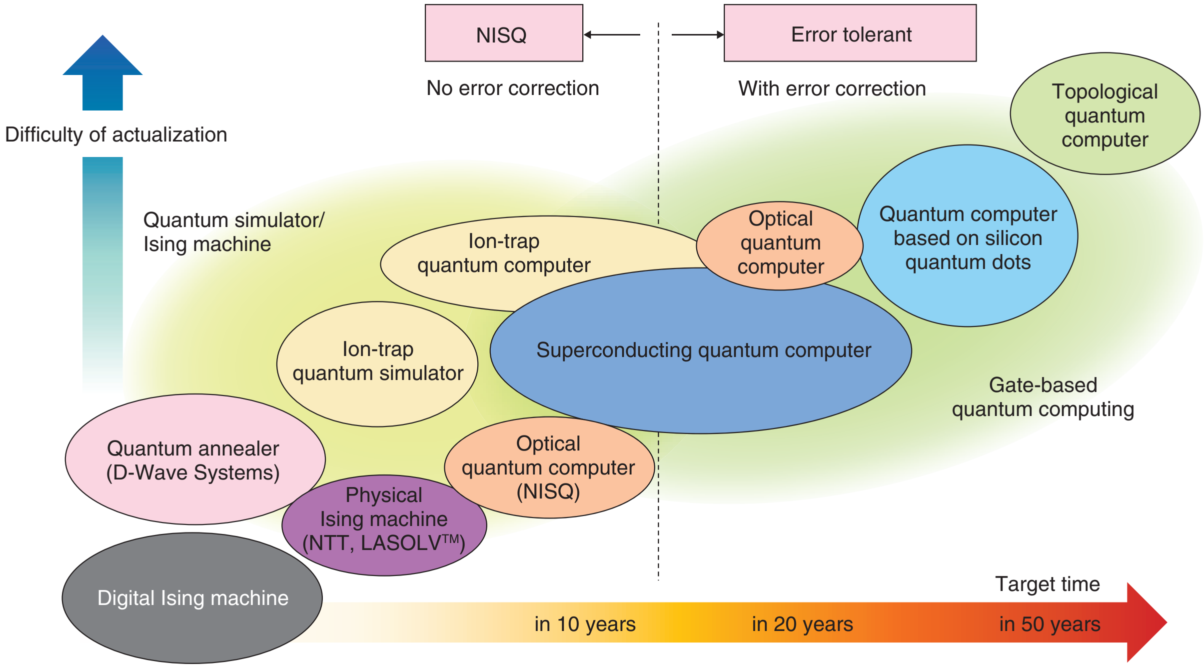


Fig. 4. Overview of quantum-computer development.

problems (maximum cut problems) of a 100,000-node graph 1000 times faster than a digital machine [4]. Annealing machines to solving combinatorial optimization problems using digital technology have also been commercialized by several Japanese companies, which are thereby giving Japan a strong presence in this field.

The development of quantum computers is illustrated on the basis of NTT's own indexes in **Fig. 4**. The current gate-based quantum computer is called a noisy intermediate-scale quantum computer (NISQ), namely, a quantum computer that cannot be scaled up due to noise, and its applications are limited by its lack of error-correction capability. To implement quantum error correction, a large number of qubits (several dozen to ten thousand) are combined to form a single logical qubit, which requires large-scale integration and connection between qubit chips via a quantum network. Many technical challenges, such as the enormous size of the refrigerator and the complexity of the control system, must also be overcome. Under these circumstances, it is still unclear which quantum bit will be the most favored approach. Superconducting qubits are not suitable for integration of 1000 qubits or more owing to their large element size; accordingly, silicon qubits based on semiconductor processing technology are promising for achieving higher integration. Optical quantum systems—which can place a large number of qubits on a time axis—are also being studied. Topological quantum computers, which are protected by the inherently stable property of matter called *topology*, thus do not require error correction, are also attracting attention. On top of these developments in hardware, research and development of quantum algorithms, which exploit the high speed of quantum computers, is also continuing apace.

3.2 Quantum communications and quantum security

Since the Ministry of Internal Affairs and Communications took the lead in launching the world's first quantum-cryptography testbed called the TOKYO QKD network in 2010, Japan has possessed world-class technological capabilities in quantum-cryptography communications, and verification experiments for genome information, electronic medical records, financial transactions, etc. using the TOKYO QKD network are underway. China has established a 2000-km-long quantum-cryptography network stretching from Shanghai to Beijing, and is further extending it by using satellites. Since quantum cryptography requires the use of extremely weak light, namely, a single photon (the smallest unit of light), the transmission distance of quantum cryptography is limited due to transmission loss in optical fibers, and that limit is thought to be about 100 km for actual use.

Post-quantum cryptography (PQC), a cipher that cannot be solved even by a quantum computer, is under development, mainly in the U.S., and hybrid schemes combining quantum cryptography and modern cryptography such as PQC are also being developed. Quantum relay technology is an essential element of the quantum internet, and quantum memory to retain the received quantum state is being actively researched. All-photonic quantum repeaters, which do not use quantum memory, are also being demonstrated.

3.3 Quantum sensing devices and materials

One type of quantum sensing is diamond nitrogen-vacancy (NV) centers, in which quantum effects exist even at room temperature, and are expected to be used to detect magnetic fields and temperature with higher sensitivity than possible with conventional sensors. Applying quantum sensing to medicine and drug discovery is also being investigated, and technologies for real-time observation of drug efficacy using magnetic resonance imaging by combining materials containing isotope-controlled elements and nuclear-spin hyperpolarization technology are rapidly emerging.

Other developments include quantum inertial sensors based on atom-wave interferometers, which theoretically offer ten orders of magnitude higher performance than fiber-optic gyroscopes, and ultra-high-precision clocks (optical lattice clocks). Quantum devices, including single-photon and entangled-photon light sources, highly sensitive photodetectors, single-electron devices, and spin Seebeck devices and quantum materials, including diamond NV centers, quantum dots, topological materials, and atomic-layer materials, have attracted attention.

4. Future prospects for quantum technology

As mentioned above, the creation of a quantum computer that can surpass current digital computers in terms of computational power is still a long way off; even so, quantum cryptography and quantum sensing are expected to be implemented in society in the near future if the cost issues can be overcome. It is envisioned that there will be a demand for quantum connections between quantum computers and between quantum sensors and quantum computers, which will require a network capable of transmitting quantum states, that is, a quantum internet. The current structure of the Internet, however, cannot handle quantum states, so innovative infrastructures such as the IOWN (Innovative Optical and Wireless Network) All-Photonics Network will become increasingly important. Quantum computing is also important from the perspective of energy consumption in the IT industry because, in principle, it is energy-neutral computing.

The Feature Articles in this issue discuss an optical quantum computer [5], quantum-information technology with superconducting qubits [6], an optical lattice-clock network [7], fast algorithms for quantum computers [8], high-performance quantum-key distribution [9], and the all-photonic quantum internet [10] as representative examples of NTT's quantum technology.

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Optical Technologies for Optical Quantum Computing with Continuous Variables

*Toshikazu Hashimoto, Takeshi Umeki,
Takahiro Kashiwazaki, and Asuka Inoue*

Abstract

Quantum computers are increasingly seen as a potential solution for computing problems that are difficult to solve with conventional technologies. A photon-based quantum computer is a promising technology that enables the development of large-scale, universal quantum computing at high speeds at room temperature with large-scale quantum entanglement thanks to photons' inherent characteristics. This article explores NTT's efforts to develop optical quantum computers using optical fiber communication technology.

Keywords: continuous-variable quantum state, quantum computer, optical component

1. Introduction

For sustainable development of society, computer technology must also be developed sustainably to address increasingly complex and challenging issues such as the economy, climate change, energy, and exploration of materials and living phenomena beyond our current knowledge. The rapid growth of semiconductor technology, as exemplified by Moore's law, is reaching its limits. Consequently, there are growing expectations for new computing technologies that can solve problems beyond the capabilities of conventional computers in a practical timeframe. Quantum computers that leverage quantum properties to execute calculations are attracting attention as a potential solution. Quantum algorithms use physical states with quantum properties, such as superconductivity, ion traps, cooled atoms, and electrons, as a medium for calculation. Using a quantum of light as a computational medium is emerging as a leading candidate of an enabler for quantum computers. It possesses three key features: (1) it operates at room temperature[*1], (2) can achieve large-scale quantum entanglement, and (3) operates at high speeds. While feature (1) is intrinsic to photons, features (2) and (3) require technology that uses the characteristics of photons. NTT is working toward developing a photon computer by applying optical device technology for optical fiber communications. This article outlines NTT's efforts toward optical quantum computers.

2. Continuous-variable optical-quantum-information processing and large-scale quantum-entanglement generation

In many quantum computers, physical states called qubits are spatially arranged, and quantum information is processed using the superposition of these states or quantum correlations (quantum entanglements). The optical quantum computer introduced in this article, however, processes quantum information on the basis of the quantum state of the amplitude of

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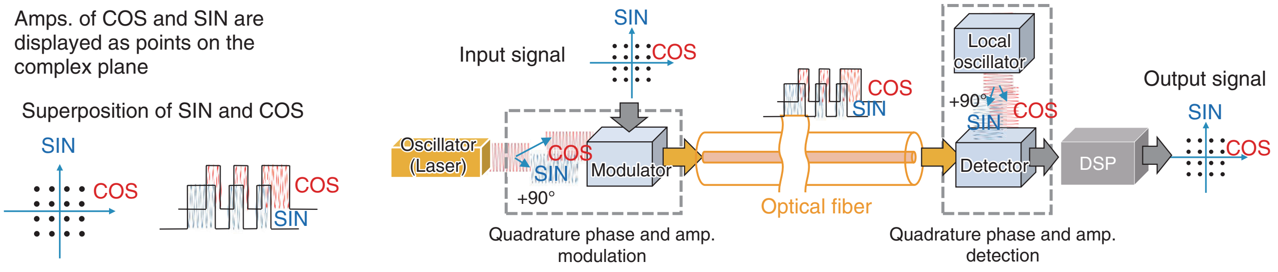
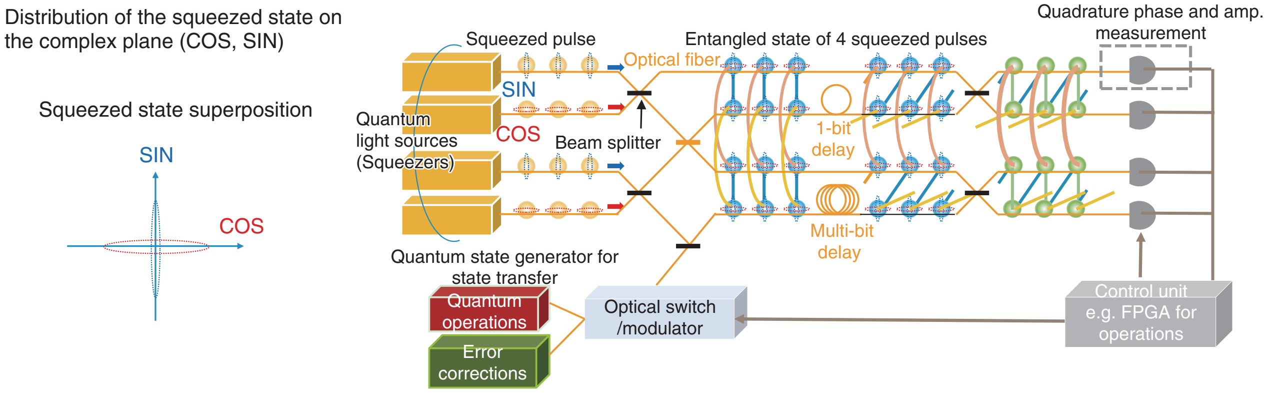
[*1] It operates at room temperature: By converting the photon energy ε to a temperature T using Boltzmann's constant (k_B), $T = \varepsilon/k_B$ is 2.93×10^4 K. This temperature is high enough for the thermal noise generated at room temperature, suggesting that the system can effectively operate at room temperature.



(a) Optical fiber communications (Digital coherent transmission)



(b) Continuous-variable optical quantum computer

DSP: digital signal processor
FPGA: field-programmable gate array

Fig. 1. Configuration of optical fiber communications and continuous-variable optical quantum computer.

light. (The amplitude of light is represented by a continuous complex number. When it is quantized, it becomes what is called a continuous-variable quantum state.) It takes advantage of the fact that wave superposition, interference, and so on are phenomena that correspond directly to quantum operations. Optical quantum computing makes arranging pulse-like photon states in the time domain possible. It thus enables an optical quantum computer to execute large-scale operations without restrictions due to the spatial arrangement of quantum qubits used with other physical quantum computers. Large-scale entanglement states to execute large-scale operations can also be generated relatively easily using simple devices such as beam splitters, thanks to the wave nature of photons. Continuous-variable optical quantum computers use superposition of optical quadrature phase amplitudes, similar to that used in digital-coherent transmission technology for optical fiber communications (**Fig. 1(a)**). The digital coherent transmission superposes modulated quadrature components (cosine and sine components) of laser light (coherent light) for transmitting. Each quadrature is acquired by interfering with the light of a local oscillator reconstructing the original signal by using digital signal processing for receiving. However, simply adding the cosine and sine components does not produce a superposition of quantum states used in continuous-variable optical quantum computers. To obtain quantum effects, we need to use a quantum state of light called squeezed light, which has intentionally distorted distribution. **Figure 1(b)** shows an intentionally biased distribution of squeezed light as a dotted ellipse, superposing two quantum states spread in the cosine and sine directions. A continuous-variable optical quantum computer calculates by executing quantum operations on squeezed light. Pulses of squeezed light (the spheres in Fig. 1(b)) emitted from a squeezed light source (quantum light source) propagate through an optical fiber and are separated by a beam splitter that functions as a half mirror to achieve a state in which different squeezed

Table 1. Correspondence and differences between optical fiber communications and continuous-variable optical quantum computer.

	Optical fiber communications	Continuous-variable optical quantum computer
Operations	Digital coherent transmission (compensates for large dispersion)	Measurement-based quantum computing (computation with large quantum entanglement)
Representation space for signals and information	Coherent light (carrier wave) and quadrature phase and amp.	Squeezed light and quadrature phase and amp.
Generation of carrier waves	Laser light source (coherent light source)	Quantum light source (squeezed light source)
Signal generation and quantum operations	Beam splitter Phase shifter Modulator	Beam splitter Phase shifter Displacement operator (modulator) Squeezing operator Third-order nonlinear operator
Signal demodulation	Quadrature phase and amplitude detection	Quadrature phase and amplitude measurement

Red text indicates differences.

light pulses are superposed simultaneously. These states are entangled quantum-mechanically, and huge entangled states can be created by shifting light pulses in the time domain and repeatedly mixing them with beam splitters [1]. This massively entangled state enables measurement-based quantum calculations, which are known to correspond to gate-type quantum calculations. Measurement-based quantum computing*2 is a very interesting computational method. However, we focus on the technology required for continuous-variable optical quantum computers and the correspondence of optical fiber communication technology as an optical technology for continuous-variable optical quantum computers.

3. Application of optical fiber communication technology to a continuous-variable optical quantum computer

Table 1 shows the similarities and differences between optical fiber communications and continuous-variable optical quantum computers. To conduct arbitrary continuous-variable quantum calculations, a squeezer, demultiplexer (beam splitter), phase shifter, displacement operation (optical modulator), and third-order nonlinear gate are all necessary [2, 3]. The beam splitter, phase shifter, and optical modulator are elements used in classical optics and components of optical fiber communications. Continuous-variable optical quantum computers also use quadrature amplitude measurements with the same configuration as that used for quadrature amplitude detection in optical fiber transmissions. The squeezers and third-order nonlinear gates require technologies not directly used in optical fiber communications. As a quantum light source corresponding to a laser light source in optical fiber communications, a squeezer is an essential element of an optical quantum computer. However, a squeezer with good characteristics applicable to an optical quantum computer had not been implemented because it requires large optical nonlinearity to generate squeezed light.

To achieve squeezer characteristics suitable for optical quantum computing, NTT has implemented a waveguide-type periodically poled lithium niobate (PPLN), which has been researched and developed for optical fiber communications. For optical fiber communications, phase-sensitive amplification, a state of an optical parametric amplifier, has been considered a preferred technology that does not increase noise. NTT has been developing waveguide-type PPLN technology to provide high-performance optical parametric amplifiers. PPLN is an optical device that enhances nonlinear conversion efficiency by periodically inverting the polarization of lithium niobate, a nonlinear optical crystal. NTT further

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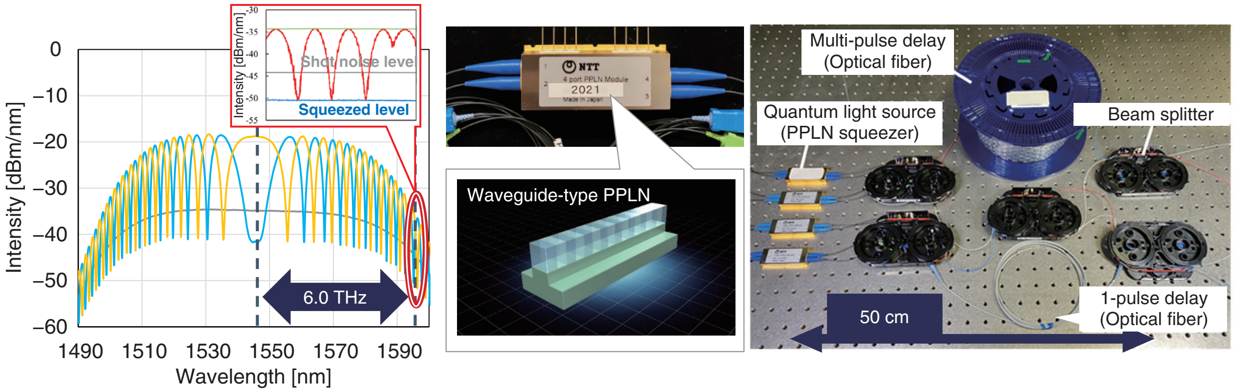
*2 Measurement-based quantum computing: A method of quantum computation that achieves operations equivalent to quantum operations by repeatedly changing the projection direction of a projection-valued measure for subsequent pulses on the basis of the measurement results. A projection-valued measure obtains a specific state component as output by changing the incident state or reference state in a quadrature phase amplitude measurement. A typical example is a Bell measurement that determines the components of a quantum entangled state called a "Bell state."



(a) Bandwidth of quantum light source

(b) Quantum-light-source module

(c) Components of a large-scale quantum-entanglement generator

Fig. 2. Quantum-light-source module and fiber-based continuous-variable optical quantum computer (components of a large-scale quantum-entanglement generator).

processed the optical waveguide structure on the PPLN and demonstrated that it is applicable as an amplifier for long-distance transmission, which had been difficult, by confining the light propagating in the optical waveguide in a narrow area and increasing the nonlinearity [4]. We have confirmed that this high-performance waveguide PPLN technology has advantages not only in phase-sensitive amplification but also in quantum light sources, or squeezers, by fabricating quantum light sources. **Figure 2** shows a large-scale quantum-entanglement generator for a continuous-variable optical quantum computer consisting of a quantum-light-source module and fiber-type devices. The quantum-light-source module uses a waveguide-type PPLN to improve nonlinear conversion efficiency, eliminating the need to reciprocate inside the resonator to obtain the optical path length required for conversion, which causes frequency dependence, and expands the bandwidth to 6 THz. It also achieves a squeezing level of 6 dB, an index of the asymmetry of compression in the distribution of the squeezing light. It was the highest squeezing level achieved by a non-resonator type of squeezer [5]. This wide bandwidth can accommodate many quantum pulses and various quantum states corresponding to waveforms in optical fiber communications. We have demonstrated that the module can generate pulses of arbitrary quantum states in time slots [6].

It has been too difficult to achieve third-order nonlinear gates because they require larger optical element nonlinearities than those needed for squeezers. However, an alternative method of generating third-order nonlinearity using quantum teleportation has been proposed [7] and is becoming feasible as technology advances.

4. Summary and future prospects

We have shown that we can provide the components of a continuous-variable optical quantum computer by using optical fiber communication technology. As well as optical communication components acting as components of optical quantum computers, further developments in component technology for optical fiber communications will enable the implementation of important optical quantum computer components such as squeezers and third-order nonlinear gates. For a continuous-variable optical quantum computer to operate as a system, in addition to the optical devices, it is necessary to develop the electronic devices that control optical components and the software that operates them. Measurement-based quantum calculations executed by a continuous-variable optical quantum computer require the high-speed operation of electronic circuits and control systems because the measurement results must reflect instantaneously to update the projection-valued measure system and quantum states. The middleware will also become essential to reflect quantum algorithms in actual devices. By addressing these challenges, NTT aims to develop a continuous-variable optical quantum computer using optical components by 2030 and a chip for an optical quantum computer by 2050, as shown in **Fig. 3**. A challenge is

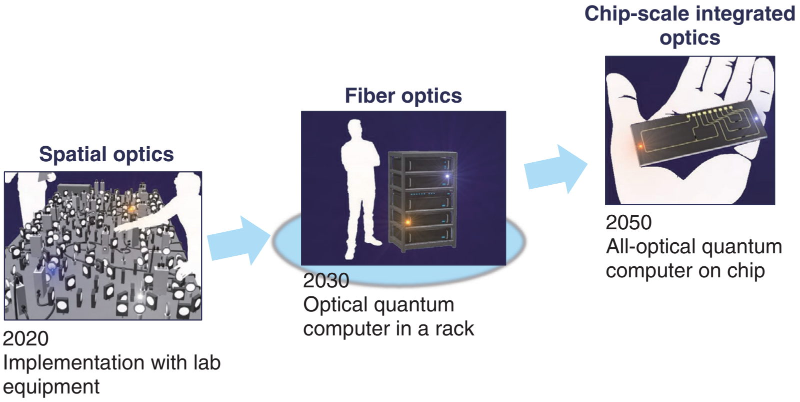


Fig. 3. Roadmap for continuous-variable optical quantum computers.

improving the characteristics of current optical devices. For example, the squeezing level of the squeezer as a quantum light source for fault-tolerant operations, which use GKP codes to error-correct large-scale quantum entangled states, must be several dB higher than the current level of 6 dB [8]. The losses introduced by the constituent optical components also remain a significant noise source that disturbs the quantum state, thus must be reduced. These are challenges that are difficult to overcome even with the high-performance device technology cultivated in optical fiber communications. Through our efforts to achieve a continuous-variable optical quantum computer, we aim to further advance optical technology and bring about explosive developments in quantum computing and optical fiber communications.

