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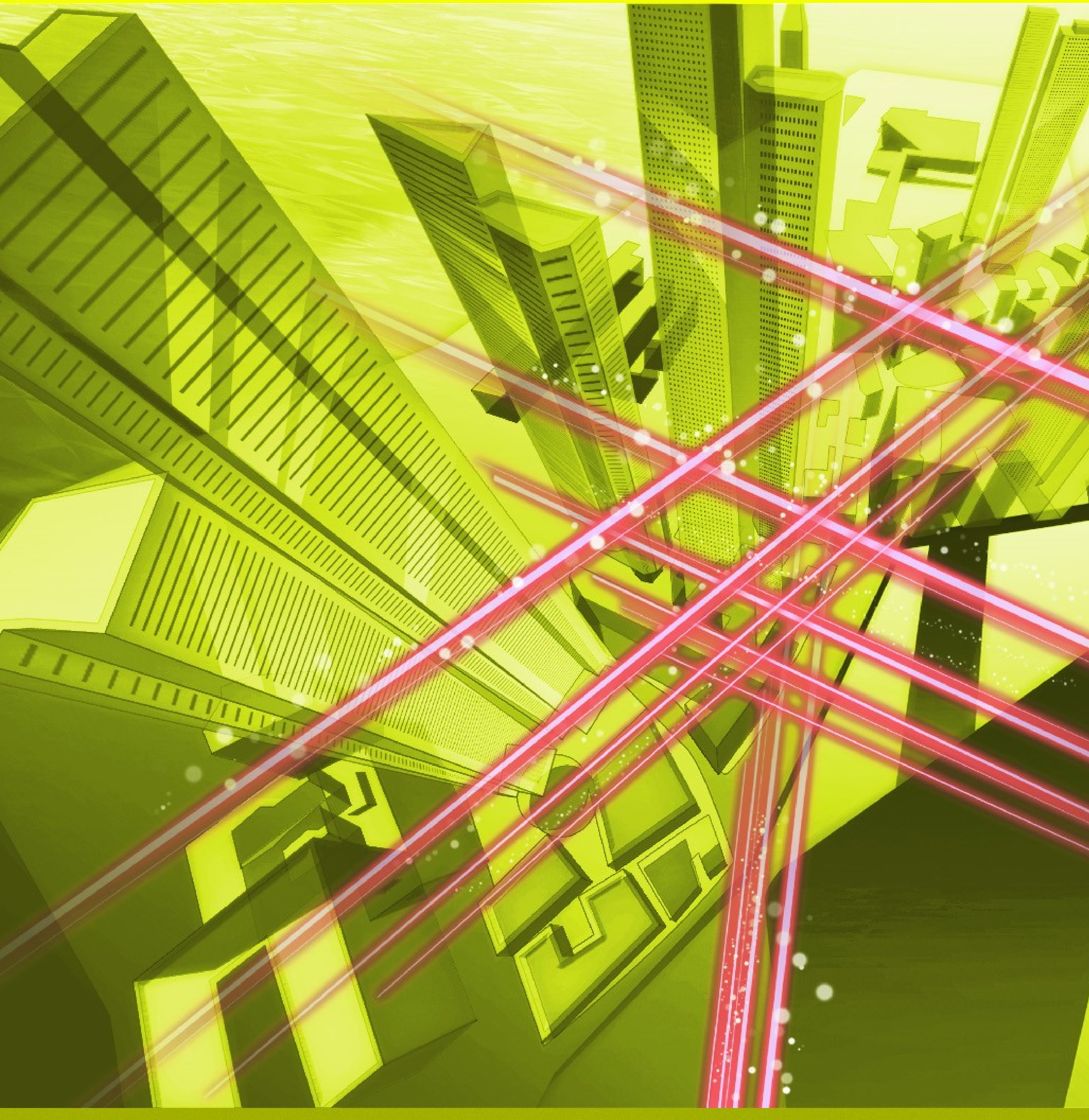

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Live Under the Same Roof and Pass Down Tacit Knowledge for NTT WEST to Become a Social ICT Pioneer

Teruyuki Kishimoto
Executive Vice President, NTT WEST

Overview

According to a survey conducted by the Tokyo Chamber of Commerce and Industry in early June during the novel coronavirus pandemic, 67.3% of small- and medium-sized enterprises based in Tokyo have implemented teleworking (remote working). Companies that have not yet introduced teleworking have cited changing internal systems and ensuring security as issues preventing implementing teleworking and have asked the government for support (relaxation of requirements for subsidy programs, expansion of target costs covered by such programs, etc.) and to provide usage examples of teleworking. We interviewed Teruyuki Kishimoto, executive vice president of NTT WEST, about how the company should respond to these needs and the outlook and attitude of the company, which has reached a turning point since its founding 20 years ago.

Keywords: ICT, remote-friendly, digital transformation

NTT WEST has achieved its highest profit since inception 20 years ago

—First, could you tell us about the current business environment concerning NTT WEST?

NTT WEST marked its 20th anniversary in July 2019, and achieved its highest operating profit since its founding, i.e., 132.2 billion yen, in fiscal year 2019 (April 1 2019 to March 31, 2020). I was delighted to welcome our 21st year with our employees who have worked together with the aim of pulling our company from the red at the time of our founding into the black.

In 2019, the G20 was held in Osaka, and disasters such as heavy rainfall and typhoons, mainly in Kyushu but also in other regions, stuck western Japan, our operating area. Under these circumstances, operating revenue has been declining mainly for land-line telephone services; however, the range of this decline is decreasing, and the long-awaited increase in revenue is close at hand. On top of that, our Hikari fiber-optic services exceeded our annual target for a net increase of 200,000 subscribers, i.e., increasing 220,000 subscribers, and, for the first time, corporate sales and new business fields accounted for more than half the total revenue. We were also able to reduce costs by thoroughly improving efficiency through digital transformation (DX). I believe that we have been able to achieve our highest profit thus far as a result of these company-wide efforts.

However, as we all know, the spread of the novel coronavirus is causing society as a whole to stagnate, and I think that many of our stakeholders are worrying about our financial results in the 2020 fiscal year. We can see into the future when a natural disaster will subside and the affected area will recover. However, the cause of anxiety differs regarding this pandemic in that we cannot see into the future because no one can predict, for example, how long the battle with the virus will last.

—Anxiety is certainly widespread today. How will NTT WEST handle this as a designated public institution under the Disaster Countermeasures Basic Act?

Under these difficult circumstances, we are striving to take the lead in solving social issues using the power of information and communication technology (ICT) to become a "social ICT pioneer." We will continue transforming ourselves to become a trusted company respected by the community and play a role as a "vitamin" that makes the community vibrant.

We are addressing people's anxiety by introducing three key phases. The first phase is "business continuity and safety." As a designated public institution, we have a mission to fulfill requests for improving the communication environment for accessing local government, companies, medical care, and public services even under today's difficult circumstances. It is also very important to balance that mission with due consideration for the health and anxiety of our employees. Regarding this balance, we put a system in place, which was prepared as a countermeasure against a new strain of influenza (H1N1) that spread about ten years ago. The present pandemic is the first time we have called upon this system, and we are working to maintain business continuity and the health and safety of our employees through measures such as introducing company-wide teleworking and staggered working hours.

The next phase is "recovery from confusion." In response to the resumption of social activities, we will endeavor to solve a variety of social problems based on the keywords "remote" and "online" by marshaling the products of the NTT WEST Group and assuming requests from customers to expand coverage. Moreover, I believe that these efforts will not only extend across the NTT WEST Group but will harness the power of the NTT Group, which will lead to optimizing the entire Group.

When I joined the company, I was at the forefront of my field. Frontline workers are needed when a disaster strikes or problems occur, and I feel that our

frontline employees are NTT's "face" for directly communicating with customers. The expectations that customers have toward NTT are high. With these experiences in mind, I think our important tasks are how we can do our best in the event of a disaster or other difficult situations and how we can fulfill our mission as a designated public institution. All departments and employees must also listen to customers and respond to their requests in the same manner as frontline employees.

The last phase is "growth." The reform of work styles and creation of a remote-friendly society—with a focus on the new normals of "during corona" and "after corona"—are ongoing. As remote working becomes more widespread, Japan's businesses, which are currently over-concentrated in Tokyo, will be dispersed. In this transitional era, the ICT infrastructure is considered to be the blood vessels of society. As well as providing traditional network services and solutions, through cybersecurity and other user support, we will strive to ensure that customers will be able to use our services safely and in a stress-free manner.

To give an example of our efforts, ELGANA, a business service that provides a secure business communication environment, enables an efficient way of working regardless of time and place. As of the end of June 2020, the number of subscriber identifiers registered for ELGANA has already exceeded 50,000. We are planning to enhance services that can meet a wide range of customer demands concerning, for example, safety and security, for promoting a remote-friendly society. The spread of the novel coronavirus is a crisis; however, we can think of it as taking up a new challenge.

How to attract loyal customers in a rapidly advancing society

—How is the new medium-term business plan being affected by the novel-coronavirus pandemic?

We are conducting business while taking steps to prevent the further spread of the novel coronavirus. In our New Year's in-house presentation, the trend in 2020 was compared to an ice-hockey stick. At the beginning of 2020, we considered ourselves at a point of an upturn, namely, the contact point between the shaft (handle) and the blade (the part that hits the puck) of the stick. Therefore, we started 2020 stating that we would like to follow that upward trend. Despite the unprecedented situation brought by the pandemic, I am convinced that we are steadily progressing to increase revenue.

Under our new medium-term business plan, we aim to achieve operating revenue of 1.5 trillion yen by 2025, an operating income ratio of 10%, and 10 million subscribers of Hikari fiber-optic services. The year 2020 is very important. First, to become a social ICT pioneer, we aim to be a trusted company that continues to be the choice of local customers. We will endeavor to contribute to making local communities "smart" (*smartization*) by focusing on customer success, that is, helping customers to achieve their business goals by carefully responding to their requests and challenges.

Ever more speed is now demanded, and progress is measured in seconds and minutes, rather than days. Therefore, the period from when we reform our work styles to improve efficiency to providing the results of that reform as a product use case to customers is shortening. We believe that if we can meet this demand swiftly, increased sales figures will follow. I think it is natural to provide solutions specialized for ICT and important to know how to add value to them and use conventional infrastructure. Moreover, the failure of communication equipment should theoretically occur once every ten years. However, natural disasters have been occurring one after another, and communications have been disrupted in the affected areas. If we don't take these types of problems affecting our customers seriously, customers will immediately become anti-NTT. However, if we work sincerely and improve, they will become loyal customers. Repairing equipment and fixing faults is one of our important successes, i.e., satisfying our customers. I'd like us to keep responding sincerely and gaining loyal customers regardless of the circumstances.