Acknowledgments

This research was conducted in collaboration with the Furusawa Laboratory, The University of Tokyo. Part of this research was also supported by Japan Science and Technology Agency (JST), Moonshot R&D program JPMJMS2064.

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Quantum Information Technology Based on Superconducting Quantum Circuits

Shiro Saito, Kosuke Mizuno, Takaaki Takenaka, Hiraku Toida, and Kosuke Kakuyanagi

Abstract

The research on superconducting quantum circuits has expanded greatly, from applications of magnetic field sensors using superconducting quantum interference devices to the development of quantum computers based on superconducting quantum bits (qubits). Superconducting quantum circuits have been progressing rapidly, and as examples of applying these circuits to quantum sensing, this article introduces electron spin resonance spectrometers having high sensitivity and high spatial resolution and an ultrasmall high-sensitivity thermometer operating at extremely low temperatures. As an application to quantum computing, this article also introduces a bosonic qubit that executes quantum error correction using the many degrees of freedom within a superconducting resonator.

Keywords: superconducting quantum circuits, quantum sensing, quantum computers

1. Superconducting quantum circuits

Superconducting quantum circuits*1 are being studied extensively from basic to application research by taking advantage of the degrees of freedom in their circuit design. We first introduce an example of basic research. The origin of research into superconducting quantum circuits lies in the fundamental question: To what extent can quantum mechanics that holds in the microscopic world be applied to macroscopic systems? To answer this question, we conducted an experiment using a superconducting flux qubit*3 and demonstrated that a qubit loop can achieve quantum superposition in which a trillion electrons per second are flowing in a clockwise current state and counterclockwise current state [1]. This result indicated that quantum mechanics holds in macroscopic artificial structures on a micrometer order as well as in microsystems consisting of electrons and atoms. Next, through collaborative research with the National Institute of Information and Communications Technology (NICT), we devised a circuit design that can achieve strong coupling between an artificial atom and light, which cannot be achieved in ordinary atom/light coupling. This achievement has opened the door to the new field of cavity quantum electrodynamics*4. We used a superconducting artificial atom (superconducting flux qubit) and microwave photons to achieve a deep-strong coupling regime, in which the coupling energy of both is greater than the energy of

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*1 Superconducting quantum circuits: Superconducting circuits that include circuit elements described by quantum mechanics. Circuit elements making up superconducting quantum circuits include Josephson junctions*2, inductors, and capacitors.

*2 Josephson junctions: A structure in which an extremely thin insulator is sandwiched between two superconductors. Since a nonlinear superconducting current flows in relation to the superconductor phase, Josephson junctions can be used as nonlinear devices in superconducting quantum circuits. In a superconducting qubit, aluminum and aluminum oxide are widely used as the Josephson junction's superconductor and insulator, respectively.

*3 Superconducting flux qubit: A superconducting circuit consisting of a superconducting loop including multiple Josephson junctions. Applying an optimal magnetic-field bias to this circuit generates two states—a clockwise current state and counterclockwise current state—that can be treated as a quantum two-level system.

each, and measured a previously unknown physical phenomenon [2].

From the above studies, superconducting quantum circuits are breaking new ground in basic physics research, but there is also much activity in application research. The most well-known example of such applications is the superconducting quantum computer being developed by Google, IBM, University of Science and Technology of China, RIKEN, and other research institutions. The superconducting quantum circuits used for this application are qubits called transmons, which can be used as the basic elements of a quantum computer since their transition frequency remains nearly unchanged under an external magnetic field and their coherence time[*5] is long. However, the transition frequency of a superconducting flux qubit changes significantly under an external magnetic field, so its application to magnetic field sensors is expected. Progress is also being made at D-Wave Systems, National Institute of Advanced Industrial Science and Technology (AIST), and elsewhere in applying superconducting flux qubits to a quantum annealer[*6] by using the tunability of the transition frequency.

In this article, we introduce local electron spin detection and a hybrid thermometer based on flux qubits as examples of quantum sensors. We also describe the prospects for a new type of quantum bit (bosonic qubit) that uses a transmon as an ancilla qubit.

2. Magnetic field sensors

A superconducting flux qubit can detect changes in the magnetic field penetrating a loop with high sensitivity by measuring the transition frequency between quantum levels. As described below, such a magnetic field sensor is sensitive enough to detect a magnetic field created by a small number of electron spins. Since the loop size of a flux qubit is about several micrometers, it also enables magnetic-field measurements with high spatial resolution. Taking the above features into account, NTT began research on high-sensitivity, high-spatial-resolution electron spin resonance (ESR) spectrometers.

Since ESR can be used to obtain information on electrons that are not paired with each other (unpaired electrons) in a substance, it has become an indispensable analytical technique in such fields as material science, solid state physics, drug discovery, and medical care. A typical ESR spectrometer operates by placing a several-milliliter spin sample in a cavity and measuring the microwave response at the cavity's resonance frequency. Since the interaction between the cavity and one electron spin is weak, it is necessary with this technique to include about 10^{13} electron spins in the sample to measure an ESR signal. The ESR signal is averaged over the entire spin sample, so local information cannot be obtained.

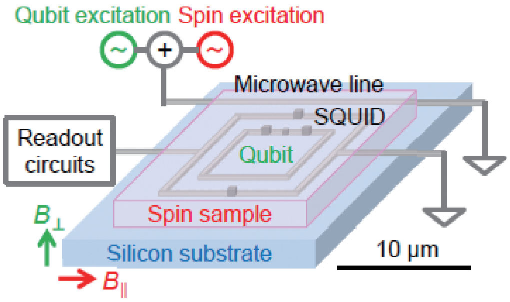

Fig. 1. Local ESR spectrometer.

In contrast, a local ESR spectrometer using superconducting quantum circuits consists of a sensor, such as a flux qubit or superconducting quantum interference device (SQUID), and a readout circuit to extract the information from the sensor (**Fig. 1**). On irradiating the electron spin sample with microwaves, the magnetic field created by the spins changes and the sensor detects that change. We apply magnetic field $B_\perp$ on the microtesla (μT) order for sensor control and magnetic field $B_\parallel$ on the millitesla (mT) order for electron spin polarization. In this spectrometer, the irradiation of microwaves is executed from a wideband microwave line for electron spin detection without a resonator, so there is no limitation to the frequency range in which ESR spectra can be measured. In other words, this spectrometer makes it possible to measure ESR spectra in a broad parameter region while sweeping the device with frequencies and magnetic field $B_\parallel$ to therefore obtain even more information from the measurement target [3].

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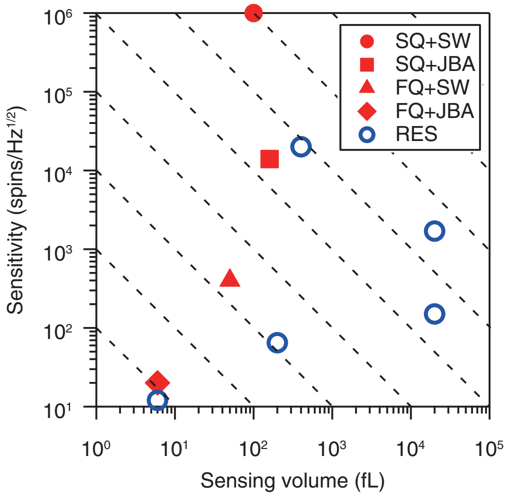
*4 Cavity quantum electrodynamics: Quantum theory that describes the interaction between an atom and light confined within a cavity. It is also called circuit quantum electrodynamics when describing an interacting system between an artificial atom configured from a superconducting quantum circuit and microwaves in a superconducting resonator.

*5 Coherence time: The length of time that a qubit can retain its quantum information.

*6 Quantum annealer: Equipment that uses the properties of quantum mechanics to solve optimization problems that are difficult to solve with current computers as the scale of the problem increases.



FQ: flux qubit
JBA: Josephson bifurcation amplifier
RES: resonator
SQ: SQUID
SW: SQUID switching readout circuit

Fig. 2. Figure of merit of local ESR spectrometers.

Next, we introduce our efforts to date in improving the figure of merit of local ESR spectrometers. At the beginning of this research, we used SQUID as a magnetic field sensor and a SQUID switching readout circuit to extract the sensor information. With this configuration, we succeeded in detecting electron spins originating in erbium atoms within an optical crystal (Y_2SiO_5) at a sensitivity of 10^6 spins/√Hz [4]. We then replaced SQUID as the magnetic field sensor with a flux qubit and changed the readout circuit from a SQUID switching readout circuit to a switching readout circuit using a Josephson bifurcation amplifier[*7]. We achieved a sensitivity of 20 spins/√Hz, resulting in an improvement of approximately five orders of magnitude [5]. By making the loop size of the magnetic field sensor smaller, we also succeeded in decreasing the detection volume from 150 to 6 fL. These results along with the figure of merit of a sensor using a two-dimensional superconducting resonator from other research groups are shown in **Fig. 2**.

3. Thermometers

We have succeeded in developing an extremely small thermometer (**Fig. 3**) and making precise measurements of temperature at very low temperatures by using an electron spin ensemble within a nanodiamond as a thermometer and a flux qubit as an electron spin detector [6].

A compact temperature sensor has a small heat capacity, and the quantity of heat flowing into the thermometer from the measured system is small. This enables fast response speeds and measurements that suppress the back action to the measured system. Such a temperature sensor can also improve the spatial resolution of temperature measurements, which suggests new applications as in measuring the spatial distribution of temperature in a very small region. However, developing a compact temperature sensor and achieving high sensitivity at the same time is difficult. The reason for this is as follows. Temperature sensing involves measuring the change in temperature of the amount of physical material making up the thermometer, but the amount of material decreases when making the thermometer smaller, which lowers measurement sensitivity. To solve this problem, we achieved quantum sensing on the basis of a hybrid system that couples a flux qubit and paramagnetic electron spins within a nanodiamond (Fig. 3).

Various types of defects exist within a nanodiamond including nitrogen-vacancy (NV) centers[*8] and P1 centers[*9] that confine an electron. This electron has spin, and applying a magnetic field from the outside creates a Zeeman split in which energy changes in accordance with the spin state. The energy level of an electron spin system is determined by the magnetic field as well as by hyperfine interaction with nuclear spin and the energy of magnetic anisotropy that appears when there is spin greater than or equal to one. Under thermal equilibrium, the occupancy of each spin state is determined by temperature and energy, so a nanodiamond gives rise to magnetization dependent on temperature. This change in magnetization can be measured as a change in the magnetic flux

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[*7] Josephson bifurcation amplifier: A resonator that includes a Josephson junction exhibits a bistable state due to the nonlinearity of the junction. A device that uses this state to amplify an extremely small signal is called a Josephson bifurcation amplifier. When reading a flux qubit, it makes use of the fact that the final state of the resonator differs depending on the state of the qubit. In contrast to a readout circuit using SQUID switching, a readout circuit using a Josephson bifurcation amplifier features no generation of voltage by the resonator's final state, negating the need for cooling time to suppress heat buildup. This makes it possible to make repeated measurements in a short period, thereby improving signal accuracy by averaging.

[*8] NV centers: A compound defect in which a nitrogen atom replaces a carbon atom in diamond and lies adjacent to a carbon vacancy is called an NV center. It is a color center that produces a color close to pink in diamond.

[*9] P1 centers: A defect in which a nitrogen atom replaces a carbon atom in diamond is called a P1 center. It is a color center that gives diamonds their yellowish tint.

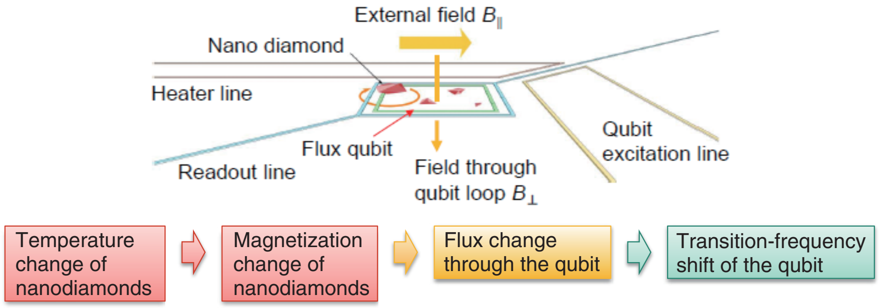

Fig. 3. Hybrid thermometer.

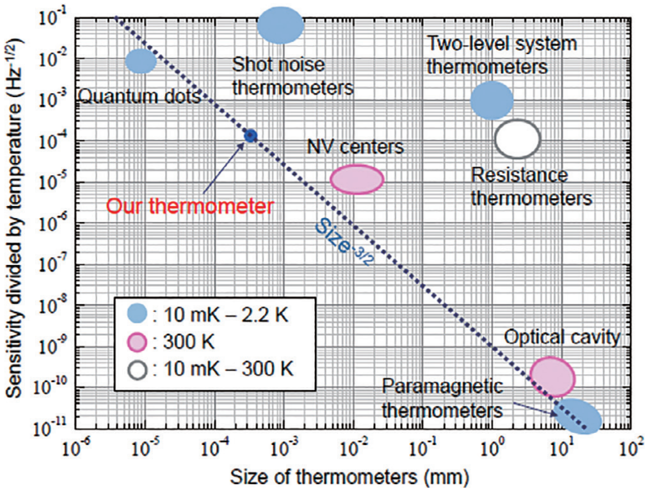

Fig. 4. Figure of merit of thermometers.

penetrating the flux qubit (Fig. 3). On converting the magnetic-field sensitivity of the flux qubit to temperature sensitivity, we confirmed a high-sensitivity figure of merit at 1.3 μK/√Hz at the base temperature of 9.1 mK in a dilution refrigerator.

On comparing the figure of merit for various thermometers (**Fig. 4**), the above results enable the development of a compact and high-sensitivity thermometer. Commonly used resistance thermometers must be calibrated for all temperature regions, but the temperature change associated with the measured magnetization can be theoretically predicted, which means that measurements across all temperature regions can be conducted by calibrating at only one temperature point. There is also a type of sensor using a single quantum dot that can serve as a compact thermometer, but our thermometer has the advantage of enabling the measurement of lattice temperature, not the electron temperature, as with the quantum dot thermometer. While the temperatures that can be measured with our thermometer are extremely low, it is expected to contribute to measuring extremely low temperatures at the region where accurate measurements have been difficult due to slow response caused by thermometer self-heating and large heat capacity.

4. Bosonic qubits

Research and development of superconducting quantum computers is progressing steadily, as reflected by the 2019 announcement from Google that it had proven “quantum supremacy” with a 53-qubit processor that outperformed a conventional supercomputer [7] and the 2022 announcement from IBM of a 433-qubit processor. However, a massive

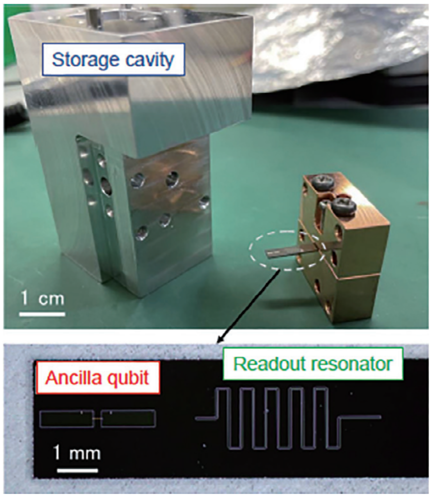

Fig. 5. Components of a bosonic qubit.

Table 1. Designed and measured parameters of a bosonic qubit.

(MHz)	Designed	Measured
Storage cavity (S)	4419	4425
Ancilla qubit (A)	5368	5531
Readout resonator (R)	7534	7400
Anharmonicity of A	129	152.3
Coupling between S and A	2.06	4.2
Coupling between A and R	0.34	0.32

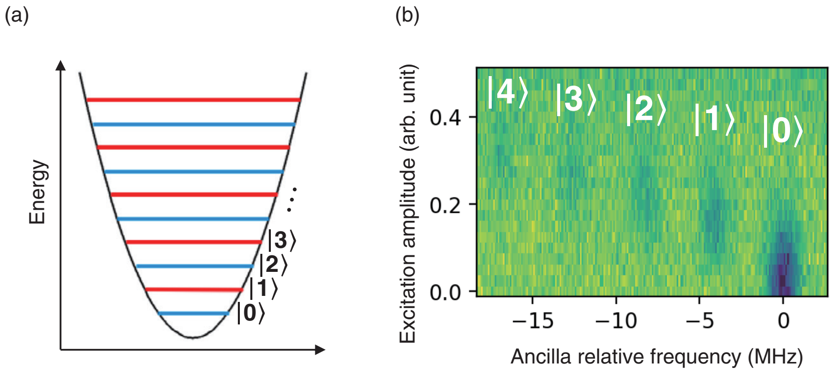

Fig. 6. (a) Photon number state in the storage cavity and (b) spectrum of the ancilla qubit while the storage cavity is excited.

number of qubits will be necessary to achieve a practical and fault-tolerant universal quantum computer. This is because redundant qubits are needed for quantum error correction since qubits are vulnerable to external noise and errors occur frequently. For example, a trial calculation indicated that 20,000,000 qubits would be needed to factor a 2048-bit number [8]. In current designs, about 1000 qubits can be arranged on a chip, and any greater number would require new technologies such as for inter-chip wiring. There would also be a need for breakthroughs in high-frequency wiring to control such a massive number of qubits, refrigeration technology, etc.

The bosonic qubit is a technology that is attracting attention as a means of satisfying the need for a massive number of qubits. This technology encodes quantum information into an infinite number of energy levels within a superconducting cavity and uses that redundancy to execute quantum error correction. It uses a transmon as an ancilla qubit to prepare complex quantum states in the cavity. A resonator is needed to read out the transmon state. The components of this bosonic qubit are shown in **Fig. 5**. We carefully designed the frequencies of each component (storage cavity, ancilla qubit, readout resonator) and the coupling strength between components (**Table 1**) and successfully identified photon number states[*10] in the storage cavity (**Fig. 6**). This is the first step toward accessing each photon number state and preparing complex quantum states.

5. Outlook

This article introduced local ESR spectrometers, an ultrasmall thermometer, and bosonic qubit as examples of applying advanced superconducting quantum circuits to quantum information technology.

Our objective in developing local ESR spectrometers is to enhance sensitivity to the level of detecting a single electron spin using a long-lived flux qubit [9] and a readout circuit applying quantum electrodynamics. We also plan to expand our measurement targets with this spectrometer beyond solid-state electron spin samples to biological electron spin samples such as neurons and cell lines.

Our objective in researching bosonic qubits is to encode quantum information in a superconducting cavity using the lowest order binomial code[*11], a bosonic quantum-error-correcting code. We will then seek to achieve a long-lived bosonic qubit beyond its cavity lifetime by quantum error correction, in other words, to reach the *break-even point*.

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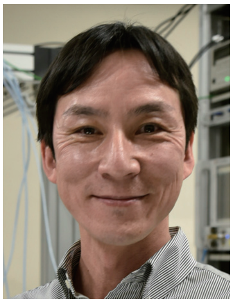
[*10] Photon number states: The state in which *n* microwave photons exist within a cavity is called a photon number state and denoted as $|n\rangle$. On exciting a storage cavity with microwaves, the superposition state of photon number states called a coherent state appears. Therefore, a single photon number state cannot be prepared. The nonlinearity of an ancilla qubit is necessary to prepare photon number states.

[*11] Lowest order binomial code: One type of quantum-error-correcting code for a bosonic qubit. It is a relatively simple code in which the logical words are defined as $|0_L\rangle = (|0\rangle + |4\rangle)/\sqrt{2}$, and $|1_L\rangle = |2\rangle$ using photon number states in a cavity. If using an ancilla qubit, photon number parity can be measured while maintaining the quantum states in the cavity. A measurement result of odd parity can be taken to mean that a photon loss has occurred, so adding a photon back to the cavity makes quantum error correction possible.



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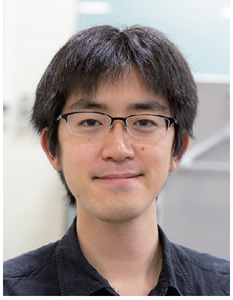

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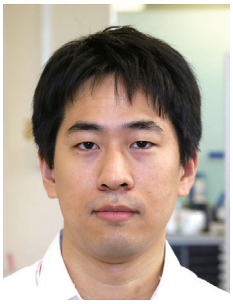

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Optical-lattice-clock-network Technology for Gravitational Potential Sensing

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Abstract

Optical lattice clocks have an ultrahigh frequency accuracy that exceeds that of cesium atomic clocks by a few orders of magnitude, enabling quantum sensing of gravitational potential equivalent to an altitude difference of only 1 cm on the Earth's surface. An optical-lattice-clock network, in which multiple optical lattice clocks are interconnected by optical fibers, is expected to become a new infrastructure, such as for a real-time sensing network of crustal movements with 1-cm-level accuracy. In this article, we introduce the elemental technologies comprising an optical-lattice-clock network. We also report on the construction of the ultrahigh-precision optical frequency transmission fiber link in the Tokyo metropolitan area and the experiment to evaluate its transmission stability.

Keywords: optical lattice clock, ultrastable optical frequency distribution, planar-lightwave-circuit-based optical repeater

1. What is an optical lattice clock?

An optical lattice clock refers to the world's most accurate atomic clock[*1], which uses the electronic transition in the optical wavelength region in the neutral atoms captured in a light cage (optical lattice) as a standard for clock ticking (frequency). It was proposed by Professor Hidetoshi Katori of the University of Tokyo (UTokyo) in 2001 [1]. Its time accuracy has reached the level of "1 second difference in 30 billion years." When one considers that general quartz clocks are accurate to "1 second off in a day," one realizes the tremendous accuracy of optical lattice clocks. The accuracy of a clock is generally evaluated by the ratio of frequency uncertainty (Δf) to a clock frequency (f), and the accuracy of a current optical lattice clock is $\Delta f / f \sim 1 \times 10^{-18}$. Our common time is based on the cesium atomic clock, and 1 second in the world is defined as the time which an electron in cesium atom oscillates 9,192,631,770 times. The typical accuracy of cesium atomic clocks today is at the level of $1 \times 10^{-15} – 1 \times 10^{-16}$, or "1 second difference in 30 million years." Optical lattice clocks are already 2–3 orders of magnitude more accurate, so they are being studied worldwide as potential candidates for the next-generation definition of the second. The mechanism of an optical lattice clock is shown in **Fig. 1**. The heart of an optical lattice clock is an atom cooled to a very low temperature (–1 mK), trapped in an optical lattice[*2] made at a special wavelength called a magic wavelength. According to

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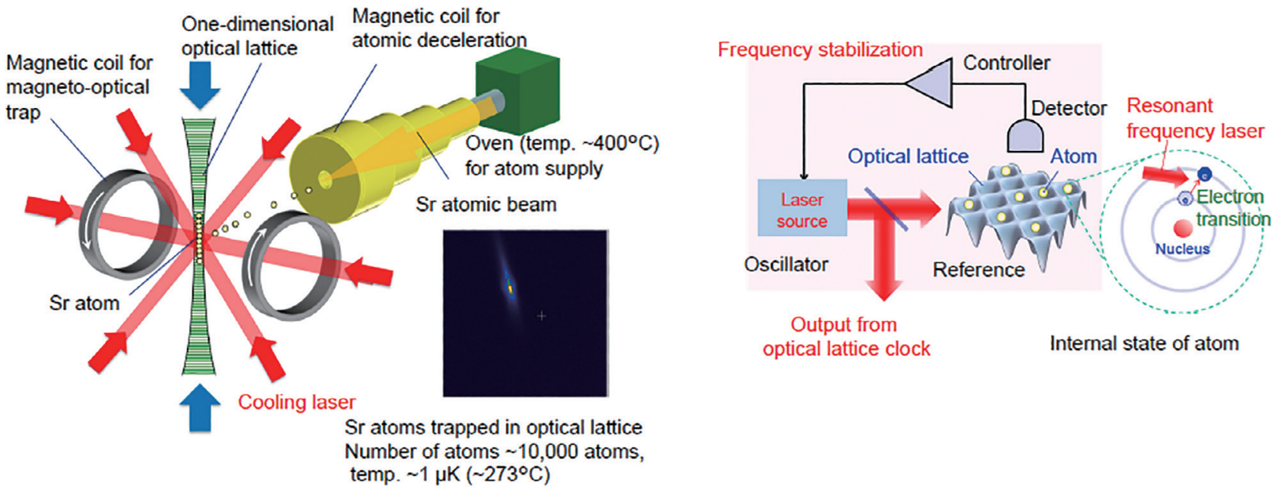
[*1] Atomic clock: A standard frequency generator that uses the resonant absorption frequency of an atom (the property of absorbing and radiating electromagnetic waves of a fixed frequency or its frequency) as a frequency reference. We refer to frequency as a clock in the sense that it is equivalent to a time reference rather than being the inverse of time. The definition of seconds in the SI (International System of Units) unit system also uses an atomic clock based on this principle.

[*2] Optical lattice: A periodic electronic potential is formed by creating a standing wave by the light of an opposing laser. We can arrange laser-cooled atoms in a lattice with this periodic light-induced potential.



(a) Capture atoms with an optical lattice. A beam of atoms is ejected into a vacuum at high temperatures (about 640 K) to be slowed and cooled with a laser. Magnetic fields are also used to gather about 100,000 atoms in one place then trap each atom in an optical lattice, arranging about 10,000 atoms well apart from each other. The photo shows an example of a Sr atom.

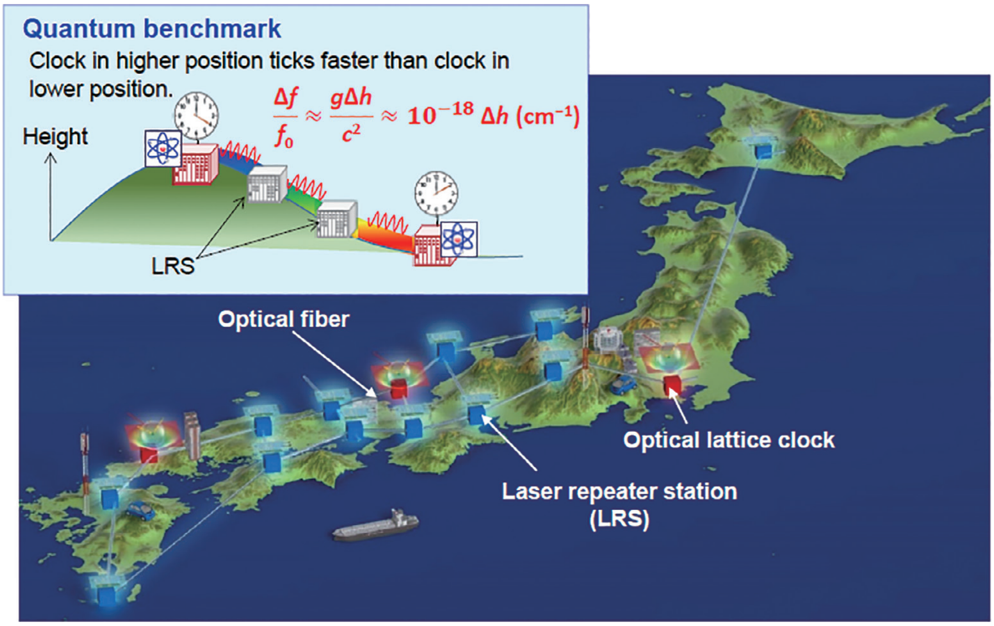
(b) Clock-frequency reading. The frequency of the laser source is stabilized by matching it exactly to the resonant frequency (clock frequency) of the atoms caught in the optical lattice. The figure is drawn as a two-dimensional optical lattice for clarity.

Fig. 1. How an optical lattice clock works.

quantum mechanics, the electrons in an atom absorb electromagnetic waves only at a specific frequency called the resonance frequency (electronic transition). An optical lattice clock enables us to read the resonance frequency by making the frequency of a laser oscillator copy (stabilize) to exactly match this resonant frequency. For example, in the case of strontium (Sr), the most commonly used atom, the resonant frequency is 429 228 004 229 873.0 Hz, roughly equivalent to 698 nm in wavelength. This resonant frequency is extremely accurate and can become the frequency standard when we assume no interaction with the various environments surrounding the atom (temperature, density, electric, magnetic fields, etc.). However, the resonant frequency is easily affected, and environmental fluctuations cause it to fluctuate from the value of the frequency that would be expected if it were not affected by the environment at all. The optical lattice is designed to minimize the effects of the environment by creating electronic potential on the basis of the interference of light and catching each atom cooled to extremely low temperatures. The most outstanding feature of optical lattice clocks is the ability to accurately read the resonant frequency of atoms in a short period by simultaneously measuring many atoms with reduced environmental fluctuations.

2. Expectations for relativistic geodesy by networking optical lattice clocks

According to Einstein's general theory of relativity, when one compares two clocks placed at different heights, the higher clock ticks faster (with higher frequencies) due to the effect of Earth's gravitational potential. Using this principle, a network that enables altitude-difference measurement using relativistic effects (relativistic geodesy) is attracting attention as an application of new ultrahigh-precision clocks. This network will become possible by installing many optical lattice clocks in multiple remote locations nationwide and connecting them via optical fibers and measuring their frequency differences remotely (**Fig. 2**). In fact, the relativistic effect on this clock is well known in conventional atomic clocks. For example, an atomic clock mounted on a satellite orbiting at an altitude of 20,000 km has a frequency about 10^{-10} higher than the Earth's surface because the Earth's gravitational potential is larger than that of the Earth's surface. Optical lattice clocks with much improved accuracy compared with conventional atomic clocks have made it possible to detect relativistic effects arising from slight differences in gravitational potential (differences in height) at the surface of the Earth. Relativistic effects that appear



According to Einstein's theory of general relativity, height shift of an atomic clock of 1 cm causes fractional frequency shift of 1×10^{-18}. Optical lattice clocks connected by an optical-fiber network will provide a space-time information infrastructure based on gravitational-potential measurement.

Fig. 2. Relativistic geodesy with a nationwide optical-lattice-clock network.

only on the enormous spatial scale of space, such as outer space, can now be recognized as everyday effects via optical lattice clocks. This is a revolutionized aspect of such clocks. An optical lattice clock with a frequency accuracy of 1×10^{-18}, which is currently the most accurate in the world, has a detectable gravitational potential equivalent to an elevation difference of approximately 1 cm [2]. If the elevation of each area is constantly monitored with an accuracy of 1 cm using an optical-lattice-clock network, we can expect to expand the role of optical-fiber networks into a new infrastructure, such as a type of benchmark based on gravitational-potential measurements (quantum benchmark) and long-term monitoring of crustal movements. Not only will it be possible to detect altitude-difference measurements with an accuracy of 1 cm, which is difficult with the current geodetic accuracy of the Global Navigation Satellite System (GNSS), but it may also be applicable to long-term monitoring of the movement of massive underground materials, such as magma in volcanoes, which must greatly affect the gravitational potential. It goes without saying that optical-lattice-clock networks play a role in precise frequency-reference delivery, such as what the current GNSS offers, as well as applications such as quantum sensing. If we think back on the fact that the frequencies provided by optical-lattice-clock networks are in the optical domain, they can also be an extremely accurate optical-wavelength reference. If the backbone is an infrastructure capable of synchronizing timing and wavelengths with ultrahigh precision, it is expected to be a platform that encourages development of new optical-communication architectures as well as contributes to current wavelength-division-multiplexing communications.

3. Ultrahigh-precision optical-frequency-transmission device (repeater)

Optical-lattice-clock networks require multiple optical lattice clocks to be connected by optical fibers and their frequency differences measured, but optical fibers are noisy media for transmitting such ultraprecise optical-frequency standards. Optical fiber is always affected by various noise, such as stretching of the fiber due to daily temperature changes and vibrations derived from the surrounding environment, which deteriorates the accuracy of the transmitted optical frequency. Amplifier devices, such as fiber

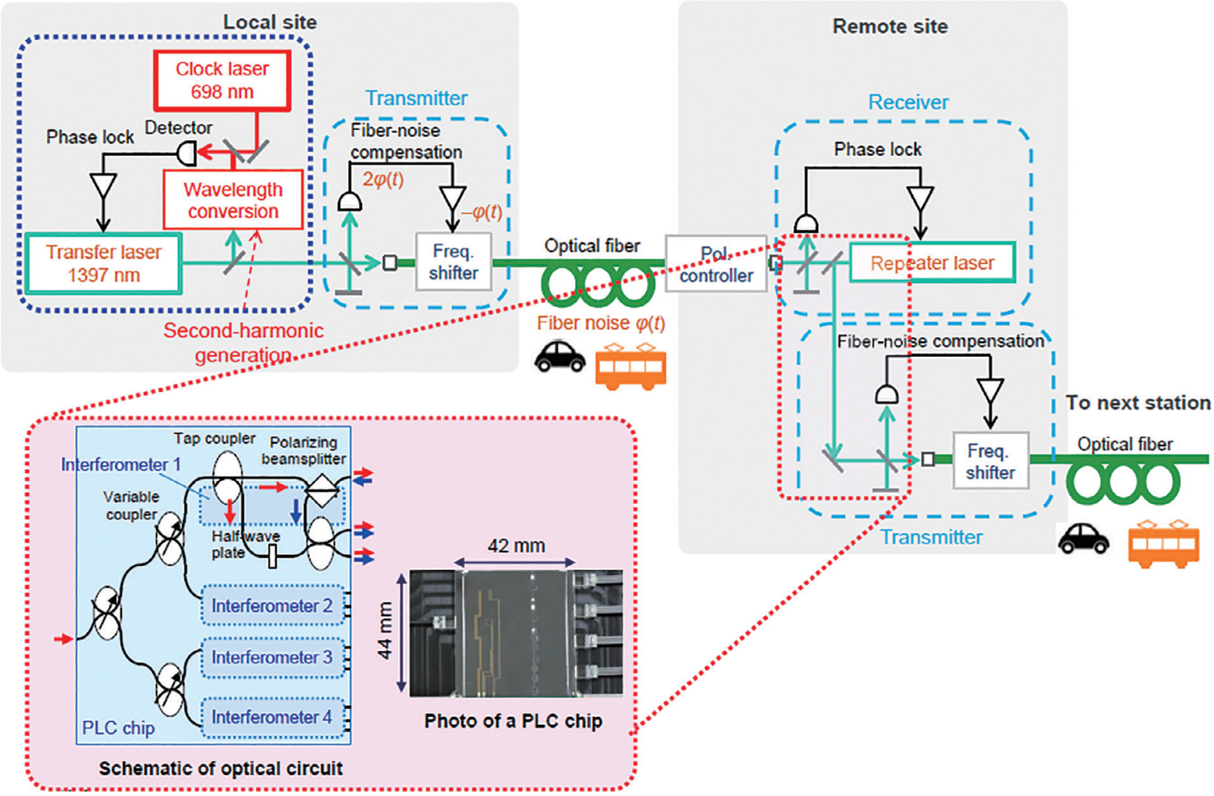


Fig. 3. Optical frequency transmission based on LRS with planar lightwave circuit (PLC).

amplifiers, which are usually used in an optical communication system, are also difficult to use because they can degrade frequency accuracy. An ultrahigh-precision optical-frequency transmission and relay device (repeater) compensates for the noise caused by fiber transmission, maintains accuracy, recovers the propagation loss associated with fiber transmission, and transmits and relays the signal to remote locations (**Fig. 3**). The repeater combines the fiber-noise-compensation function and relay function into a single device, which transmits the fiber-noise-compensated optical frequency to the next section. By the repetitive (cascade) connection of fiber-noise compensation, the optical frequency can be transmitted to a remote location with as little degradation in accuracy as possible. The transmission wavelength of the ultrahigh-precision optical frequency was 1397 nm, which is exactly 2 times the wavelength of 698 nm and corresponds to the resonance frequency of a Sr optical lattice clock. Because of the sub-harmonic relationship, it is possible to convert the optical-frequency reference of a Sr optical lattice clock into a wavelength band capable of fiber transmission with a simple configuration using a single wavelength-conversion device [3].

The most important component in the repeater is an optical interferometer, which achieves two main functions of the repeater. One is fiber-noise cancellation, which compensates for the fiber noise by interfering with the source light and the same fiber being sent back in the opposite direction from the receiver after fiber transmission, detecting the frequency noise coming from the transmitted fiber, and adding the noise in antiphase to that of the source light. The other function is frequency-coherent relaying, in which the frequency accuracy is copied to the transmitting laser by interfering with the ultrahigh-precision optical frequency one wants to copy with the transmitting laser, detecting the frequency difference between the two, and controlling the frequency of the transmitting laser by feedback. Optical interferometers used in conventional repeaters consist of spatial optics and fiber couplers, but there is a problem in that the optical interferometers cannot eliminate interferometer noise. Therefore, the use of a differential detection Mach-Zehnder interferometer based on a quartz-based planar lightwave circuit (PLC)*3 developed by NTT Device Technology Laboratories has resulted in a smaller repeater and improved stability and detection sensitivity. By building an interference circuit in the optical chip with a precisely designed optical-path length, it is resistant to environmental fluctuations, such as temperature, and has succeeded in reducing noise from the optical interferometer. Differential detection of optical-interference signals is also possible by using the optical interferometer's differential output of light to improve detection sensitivity.

4. Construction of ultrahigh-precision optical-frequency-transmission fiber link in metropolitan area

Toward the implementation of this optical-lattice-clock network, NTT Basic Research Laboratories has been conducting field demonstrations since 2015 in collaboration with the Katori Laboratory in UTokyo, RIKEN, and NTT EAST. Optical lattice clocks with the world's highest accuracy level can currently achieve a frequency stability of 1×10^{-18} with an averaging time (data integration) of more than 10,000 seconds. Therefore, to transmit an optical lattice clock without degrading its stability, optical-fiber transmission must reach 18 digits of frequency stability in less than 10,000 seconds of measurement time. The scalability of the fiber distance is also an important factor if we assume that we will expand such an optical-lattice-clock network on a nationwide scale. Using the repeater developed by NTT, we constructed an ultrahigh-precision optical-frequency-transmission fiber link for a demonstration experiment involving connecting multiple relay stations (telecommunications offices) from RIKEN's Wako location (in Saitama Prefecture) to the NTT Atsugi R&D Center (in Kanagawa Prefecture) via the UTokyo's Hongo campus (in Tokyo) (**Fig. 4**). This is a demonstration of an optical-lattice-clock network within an area corresponding to one region consisting of several prefectures in Japan. The relay station was equipped with a compact remote-controllable repeater system that can be set in a 19-inch-rack unit. The transmission accuracy was evaluated using a 240-km-long loop network in which an ultranarrow linewidth laser was transmitted from Wako to Atsugi via the repeater at UTokyo then transmitted back to UTokyo through the other optical fiber installed on the same path. At UTokyo, we measured the frequency stability*4 by detecting the interference between the optical frequencies transmitted to Atsugi and those returned by the loop network. By measuring the frequency difference between the transmitted light and the light returning through the fiber network, we can assess the noise (how much it degrades frequency stability) that originates from the transmitted fiber. We demonstrated transmission with frequency stability and accuracy of 3×10^{-16} for 1-second averaging time and 1×10^{-18} for 2600-second averaging time [4]. This frequency-transmission stability is an achievement that will lead to future application of relativistic geodesy with 1-cm accuracy, which does not deteriorate the accuracy of the world's most accurate optical lattice clock. Previously, UTokyo and RIKEN carried out relativistic geodetic experiments between Hongo and Wako by comparing the frequencies of 2 optical lattice clocks with 30 km of non-relaying fiber transmission. They demonstrated the principle of remote altitude difference measurement with accuracy of several centimeters [5]. Since the transmission distance without relaying is roughly limited up to 100 km due to the fiber-propagation loss, the cascade-relaying method through repeaters we demonstrated will enable us to extend to a regional level of several hundred kilometers or national level of several thousand kilometers with ultrahigh precision.

5. Summary and future outlook

We introduced an ultrahigh-precision transmission technology of an optical frequency standard, which enables optical-fiber transmission over 200 km without deteriorating the accuracy of the world's highest-performance optical lattice clock. We plan to conduct frequency-comparison experiments on optical lattice clocks installed at Wako and Atsugi using the fiber link we constructed. This will enable the demonstration of relativistic geodesy to detect height differences with several-centimeter-accuracy between remote locations on the 200-km scale. On the assumption of a nationwide optical-lattice-clock

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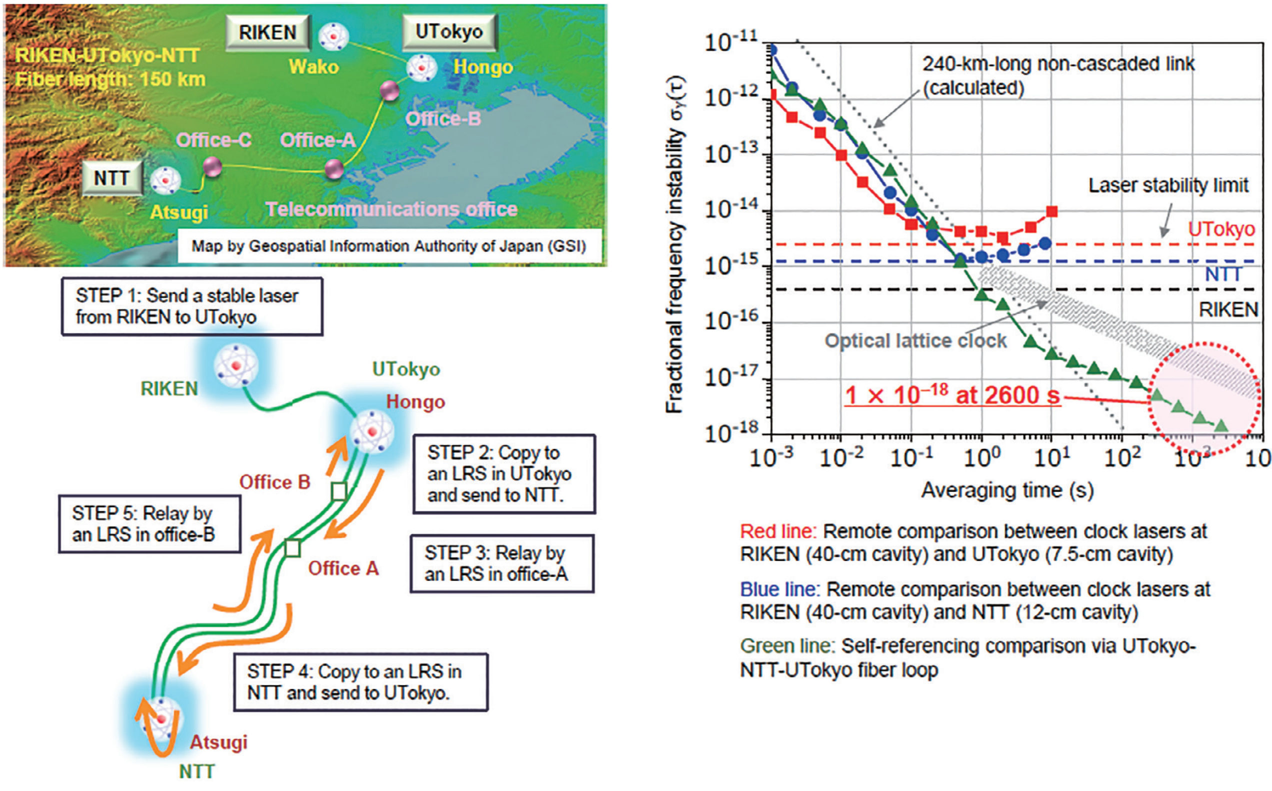
*3 Quartz-based PLC: This optical waveguide technology, which has been put into practical use by NTT, enables optical waveguides to be manufactured in a process similar to large-scale integrated circuits and integration of various interferometers. PLCs are superior for mass production because of their ability to automate manufacturing and are highly effective in reducing costs during mass production. They are also characterized by low loss and high reliability because they can form waveguides with the same glass materials as optical fibers.