The important duty of decision and execution

—Could you tell us what is important to you as a senior manager in such an unprecedented situation?

I think all our employees and customers are worried. Although the sources of those worries are varied, I think it is important to try to dispel them. While the current situation is eliciting an emergency response, I think we should show them that we are moving toward the future beyond this emergency. The department concerning facility planning addresses matters from a long-term perspective and creating a grand design of telecommunication infrastructure. For example, the Innovative Optical and Wireless Network (IOWN) is aimed for commercial application in 2030, and the Osaka Expo, which will be held in 2025, will be a test case towards the commercial application of IOWN. The facility planning department is also required to improve efficiency. It will be necessary to streamline and simplify the large amount of equipment and facilities and switch to new services.

I believe that senior managers are required to create an environment in which employees can talk about their long-term goals while keeping practical necessities in mind.

To create such environments, we, senior managers, have two important duties, namely, decision and execution. You may not achieve 100% (i.e., perfection) in one go, or you may make a detour instead of taking the shortest distance. Even so, I feel that we need to make decisions and steadily implement them. I think that not only myself but all senior managers are solving problems at our respective managerial positions every day. For example, even if the medium-term business plan that we are currently working on takes us in the right direction, we may sometimes not be able to make judgements and decisions. I think it is my job to make those decisions and encourage others at such times. What's more, as I mentioned earlier, progress is accelerating, so rather than waiting to find the means to achieve 100%, I'd like to start with 50 or 60% and make fine adjustments through collective effort.

—Senior managers taking responsibility for decisions is assuring. How are bonds between you and department managers created?

To address the situation concerning the novel coronavirus, I have a conference call every day and a face-to-face meeting at least once a week. It is important for department managers to understand what is happening and share that knowledge. In fact, this morning's meeting followed what my superior was doing around 2011. I have also drawn on my experiences in projects such as the Kyushu-Okinawa Summit in 2000, and I'm glad that my colleagues who shared that past with me are leading the present, and my present colleagues have inherited that knowledge. To that end, I'd like to create an environment in which employees inspire each other. There is a saying, "live under the same roof," which expresses exactly what we are doing. Previous employees built telephone exchanges and pulled cables during the period of Japan's rapid growth (from 1954 to 1970). These facilities are about to be renewed. It is natural that the way of thinking back then and the way of thinking now differ. However, the process of technology migration requires understanding the thoughts and background concerning those days and drawing a grand design for the future. Goods, construction methods, and DX and other tools have all changed; however, the important things have not.

About 10 years ago, we established the Gold Meister system at NTT WEST to maintain a tradition of craftsmanship. That is because our senior employees have tacit knowledge and skills that match customers' businesses and the situation at work sites. However, they neither express such knowledge and skills in spoken word nor write them down. Therefore, we get our young employees to ask their seniors many questions so that tacit knowledge can be passed from person to person. Young employees absorb information like sponges, so they are better at responding to ever-changing technologies and services; therefore, I think that we are making good use of one another's characteristics.

Always keep your antenna up to spot social trends

—Please tell us what you want from researchers and engineers inside and outside the company.

You need to go out and see the world so that the Japanese/Chinese saying, "The frog in the well knows nothing of the great ocean (i.e., He that stays in the valley shall never get over the hill)" will not ring true. Technology has changed drastically since the land-line era. Even elementary-school students are making apps. In the era of open technological development, it is necessary to keep your antenna raised and know how companies and people other than telecommunications carriers are doing business.

NTT Group's basic research is our backbone. I hear from many customers that this research is "fantastic." I feel that we can provide customers with products and services with confidence thanks to the efforts of our research laboratories. In 2020, NTT WEST established a technology strategy with the following five pillars: (i) further promotion of local business, (ii) promotion of DX/data-utilization business, (iii) promotion of carrier's carrier business, (iv) initiatives for the IOWN era, and (v) initiatives for the migration from the public switched telephone network to the Internet protocol network.

We are an operating company, so our role is not just selling our products but also ensuring our products be used properly and will not easily fail. Even if our products fail, it is important to keep the repair time as short as possible through remote support. I'd like you to pursue technological development that supports our core operations and maintenance work while advancing the research that supports troubleshooting. I'd also like researchers of the NTT Group to continue their efforts to overcome the global competition in research and development (R&D). I'd also like to see these efforts organically connected and develop into a business.

Since research and telecommunication are advancing rapidly, I want to make a road map and work on what to do next and with whom to form alliances by interacting with the outside world and understanding social trends. I believe that setting goals and running towards them will certainly lead to further trust in the NTT Group and organically connecting our business with R&D.

Interviewee profile

■ Career highlights

Teruyuki Kishimoto joined NTT in 1986 and became president and CEO of NTT Field Techno in 2014. In 2017, he became a member of the board of NTT WEST, senior executive manager of Kansai Regional Headquarters, and general manager of the Osaka Branch. He has been executive vice president and concurrently executive manager of Network Department, Plant Headquarters since June 2019.

Sharing Moments of "This Is It!" with Colleagues to Research and Develop Optical Communication Technology for Revolutionizing Society

Yutaka Miyamoto
NTT Fellow, NTT Network Innovation Laboratories

Overview
The development of information and communication technology (ICT) has revolutionized people's social lives. Amidst the current unprecedented situation due to the worldwide spread of the novel coronavirus, services and applications that use ICT, such as teleworking and online diagnosis, have been supporting people's lives and economic activities. According to the White Paper on Information and Communications in Japan issued by the Ministry of Internal Affairs and Communications, the number of Internet-of-Things devices installed worldwide is said to reach 40 billion in a few years. We asked NTT Fellow Yutaka Miyamoto, NTT Network Innovation Laboratories, about his research and development on the optical communication infrastructure that supports these ICT services and application and path to its practical application and his attitude as a researcher.

Keywords: high-capacity optical communication, capacity crunch, scalable optical-communication technology

Challenge to overcome the capacity crunch

—Please tell us about the research you are currently undertaking.

NTT has been a world leader in the research and development (R&D) of optical communication technology. We started practical application of time-division multiplexing (TDM) optical-fiber transmission systems in 1981. By triggering three paradigm shifts concerning optical transport systems, namely, the development of optically amplified transmission systems, wavelength-division-multiplexing (WDM) systems, and digital coherent systems, we have increased transmission capacity by about 10^6 times over the past 40 years. The amount of data traffic continues to increase at an annual growth rate of

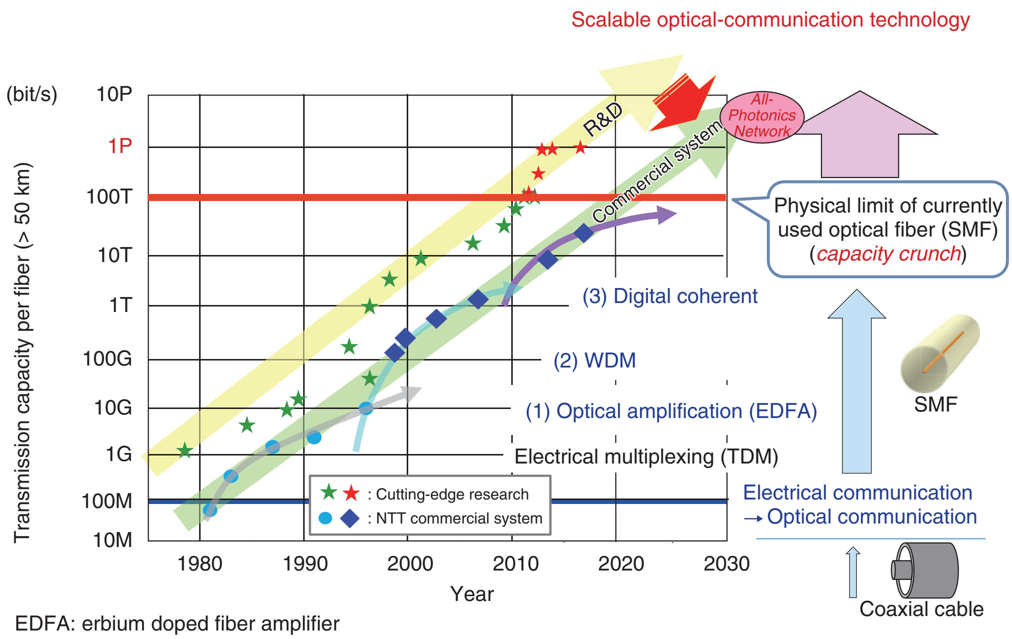

Fig. 1. Challenge to overcome the capacity crunch by using scalable optical-communication technology.

about 1.4 times, and as the full-scale introduction of fifth-generation mobile communication systems (5G) and the Internet of Things progresses, it is expected to continue to increase exponentially [1].

A high-capacity WDM system using digital coherent detection with a channel capacity of 100 to 400 gigabits per second (Gbit/s) per wavelength has recently been developed and installed in our network, enabling high-capacity long-distance transmission with the total system capacity of 8 terabits per second (Tbit/s) via a single fiber [2, 3]. Through further upgrading of the digital coherent system, a channel capacity of 600-Gbit/s per wavelength will soon be commercially available. It is expected that high-speed transmission exceeding 1 Tbit/s per wavelength will be achieved by pursuing cutting-edge R&D [3, 4].

If the development of the optical-communication infrastructure over the next 10 years is predicted based on the trend concerning commercial systems shown in **Fig. 1**, it becomes clear that long-distance transmission with petabit-per-second (Pbit/s)-class capacity will be required by the 2030s. According to recent research, however, the ultimate physical limit of transmission capacity in long-distance transmission using an installed optical fiber, that is, single-mode fiber (SMF), has become apparent near 100 Tbit/s—the so-called *capacity crunch*. The R&D that we are conducting to overcome this capacity crunch and create a petabit-class optical communication infrastructure that can economically accommodate 100 times or more the current data traffic while ensuring low power consumption is called *scalable optical-communication technology* [1]. To achieve this, I believe that we must pursue technological innovation that combines the optical transmission technology that we have been developing with new transmission medium technology (optical fiber). In other words, a *fourth paradigm shift* is necessary.