*4 Frequency stability: A measure of frequency precision and defined as how constant the frequency is for a specified time interval.



Red line: Remote comparison between clock lasers at RIKEN (40-cm cavity) and UTokyo (7.5-cm cavity)

Blue line: Remote comparison between clock lasers at RIKEN (40-cm cavity) and NTT (12-cm cavity)

Green line: Self-referencing comparison via UTokyo-NTT-UTokyo fiber loop

(a) 240-km-long link stability is estimated by measuring a beat signal at UTokyo.

(b) Frequency instabilities measured with UTokyo-NTT fiber link

Fig. 4. Optical frequency transmission experiment in Tokyo area.

network, we plan to develop repeaters capable of stable operation with more relays and extend this ultrahigh-precision optical-frequency-standard fiber-transmission technology to the 1000-km scale.

Acknowledgments

This research was conducted in collaboration with Prof. Hidetoshi Katori and Prof. Ichiro Ushijima (the University of Tokyo), Dr. Masao Takamoto (RIKEN), Prof. Noriaki Ohmae (Fukuoka University at present), Dr. Takashi Go (NTT Electronics at present), Prof. Atsushi Ishizawa (Nihon University at present), and Prof. Hideki Gotoh (Hiroshima University at present). This research was partially supported by JSPS Grant-in-Aid for Specially Promoted Research (JP 16 H06284) and JST-Mirai Program Grant Number JPMJMI18A, Japan.

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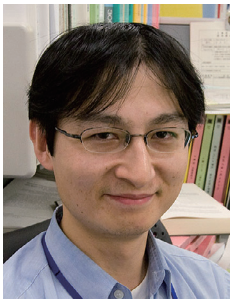

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Extracting Quantum Power by Using Algorithms and Their Verification

Seiichiro Tani, Seiseki Akibue, and Yuki Takeuchi

Abstract

Quantum computers are expected to increase computational speed compared with current and future computers that work in accordance with the conventional computational principle and to revolutionize information processing. Such an increase in speed is achieved using quantum algorithms that extract computational power from quantum-computer hardware. This article briefly introduces our recent results on quantum algorithms, quantum-circuit optimization to support their efficient implementation, and quantum-circuit verification necessary for their reliable execution.

Keywords: quantum computer, quantum algorithm, quantum information processing

1. Quantum algorithm as core technology

Just as with current computer systems, the performance of quantum-computer systems will heavily depend on what software (i.e., algorithms) we use on quantum-computer hardware. In this sense, quantum algorithms can be considered a core technology for increasing quantum speed. Many studies developed sophisticated quantum-algorithmic techniques and proposed a variety of applications for them with quantum advantage. However, there are still issues regarding quantum algorithms that we need to better understand. To achieve an effective increase in quantum speed, it is also essential to implement quantum algorithms as compact quantum circuits and ensure the reliability of circuit execution.

2. Quantum algorithms for classical problems

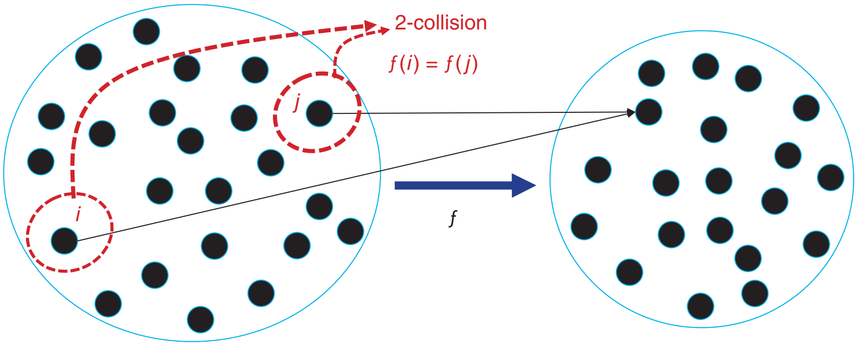
Most problems we encounter in daily life are unrelated to the concept of quantum mechanics, i.e., classical problems. If quantum computers can solve classical problems much faster than any computer based on the conventional computational principle, i.e., any classical computer, they will significantly impact our lives and society.

Previous theoretical studies have revealed many problems that quantum computers can solve much faster [1]. In particular, the collision problem has been central in developing various quantum-algorithmic techniques, such as quantum walk, which increase quantum speed in solving practically important classical problems such as matrix multiplication. We take the collision problem as an example to consider quantum-algorithmic techniques from a different point of view, that is, from the viewpoint of information-communication security.

Quantum computers can be used not only for improving our lives but for malicious attacks such as cracking ciphers. It is thus essential to assess the security of ciphers against strong attacks involving quantum computers (i.e., quantum attacks). For such an assessment, one needs to know how much ability attackers have by devising quantum-attack methods, which are simply quantum algorithms. We devised the fastest quantum-attack method against random hash functions, a core technology in cryptography, on the basis of the knowledge of quantum algorithms that we have accumulated [2].

A hash function takes long data as input and outputs short data. The hash functions used in ciphers are unique in that the input data are hard to infer from the output data. Such hash functions have many applications that require falsification prevention, such as electronic signatures and public-key cryptography.

Let us explain an attack against hash functions



A 2-collision of a hash function f is a pair (i, j) of two distinct elements mapped via f into the same value, i.e., a pair (i, j) such that $f(i) = f(j)$. Similarly, an ℓ-collision is an ℓ-tupple of ℓ distinct elements mapped via f into the same value.

Fig. 1. Collision of hash function.

1. Sample a subset $I \subset [N]$ and compute its image $f(I)$, where $[N] \equiv \{1, \cdots, N\}$.
2. Quantum search the preimage of $f(I)$ for a set $J \subset [N] \setminus I$ and compute its image $f(J)$.
3. Quantum search the preimage of $f(J)$ for an element $k \in [N] \setminus (I \cup J)$.
4. Output 3-collision (i, j, k).

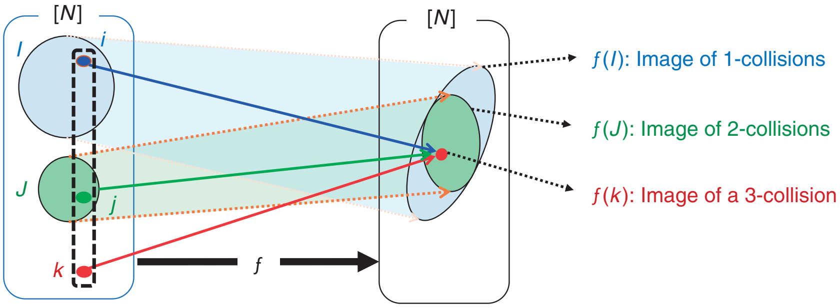


Fig. 2. Quantum algorithm for finding a 3-collision.

using the concept of collisions. We say that multiple elements are a collision of a hash function f if they are mapped via f to the same value. More concretely, we say that ℓ elements mapped via f into the same value are an ℓ-collision. We also say that ℓ is the multiplicity of the collision. In **Fig. 1**, since two elements i, j are mapped into the same value by f, the pair (i, j) is a collision.

One can falsify electronic documents even with message authentication codes if they find a collision of a hash function. It is thus required to assess the computational hardness of finding a collision (i.e., how long it takes to find a collision) before using a hash function as part of a cryptographic system. This assessment requires concrete algorithms for finding a collision. We designed a quantum algorithm that quickly finds an ℓ-collision for any given ℓ (**Fig. 2**). The computation time of this algorithm is optimal in the sense that it achieves the theoretical limit, which makes it possible to rigorously assess the security of cryptographic systems that include hash functions.

Figure 3 compares our algorithm with the previously best algorithm [3] in terms of the number of evaluations of a hash function to find an ℓ-collision of the function, approximating the time taken to execute our algorithm. For every $\ell \geq 3$, our algorithm is superior to the previous one. When $\ell = 2$, both algorithms have the same number of evaluations

ℓ (multiplicity)	2	3	4	5	…	ℓ
Previously best algorithm [3]	$N^{\frac{1}{3}}$	$N^{\frac{4}{9}}$	$N^{\frac{13}{27}}$	$N^{\frac{40}{81}}$	…	$N^{\frac{1}{2}\left(1-\frac{1}{3^{\ell}-1}\right)}$
Our algorithm	$N^{\frac{1}{3}}$	$N^{\frac{3}{7}}$	$N^{\frac{7}{15}}$	$N^{\frac{15}{31}}$	…	$N^{\frac{1}{2}\left(1-\frac{1}{2^{\ell}-1}\right)}$

Fig. 3. Comparison of our algorithm with the previously best algorithm provided in [3] in the number of evaluations of a hash function, approximating the time taken to find an ℓ-collision for every ℓ, where N is the image size of the hash function.

since the previous algorithm achieves the theoretical limit. As a numerical example, let us consider when N is 2000 bits, in which case our algorithm is a billion times faster than the previous one.

To execute a quantum algorithm efficiently, we must consider optimizing the quantum circuit that implements the algorithm. In the next section, we introduce some of our results on quantum-circuit optimization.

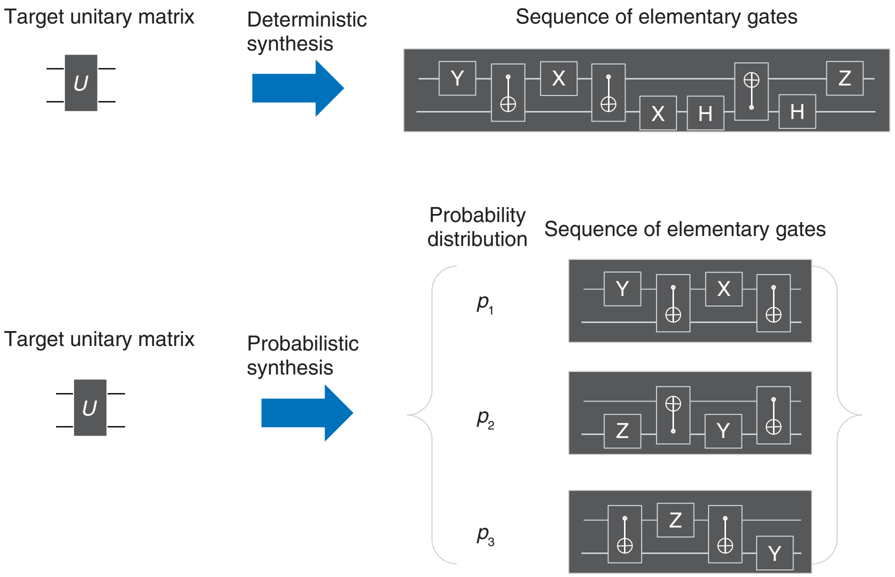
3. Quantum-circuit optimization

We can represent the dynamics of any quantum system, such as photons and electrons, as a unitary matrix. Thus, a ‘command’ sent by a quantum algorithm to a quantum computer is also essentially represented by a unitary matrix. For example, Shor’s algorithm, which efficiently solves the factoring problem, uses the unitary matrix called the quantum Fourier transformation as an essential command. However, we cannot accurately implement such unitary matrices as the corresponding dynamics since quantum systems are fragile against noise. We thus implement a desired unitary matrix by sequentially implementing unitary matrices selected from a finite set (called an elementary gate set), the elements of which are implementable with negligible error.

Hence, it holds that (a) the number of elementary gates = (b) the number of commands × (c) the number of elementary gates used to implement the unitary matrix representing a single command. Since the runtime of a quantum algorithm can be estimated by (a), many studies have been devoted to reducing it. There are two types of such studies: for reducing (b) by exploiting the structure of the algorithm and for reducing (c) without using the structure. It might seem that reducing (c) is unnecessary if we design algorithms by regarding each command as an elementary gate. However, it is necessary to design algorithms independently of the quantum system we use to implement the algorithms since the elementary gate set heavily depends on the system.

To reduce (c), we search for a sequence of elementary gates that approximately implements a target unitary matrix (this procedure is called *synthesis*) since it is impossible to accurately implement an arbitrary unitary matrix by using a sequence of elementary gates chosen from a finite set. We can implement an arbitrary unitary matrix within an arbitrarily small approximation error by using a sufficiently long sequence of appropriate elementary gates. Therefore, traditional synthesis approaches, called *deterministic synthesis*, are used to find the shortest single sequence among all sequences that approximate a target unitary matrix within the desired approximation error. A new synthesis approach, called *probabilistic synthesis*, has been demonstrated to improve the approximation by probabilistically implementing the target unitary matrix. This also indicates that probabilistic synthesis can achieve the desired approximation error with a shorter sequence than the deterministic one (see **Fig. 4**). However, the optimality of current probabilistic-synthesis algorithms was unknown.

We have shown the fundamental limitations on the smallest approximation error achievable with probabilistic synthesis [4]. We have also designed a probabilistic-synthesis algorithm that is efficiently executable and outperforms current probabilistic-synthesis algorithms with respect to approximation error. Numerical simulation showed that our algorithm can reduce (c) by about 50% compared with the best deterministic-synthesis algorithm. The mathematical tools we developed for analyzing optimal probabilistic synthesis are expected to be beneficial to optimizing various types of quantum-classical hybrid information processing.



(Top) Deterministic synthesis is used to find the shortest single sequence among all sequences that achieve a target unitary matrix within the desired approximation error. (Bottom) We can shorten the sequence without increasing the approximation error by probabilistic synthesis.

Fig. 4. Reduction of elementary gates by probabilistic synthesis.

To reliably execute quantum algorithms, it is necessary to verify the operation achieved on a real device by a sequence of elementary gates.

4. Verification methods for quantum computing

Quantum computers are susceptible to errors caused by noise. Two typical techniques for mitigating such errors are *quantum error correction and mitigation* and *verification of quantum computation*. These techniques complement each other. As the name suggests, quantum error correction and mitigation can correct and mitigate the errors, respectively, but they require information such as error models and error probabilities. Verification of quantum computation, however, is applicable to any error, which may be completely unknown, but cannot correct errors and can only determine whether they exist. Verification of quantum computation is a helpful technique for handling errors because only correct (i.e., errorless) computational results can be selected by evaluating the presence or absence of errors.

In cloud quantum computing that enables us to access a remote quantum computer, it should be difficult to characterize errors. Therefore, verification of quantum computation works well for this application. Verification of quantum computation has recently been applied to mitigate errors. The rest of this section describes our recent results on verifying quantum computation.

Although several verification methods have been proposed, almost all are tailored for fault-tolerant universal quantum computers. However, the current or near-term quantum computers called noisy intermediate-scale quantum (NISQ) computers have no error-correction capability. That is why we tried to close this gap by proposing a verification method for NISQ computers [5]. To verify the outputs of NISQ computers, a simple and trivial verification method requires another quantum computer with the same number of qubits. We solved this problem by using the idea of dividing quantum-verification circuits into two small quantum circuits (see **Fig. 5**) and succeeded in efficiently verifying the outputs of NISQ computers with small-scale quantum devices.

5. Outlook

Research on software (i.e., algorithms), as well as hardware for quantum computers, is essential for high-speed quantum computing. With our theoretical expertise, we will explore how to design algorithms that quickly solve fundamental problems on quantum computers and develop theoretical techniques, such

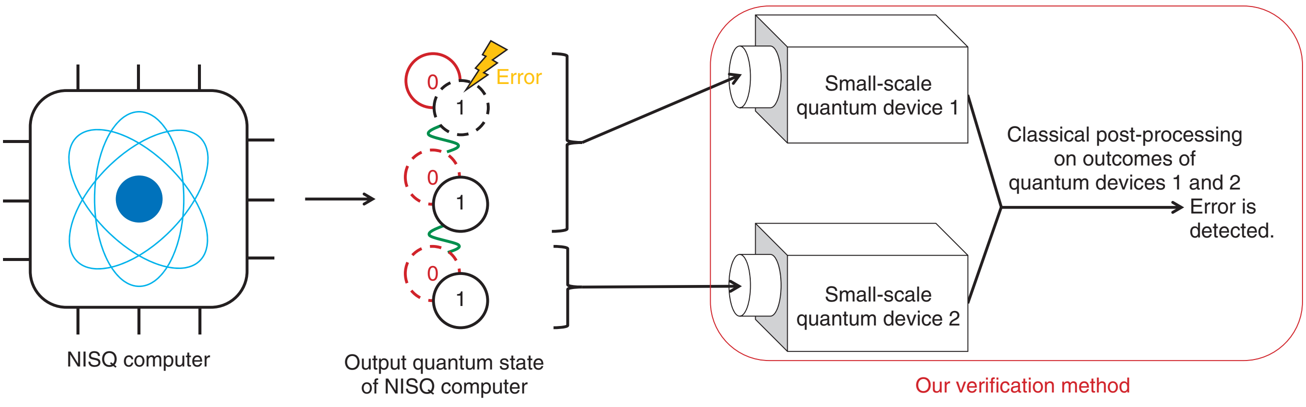


Fig. 5. Our verification method for NISQ computers.

as those presented in this article, to extract the maximum computational power from quantum-computer hardware.

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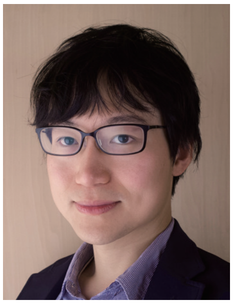

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Improving the Performance of Quantum Key Distribution

Takuya Ikuta and Seiseki Akibue

Abstract

Encryption is an essential technology for secure communications. Quantum key distribution (QKD) can enable ultimately secure cryptographic communications by using quantum mechanics. Toward secure networks using QKD, NTT has been conducting various studies from theoretical security analysis to experimental control of optical quantum states. In this article, we introduce our recent activities on QKD using multi-valued information (high-dimensional QKD) and a scalable measurement device for improving its error robustness.

Keywords: quantum key distribution, high dimension, error robustness

1. Basics of quantum key distribution and research in NTT

It is necessary to encrypt information for secure communications via the Internet. For example, malicious eavesdropper can read information about a credit card if we send it without encryption. Public-key cryptography, such as Rivest–Shamir–Adleman (RSA), is used for this purpose. Its security is based on a problem that is difficult to solve using a modern digital computer, so called computational security. However, a quantum computer having error correction capability can break RSA efficiently. There is another encryption called one-time pad, which is a common-key cryptography. This cryptography uses the fact that a third party does not have enough information to break the encryption. Such an information-theoretic security cannot be broken by any type of computer. Despite its strong encryption, it has a serious disadvantage in that it is difficult to create a situation in which the third party does not have enough information. We use a bit represented by 0 and 1 in a communication system. To make one-time pad ultimately secure, only the legitimate users for the communications need to share random numbers[*1] (secret key), the length of which is equal to the bit length of the information they really want to send. If we can send the secret key securely, one-time pad looks useless because, in a rough consideration, we can directly send the information using such a secure method used for sharing the secret key instead of one-time pad.

Quantum key distribution (QKD) is a technique that solves this problem. QKD uses the fact that an attempt to clone a quantum state changes the original state (**Fig. 1**). By monitoring such a change in the state, we can estimate how much information was leaked during communications. We cannot directly send a massage we want to encrypt because we cannot prevent the message from being leaked. However, if we send random numbers having no meaningful information, we can generate a secret key by erasing the leaked information from the shared random numbers after the communication. By using this secret key for one-time pad, we can enable unbreakable secret communications.

While we often hear about QKD on the news, it has been studied since its invention in 1984 [1]. NTT has continued its long-term research on QKD [2], such as security analysis, experimental demonstration, and the proposal of our unique QKD protocol called differential phase shift QKD. Let us introduce our recent activities on high-dimensional QKD and a technology

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[*1] Random number: A random value that is impossible to predict beforehand.

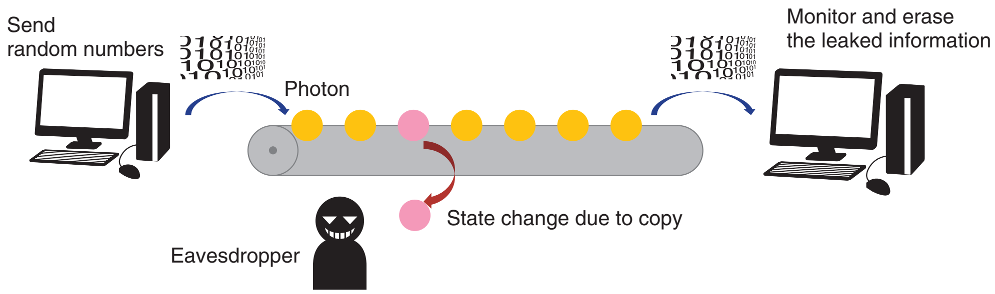

Fig. 1. Schematic diagram of QKD.

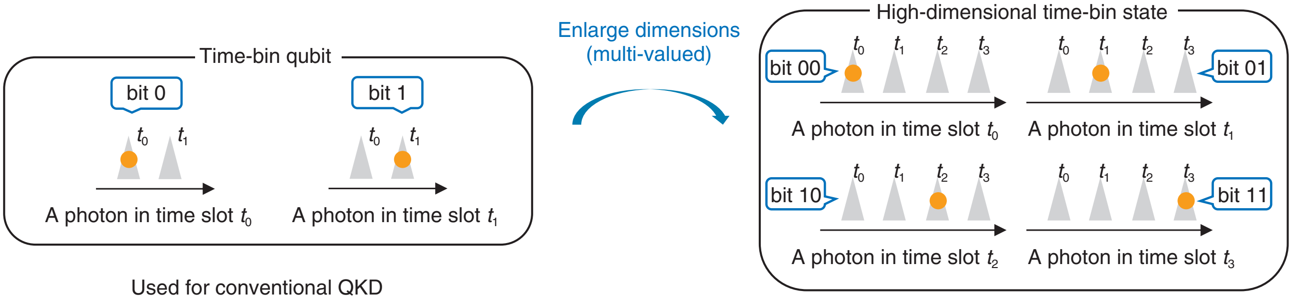

Fig. 2. Schematic diagram of time-bin state.

for improving its error robustness.

2. High-dimensional QKD and scalable measurement device

High-dimensional QKD uses a high-dimensional quantum state to enhance the secret-key rate, which corresponds to the communication speed of QKD. A conventional QKD system uses a quantum bit (qubit) representing 0 or 1. In our research group, we use a time-bin qubit, 0 or 1 of which are represented by two temporal positions of a photon[*2] (**Fig. 2** left). If we can encode multiple values, such as 0, 1, 2, …, instead of a bit value, we can increase the amount of information per photon (Fig. 2 right). A high-dimensional state is such a state representing multiple values and its concept is similar to pulse amplitude modulation (PAM)[*3] and quadrature amplitude modulation (QAM)[*4] used in modern optical communications. A very high-speed secret-key generation of 26.2 Mbit/s has been reported by using four-dimensional time-bin states represented by four temporal positions [3].

As we explained in the previous section, it is important to estimate how much information of random numbers was leaked for generating a secure secret key. For this purpose, QKD uses superposed states. A superposed state is a state in which we cannot essentially determine 0 or 1 for a qubit and 0, 1, 2, … for a high-dimensional state (**Fig. 3**). We can estimate the amount of leaked information by using superposed states that satisfy a special relation called mutually unbiased. In a d-dimensional system, we can use at most $(d + 1)$ measurements, which satisfy such a special relation. An experiment using two types of measurements to estimate the amount of leaked information achieved 26.2-Mbit/s secret key generation [3]. By using $(d + 1)$ measurements, we can more precisely evaluate the change in the quantum state during communications. Therefore, we can more precisely estimate the amount of leaked information,

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[*2] Photon: The minimum unit of an optical energy (an elementary particle), which can be observed when we drastically decrease the optical intensity.

[*3] PAM: A technique for representing multiple values using an amplitude of light or radio wave for high-speed communications.

[*4] OAM: A technique for representing multiple values using both amplitude and phase of light or radio wave for high-speed communications.

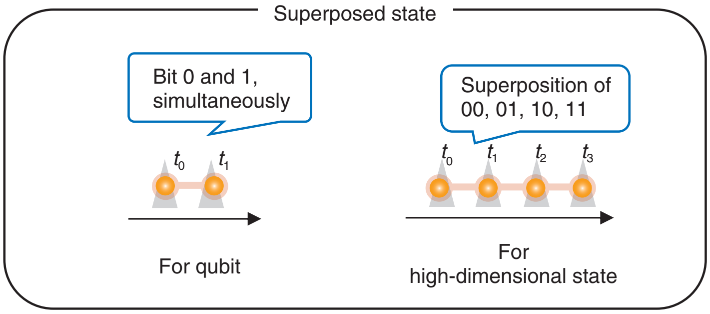

Fig. 3. Schematic diagram of superposed state.

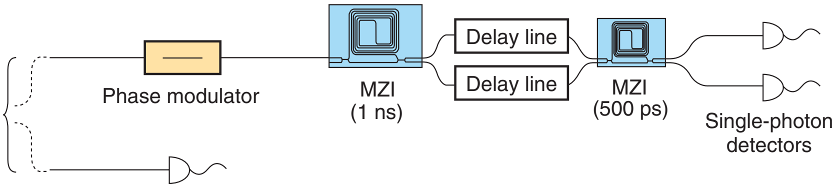

Fig. 4. Measurement device for four-dimensional time-bin states.

which results in an improvement in the secret-key rate. In other words, multiple measurements make a high-dimensional QKD system more robust against errors.

NTT developed and demonstrated an implementation of a scalable measurement device of (d + 1) measurements for high-dimensional time-bin states [4]. A measurement for time-bin states uses delay Mach-Zehnder interferometers (MZIs)*5 and single-photon detectors. In an implementation of a previous measurement device, (d − 1) MZIs and (d + 1) single-photon detectors were required even for two measurements [3]. By using the above scalable measurement device, all the (d + 1) measurements for $d = 2^N$ can be implemented using N MZIs and three single-photon detectors independent of d (**Fig. 4**). We conducted experiments involving five measurements for four-dimensional time-bin states. The experimental results indicated error rates lower than the threshold required to generate a secret key (**Fig. 5**). Hence, we expect that this device can be used for a high-dimensional QKD system that is more robust against errors.

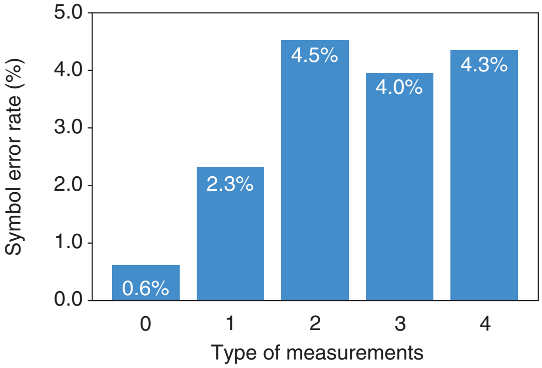

Fig. 5. Experimental results of error rate.

3. Extension of the security proof

In the previous section, we explained that (d + 1) measurements can be used for a robust high-dimensional QKD system. However, a rigorous security of this QKD protocol was proven only if d is a prime number (2, 3, 5, …). Therefore, we cannot directly apply that security proof for a four-dimensional system with the above scalable measurement device. To circumvent this problem, we also extended the previous

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*5 Delay MZI: An optical interferometer in which a light is split at the input, and combined after a temporal delay is introduced for split light. It is widely used for, for example, measuring the time-bin state and differential-phase detection in modern optical communications.

security proof [5] for prime power dimensions (e.g., $d = 2, 4, 8$, and $3, 9, 27$). In this security proof, we use operators that describe operations on a quantum state. Corresponding to the operators used in the previous security proof, there is a generalized operator using the Galois field*6, which is used in, e.g., coding theory [6]. Because we can use the Galois field as long as d is a prime power, we could extend the previous security proof by using these generalized operators for prime-power dimensions. Therefore, we can use the scalable measurement device for a four-dimensional QKD system to ensure rigorous security.

4. Toward a practical QKD system

We introduced high-dimensional QKD and a scalable measurement device to enhance the error robustness as recent activities in NTT to improve the performance of QKD. We conducted a proof-of-principle experiment on generations and measurements of high-dimensional quantum states for such a QKD system. To implement a practical QKD system, we also need to consider other problems, for example, a finite key analysis which is a detailed treatment of statistical errors due to a finite number of measurement results. It is also important to explore other applications of the scalable measurement device because the mutually unbiased relation can be found in quantum communications and information processing other than QKD. Although we introduced only the approach of using a high-dimensional state in this article, NTT will continue to conduct research on other approaches toward practical quantum information technologies.

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*6 Galois field: A set of finite number of elements associated with appropriately defined four arithmetic operations (+, –, ×, ÷). It is also known as finite field.

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Toward a Quantum Internet

Koji Azuma

Abstract

A quantum internet holds promise for accomplishing quantum metrology and quantum computer networks as well as quantum communication among arbitrary clients all over the globe. Its actualization is an important long-term scientific and technological goal. In this article, I explain what a quantum internet is and what is needed for its actualization as well as recent relevant progress in the field of quantum information.

Keywords: quantum internet, quantum repeaters, all-photonic approach

1. Introduction

In modern physics, quantum mechanics gives the most precise description of nature in the range of phenomena from the level of elementary particles to our universe. Quantum mechanics just predicts the probability of an event occurring, in contrast to the determinism given by classical mechanics, and it is a broader paradigm than classical mechanical views. Even if there is a theory with the view of determinism, quantizing it is still one of most important attempts in physics. At the end of the last century, the possibility of applying the quantum mechanical point of view to information processing began to be explored; as a result, quantum information processing was established. Quantum information processing accomplishes tasks that are intractable by conventional means and the concept includes the paradigm of conventional information processing [1].

For instance, a quantum computer can factor large integers efficiently. Thus, if a quantum computer is handed to an eavesdropper, most widely used public-key cryptosystems, such as RSA (Rivest–Shamir–Adleman), can be cracked. Quantum key distribution (QKD), however, presents information-theoretically secure communication even if eavesdroppers can use arbitrary attacks enabled by quantum mechanics (including eavesdropping by using an arbitrarily large quantum computer). As long as quantum mechanics is correct in the description of nature, such quantum information processing allowed by the laws of quantum mechanics must be the ultimate form of achievable information processing.

What is the ultimate form of quantum information processing? Given that the current internet could be regarded as the largest information-processing network on Earth, its quantum version, called a *quantum internet* [2], would be the ultimate form of information-processing networks. In this article, I explain what a quantum internet is and what is needed for its actualization as well as recent relevant progress in the field of quantum information (see review paper [3] for detail).

2. What is a quantum internet?

A quantum internet is a quantum-information-processing network (**Fig. 1**) in which quantum-information-processing nodes (such as quantum computers and quantum memories) are connected by quantum communication channels (such as optical fibers and free space). It enables arbitrary clients around the globe to achieve various quantum-information-processing tasks beyond those served by the current internet [4]. For example, it enables arbitrary clients in the network to use QKD, which could be the basis of a referendum, top-level meeting, financial deal, exchange of genetic/biological information and so on, thanks to its feature of high security. A quantum internet would also make it possible to transfer unknown quantum states faithfully to a distant place at the speed of light. This is the basis of distributed quantum computation, cloud quantum computing, and networking of quantum computers. A quantum

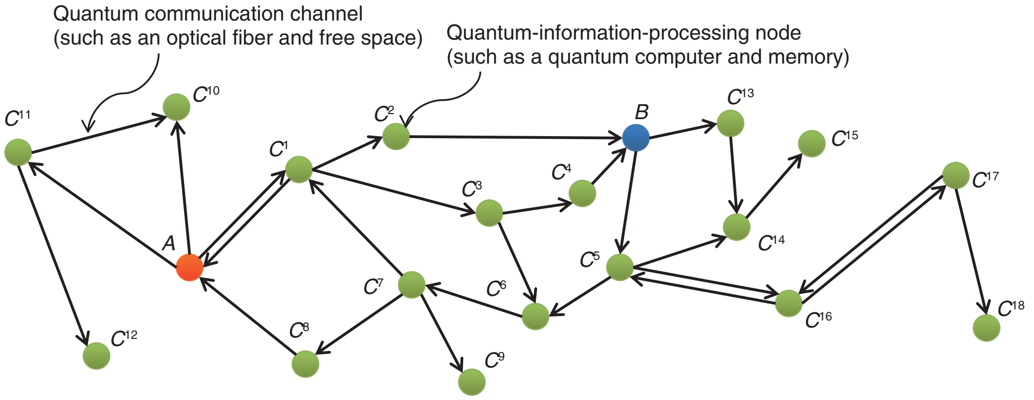

Fig. 1. Schematic of a quantum network.

internet would also be used for synchronizing atomic clocks with unprecedented stability and accuracy in a secure manner. It would also enable us to make baselines of telescope arrays unprecedentedly longer, contributing to progress of astronomy.

3. Constructing a quantum internet

How can we construct a quantum internet? The role of a quantum internet is to distribute *quantum entanglement* to clients efficiently. Quantum entanglement can be demonstrated only with quantum systems such as atoms and photons, and it is a peculiar correlation that cannot be explained in the framework of classical mechanics. This correlation was used by Einstein, Podolsky, and Rosen to point out that quantum mechanics includes a prediction contradicting the local realism (which ought to hold in classical mechanics), that is, to pose a question on the validity of quantum mechanics [5]. Ironically, the existence of quantum entanglement has been confirmed experimentally. In 2002, Aspect, Clauser, and Zeilinger, who had conducted these experiments, were awarded the Nobel Prize in Physics [6]. Quantum entanglement is now identified as a universal resource not only for quantum communication but also for quantum computation. Therefore, by distributing entanglement as such a universal resource efficiently, a quantum internet will serve clients with various functions.

Quantum networks for QKD have been developed worldwide, as exemplified by the SECOQC network in Europe [7], the Tokyo QKD network in Japan [8], and the 2000-km Shanghai-Beijing network in China [9]. However, all the nodes in these networks, including repeater nodes, are not quantum-information-processing nodes but *classical* information-processing nodes that can process only classical signals at best even if they receive quantum signals. Therefore, we cannot distribute quantum entanglement to arbitrary clients in those networks. Even if we specialize the use of the networks only for QKD, we cannot distribute a secret key unless we can fully trust all the nodes in the networks. In this regard, such existing networks are categorized as trusted-node networks, different from a quantum internet, and they cannot be used to actualize a quantum internet.

If all clients are connected completely with quantum communication channels, that is, if all the clients can communicate with each other by using point-to-point quantum communication schemes, the network can work as a secure QKD network, which could be used to actualize a quantum internet. However, it is not realistic in terms of cost and efficiency if we actualize a quantum internet by expanding such a point-to-point quantum communication network worldwide. For example, if we use a standard optical fiber as the quantum communication channel, its transmittance decreases exponentially with its length. In particular, the probability with which a single-photon level of light emitted by a sender to convey quantum information is detected by a receiver is about 10% for a distance of 50 km, about 1% for 100 km, and about 0.1% for 150 km, decreasing as it is multiplied by 0.1 every 50 km. Therefore, if a sender and receiver execute point-to-point quantum communication with a 1000-km optical fiber, even with the use of a GHz clock system, the expectation time needed to establish an entanglement pair between them is on the order of hundreds of years, which is not realistic.

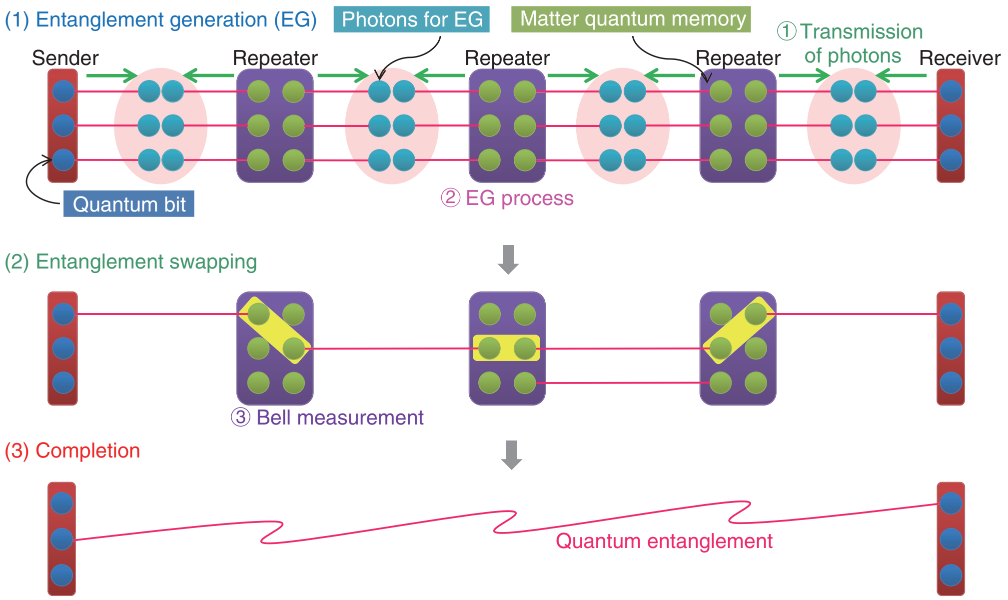

Fig. 2. Memory-based quantum repeaters.

Hence, it is impossible to actualize a quantum internet only by combining point-to-point quantum communication schemes. To do so, we need to construct a network in which quantum-information-processing nodes, called quantum repeaters, are installed between clients [10, 11].

4. What is a quantum repeater?

Even in conventional communication, if a sender and receiver are far apart, their communication is established not with point-to-point means but via repeater nodes set between them. In conventional communication, the role of *classical* repeaters located on the repeater nodes is to amplify the received weakened signal then send the amplified signal to the next repeater node (or the receiver if the repeater is neighboring the receiver). However, this method does not work for quantum communication because the quantum no-cloning principle forbids copying and amplifying quantum signals [12]. Thus, quantum repeaters do not rely on signal amplification, although they are located on the repeater nodes between a sender and receiver similarly to classical repeaters.

The quantum repeater protocol based on the use of quantum repeaters is composed of two processes; entanglement generation and entanglement swapping. In a memory-based approach [10] (**Fig. 2**), quantum repeaters, equipped with matter quantum memories and quantum interfaces, are connected to each other by optical fibers. By exchanging photons between adjacent repeater nodes, we attempt to generate quantum entanglement between them and store the entanglement in quantum memories in the quantum repeaters once the attempt succeeds. By repeating this entanglement-generation process, if all the adjacent repeater nodes are connected with entanglement, we then move on to entanglement swapping. In this process, by applying a measurement—called the Bell measurement—to halves of entangled pairs, the entanglement pairs are transformed into an entangled pair that directly connects the sender and receiver. Therefore, in the memory-based approach, we can present entanglement between the sender and receiver by conducting entanglement generation, followed by entanglement swapping.

An all-photonic approach [11] is based on a time-reversed version of the memory-based repeater protocol, where we first carry out operations associated with entanglement swapping, followed by entanglement generation (**Fig. 3**). In this approach, all the repeater nodes first prepare photons in an entangled state, called a graph state, to execute entanglement swapping. The halves of the graph states are sent to neighboring repeater nodes. On receiving the halves, the receiving nodes apply entanglement generation to the received pulses and, depending on this result, execute measurements on remaining photons. With a

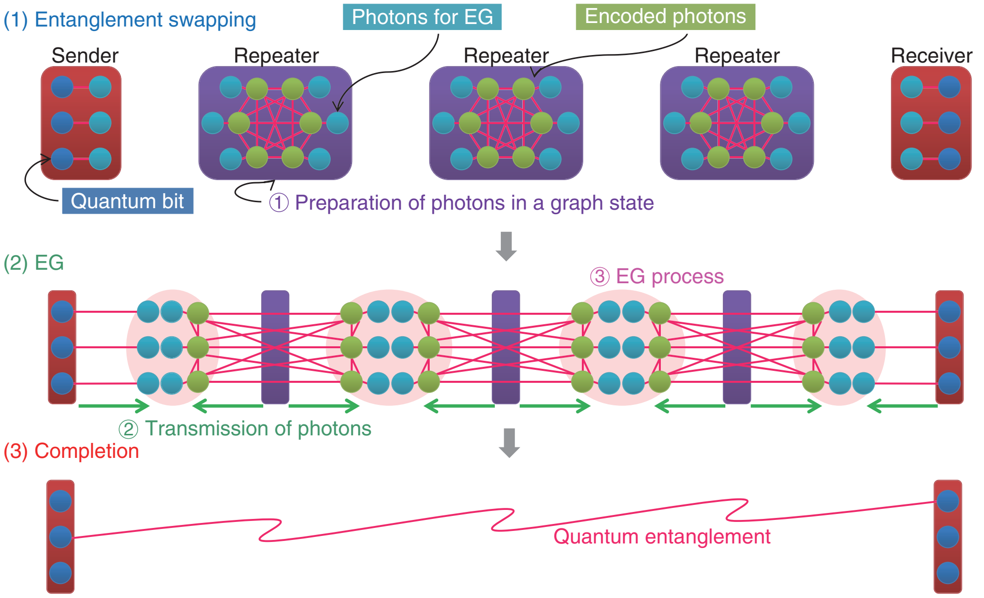

Fig. 3. All-photonic quantum repeaters.

high probability, an entangled pair is then presented to the sender and receiver. Quantum repeaters in this all-photonic approach do not necessitate matter quantum memories and quantum interfaces and the protocol works only with optical devices (such as single-photon sources, linear optical elements, active feed-forward controllers, and photon detectors), in contrast to the memory-based approach. Therefore, its repetition rate does not depend on the communication distance and is determined only by the clock speed of optical devices. Therefore, the all-photonic approach has high affinity with the current all-optical trend in conventional communication, and the served communication speed will be faster.

5. Discussion

Thanks to recent theoretical progress in the understanding of quantum networks (see review article [13]), the quantum capacity—the number of transmittable quantum bits per optical mode—and the private capacity—the number of securely transmittable bits per optical mode—of an optical fiber with a transmittance η are identified as $-\log_2(1-\eta)$. This describes the fundamental limit of the point-to-point quantum communication based on the use of an optical fiber, showing the impossibility of long-distance quantum communication as well as a quantum internet, without quantum repeaters (on considering $\eta = e^{-l/l_{\mathrm{att}}}$ for the length l of the fiber and a constant l_{att}). The quantum/private capacity for two-party communication over any optical-fiber network with arbitrary topology was derived and achieved by aggregating quantum repeater protocols. This indicates that quantum repeaters play essential roles in establishing a quantum internet that achieves or approaches such ultimate performance.

There is a technological and conceptual gap between currently available point-to-point QKD technology and quantum repeater technology necessary for a quantum internet. Exploring and implementing schemes to bridge this gap is now being investigated in QKD [14]. For instance, the adaptive measurement-device-independent QKD protocol and twin-field QKD protocol have been found to be candidates for bridging such a gap. Proof-of-principle experiments on quantum repeaters, with the all-photonic approach as well as the memory-based approach, have been conducted. For the memory-based approach, experiments of the working principle of entanglement swapping have been conducted with the use of quantum memories, such as silicon-vacancy color centers integrated inside a diamond nanophotonic cavity at Harvard University and Massachusetts Institute of Technology in the US [15], ensembles of Rubidium atoms at Tsinghua University in China [16], and nitrogen-vacancy centers in diamond at Delft University of Technology in the Netherlands

[17]. For the all-photonic approach, experimental demonstration of the principle of time-reversed entanglement swapping has been carried out using an entangled graph state, called a Greenberger-Horne-Zeilinger state, generated through the parametric-down conversion process, at Osaka University, NTT, the University of Toyama, and the University of Toronto [18], and at the University of Science and Technology of China [19, 20].