As an example of such R&D, working closely with the optical materials and devices research group at NTT, we are researching a space-division multiplexing (SDM) optical-communication technology that can increase transmission capacity per optical fiber exceeding 1 Pbit/s, which is more than 125 times that of a practical system using SMF. In 2012, in collaboration with domestic and overseas research institutes, we experimentally demonstrated a transmission capacity of 84 Tbit/s per core, namely, transmitting optical signals at 1.01 Pbit/s per fiber (i.e., 84 Tbit/s × 12 cores) over 52.4 km. This was the world's first 1-Pbit/s transmission experiment by using a multicore fiber (MCF) housing with 12 cores (i.e., paths of optical signals transmitted within the optical fiber) in one optical fiber and by wavelength multiplexing 32 quadrature-amplitude modulation (32QAM) signals

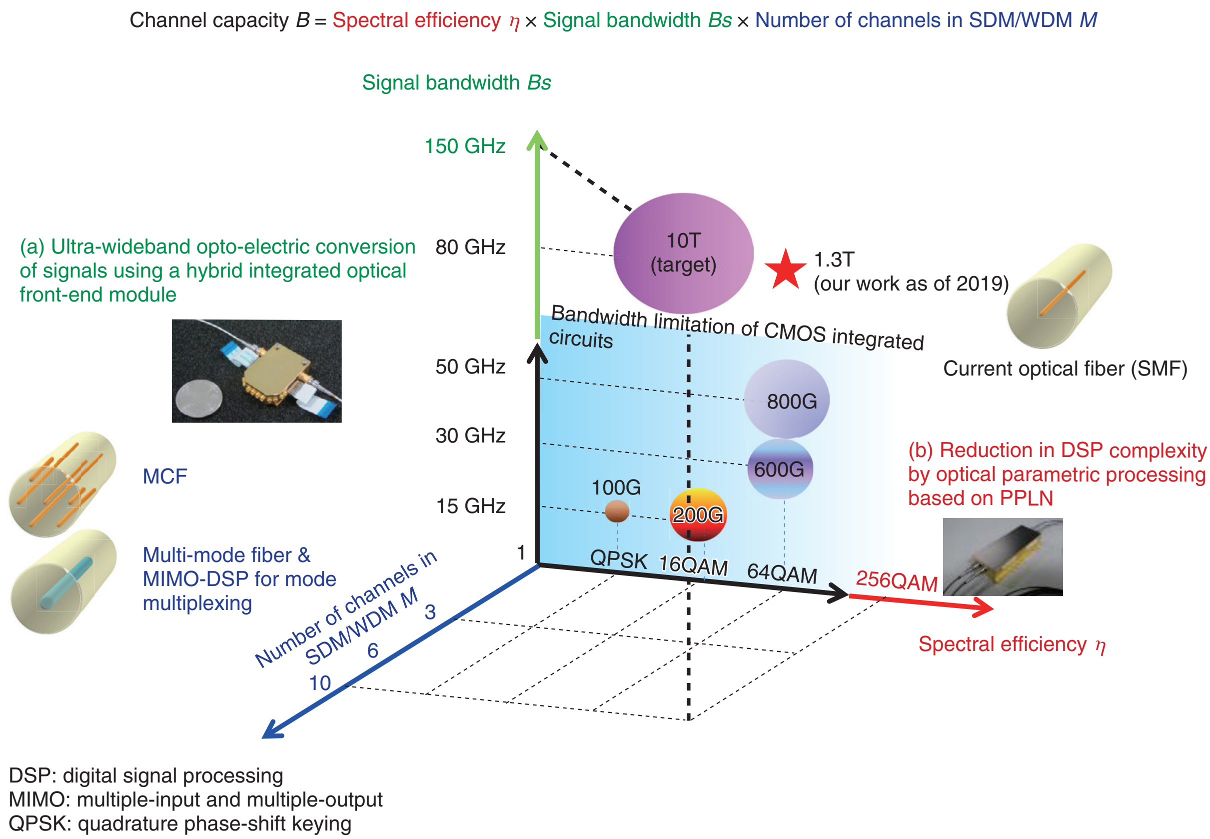

Fig. 2. Efforts to achieve 10-Tbit/s capacity per channel.

(an advanced higher-order QAM digital-coherent technology). In 2017, we confirmed the feasibility of a long-distance optically amplified transmission system over 1000 km at 1 Pbit/s using a 32-core MCF (Fig. 1).

To increase transmission capacity per wavelength (channel capacity), we are working closely with the device research group at NTT toward optical-transmission technology with 10-Tbit/s-class channel capacity. For example, by using SMF, we demonstrated the world's first long-distance WDM transmission system with a channel capacity of 1 Tbit/s, which has been difficult to achieve with conventional silicon complementary metal oxide semiconductor (CMOS) circuits and device-packaging technology. In 2019, on the basis of a new opto-electronic integrated configuration of an ultrahigh-speed optical transceiver front-end circuit, we successfully demonstrated a long-distance WDM transmission system with the world's fastest channel capacity of 1.3 Tbit/s. This was enabled by integrating an analog-multiplexer integrated circuit (AMUX IC) (with bandwidth over 100 GHz) and a broadband indium phosphide (InP) semiconductor modulator into an optical front-end module (**Fig. 2(a)**).

We are also researching and developing optical parametric amplification technologies based on periodically poled lithium niobate (PPLN) that NTT laboratories have been developing over several years. These technologies dramatically reduce the complexity of digital signal processing and significantly enhance the bandwidth of optical amplification and wavelength conversion, which are difficult to accomplish with conventional technologies only (**Fig. 2(b)**).

—You have been producing world-first achievements. Do you feel that you are driving trends and are on the cutting edge?

I feel that we have somehow caught up with the times. For the optical communication infrastructure we have been researching and developing at NTT (Fig. 1), it took about 10 years from the time target performance was first experimentally verified (yellow line) in the R&D stage until systems were installed in commercial networks (green line). The reason that so much time is needed is that once the optical communication infrastructure is introduced, it must be maintained and operated over a system life of 10 years or more. In other words, it cannot be removed immediately once installed, so careful consideration is required. During global competition in the advanced-research phase when the target performance was experimentally demonstrated for the first time was when we developed a method for achieving the desired performance. Since communication systems cannot be created with one elemental technology, researchers devise various elemental technologies during the first half of the decade and repeatedly test the system performance of various combinations of such technologies. In the later practical-application phase, through various efforts such as (i) determining which combination of elemental technologies can withstand the economic and reliability requirements and (ii) investigating the possibility of internationally standardizing the necessary components of the system while finding a development partner, we will continue to select our technology candidates. Through these considerations, we have put the selected technologies into practical use. Technologies that survive the original idea to be put to practical use account for about 20 to 30% of the technologies we are researching; the remainder have been shelved. To reach the final goal of practical application, it is therefore always important to have multiple technology portfolios regarding system development.

Various optical communication technologies developed for telecoms have recently started to be introduced into datacenters of corporations such as GAFA (Google, Apple, Facebook, and Amazon), who demand performance from a different perspective than telecom applications. Since the life cycle of technologies for these corporations is short and the approach to maintenance and operation differs significantly, the performance required by R&D and the speed of R&D are also changing significantly. In other words, R&D that matches the changing times is needed.

Interestingly, I feel that the optical communication infrastructure and new information services are developing in a balanced relationship, like a chicken-and-egg situation. I joined NTT in 1988, when the telecommunication infrastructure mainly carried telephone traffic. At that time, the paradigm shift in optical communication systems using optical amplification technology began. I was fortunate to be able to engage in R&D and practical application of a long-distance optically amplified transmission system with a total capacity of 10 Gbit/s using one wavelength per optical fiber. When such transmission was first installed in a practical network in 1996, some people said that its capacity was too large for telephone traffic and it might be unnecessary to expand that capacity further. However, in the late 1990s, as the spread of the commercial Internet in Japan accelerated, Internet providers were appearing one after another, and we entered an era in which transmission capacity was insufficient, even in regional networks. Under those circumstances, 10-Gbit/s optical-communication infrastructure was quickly introduced throughout Japan and spread globally. I have had many similar experiences. The era of using smartphones as a matter of course has recently arrived, and to adequately accommodate the demands concerning data traffic on the mobile Internet, the 100-Gbit/s per wavelength optical communication infrastructure using the digital coherent technology I mentioned earlier was deployed in a timely manner. With the spread of 5G services, which started commercial services in 2020 in Japan, it is assumed that the transmission capacity will be insufficient again as new services and industries are created. Therefore, I believe it is necessary to continue our R&D to provide the communication infrastructure required by society of a particular time.

Thus far, I couldn't have predicted all the technological trends that I mentioned above. Rather, by perpetuating the R&D cycle and practical application of transmission systems that satisfy the current required performance, we were able to catch up with current performance demands. I think that the reward of continuing this R&D cycle and practical application is being able to feel the huge impact that these practical optical fiber communication technologies have on society. For example, due to the novel coronavirus pandemic, this interview is being conducted via a web conference. Such real-time video communication, which many people now take for granted, was unthinkable a short while ago. The importance of the telecommunications infrastructure is emphasized in the event of such a sudden pandemic or natural disaster, but this infrastructure cannot evolve overnight. Therefore, it is necessary to work diligently in responding to development and future social infrastructure needs. I believe that only through steady R&D can we provide technology that meets people's expectations in a timely manner.

Timely R&D, practical application, and converting irrational ideas into common sense are required

—You have focused on creating robust technology that can quickly meet the needs of the society of a particular time. How did you actually feel on becoming an NTT Fellow? And please tell us what you have valued in your research.

Playing my part to prevent the spread of the novel coronavirus, I've been working from home, so I haven't really felt much about being an NTT Fellow yet. I think that what NTT laboratories have been constantly pursuing as a world leader on the cutting edge from before I joined until now can be condensed in the sentence, "Let's conduct research by drawing from the fountain of knowledge and providing specific benefits to society through practical applications" by Goro Yoshida, the first director of the Electrical Communication Laboratory of Nippon Telegram and Telephone Public Corporation (currently NTT).

In other words, I think this mantra has been passed from generation to generation by mobilizing all kinds of "intellectual fountains" of NTT laboratories while continuing the R&D cycle and practical application that I have talked about. I think that one of my roles as an NTT Fellow is to receive the baton that has passed the fountain of knowledge from which ideas and knowledge spring up like water from a fountain to the next generation through everyday R&D.

In the R&D cycle and practical application, common problems are identified in the first phase of R&D and many irrational ideas are brought to light. Then, the next practical phase is the act of selecting the idea with outstanding practicality and converting what was born from an irrational idea into common sense. By continuously repeating this process, we accumulate knowledge and ideas, creating the next ideas and insights, that is, it becomes a fountain of knowledge. I think it is important to develop and accumulate ideas and knowledge in this manner so that they do not wither. The words of Goro Yoshida I mentioned above are a kind of motto to me as a researcher, and as an NTT Fellow, I think they will be a guide for me to lead the people around me and implement ideas.

I remember that when I joined NTT, my superiors taught me that the Japanese Kanji character "chi" has two meanings. One is knowledge and the other is wisdom. Although I didn't really understand it at that time, as I gained experience, I finally came to understand that knowledge is an insight into various fields and wisdom is how to use that insight. As new people enter your team, new knowledge will flow in. I think making that knowledge into something useful depends on wisdom to apply that knowledge in a timely manner in accordance with the demands of the times. When we are engaged in R&D and practical application while confronting the times and the trends in technology, there are moments when we feel the inspiration of wisdom and shout, "This is it!" Although it is very difficult to express this feeling in words, I think it is very important to not let such moments get away and to focus on them. In my case, I've experienced the process from R&D to practical application about three times, and within those experiences, I've had moments in which I shared the feeling of "This is it!" with my research colleagues. This moment is exactly like when the fountain of knowledge is gushing. That is, we can share our goals and values only by repeating trial and error through daily experiments and commercialization efforts together with colleagues involved in the same R&D, and we can feel that wisdom resonate between us through the phrases, "This is it!" and "That's right!" I want to proceed with R&D by sharing such moments with as many colleagues and development partners as possible.

About five years ago, I had the opportunity to collaborate with an overseas R&D partner. I experienced that how Japanese people communicate with each other did not work in such a collaborative situation. At that time, I wondered how to handle such a situation and realized that no matter what country the partner is from, the key to success is to share the same goals and express them clearly in words. Even if there are conflicting opinions, if you can share your goals and values, you can return to the basics and overcome those conflicts.

In the early 2000s, by applying communication methods (e.g., error-correction codes and differential phase modulation) that use the properties of light waves, we experimentally demonstrated the world's first long-distance WDM transmission with a capacity of 43 Gbit/s per wavelength. However, while conducting field investigations at the practical-development stage, we discovered that sufficient performance could not be secured with a combination of elemental technologies we prepared at the beginning. Under this circumstance and to meet the performance required by a practical system, we were forced to develop additional elemental technologies.

At that time, I was the project leader for the development of signal-processing large-scale integrated circuits (LSIs) for optical transport networks, but I was pretty much overwhelmed by this situation. Even so, we managed to launch elemental technology prepared as future technology ahead of schedule and put it to practical use. In the real world, it is impossible to predict what will happen, and many things cannot be understood without actually measuring them in a real environment. It is often the case that certain tasks cannot be done by one person alone; however, I had the experience that I could somehow reach my goal even at such times if the technology portfolio was prepared. I think that having the courage to take the next step in difficult situations and overcoming various difficulties faced thus far has stemmed from being able to make the right decisions by sharing objectives and wisdom with many outstanding colleagues and development partners and resonating with them through the phrases, "This is it!" and "That's right!".

To make a calm decision even in such a difficult situation, it is sometimes important to rest the mind and body to keep your feeling fresh. As I mentioned above, I often feel run down when I don't get the desired results, so I may not be able to proceed without resetting my mind. For that reason, I think it's good to have your own reset mechanism, such as hobbies and meditation. I enjoy appreciating art. Above all, I like Rene Magritte's "The Large Family." In addition, Samuel Ullman's timeless poetic masterpiece "Youth" gives me courage. A friend read me the following line from that poem, "In the center of your heart and my heart there is a wireless station; so long as it receives messages of beauty, hope, cheer, courage and power from men and from the Infinite, so long are you young." As a researcher of telecommunications technology, I'm moved by the fact that the author uses an expression associated with wireless communication, namely, a "wireless station" of the heart. When that poem was written about 100 years ago, it was just before the first practical use of wireless communication enabling transoceanic communication, and it was the first time a maritime disaster—the sinking of the Titanic—was wirelessly detected in the middle of the Atlantic Ocean, so lives were probably saved by this first use of wireless technology. Knowing the importance of wireless communication, which enabled global real-time communication for the first time, was recognized around the world and used as a metaphor for works of art, I believe that telecommunications technology can have a huge impact on society and people's minds in any period and am encouraged every time I read that poem.

—Would you say a word or two to our young researchers?

As a researcher at NTT laboratories, I feel that although the time spent on one research theme may seem long, it is actually short. I really hope that by making the best use of the various intellectual fountains unique to NTT laboratories and using your time well, you will strive to come across research themes that only you can pursue. I believe that if you continue to make that effort, you will surely meet the moment when you say, "This is it!" Since I was assigned to NTT laboratories, I have delved into the research theme of optical communication systems, which was a completely different field from my specialty as a student. At first, I sometimes got depressed because I couldn't participate in any discussions but I continued trying and encountered challenging research themes. When such an opportunity arises, I want you to do your best to tackle the technical challenges that you will face.

I believe that one of the missions of researchers in the field of system development for corporations is to create something useful for the world while balancing R&D and practical application. In particular, R&D on communication systems cannot be done by one person because of the wide variety of elemental technologies. The happiest time for researchers is when they reach their goals. I'd like to experience such times with outstanding partners and colleagues, and I'd like all researchers who are taking up challenges in new fields to experience that happiness over and over again. As I said before, technology concerning social infrastructure is critical, and its importance is highlighted in times of emergency; however, it usually goes unnoticed. It takes ten years for time-appropriate technological development to be put into practical use. Although such development does not receive much attention, it is important to continue it, so I'll do my best to do so.

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■ **Interviewee profile**

Yutaka Miyamoto

NTT Fellow, Director, Innovative Photonic Network Research Center, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in electrical engineering from Waseda University, Tokyo, in 1986 and 1988, and a Dr. Eng. from the University of Tokyo. He joined NTT Transmission Systems Laboratories in 1988, where he engaged in R&D of high-speed optical communications systems including the first 10-Gbit/s terrestrial optical transmission system (FA-10G) using erbium-doped optical fiber amplifier (EDFA) inline repeaters. He was with NTT Electronics Technology Corporation between 1995 and 1997, where he engaged in the planning and product development of high-speed optical modules at data rates of 10 Gbit/s and beyond. Since 1997, he has been with NTT Network Innovation Labs, where he has been researching and developing optical transport technologies based on 40/100/400-Gbit/s channels and beyond. He has been investigating and promoting scalable optical transport networks with Pbit/s-class capacity based on innovative optical transport technologies such as digital signal processing, space division multiplexing, and cutting-edge integrated devices for photonic pre-processing. 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).

Digital Twin Computing Initiative

Takao Nakamura

Abstract

Digital twins, which connect the real world with cyberspace, have been achieved through advances in the Internet of Things and other information and communication technologies. NTT announced its Digital Twin Computing Initiative in June 2019 [1] for envisioning a future in which the digitalization of all types of objects (things) and their fusion with the real world accelerates in parallel with the evolution of the network and computing environment. This article provides an overview of this initiative, describes the scope of its application, and presents its architecture and main issues surrounding implementation.

Keywords: digital twin, cyberspace, virtual societies

1. What are digital twins?

Digital twins have been gathering attention as a means of linking the real world with cyberspace thanks to progress in information and communication technology (ICT). A digital twin is a mapping process that accurately represents in cyberspace the shape, state, function, etc. of a real-world object (thing) such as a manufacturing machine in a factory, airplane engine, or automobile. The use of digital twins makes it possible to analyze current conditions, make predictions, and simulate various scenarios with respect to things in cyberspace. It also enables the benefits of advanced ICT to be fed back to things in the real world in diverse ways, such as by using the results of processing in cyberspace to intelligently control those real-world things.

As digital twins are created for all types of things in the real world, we can expect a growing demand for large-scale simulations through the recombination and interaction of many and varied digital twins beyond those conventionally used in industry. For example, such simulations could start with units of industrial machines and reproducing manufacturing lines to an entire factory or even an entire supply chain including logistics. They could also reproduce an entire city by recombining buildings, roads, automobiles, residents, etc. However, conventional digital twins are only created and used for specific purposes on a field-by-field basis, so this type of unrestricted recombination and interaction of things has been difficult. Regarding human digital twins, the focus has been on reproduction in physical terms based, for example, on physiological measurement data. As a result, simulations related to social behavior, such as human communication, have been difficult to conduct.

2. What is Digital Twin Computing?

Digital Twin Computing (DTC) that we envision is a major expansion of the conventional digital twin concept. It is a new computing paradigm that enables reproduction of the real world on a totally new scale and level of accuracy by freely recombining various types of digital twins and performing diverse operations on them. It can also enable mutual interactions in cyberspace that include the inner state of humans, i.e., thoughts and decisions of individuals, above and beyond the physical reproduction of the real world (**Fig. 1**).

A key feature of DTC is the ability to arrange a variety of digital twins in cyberspace and create a single world, i.e., a virtual world, driven on the whole by the mutual interaction among those digital twins. To enable various types of digital twins to be freely recombined and subjected to analysis, trials, and predictions, we will develop a common means of performing large-scale and complex interactions among digital twins. In addition to digitalization of the real

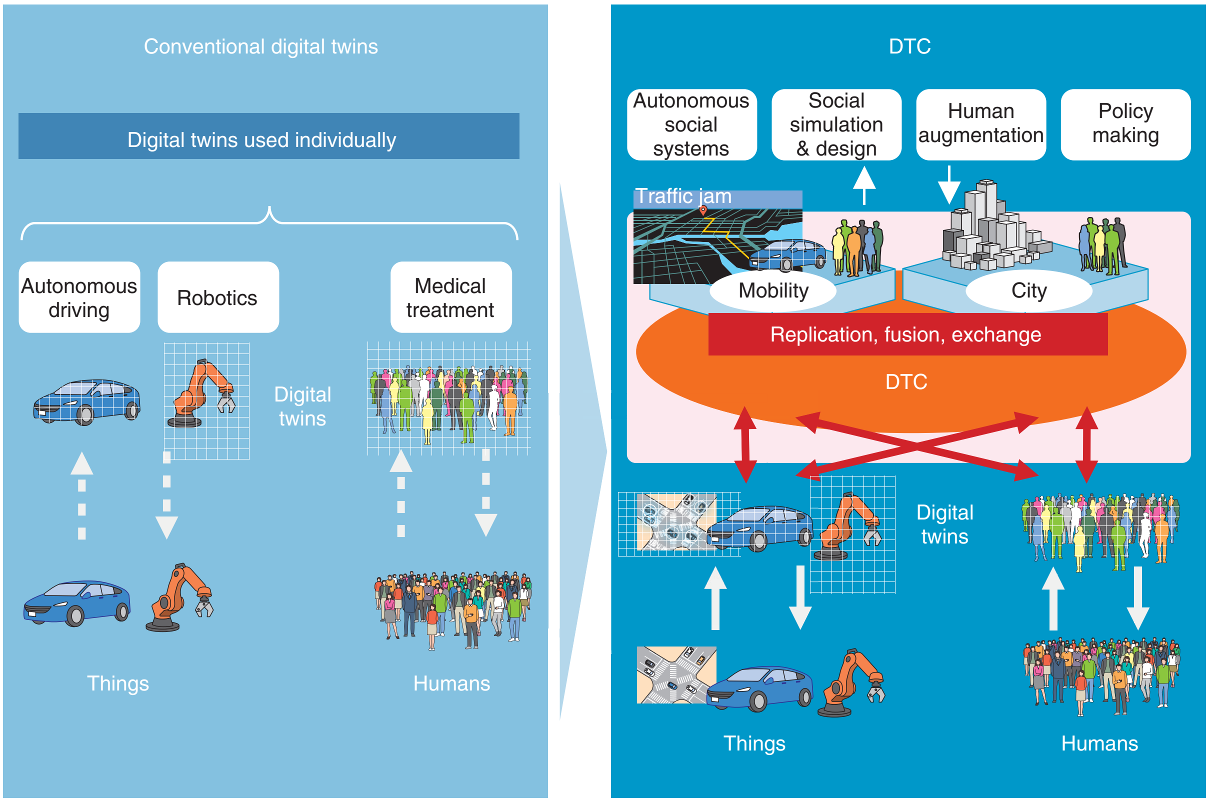

Fig. 1. Concept of Digital Twin Computing (DTC).

world as it actually is, DTC will make it possible to configure a virtual society with environmental conditions different from the real world and with things that do not exist in reality. This, in turn, will make it possible to conduct experiments and trials for a world that does not really exist, as in the design of a future society.