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Identification of Transcription Factors and the Regulatory Genes Involved in Triacylglycerol Accumulation in a Unicellular Red Alga

Sousuke Imamura

Abstract

Triacylglycerols (TAGs) generated by microalgae are a raw material for liquid biofuel production, so increasing the amount of TAGs generated will contribute to reducing the environmental impact of, for example, greenhouse gas emissions. Since transcription factors (TFs) regulate the expression of a group of genes with related functions, it is thought that TAG accumulation can be enhanced by identifying TFs involved in TAG accumulation and enhancing their functionality. In this study, my research colleagues and I used transcriptomic and phosphoproteomic data—obtained under conditions of TAG accumulation in a unicellular red alga, *Cyanidioschyzon merolae*, to identify 14 TFs that may regulate TAG accumulation. To verify the function of these TFs, we constructed functionally enhanced strains overexpressing each TF and analyzed changes in TAG accumulation. The analysis results indicate that the amount of TAGs regarding the four overexpressing strains increased 2.2 to 3.8 times compared with that regarding the control strain, so we can consider that those four TFs are involved in TAG accumulation. Transcriptome analysis of each of the four TF overexpression strains showed that among the group of genes related to TAG synthesis, only a gene-encoding endoplasmic reticulum-localized lysophosphatidic acid acyltransferase 1 (LPAT1) significantly enhanced. In strains that overexpressed LPAT1 and enhanced its functionality, TAG accumulation increased 3.3 times compared with that in the control strain. These results (i) explain the mechanism by which four types of TFs regulate the TAG amount in *C. merolae* by altering the expression of a group of target genes, including LPAT1, and (ii) indicate that enhancing TAG accumulation by strengthening functionality TF is useful.

Keywords: algal biofuel, lysophosphatidic acid acyltransferase, red alga, transcription factor, triacylglycerol

1. Introduction

Microalgae store excess energy in lipid droplets (LDs), which are mainly composed of neutral lipids, in their cytoplasm. Neutral lipids contained in LDs are mainly triacylglycerols (TAGs), which can be used as a raw material for producing biofuel. Since the carbon that constitutes TAGs is derived from carbon dioxide (CO_2) fixed by photosynthesis, biofuel production using microalgae is expected to contribute to reducing environmental load such as mitigating global warming [1–3]. However, a large-scale system for industrial biofuel production using microalgae has not been established. The main reason is due to the lack in the understanding of the underlying molecular mechanisms that control TAG accumulation in microalgae.

Our research group has aimed to explain the regulatory mechanism of TAG accumulation by using a model unicellular red alga *Cyanidioschyzon merolae*

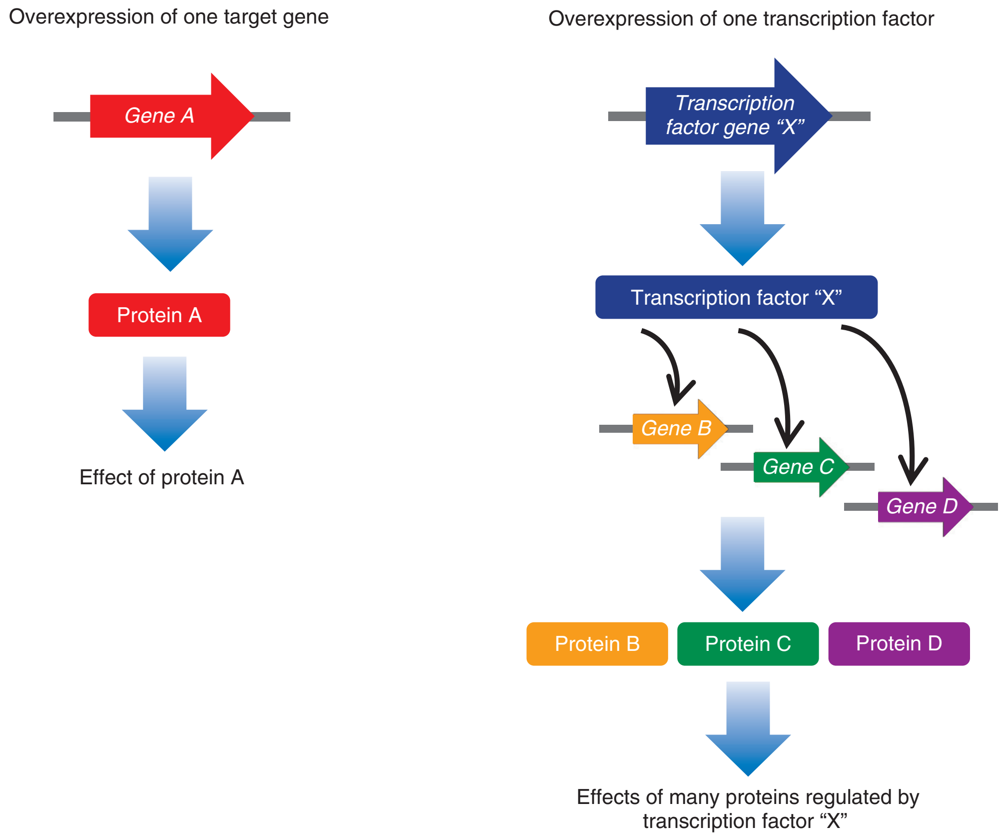


Fig. 1. Comparison of effects of functional modification of a target gene and a transcription factor.

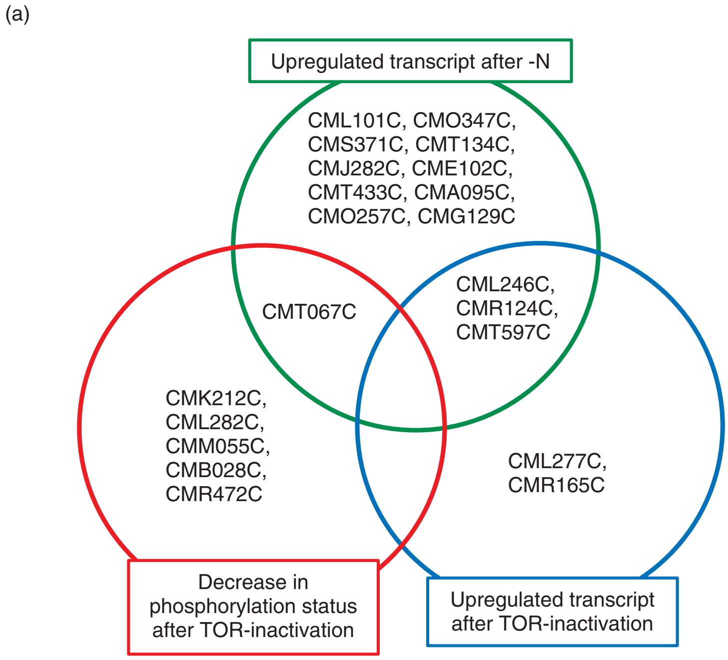
[4]. It has been observed that exposure of *C. merolae* to nitrogen-deficient (-N) conditions enhances TAG accumulation [5], which has been observed for many other microalgae. The target of rapamycin (TOR) has also been shown to govern the accumulation of TAGs under -N conditions [5]. TOR is a highly conserved protein kinase among eukaryotes and plays a central role in cell growth and stress response by sensing environmental conditions [6]. The kinase activity of TOR is specifically inhibited by rapamycin, an inhibitor of TOR [7]. In our previous studies, when rapamycin-sensitive *C. merolae* strains F12 or SF12 [8, 9] were grown under normal culture conditions in which TAGs do not accumulate, the addition of rapamycin to the culture medium resulted in accumulation of almost the same amount of TAGs as observed under -N conditions [5, 9]. TAG accumulation after inhibition of TOR activity has also been observed in other algae [10–12], in other words, the mechanism that regulates TAG accumulation by TOR has been shown to be common to all algae [13].

Several studies have reported on the use of *overexpression* of a single gene involved in synthesis of TAGs as a method for enhancing TAG accumulation [14, 15] (**Fig. 1**). Compared with such methods, simultaneously enhancing the expression of multiple genes involved in TAG synthesis could further enhance TAG accumulation. One way to achieve this simultaneous multiple-gene enhancement is to enhance the function of the transcription factors (TFs) that control gene expression. This is possible because each TF regulates a group of genes with related functions [16] (Fig. 1).

The aims of this study were (i) identify TFs involved in TAG accumulation in *C. merolae*, (ii) enhance TAG accumulation by strengthening the functions of the TFs, and (iii) identify genes that are regulated by the identified TFs.

2. Identification of candidate TFs involved in TAG accumulation

Using previously reported microarray data [5, 10] and phosphoproteome data [17] obtained under -N- and



(b)

Gene number	Predicted enzyme
CMB028C	Bromodomain-containing protein
CMK212C	Bromodomain-containing protein
CML101C	MYB-related protein
CML282C	Basic leucine zipper domain TF
CML246C	MYB-related protein
CML277C	Heat shock TF
CMM055C	Protein containing DNA-binding domain SAP
CMO347C	MYB-related protein
CMR124C	MYB-related protein
CMR165C	RNA polymerase sigma factor
CMR472C	PHD-type zinc finger protein
CMS371C	MYB-related protein
CMT067C	E2F TF
CMT597C	Heat shock TF

Fig. 2. Identification of candidate TFs involved in TAG accumulation. (Figure modified from Takahashi et al. 2021)

TOR-activity-inhibiting conditions (under which TAG accumulation in *C. merolae* is enhanced), we identified genes encoding TF with an increase in transcripts and TFs with varying degrees of phosphorylation. The TFs identified for each condition are shown in the Venn diagram in **Fig. 2(a)**. The notation of each TF corresponds to the number in the *C. merolae* database (http://czon.jp).

For the ten TFs with expression enhanced only under -N conditions, the number of TF candidates was narrowed due to their large number. In green algae, ROC40 (an MYB-type TF) has been reported to be involved in TAG accumulation under -N conditions [18]. Accordingly, among the ten candidate TFs, the ROC40 homolog CML101C, CMO347C, and CMS371C were analyzed. A total of 14 types of TFs (as listed in **Fig. 2(b)**) were therefore analyzed. Note that the four TFs, CML246C, CMR124C, CMT597C, and CMT067C, showed enhancement under two conditions.

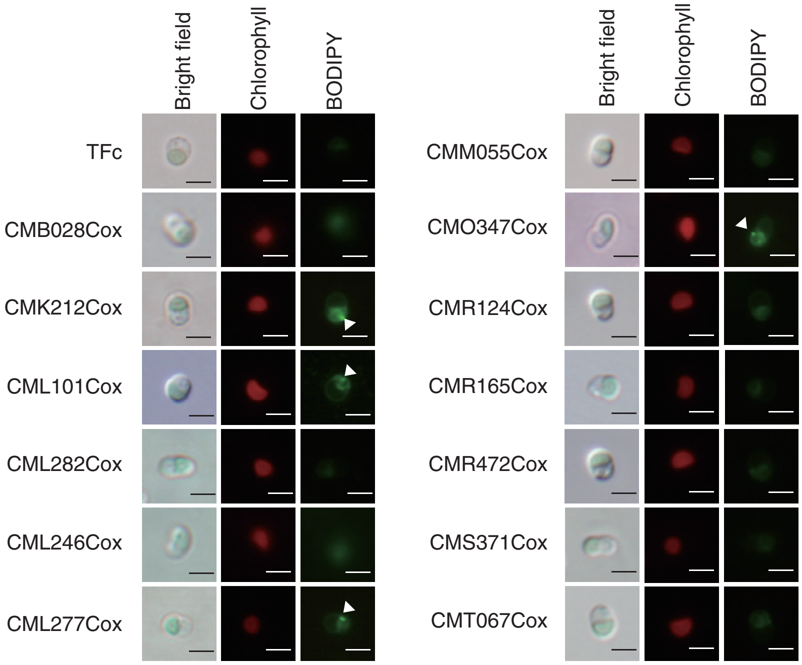


Fig. 3. Accumulation of lipid droplets by overexpression of each TF. (Figure modified from Takahashi et al. 2021)

3. Enhancement of LD formation and TAG accumulation by strengthening the function of TFs

If the 14 candidate TFs play critical roles in TAG accumulation in *C. merolae*, overexpression of each TF would potentially lead to an accumulation of cytoplasmic LDs that contain TAGs. To examine this possibility, we constructed overexpression strains for each candidate TF. It should be noted that the overexpression strain for CMT597C has not yet been successfully constructed. The reason is unknown, but it is conceivable that enhanced expression of the CMT597C protein may lead to cell death. Accordingly, CMT597C was excluded from subsequent analysis, leaving a total of 13 TFs included in the analysis (**Fig. 3**). The name of each overexpression strain is shown with "ox" after the gene number. For example, for CMB028C, the name of its overexpression strain is CMB028Cox.

Each of the generated overexpression strains was grown under normal culture conditions under which TAGs do not accumulate as the wild type, and the presence or absence of LD formation was determined. LDs were stained with BODIPY (4,4-difluoro-1,3,5,7-tetramethyl-4-bora-3a,4a-diaza-s-indacene), i.e., a fluorescent reagent for neutral lipids, and observed using a fluorescence microscope. The observation results indicate clear LD formation in the CMK212Cox, CML101Cox, CML277Cox, and CMO347Cox strains (Fig. 3, white arrowheads). Chlorophyll indicates the autofluorescence of chloroplasts, namely, the localization of chloroplasts, and scale bars indicate 2 µm. TAG accumulation in each strain was then measured using gas chromatography under the same conditions as when LD formation was observed. The results indicate that TAG accumulation in the CMK212Cox, CML101Cox, CML277Cox, and CMO347Cox strains significantly enhanced—2.2, 3.2, 3.8, and 2.7 times, respectively—compared with the control strain TFc (**Fig. 4**). These results indicate that these four TFs function positively in regard to TAG accumulation in *C. merolae*.

4. Comparison of expression levels of TAG and fatty-acid synthesis-related genes in CMK212Cox, CML101Cox, CML277Cox, and CMO347Cox strains

The results described in the previous section indicate that the increase in TAG accumulation due to overexpression of the four TFs strains (CMK212Cox, CML101Cox, CML277Cox, and CMO347Cox) is

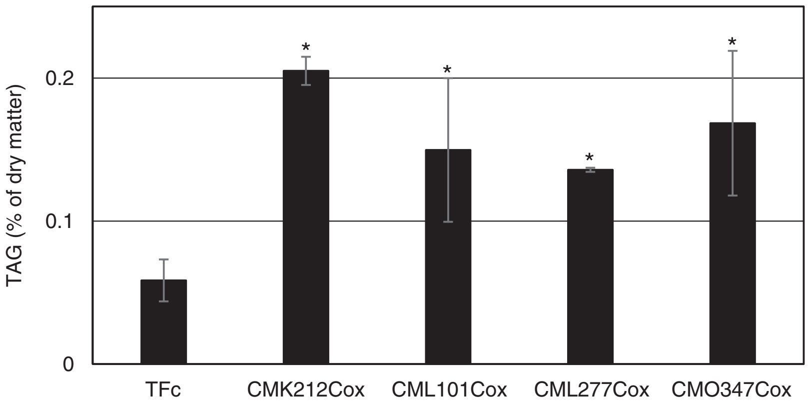


Fig. 4. Accumulation of TAGs induced by CMK212C, CML101C, CML277C, or CMO347C overexpression. (Figure modified from Takahashi et al. 2021)

Table 1. A list of the predicted fatty acid- and TAG synthesis-related genes and their expression ratios in CMK212Cox, CML101Cox, CML277Cox, and CMO347Cox strains.

Gene number*	Predicted enzyme	Ratio (vs TFc)			
		CMK212Cox	CML101Cox	CML277Cox	CMO347Cox
CMS299C	Biotin carboxylase, chloroplast precursor	0.9	1.2	1.5	1.2
CMT420C	Malonyl-CoA ACP transacylase	1.2	1.5	1.4	2.0
CMM286C	3-ketoacyl-ACP synthase	1.9	2.2	2.4	1.9
CML329C	3-ketoacyl-ACP synthase	1.0	1.0	1.0	1.0
CMD118C	3-ketoacyl-ACP synthase	0.9	1.4	1.1	1.5
CMS393C	3-keotacyl-ACP reductase	1.0	1.4	1.5	1.7
CMI240C	3-hydroxyacyll-ACP dehydratase	0.6	1.0	0.8	1.2
CMT381C	Enoyl-ACP reductase	1.3	1.5	1.6	1.6
CMJ027C	Glycerol-3-phosphate acyltransferase	1.1	1.5	1.9	2.1
CMA017C	Glycerol-3-phosphate acyltransferase	1.0	1.4	1.4	1.8
CMK217C	Glycerol-3-phosphate acyltransferase	1.1	1.2	1.3	2.1
CME109C	Lysophosphatidic acid acyltransferase	1.0	1.3	1.4	1.9
CMF185C	Lysophosphatidic acid acyltransferase	0.9	1.0	1.2	1.8
CMJ021C	Lysophosphatidic acid acyltransferase (LPAT1)	39.9	2.0	133.5	13.0
CMR054C	Phosphatidic acid phosphatase	0.8	1.2	1.7	1.6
CMR488C	Phosphatidic acid phosphatase	1.5	1.6	2.3	1.8
CMQ199C	Diacylglycerol acyltransferase	1.0	1.2	1.3	1.9
CME100C	Diacylglycerol acyltransferase	0.7	0.8	0.8	1.4
CMJ162C	Diacylglycerol acyltransferase	1.1	1.4	1.5	2.1
CMB069C	Diacylglycerol acyltransferase	1.1	1.3	2.4	1.9

* Gene number in C. *merolae* database, http://czon.jp
(Table modified from Takahashi et al. 2021)

caused by changes in the expression of genes regulated by those TFs, particularly a group of genes involved in TAG synthesis. Therefore, we conducted transcriptome analysis (using a next-generation sequencer) on ribonucleic acid (RNA) isolated from cells of each overexpression strain and control strain TFc under normal culture conditions. **Table 1** shows the variation in gene-expression ratios of the gene groups involved in synthesis of TAGs and synthesis of fatty acids, which are materials for TAG synthesis, with the relative value of TFc taken as 1. As shown in Table 1, only CMJ021C, which encodes lysophosphatidic acid acyltransferase (labelled "LPAT1" on the table), showed enhanced expression for all four overexpression strains, i.e., expression ratio increased (compared with that of TFc) 39.9 times for CMK212Cox, 2.0 times for CML101Cox, 133.5 times for CML277Cox, and 13.0 times for CMO347Cox. These results suggest that the TAG accumulation observed in the four overexpression strains may be

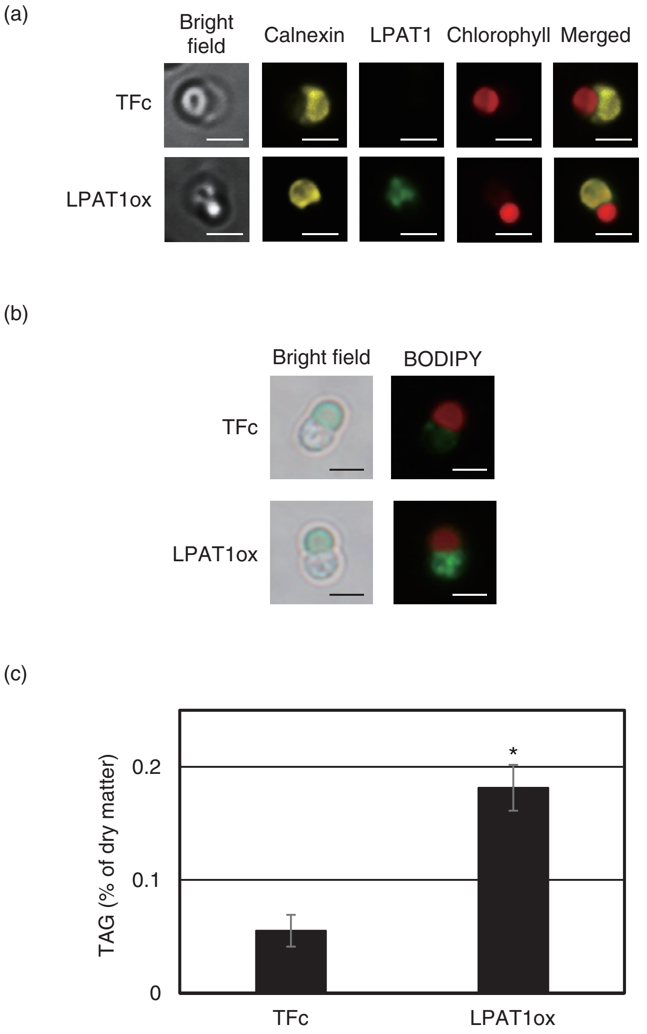


Fig. 5. Accumulation of TAGs by LPAT1 overexpression. (Figure modified from Takahashi et al. 2021)

due to increased expression of LPAT1.

5. Enhancement of LD formation and TAG accumulation by enhancing functionality of LPAT1

To investigate the role of *C. merolae* LPAT1 in TAG synthesis and its subcellular localization, we generated an overexpression strain of LPAT1, i.e., LPAT1ox. In accordance with the results of the immunostaining analysis shown in **Fig. 5(a)**, a signal derived from LPAT1 (green in the figure) was detected at the same location as calnexin (yellow in the figure) localized in the endoplasmic reticulum, which is the site of TAG synthesis. Chlorophyll (red in the figure) indicates chloroplast autofluorescence and chloroplast localization, and “Merged” is a superimposed image of the calnexin, LPAT1, and chlorophyll images in which the scale bar indicates 2 μm.

In accordance with the results of the analysis of LD formation and TAG accumulation in the LPAT1ox strain shown in **Figs. 5(b)** and **(c)**, respectively, LD formation enhanced, and TAG accumulation increased significantly (3.3 times compared with that for TFc). These results indicate that the reaction catalyzed by LPAT1, which localizes to the endoplasmic reticulum, is the rate-limiting step of TAG synthesis in *C. merolae* and is a key factor in TAG accumulation (**Fig. 6**).