Another feature of DTC is digital twin operations that enable digital properties, such as replication and processing, to be used to the fullest. These operations can be used, for example, to replicate digital twins any number of times and conduct a variety of trials or to exchange or converge some of the constituent elements of different digital twins to create digital twins having properties that do not exist in reality (derivative digital twins). Combining derivative digital twins and constructing a virtual society can expand real-world functions and interaction.

Yet another key feature of DTC and a major challenge is the reproduction of the inner state of humans. For example, with respect to social aspects such as human behavior and communication, reproducing and representing in cyberspace the thoughts and decisions of individuals should enable interaction based on diversity arising from individuality (personality) in contrast to interaction between individual digital twins with no personality based solely on statistically rounded-off values. This feature is described in detail in the article "Challenges Facing Human Digital Twin Computing and Its Future Prospects" [2] in this issue.

With DTC, the plan is to create diverse virtual societies in which all types of things and people interact in sophisticated ways beyond the constraints of the real world and to extend and transcend the real world by fusing together virtual societies. The aim is to expand human possibilities by extending the range of human activities as far as virtual societies and to create innovative services that could not have heretofore been achieved such as social design and decision-making support for solving complex social problems through large-scale simulations or future predictions.

3. Application areas and use cases

Application areas and use cases of DTC are shown

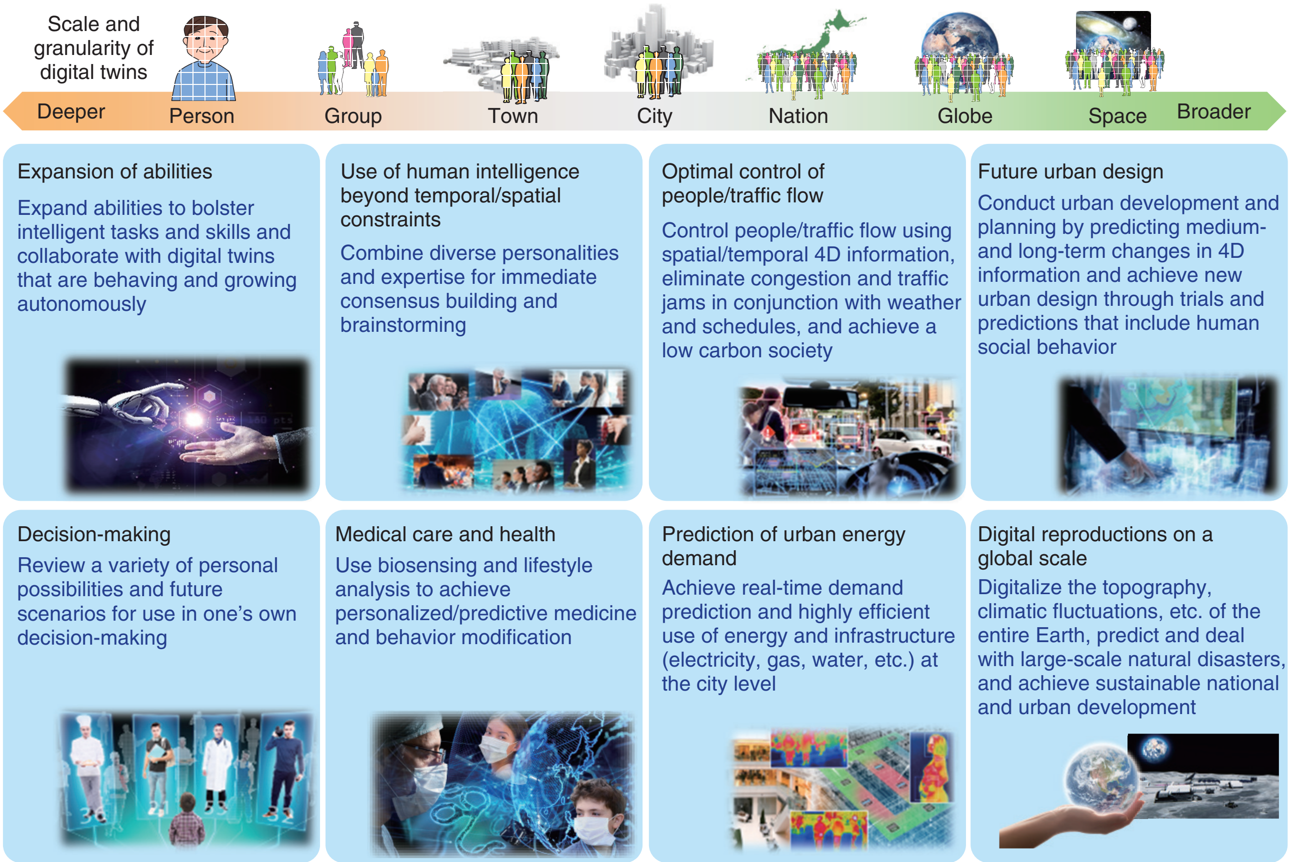

Fig. 2. Application areas of DTC.

in **Fig. 2**. In DTC, digital twins of diverse scale and granularity can be taken up from a deep micro level, such as a single person, to a broad macro level, such as a human group, city, nation, and even the entire globe. Therefore, the following use cases in a wide range of applications can be considered.

- Digitalize advanced decision-making processes and expert skills and feed results back to real people and things to reduce personnel training costs and deal with labor shortages
- Hold conversations with *multiple future selves* that simultaneously lead multiple lives to provide detailed support for making choices in one's real life
- Hold high-speed debates among digitalized experts in various fields to quickly derive responses to disasters, accidents, crime, etc. according to current conditions
- Control people/traffic flow using spatial/temporal fourth-dimensional (4D) information to eliminate congestion and traffic jams in conjunction with weather and schedules and achieve a low-carbon society
- Conduct trials and make predictions of medium- and long-term social activities in a city and simulate the views of future inhabitants then feed the results back to urban designers to plan appropriate urban development
- Digitalize the topography, climatic fluctuations, etc. of the entire Earth and predict and deal with large-scale natural disasters to achieve sustainable national and urban development

4. Architecture and main issues surrounding implementation

DTC generates digital twins through the sensing of real-world things and humans, generates derivative digital twins through digital twin operations, and constructs virtual societies that recombine them then feeds the results of those virtual societies back to the real world. The layered structure shown in **Fig. 3** and

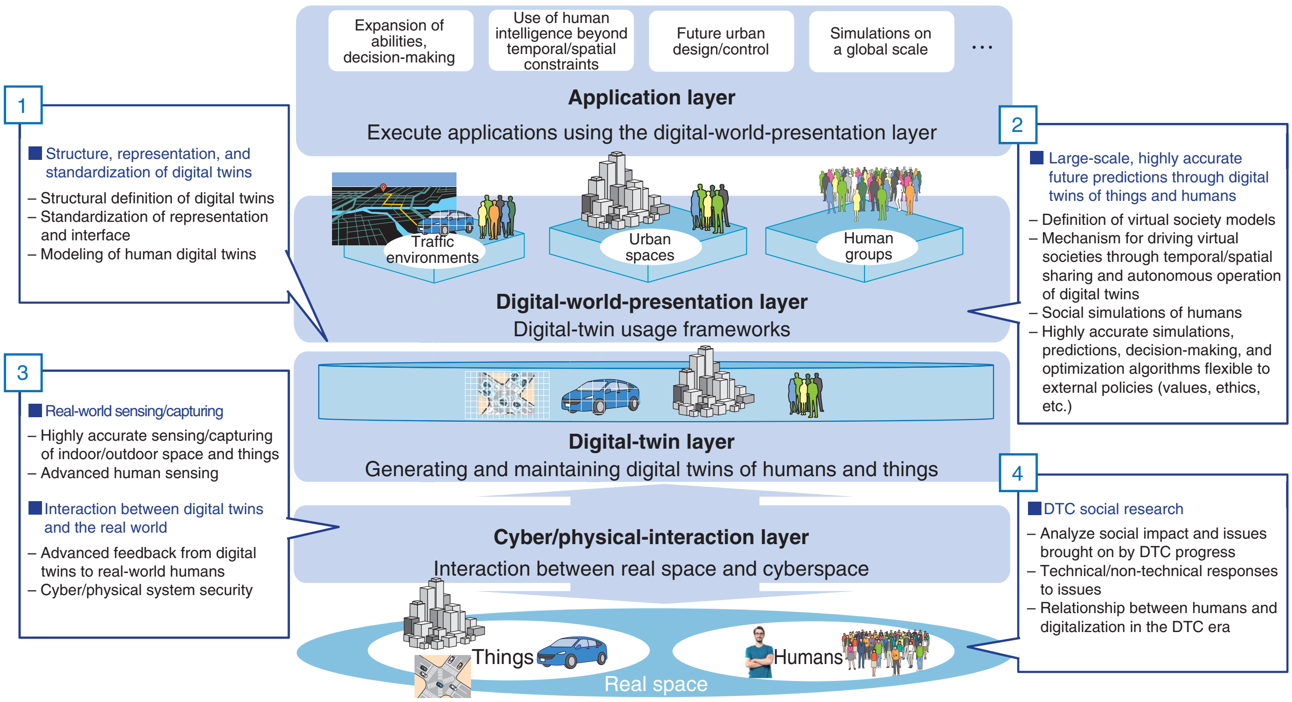

Fig. 3. DTC architecture and main issues surrounding implementation.

summarized below is assumed with this DTC architecture.

- Real space: Consists of things and humans existing in the real world and the real space that includes them
- Cyber/physical-interaction layer: Provides functions for collecting essential data to generate digital twins through the sensing of things and humans in real space and functions for feeding the results of trials and predictions in virtual societies back to the real space
- Digital-twin layer: Stores collected data, models, etc. and generates and stores digital twins using those data
- Digital-world-presentation layer: Generates derivative digital twins by performing operations (replication, fusion, and exchange) on digital twins stored on the digital-twin layer and creates virtual societies by combining derivative digital twins
- Application layer: Implements and executes applications using the digital-world-presentation layer

The following summarizes the main issues that need to be addressed to achieve DTC including the above use cases in accordance with this architecture.

(1) Structure, representation, and standardization of digital twins

On the digital-twin layer, there is a need for a structural definition, representation format, and standard interface for digital twins as frameworks for mutual interaction among digital twins, which is the aim with DTC. In addition, the constituent elements of human digital twins including reproduction of a person's inner state and individuality must be defined and technology for modeling and reproducing humans from sensing data must be established.

(2) Large-scale, highly accurate future predictions through digital twins of things and humans

On the digital-world-presentation layer, there is a need for a model definition of virtual societies as a place that recombines various types of digital twins and for a mechanism that can drive virtual societies based on temporal/spatial sharing and mutual interaction among those digital twins and on the autonomous operation of individual digital twins. Social simulation methods targeting human communication, such as conversation and consultation, as well as group behavior must also be established based on reproducing the inner state of humans. Based on all the above, there will be a need to establish highly accurate simulations, predictions, decision-making, and optimization algorithms that can derive appropriate calculation results flexible to external policies on social norms, values, and ethics. These needs are described in the article "Digital Twin Computing of Things Opens Up a New Society" [3] in this issue.

(3) Real-world sensing/capturing and interaction between digital twins and the real world

On the cyber/physical interaction layer, there will be a need for highly accurate sensing and capturing of not only of spaces and static subjects, such as outdoor buildings, roads, and indoor structures, but also of dynamic subjects such as moving cars. To enable a human digital twin to reproduce the user's inner state and individuality, there will also be a need for advanced human sensing technology that can integrate measurement data from wearable devices, cameras, and microphones and behavior data on the Internet, etc. There will also be a need for feedback methods using advanced human-machine interaction devices to feed experiences in cyberspace back to real-world humans and to enable activities in virtual societies via digital twins and expansion of real-world abilities through the help of cyberspace. These needs are described in the article "Approaches to Cyber-physical Interactions Linking the Real World and Cyberspace" [4] in this issue.

Finally, in the world of DTC that promotes the fusion of the real world and cyberspace, there will be an even greater need for cyber/physical system security.

(4) DTC social research

There will be a need to analyze the social impact and issues brought on by progress in DTC, such as privacy concerns, risk of digital crime, ethical concerns in relation to future predictions, free will, personal responsibility, and transformation of values in a borderless digital society, and to deal with these issues in technical and non-technical ways. To gain social acceptance of DTC, cultural and sociological studies must also be conducted on the new relationship between humans and digitalization. Please refer the article "Social Issues with Digital Twin Computing" [5] in this issue for more details.

5. Conclusion

As described above, the issues that must be tackled to implement the DTC initiative are extremely broad in scope. NTT laboratories aim to solve these issues and implement the DTC initiative in society through collaboration with a wide range of experts in science and technology and diverse partners in industry. For more details on the DTC initiative, please see the Digital Twin Computing white paper [6].

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Takao Nakamura
Senior Research Engineer, Supervisor, NTT Digital Twin Computing Research Center.

He received a B.S. in mathematics from Waseda University, Tokyo, in 1994, and a Ph.D. in informatics from the Graduate University for Advanced Studies, Kanagawa, in 2008. He joined NTT Human Interface Laboratories in 1994 and studied media processing technologies, content distribution systems, artificial intelligence, and their applications. He was seconded to the Ministry of Internal Affairs and Communications of Japan from 2007 to 2009, where he was responsible for policy making and promoting national information security policies. He is working on research and development of the concepts and technologies for Digital Twin Computing.

Challenges Facing Human Digital Twin Computing and Its Future Prospects

Iwaki Toshima, Satoshi Kobashikawa, Hajime Noto, Takao Kurahashi, Keiichi Hirota, and Shiro Ozawa

Abstract

Human Digital Twin Computing (DTC) aims to digitally express not only a person's *outer self*, such as physical characteristics, but also that person's *inner self* such as personality and thoughts. We believe that digitizing information that includes the inner self can create unprecedented value. Collective consensus building, creating empathy and understanding of others, and future prediction and growth support for individuals and societies are described as characteristic use cases of human DTC in this article. The direction of future human-DTC projects, such as challenges in spreading human DTC throughout society, is also described.

Keywords: things DTC, human DTC, spatial DTC

1. Introduction

A human digital twin makes it possible to expand the range of human activities from the real world to cyberspace. Interaction between oneself in the real world and all digital twins in cyberspace is done through one's digital twin. Moreover, feeding back the results of that interaction to oneself in the real world makes it possible to use the experience gained from activities in cyberspace in the real world (**Fig. 1**). The aim of human Digital Twin Computing (DTC) is to not only digitally represent a person's outer self in terms of, for example, physical and physiological characteristics but also the person's inner self, for example, personality and thoughts.

A human DTC model that reproduces the individuality and characteristics of humans (for example, a *personality/thinking model* that models behavioral tendency, personality, and values or an *ability model* that models perception, knowledge, language ability, physical ability, etc.) defines the behavior of a digital twin. By reacting to other people's actions in cyberspace as if they were our real-world selves and by making them behave autonomously in a virtual society, human digital twins can engage with others as our real-life selves (**Fig. 2**). Human DTC is defined as a whole system that develops and enables human digital twins.

In this article, the advantages that human DTC provides are first summarized, then specific use cases demonstrating these advantages are explained. Next, the unavoidable considerations necessary for human DTC to be accepted in society are summarized, and the long-term prospects of human-DTC projects are described after that.

2. Value of human DTC

A human digital twin is not only composed of data showing your state and behavior, it is also composed of a model that expresses your individuality and emotions such as your tendencies regarding judgment and behavior. As a result, it enables you to interact with others in a virtual society and carry out autonomous activities there as if it were yourself. We believe that this interaction essentially has three advantages. The

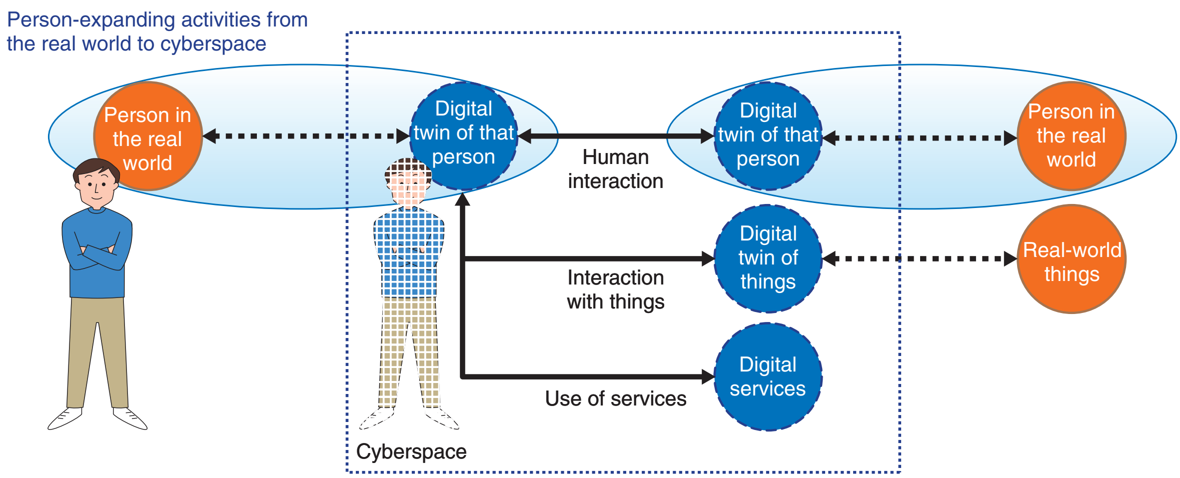


Fig. 1. Human interaction in cyberspace via a digital twin.

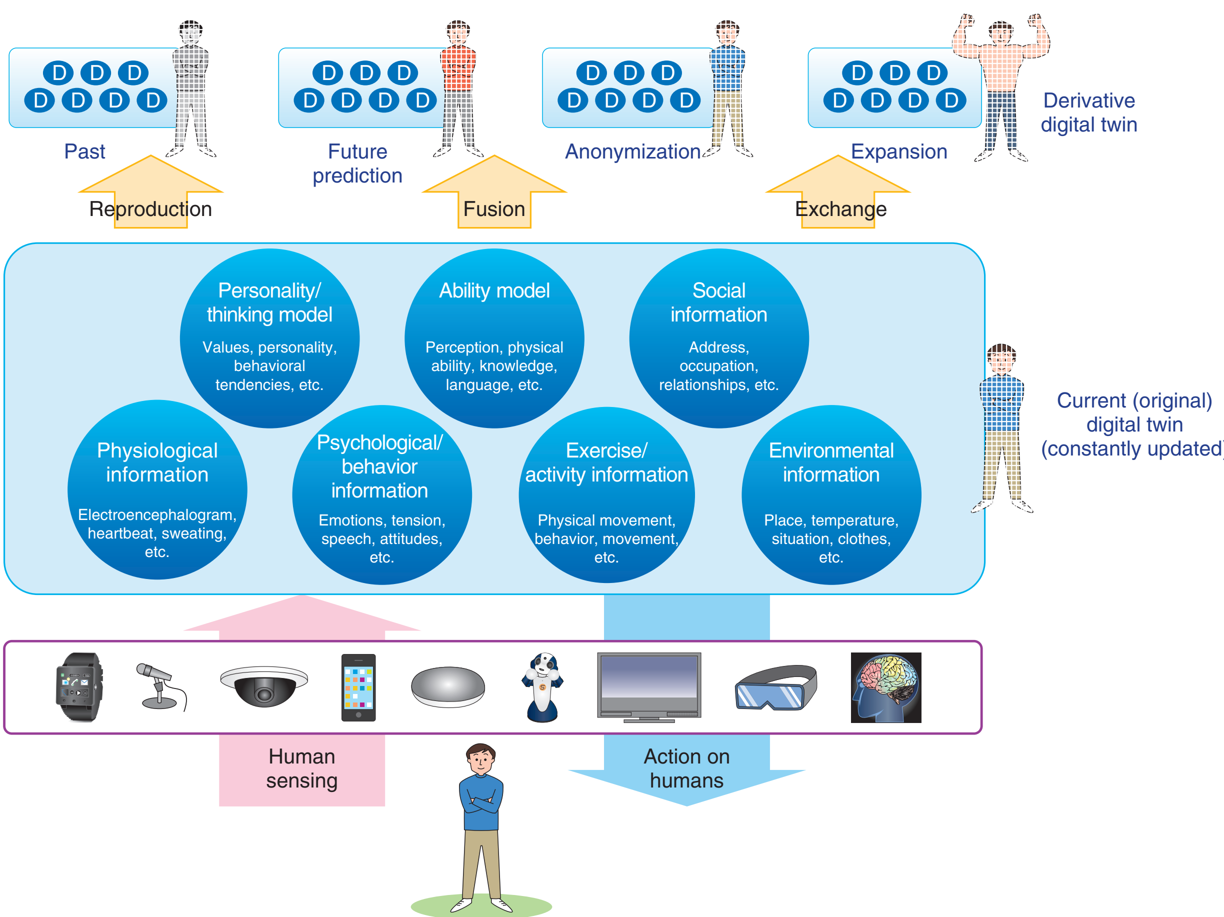


Fig. 2. Human digital twin created using DTC.