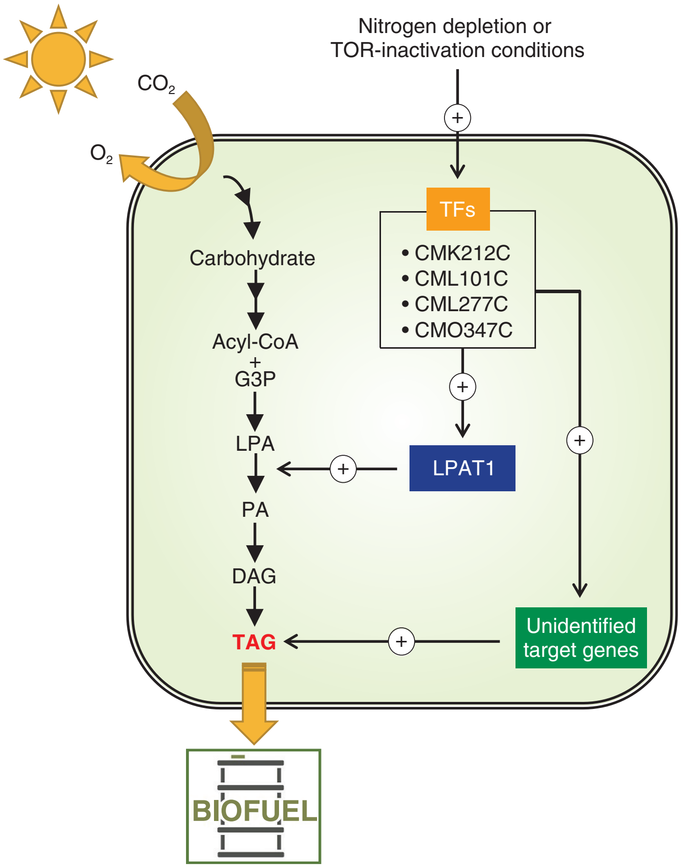


Fig. 6. Possible model for the regulation of TAG synthesis in *C. merolae*.

6. Conclusion and future directions

Analysis based on transcriptomic and phosphoproteomic data identified four TFs involved in TAG accumulation. No other large-scale analysis has identified multiple TFs involved in TAG accumulation in a single algal species. Moreover, the results of analyzing those target genes revealed that (i) LPAT1 localized in the endoplasmic reticulum and (ii) enhancement of its function enhanced accumulation of TAGs. On the basis of the above results, Fig. 6 shows a possible model in which G3P, LPA, PA, DAG, and TAG respectively stand for glycerol-3-phosphate, lysophosphatidic acid, phosphatidic acid, diacylglycerol, and triacylglycerol, and the circled + indicates a positive effect. Conditions under which TAG accumulates, such as -N conditions or inhibition of TOR activity, the expression of four TFs, CMK212C, CML101C, CML277C, and CMO347C, is enhanced, and subsequent upregulation of LPAT1 of their target genes leads to TAG accumulation [19].

Target genes other than LPAT1 of the four TFs (labelled “Unidentified target genes” in Fig. 6) are unknown at this time and should be further analyzed. Simultaneous enhancement of these genes (after they are revealed) in addition to the function of LPAT1 is expected to further enhance TAG accumulation. It is thus concluded that identification of TFs involved in TAG accumulation is an excellent strategy for increasing TAG content and will provide important information for biofuel production using microalgae.

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Recent Activities of QoE-related Standardization in ITU-T SG12

Yoichi Matsuo, Kazuhisa Yamagishi, and Masanori Koike

Abstract

This article introduces recent standardization activities related to the evaluation of the quality of experience (QoE) of speech, audiovisual, and other new services such as extended reality and chatbots, focusing on the activities of the Study Group 12 of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T SG12), which is responsible for standardization work on performance, quality of service, and QoE.

Keywords: quality of experience, adaptive bitrate streaming, extended reality, chatbots

1. ITU-T Study Group 12

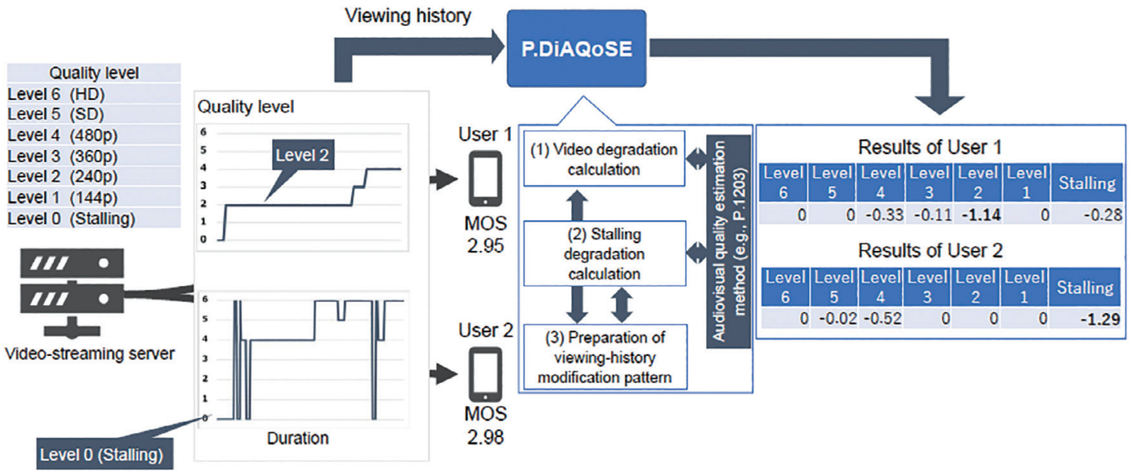
The Study Group 12 of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T SG12) is a lead SG on network performance, quality of service (QoS), and quality of experience (QoE) in the worldwide standardization of speech and video quality evaluation that takes into account achievements in regional standardization bodies such as ETSI (European Telecommunications Standards Institute) and ATIS (Alliance for Telecommunications Industry Solutions). Since standardization work is carried out in various standardization organizations regarding network performance parameters, all these organizations have confirmed that their work matches that of SG12.

2. Full-band and super-wideband E-model (G.107.2)

Recommendation G.107, called the E-model, has been standardized as a quality-planning tool for telephony services and is used worldwide. For instance, in Japan, JJ201.11, which specifies the quality of Internet Protocol (IP) telephony services, uses R values calculated on the basis of the E-model. In Question 15/12 (Parametric and E-model-based planning, prediction and monitoring of conversational speech quality), the extension of the E-model was studied for evaluating full-band (20 to 20,000 Hz) speech communication services, and the basic algorithm was standardized as Recommendation G.107.2 in 2019. As the next step, the revision of G.107.2 was studied for enabling the full-band E-model to be used under various conditions. Therefore, G.107.2 was revised by updating the calculation algorithm of the effective equipment impairment factor (le, eff), delay impairment factor (ld), basic signal-to-noise ratio (Ro), and simultaneous impairment factor (ls) so that it can handle background noise, burst packet loss, and delay.

3. Quality-estimation model and degradation-analysis procedure for adaptive bitrate streaming (P.1203, P.1204, and P.DiAQoSE)

For monitoring adaptive-bitrate-streaming quality, Recommendation P.1203, which specifies quality-monitoring techniques for high-definition resolution coded in H.264/AVC (Advanced Video Coding), and Recommendations P.1204.3, P.1204.4, and P.1204.5, which specify quality-monitoring techniques for 4K video and H.265/HEVC (High Efficiency Video Coding), have been standardized. Adaptive bitrate streaming using AV1 codec (AOMedia Video 1) has been increasing. Thus, the extension of P.1203 and P.1204 to support the new codec is being studied.



Results of User 1

Level 6	Level 5	Level 4	Level 3	Level 2	Level 1	Stalling
0	0	-0.33	-0.11	**-1.14**	0	-0.28

Results of User 2

Level 6	Level 5	Level 4	Level 3	Level 2	Level 1	Stalling
0	-0.02	-0.52	0	0	0	**-1.29**

HD: high definition
SD: standard definition

Fig. 1. Overview of P.DiAQoSE.

A procedure for interpreting the quality-degradation factors is also being studied for monitoring the adaptive-bitrate-streaming services (**Fig. 1**). A work item, P.DiAQoSE, calculates the degree to which quality parameters (i.e., bitrate, resolution, frame rate, and stalling information), which are inputs to audiovisual quality-estimation models such as P.1203, P.1204.3, P.1204.4, and P.1204.5, reduces the audiovisual quality estimated using audiovisual quality-estimation models. Specifically, the amount of degradation due to the quality parameters for a given session is calculated by distributing the difference between the maximum estimated audiovisual quality, which is calculated by selecting the highest quality parameters, and the current estimated audiovisual quality to each quality parameter on the basis of Shapley theory. In the example in Fig. 1, the mean opinion score (MOS) estimated by P.1203 for the video viewing of Users 1 and 2 are 2.95 and 2.98, respectively. However, when the degradation amount for each quality parameter is calculated using P.DiAQoSE, the MoS of User 1 is more affected by video-quality level 2, while the MOS of User 2 is significantly reduced by stalling. Thus, in addition to audiovisual quality-estimation models, the amount of degradation for each quality parameter makes it easier to take action to improve service quality.

4. Object-recognition-rate-estimation model in surveillance video of autonomous driving (P.obj-recog)

SAE International (formerly, Society of Automotive Engineers) defines six levels of automated driving, from Levels 0 to 5, depending on the driver and area where the vehicle can be driven [1]. For Level 2, a remote monitoring center detects objects on the basis of video from an in-vehicle camera and assists driving in emergency situations. In this service, an observer in a remote monitoring center checks for objects on the road on the basis of the video from the in-vehicle camera that is encoded and transmitted to the remote monitoring center. Therefore, the video quality transmitted from the in-vehicle camera should be clear enough for observers to recognize objects. To confirm that the video is always transmitted in sufficient quality for object recognition, P.obj-recog was launched as a work item to study a technique to derive the probability that an observer can recognize an object from the encoded video, as shown in **Fig. 2**. This will enable quality monitoring of video transmitted from in-vehicle cameras.

5. QoE factors for augmented reality services and objective quality-evaluation method for extended reality services (G.1036, PSTR-OQMXR)

Recommendation G.1036, which specifies QoE

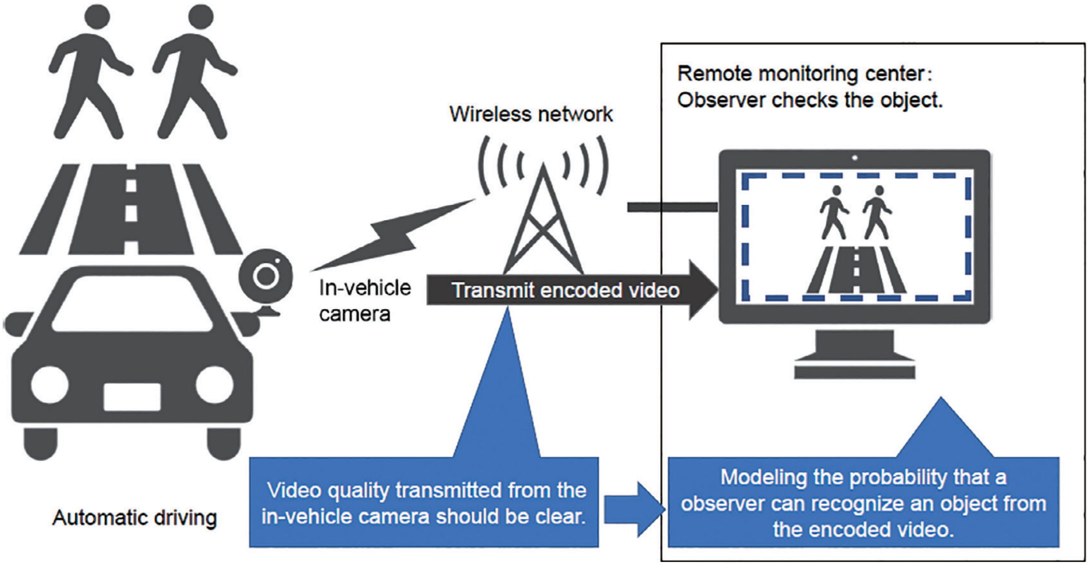


Fig. 2. Estimation method for object-recognition ratio in P.obj-recog.

factors for augmented reality (AR) services, was standardized to enable the evaluation of the quality of AR services. This Recommendation specifies QoE factors of two AR services that add objects around the user’s face and objects to the real space. In addition to quality-influencing factors used in conventional audio and video quality factors such as bitrate, resolution, frame rate, transmission delay, and device size, the factors related to the degree of integration between virtual objects and objects in the real space, such as detection performance of user faces and objects in the real space, and response performance of AR services are described. The quality related to the interaction between the user and AR service is also specified.

In addition, PSTR-OQMXR has been launched as a work item for a technical report on objective quality modelling for extended reality (XR) services. The purpose of this technical report is to identify the current status and issues of current objective quality-assessment methods for XR services as well as issues that need to be addressed to construct an estimation model.

6. Guidance for the development of machine-learning-based solutions for QoS/QoE prediction and network-performance management in telecommunication scenarios (P. 1402)

Recommendation P.1402, which specifies guidelines for applying machine-learning methods to the prediction of QoS/QoE, has been standardized, enabling machine-learning methods to be applied to studied work items in SG12. This Recommendation describes the basics of using machine learning, including how to construct training and evaluation data, categorization of machine-learning methods, and how to avoid over-fitting. Specific use cases, which are input/output examples and methods when machine learning is used for voice and video QoS/QoE prediction, are also described such as in the P.565 series.

7. Subjective quality evaluation of text-based chatbots (P.852)

Recommendation P.852, which specifies a subjective-quality-evaluation method for text-based chatbots, has been standardized. This Recommendation describes the quality factors for chatbots, which are overall impression, system information, system behavior, and user impression of the system. It also describes the subjective experiments for chatbots and the evaluation procedure.

8. Outlook

This article described subjective assessment and quality-estimation models for speech, video streaming, XR, and chatbots. SG12 has recently studied the extension of recommendations, such as support for a new codec for adaptive-bitrate-streaming services and revision of the full-band E-model. A study on the quality of transmitted monitoring video for automated driving services has also been launched.

Since various services are expected to be launched along with the deployment of the fifth-generation mobile communication system (5G)/6G, the design and management of QoS/QoE for various services should be considered. Therefore, it will be important to investigate the activities of SG12.

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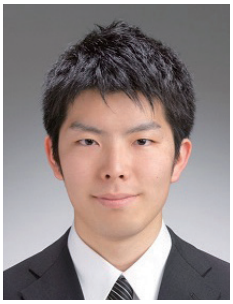

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Deterioration of Telecommunication Equipment and Facilities in Salt-damage Environments—Case Studies of Corrosion in Guy Wires and Maintenance Holes

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Abstract

This article presents examples of equipment and facility deterioration due to corrosion of guy wires and maintenance holes installed in coastal areas as well as examples of countermeasures to protect equipment and facilities from salt damage. This is the seventy-sixth article in a series on telecommunication technologies.

Keywords: salt damage, corrosion, maintenance hole

1. Introduction

NTT's telecommunication equipment and facilities are installed throughout Japan in a variety of natural environments. Metals, concrete, and plastics are used as materials for telecommunication equipment and facilities, which deteriorate over time due to the effects of the surrounding environment such as ultraviolet rays, rainwater, and seawater.

In response to requests from the field, the Technical Assistance and Support Center (TASC) has been investigating the causes of telecommunication failure due to salt damage in outdoor facilities and indoor equipment. Examples of equipment deterioration due to corrosion of guy wires and maintenance holes installed in coastal areas as well as examples of countermeasures to protect equipment and facilities from salt damage are presented in this article.

2. Factors causing salt damage

As shown in **Fig. 1**, salt damage, which is one of the causes of deterioration of materials, is a phenomenon by which particles of sea salt are blown into the air by strong winds and adhere to equipment containing metal, and the adhered salt accelerates the corrosion of that metal. Corrosion reactions caused by salt damage are accelerated by electrolytes containing salt, which increase electrical conductivity and facilitate the flow of the corrosion current. Since salt is hygroscopic, it absorbs moisture from the atmosphere and becomes wet, which increases risk of equipment corrosion. Since Japan has a long coastline, salt damage is an unavoidable phenomenon. Sea-salt particles originating from sea spray fall in coastal regions due to the limited distance they can travel, so the effects of salt damage are more pronounced on equipment closer to the shoreline, thus prematurely deteriorating the equipment.

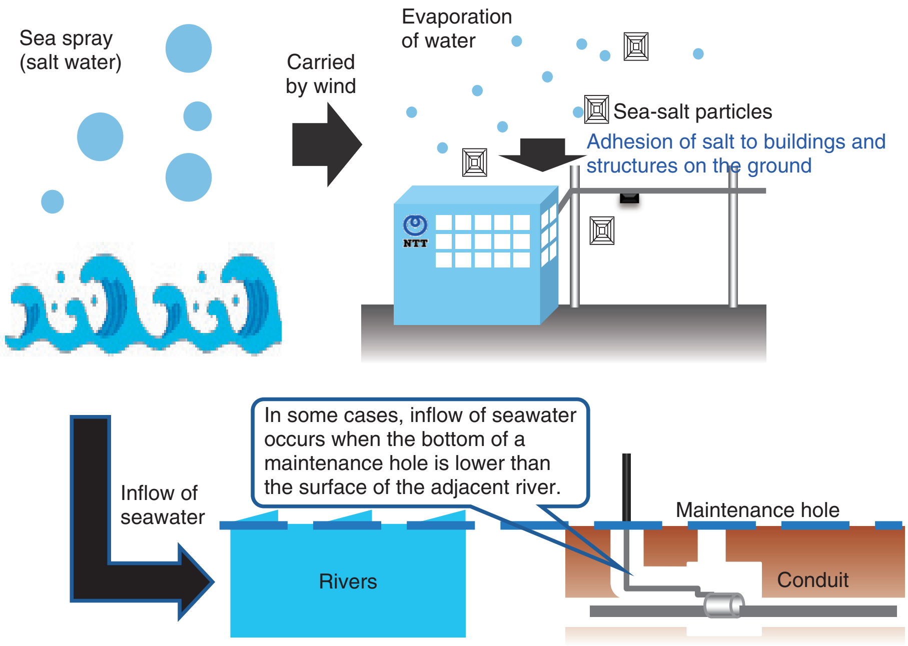


Fig. 1. Causes of salt damage (airborne salt and inflow of seawater).

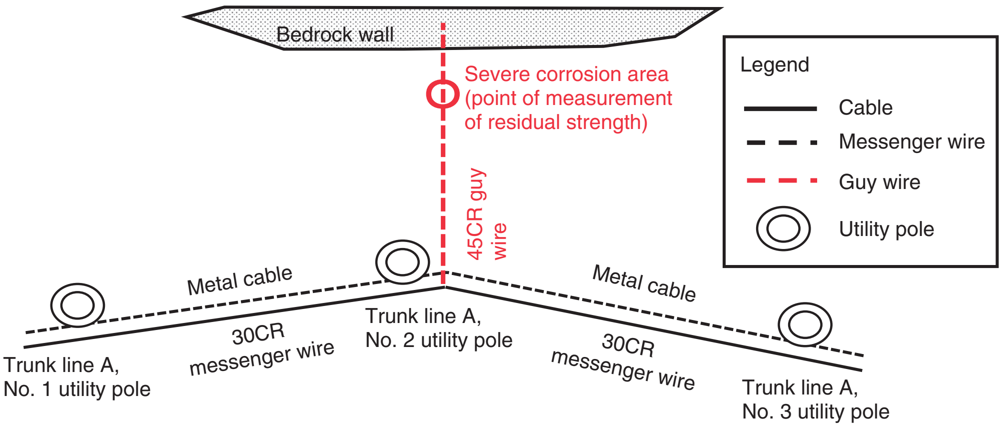


Fig. 2. Facility configuration.

3. Cases of equipment and facility deterioration due to salt damage

3.1 Corrosion of a guy wire due to salt damage

First, we present a case study of guy wire deterioration along the coastline. The middle part of a guy wire of a utility pole had significant corrosion. The guy wire is installed about 30 m from the sea, and the region is designated as a high-salt-damage area on a “salt-damage map” developed and provided by TASC [1, 2]. The configuration of the facility in this corrosion case is shown in **Fig. 2**.

3.1.1 Investigation method

We investigated the guy wire recovered from the site from two perspectives: (i) residual strength of the severe corrosion area and (ii) progress of corrosion in areas other than the severe corrosion area.

3.1.2 Results of investigation

The cross section of the severe corrosion area of the guy wire is shown in **Fig. 3**. We measured the residual

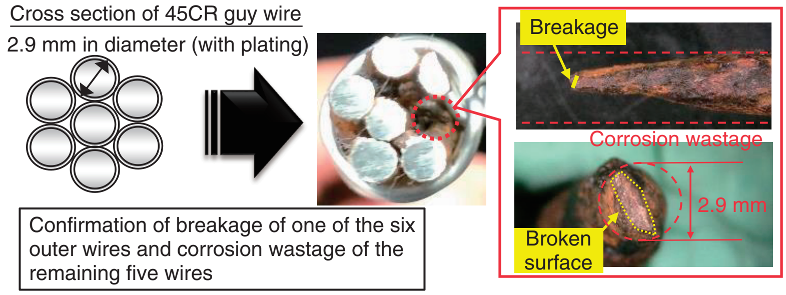


Fig. 3. Cross section of the severe corrosion area of the guy wire and the state of corrosion of the outer wires.

Table 1. Residual strength of wires of the severe corrosion area.