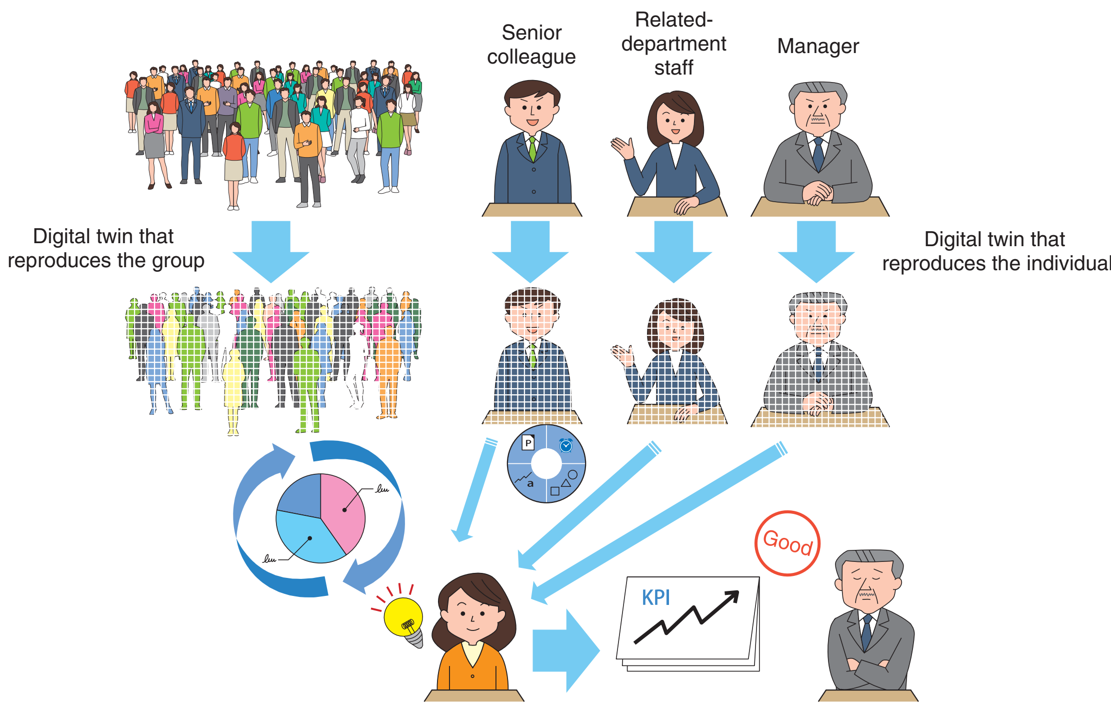


Fig. 3. Group consensus building with human digital twins.

first is being able to be used for various tasks that are beyond our physical constraints. Regarding communication in cyberspace, a huge amount of processing can be performed at high speed beyond the real-time processing performed during communication between real people. The second advantage is that having a model that expresses emotions makes it possible to transmit various emotions as they are. In this virtual society, you can convey nuances, so you can create a world in which your thoughts do not have discrepancies. The third advantage is being able to interact with people on the basis of social aspects and diversity, and this ability will make it possible to (i) precisely analyze those interactions while taking into account the individuality of humans and (ii) predict the future. It is an advantage that can be taken in various ways, such as for consultations aimed at changing a person's behavior. The source of these advantages lies in the implementation of human personality and the creation of models of emotions. We will promote research and development by treating this *human individuality* as one of the most important issues regarding human DTC.

3. Use cases of human DTC

3.1 Collective consensus building

A human digital twin has a memory of personal knowledge, experience, etc., so it can think and judge while having the same personality and sense of values as the real-life person and engage in various tasks (**Fig. 3**). Regarding DTC, a digital twin replicates communication that takes place in the real world, so it can engage in advanced tasks that require communication with multiple people. A typical example is consensus building during a meeting.

In this use case, it is possible to simulate the thinking of a group consisting of multiple digital twins and visualize it in a timely manner without involving people in the real world. Moreover, the tacit knowledge inside the individual can be drawn out by working with a digital twin of an expert who is not there. As a result, it is expected that the group will be able to smoothly facilitate the emergence of new ideas and decision-making. Moreover, through *reproduction* of a digital twin, digital twins can exist in multiple virtual societies at the same time regardless of the state of the real world. Therefore, we believe that in the real world, it will be possible to instantly form a consensus among a large number of people, namely, a task that has been impossible until now due to time and space constraints.

3.2 Creating empathy and understanding of others

Digitization of sensations and emotions is also an important element in creating a human digital twin. By using DTC to convert the senses and emotions reconstructed from a person's scan information as a digital twin into a form that another person can understand and feeding them back to the real world, it is possible to create an empathetic state that is understandable to each party (**Fig. 4**). An example in which having empathy using sensations and emotions is useful is a diagnosis of a patient given by a doctor in an examination room. In a real-life diagnosis, the patient can only qualitatively convey to the doctor verbal feelings such as pain and anxiety. Even if pain can be quantified, the sensations and emotions that an individual feels will vary from person to person. As such, it is difficult to determine if the patient explained his/her symptoms correctly and if the doctor's explanation is correctly transmitted to the patient. In a diagnosis through human DTC, the digitized sensations of pain and anxiety are converted into a form that can be transmitted to the other party then fed back to the real world to enable effective communication with the other party. Creating empathy by using a person's digital twin will revolutionize communication, that is, it will be possible to create a world in which a person can not only tell the other party what he/she wants to say in words but also make the other party understand what he/she cannot say in words.

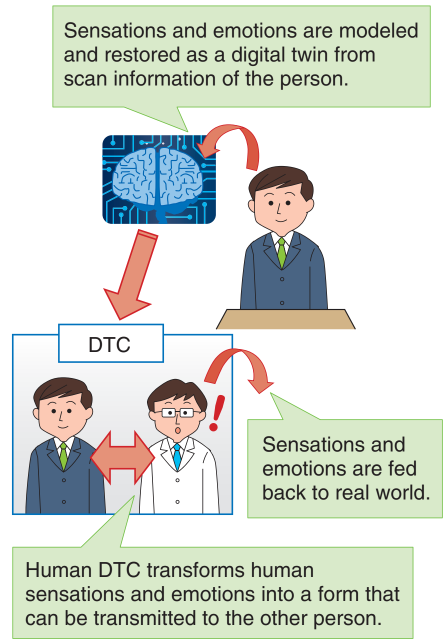


Fig. 4. Sharing sensations and emotions through a human digital twin.

3.3 Future prediction and growth support

For a human digital twin created using DTC, it is also possible to use micro-level simulation results for individuals to determine their behaviors (**Fig. 5**). It is expected that using *derivative digital twins* with new knowledge and ability on the basis of *fusion* and *exchange* will make it possible to predict other future possibilities, such as what happens if a person acquires new knowledge, and use such predictions to grow society and oneself. An example of growing oneself is learning a new language. Self-growth has its own motivation and goal setting and is gained through experience through physical and intellectual activities. With a human digital twin, you can create multiple derivative digital twins of you and simulate all the languages you want to learn by using each of your derivative digital twins. Through exchanging with other digital twins in English, German, French, etc. in a virtual society, you can learn these languages in a practical manner and receive guidance. You can also feel emotions and excitement as if you actually experienced the interaction. Based on the simulation results, new knowledge about languages that are easy for you to learn, countries that impressed more, etc. are fed back to the real world to promote and support your growth.

4. Social acceptance and security of human DTC

As mentioned above, human DTC is expected to expand people's abilities and produce beneficial results. However, for people to receive these benefits, the social acceptance of a worldview through human DTC must be fully considered. It is essential to raise people's awareness and individual acceptance concerning, for example, (i) psychological resistance to the creation of human digital twins with the same appearance and thoughts as oneself and (ii) privacy concerns about the aggregation of various types of information about oneself. Also, a human digital twin may engage in the same economic activities as the human it represents, and that situation may create new social and/or legal systems. The social and

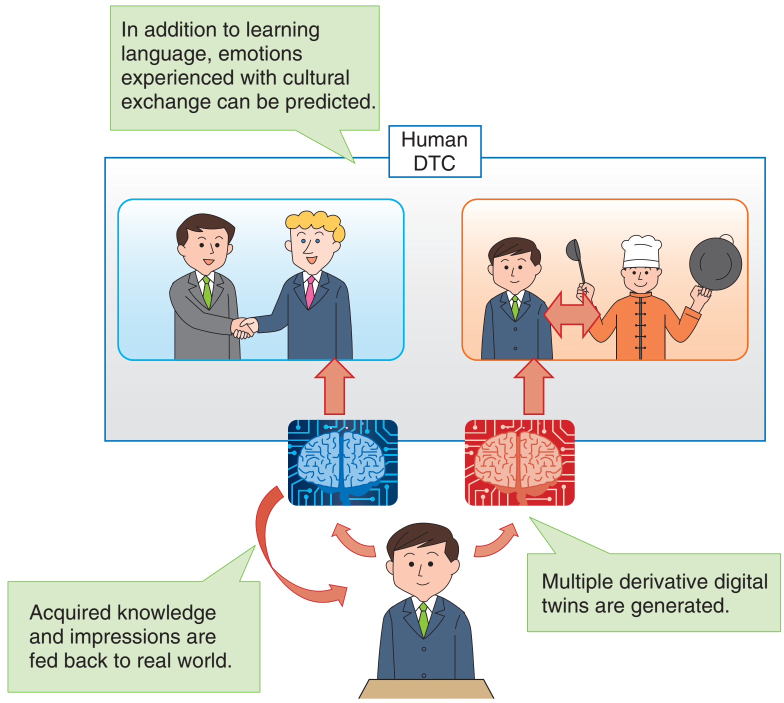


Fig. 5. Future prediction and growth support through human digital twins.

economic effects of human digital twins doubling human knowledge and abilities and multiplying the activities of people many times will cause a large paradigm shift. Concerning the various effects that creation and popularization of human DTC will have on the real world, it is necessary to search for the ideal form of human DTC while discussing those effects with experts in fields such as the humanities (philosophy, ethics, etc.), law, and sociology (social psychology, behavioral economics, etc.).