Target wire	Residual strength [kN]	Standard value [kN]	Degradation rate [%] (1 – residual strength / standard value × 100)
Outer wire (1)	2.8	8.1	–65
Outer wire (2)	2.8		–69
Outer wire (3)	2.6		–68
Outer wire (4)	1.8		–78
Outer wire (5)	1.4		–83
Outer wire (6)	0		–100
(Reference) Center wire	6.4		–21
Average residual strength of outer wires	1.9	–	–77

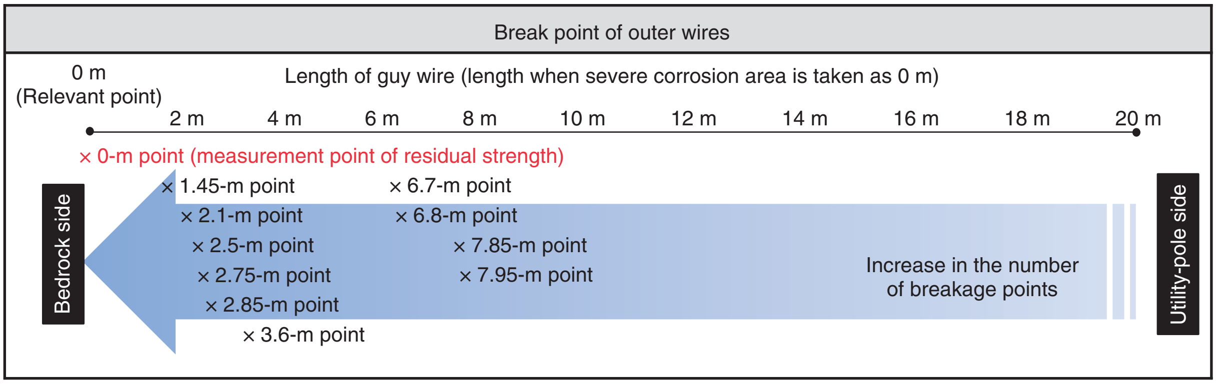
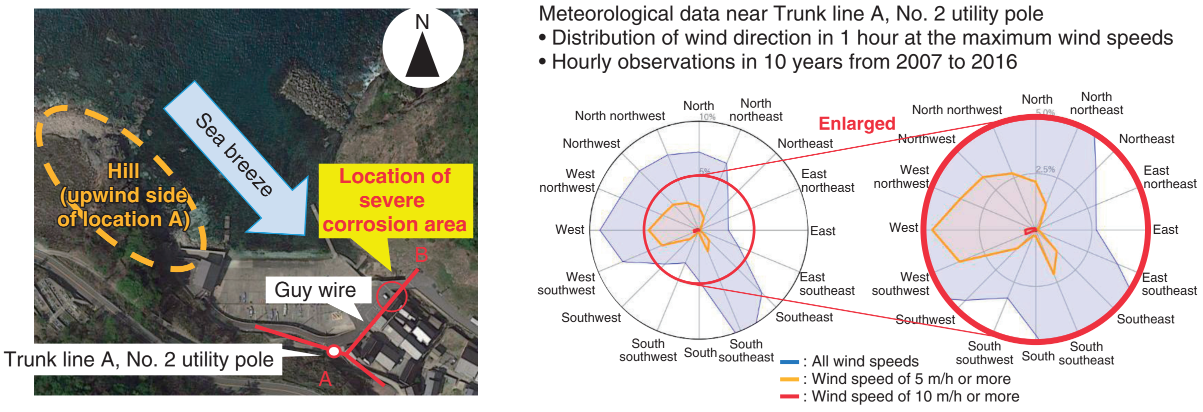


Fig. 4. Progression of corrosion in areas other than the severe corrosion area of the guy wire (partially broken outer wires: 11 locations in total).

strength of the wires within the guy wire. As listed in **Table 1**, the residual strength of the wires had decreased by an average of 77%. The progression of corrosion in areas other than the severe corrosion area is shown in **Fig. 4**, which shows the number of partially broken outer wires (“×” in the figure) increases from the utility-pole side to the bedrock side. This confirms that corrosion areas are more prevalent on the bedrock side than on the utility-pole side.



Meteorological data near Trunk line A, No. 2 utility pole
- Distribution of wind direction in 1 hour at the maximum wind speeds
- Hourly observations in 10 years from 2007 to 2016

(a) Aerial photograph

(b) Meteorological data (wind direction)

Fig. 5. Local aerial photograph and meteorological data (wind direction).

3.1.3 Estimation of the cause of corrosion and countermeasures

The reason that the guy wire had severe corrosion on the bedrock side but light corrosion on the utility-pole side was estimated as follows and illustrated in **Fig. 5(a)**. On the bedrock side, there are no obstacles blocking the air containing sea-salt particles above the sea from being carried by the sea breeze to the severe corrosion area of the guy wire. In other words, sea-salt particles in the air above the sea are blown in as they are. On the utility-pole side, however, the hill acts as an obstacle blocking the sea breeze and captures sea-salt particles blown in by the sea breeze. It can therefore be concluded that the difference in the corrosion state in those two sides of the guy wire is due to the difference in the amounts of sea-salt particles in the air blowing on those sides. This estimation is supported by the meteorological data (wind direction) shown in **Fig. 5(b)**, that is, the hill on the upwind side of location A is located in a position where it obstructs sea breeze from the most-frequent wind direction (northwest).

For a countermeasure against salt damage, it is first necessary to identify areas where corrosion progresses rapidly and requires careful inspection by referencing salt-damage maps, etc. Second, when conducting inspections, it is necessary to ensure that the entire facility is thoroughly inspected since the corrosion rate may vary—even for the same facility—owing to differences in environmental conditions such as wind exposure, which makes it possible to reliably detect unsafe equipment. When messenger wires and guy wires are renewed, implementing corrosion countermeasures such as replacement with products with stronger anti-corrosion treatment (e.g., powder coating [3]), as shown in **Fig. 6**, can be expected to extend the service life of equipment.

3.2 Metal corrosion in a maintenance hole due to salt damage

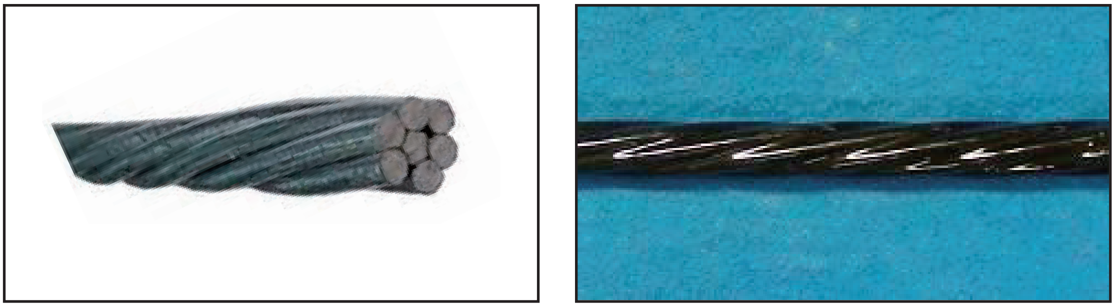
Cases of metal corrosion in a maintenance hole in a section located along a river are shown in **Fig. 7**. As shown in **Fig. 8**, the maintenance hole is located about 20 m from the river and about 400 m from the sea. It was previously confirmed that the bottom of the maintenance hole is 0 m above sea level or lower and that the water level inside the maintenance hole rises and falls due to the ebb and flow of the tide, so it was suspected that river water flows into the maintenance hole.

3.2.1 Investigation method

Water retained in the maintenance hole, corrosion fixtures, and river water were collected. Ion concentrations of the maintenance-hole water and river water were first analyzed by ion chromatography. The presence or absence of river-water inflow and the cause of corrosion were then analyzed by conducting X-ray structural analysis of the fixtures from the maintenance hole: mounting hardware with loose rust removed, a metal fixture with significant loose rust (metal-fixture adhering substance 1), and metal fixture with minor loose rust (metal-fixture adhering substance 2).

3.2.2 Results of investigation

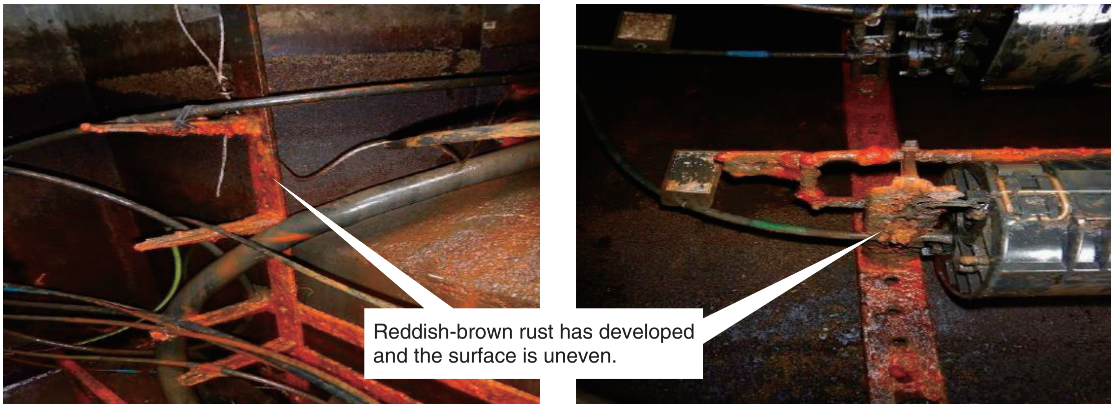
Regarding the analysis of ion concentration contained in maintenance-hole water and river water, as



Not powder coated

Powder coated

Fig. 6. Example of anti-corrosion measure for messenger wires and guy wires (powder-coated messenger wires).



Reddish-brown rust has developed and the surface is uneven.

Fig. 7. Appearance of metal corrosion on fixtures inside a maintenance hole.

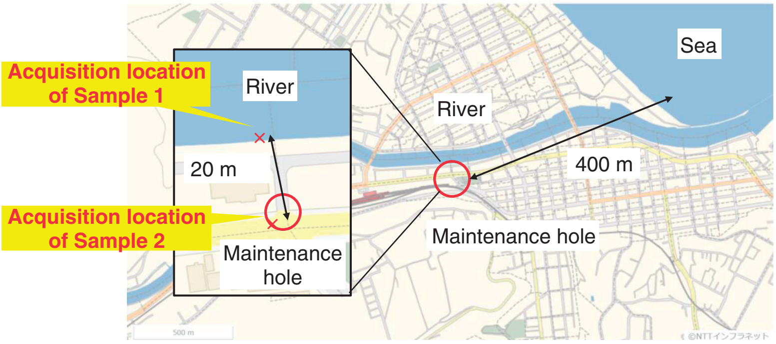


Fig. 8. Location of maintenance hole.

shown in the "Sample 1: river water" row in **Table 2**, high concentrations of chlorine and sodium ions were found in the river water. As shown in the "Sample 2: maintenance-hole water" row of the same table, the maintenance-hole water has higher concentrations of chloride and sodium ions than the maintenance-hole water from inland areas, which suggests inflow of river water into the maintenance hole.

Table 2. Ion concentrations in maintenance-hole water and river water [mg/L].

ID	Chlorine ions Cl^-	Sodium ions Na^+	Potassium ions K^+	Magnesium ions Mg^{2+}	Calcium ions Ca^{2+}
Sample 1: river water	4200	1800	140	220	78
Sample 2: maintenance-hole water	170	71	5.9	6.8	17
(Reference) Maintenance-hole water from inland areas	42	19	4.2	7.9	43
(Reference) Seawater	19000	11000	380	1300	11000

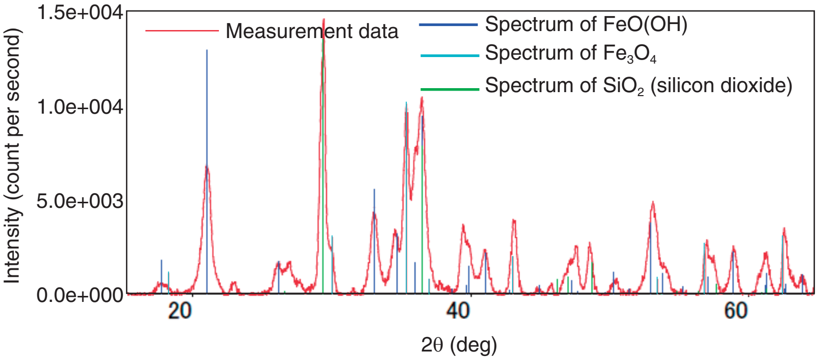


Fig. 9. Results of X-ray structural analysis of metal-fixture adhering substance 1.

The results of the X-ray structural analysis of the mounting hardware and metal-fixture adhering substances are shown in **Fig. 9**. They indicate that metal-fixture adhering substance 1 contains iron-corrosion products, indicated by peaks at the spectral positions of hydroxides (goethite: FeO(OH) and magnetite: Fe_3O_4), which are formed when iron corrodes. As shown in **Table 3**, the other samples (the mounting hardware and metal-fixture adhering substance 2) were confirmed to contain a hydroxide, FeO(OH), which is an iron-corrosion product. Since iron corrosion is accelerated as the concentration of chloride ions increases and FeO(OH) generates Fe_3O_4, the above results suggest the effect of salt damage.

Table 3. Identification results of X-ray structural analysis of mounting hardware and metal-fixture adhering substances.

Sample	Compounds
Mounting hardware	FeO(OH), SiO_2
Metal-fixture adhering substance 1	FeO(OH), Fe_3O_4, SiO_2
Metal-fixture adhering substance 2	FeO(OH), SiO_2

3.2.3 Estimation of the cause of corrosion and countermeasures

From the results of the above investigation, we estimated that salt-containing river water flowed into the maintenance hole and increased the salinity of the water retained in the maintenance hole, which in turn accelerated metal corrosion. Effective countermeasures against corrosion include (i) installing a stopcock in ducts (**Fig. 10**) to prevent inflow of seawater into the maintenance hole in question and surrounding maintenance holes in the same installation environment; (ii) replacing metal fixtures inside maintenance holes with ones that have powder coating [3] providing robust corrosion resistance (**Fig. 11**); and (iii) attaching a galvanic anode to the metal fixture, i.e., by connecting a metal with lower electrical potential than the metal of the target fixture, which sacrificially corrodes instead of the target fixture.

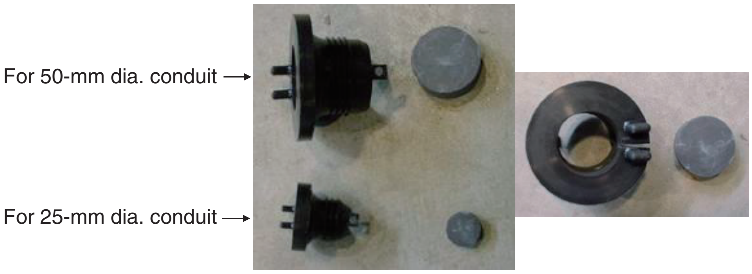


Fig. 10. Examples of stopcock.

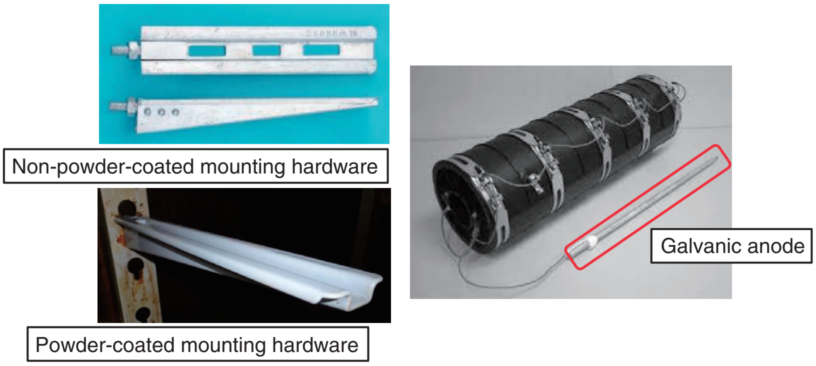


Fig. 11. Examples of corrosion countermeasures for metal fixtures.

4. Conclusion

We conclude by suggesting countermeasures to protect telecommunication equipment from corrosion caused by salt damage.

It is necessary to apply appropriate robust corrosion-resistant coatings because salt comes into direct contact with steel surfaces. It is also necessary to thoroughly inspect infrastructure equipment in accordance with the corrosion rate of the region while using salt-damage maps. For the interior of maintenance holes, it is necessary to prevent the inflow of salt-containing water from the outside and implement corrosion countermeasures for metal fixtures. Applying these countermeasures will prolong the service life of telecommunication equipment and facilities, especially in salt-affected regions along the coast.

TASC will continue to engage in technical cooperation to solve problems in the field, such as issues related to equipment and facility deterioration due to salt damage and other types of corrosion and contribute to improving the quality and reliability of telecommunication services.

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External Awards

Best Paper

Winner: Mehdi Tibouchi, NTT Social Informatics Laboratories
Date: December 6, 2022
Organization: The International Association for Cryptologic Research (IACR)

For "SWIFTEC: Shallue–van de Woestijne Indifferentiable Function to Elliptic Curves."
Published as: J. Chavez-Saab, F. Rodríguez-Henríquez, and M. Tibouchi, "SWIFTEC: Shallue–van de Woestijne Indifferentiable Function to Elliptic Curves," Advances in Cryptology – ASIACRYPT 2022, Lecture Notes in Computer Science, Vol. 13791, Springer, Cham. https://doi.org/10.1007/978-3-031-22963-3_3

AI2000 Most Influential Scholar Honorable Mention

Winner: Marc Delcroix, NTT Communication Science Laboratories
Date: February 24, 2023
Organization: AMiner, Tsinghua University

In recognition of outstanding and vibrant contributions in the field of speech recognition.

Electronics Society Activity Testimonial

Winner: Akihiro Kohno, NTT Device Technology Laboratories
Date: March 7, 2023
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Electronics Society

For contribution as a secretary of the Polymer Optical Components Technical Group Committee.

Electronics Society Activity Testimonial

Winner: Toru Segawa, NTT Device Technology Laboratories
Date: March 7, 2023
Organization: IEICE Electronics Society

For contribution to planning and management of IEICE Electronics Society.

Young Researcher's Award

Winner: Hideaki Kinsho, NTT Network Service Systems Laboratories
Date: March 9, 2023
Organization: IEICE

For "Proposal of a Method for Constructing a Throughput Estimation Model for Wireless Base Stations Based on Hierarchical Bayesian Model Considering the Number of Observations."
Published as: H. Kinsho and K. Takeshita, "Proposal of a Method for Constructing a Throughput Estimation Model for Wireless Base Stations Based on Hierarchical Bayesian Model Considering the Number of Observations," Proc. of the 2022 IEICE Society Conference, B-11-7, Virtual, Sept. 2022.

Young Scientist Presentation Award

Winner: Takuya Okamoto, NTT Basic Research Laboratories
Date: March 15, 2023
Organization: The Japan Society of Applied Physics (JSAP)

For "MHz-repetition-rate Generation of 1.7-cycle Intense Pulses Using an 80W Yb:KGW Laser."
Published as: T. Okamoto, Y. Kunihashi, Y. Shinohara, H. Sanada, M. Chen, and K. Oguri, "MHz-repetition-rate Generation of 1.7-cycle Intense Pulses Using an 80W Yb:KGW Laser," The 83rd JSAP Autumn Meeting 2022, 22p-C206-11, 2022.

Young Scientist Award for an Excellent Article

Winner: Ai Ikeda, NTT Basic Research Laboratories
Date: March 15, 2023
Organization: JSAP Superconductors Division

For "Designing Superlattices of Cuprates and Ferrites for Superconductivity."
Published as: A. Ikeda, Y. Krockenberger, Y. Taniyasu, and H. Yamamoto, "Designing Superlattices of Cuprates and Ferrites for Superconductivity," ACS Appl. Electron. Mater., Vol. 4, No. 6, pp. 2672–2681, 2022.

TELECOM System Technology Award

Winners: Takahiro Kashiwazaki, NTT Device Technology Laboratories; Taichi Yamashima, The University of Tokyo; Naoto Takanashi, The University of Tokyo; Asuka Inoue, NTT Device Technology Laboratories; Takeshi Umeki, NTT Device Technology Laboratories; Akira Furusawa, The University of Tokyo/Institute of Physical and Chemical Research
Date: March 22, 2023
Organization: The Telecommunications Advancement Foundation

For "Fabrication of Low-loss Quasi-single-mode PPLN Waveguide and Its Application to a Modularized Broadband High-level Squeezer."
Published as: T. Kashiwazaki, T. Yamashima, N. Takanashi, A. Inoue, T. Umeki, and A. Furusawa, "Fabrication of Low-loss Quasi-single-mode PPLN Waveguide and Its Application to a Modularized Broadband High-level Squeezer," Appl. Phys. Lett., Vol. 119, 251104, 2021.

Best Paper

Winners: Yosuke Todo, NTT Social Informatics Laboratories; Takanori Isobe, University of Hyogo
Date: March 22, 2023
Organization: IACR

For "Hybrid Code Lifting on Space-hard Block Ciphers: Application to Yoroi and SPNbox."
Published as: Y. Todo and T. Isobe, "Hybrid Code Lifting on Space-hard Block Ciphers: Application to Yoroi and SPNbox," IACR Trans. Symmetric Cryptol., Vol. 3, pp. 368–402, 2022. https://doi.org/10.46586/tosc.v2022.i3.368-402

Best Paper

Winners: Varun Maram, ETH Zurich; Keita Xagawa, NTT Social Informatics Laboratories
Date: March 26, 2023
Organization: IACR

For "Post-quantum Anonymity of Kyber."
Published as: V. Maram and K. Xagawa, "Post-quantum Anonymity of Kyber," Cryptology ePrint Archive, Paper 2022/1696, 2022.

CSEC Research Award

Winners: Fumihiro Kanei, NTT Social Informatics Laboratories; Ayako A. Hasegawa, National Institute of Information and Communications Technology; Eitaro Shioji, NTT Social Informatics Laboratories; Mitsuaki Akiyama, NTT Social Informatics Laboratories
Date: April 4, 2023
Organization: Information Processing Society of Japan (IPSJ) Computer Security Group (CSEC)

For "A Survey on Public and In-house Secure Development Guidelines in U.S. and Japanese Industries."
Published as: F. Kanei, A. A. Hasegawa, E. Shioji, and M. Akiyama, "A Survey on Public and In-house Secure Development Guidelines in U.S. and Japanese Industries," 100th CSEC Meeting, Mar. 2023.