Moreover, when it is assumed that human DTC and *things DTC* reflect all the information in the real world, it will become clear that various threats and risks can arise from DTC. Accordingly, it is necessary to thoroughly consider the security concerning both types of DTC and handle them from various aspects, regardless of whether those aspects are technical or non-technical. With that necessity in mind, we will introduce ethical codes and legal concepts and create an orderly DTC world equivalent to the real world. On the basis of our extensive knowledge gained from activities concerning security technology and cybersecurity cultivated over many years, we will also create DTC security based on the idea of *security by design* and *privacy by design*.

5. Concluding remarks

Envisioning some of the goals mentioned in this article, research on human DTC has just begun. However, the base technology, for example, the technology for recognition and generation of speech, language, images, etc., has greatly evolved by using artificial intelligence (AI). With respect to these technologies, we want to accelerate research and development on human DTC by focusing on the individuality of people and delving further into people's inner self. Furthermore, from the perspectives of individuality and the inner self as well as permeation into society, it is necessary to expand human DTC to fields other than AI and engineering, namely, biology and medical (including brain science) and ethics, philosophy, and the other humanities (such as behavioral economics). Our human-DTC research team is not only pursuing research but also promoting technological implementation of human DTC by linking research in these wide-ranging fields as a hub. We believe that getting people to recognize the value that human DTC brings to the world will be essential in bringing about changes to accepted social norms.

Iwaki Toshima

Senior Research Engineer, NTT Digital Twin Computing Research Center and NTT Media Intelligence Laboratories.

He received a B.E. and M.E. from the University of Tokyo in 2000 and 2002, and a Ph.D. from Tokyo Institute of Technology in 2008. He was at NTT Communication Science Laboratories from 2002 to 2013, where he researched robot-audition and auditory psychophysics. He developed NTT's home-router and FTTH (fiber-to-the-home) services while at NTT WEST from 2013 to 2019. Since 2019, he has been researching human digital twins at NTT Digital Twin Computing Research Center. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), Robotics Society of Japan, VR Society of Japan, Acoustical Society of Japan (ASJ), and the Japan Society of Mechanical Engineers.

Satoshi Kobashikawa

Senior Research Engineer, Social Knowledge Processing Laboratory, NTT Media Intelligence Laboratories.

He received a B.E., M.E., and Ph.D. from the University of Tokyo in 2000, 2002, and 2013. Since joining NTT in 2002, he has been researching speech recognition and spoken language processing. He received the Kiyasu Special Industrial Achievement Award from the Information Processing Society of Japan (IPSJ) in 2011, the 58th Maejima Hisoka Award from the Tsushinbunka Association in 2012, and the 54th Sato Paper Award from ASJ in 2013. He is a member of ASJ, IPSJ, and the Institute of Electronics, Information and Communication Engineers (IEICE).

Hajime Noto

Senior Research Engineer, Universe Data Handling Laboratory and NTT Digital Twin Computing Research Center, NTT Media Intelligence Laboratories.

He received a B.E. and M.E. in industrial engineering from Kansai University, Osaka, in 1997 and 1999. In 1999 he joined NTT Cyber Space Laboratories (now, NTT Media Intelligence Laboratories), where he researched three-dimensional (3D) input systems. He is currently involved in research and development of human digitization. He is a member of the Institute of Image Information and Television Engineers (ITE).

Takao Kurahashi

Senior Research Engineer, Cybernetic Intelligence Research Project, NTT Service Evolution Laboratories and NTT Digital Twin Computing Research Center, NTT Media Intelligence Laboratories.

He received an M.E. in industrial engineering from Hosei University, Tokyo, in 2002 and joined NTT the same year. His research interests include human-computer interaction and robotics.

Keiichi Hirota

Senior Research Engineer, Secure Data Sharing Project, NTT Secure Platform Laboratories and NTT Digital Twin Computing Research Center, NTT Media Intelligence Laboratories.

He received a B.S. and M.S. from Mie University in 1995 and 1997, and a Ph.D. in informatics from the Graduate University of Advanced Study (SOKENDAI), Kanagawa, in 2008. He joined NTT in 1997. His current research interests are security and privacy in information processing, information sharing, and data utilization. He is a member of IPSJ.

Shiro Ozawa

Senior Research Engineer, Supervisor, NTT Digital Twin Computing Research Center and NTT Media Intelligence Laboratories.

He received a B.E. and M.E. from Tokyo University of Mercantile Marine (now, Tokyo University of Marine Science and Technology) in 1997 and 1999. After joining NTT as a researcher, he worked for NTT Cyber Space Laboratories (now, NTT Media Intelligence Laboratories). His fields of interest are computer vision, video communication, user interfaces, human-computer interaction, and 3D displays. He is a member of IEICE, ITE, and the Institute of Image Electronics Engineers of Japan.

Digital Twin Computing of Things Opens Up a New Society

Masahiro Maruyoshi, Muneyuki Kawatani, and Koya Mori

Abstract

Through Digital Twin Computing (DTC), we aim to enhance the quality of people's lives by digitizing objects as well as actual humans with high accuracy and enabling the digitized objects to be used by real people. To achieve DTC, we are developing (i) digital-twin creation technology that enables interaction among people and digitized objects and (ii) large-scale, high-resolution, and highly accurate technology for simulating the flows of those digitized objects and people. Our efforts concerning these technologies are described in this article.

Keywords: digital space, simulation, smart city

1. Introduction

At Digital Twin Computing Research Center, we are developing *digital-twin creation technology for reproducing the real world* and *large-scale real-time simulation technology*.

Digital-twin creation technology for reproducing the real world aims to digitize the physical shape and state of objects and create a space (digital-twin space) in which real people can share and operate these digitized objects via real space. Three-dimensional (3D) modeling technology is used in construction and manufacturing for digitizing an object into 3D data, and we will forge ahead with creating a digital-twin space by integrating this and other technologies as elemental technologies.

Large-scale real-time simulation technology will make it possible to accurately predict people flow, traffic flow, weather conditions, energy flow, etc., which have been digitally reproduced, over a wide area such as a city or whole country in real time. We aim to use this technology for real-time control of city functions and evaluating the impact on urban life due to improvements in urban functions. This article describes current technological trends and issues related to digital-twin creation technology for reproducing the real world and current efforts concerning large-scale real-time simulation technology.

2. Digital-twin creation technology for reproducing the real world

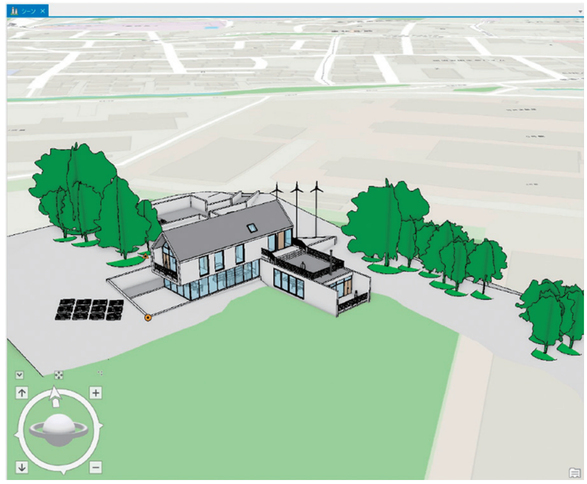
When people operate digitized objects, various devices, such as a mouse, keyboard, or touch panel, have been used. We believe that it will be more important to interact with digitized objects more intuitively and directly by using vision, hearing, and touch. In addition to previously proposed hardware technology for wearable devices such as head-mounted displays and virtual reality glasses, 3D modeling technology for digitizing physical objects in 3D will also be important. Such technology can be classified into the following three categories on the basis of the size and movability (portability) of an object.

(1) Geospatial digitization technology (for infinitely extending objects with no portability)

(2) Technology for digitizing buildings (for huge objects with no portability)

(3) Technology for digitizing things (for objects of various sizes with portability)

The following technological trends are explained in line with these categories.



Building data of Autodesk Revit (a BIM tool) [1] (*CC BY-NC-SA 3.0) are placed on the map by using Esri ArcGIS [2] (a GIS tool).
It is thus possible to construct a city model with an accurate shape, but the model must be manually aligned for precisely placing the data.

Fig. 1. Example of creating a city model based on a 3D model using GIS and BIM.

2.1 Geospatial digitization technology for infinitely extending objects with no portability

A geographic information system (GIS) has been used for digitizing geospatial information about wide areas, such as cities, topographical information, and additional information in an integrated manner. Topographical information is digitized by extracting shapes from aerial radar and satellite images. In addition to this topographical information based on the coordinate system using latitude, longitude, and altitude, layers are prepared for each analysis target (such as a plane map and its topographical information, borders, and features), and they can be overlaid. These types of information are suited for representation in a macroscopic perspective because they have the number of characteristic points and degree of accuracy with which a wide range of information can be drawn at a practical speed.

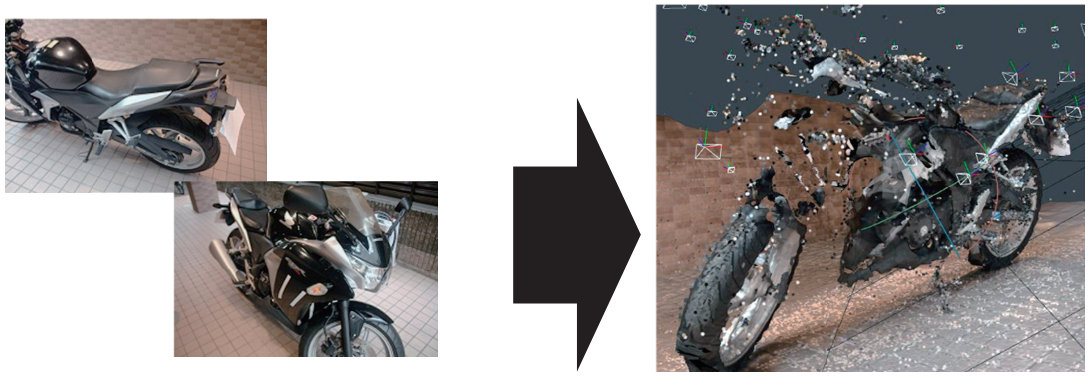
2.2 Technology for digitizing buildings for huge objects with no portability

Building-information modeling (BIM) and construction-information modeling (CIM) have been used for designing the structures of features, such as buildings, roads, and bridges, as 3D models. BIM/CIM also manages attributes such as materials used in buildings and their strength. For constructing a real building, this technology is excellent at representing a microscopic perspective because of its high accuracy. It is also possible to represent a city by placing 3D models created with BIM on a GIS (**Fig. 1**), and there has been a trend toward making such a model available—together with the GIS—as an open-city model [1, 2].

2.3 Technology for digitizing things for objects of various sizes with portability

Computer-aided design (CAD) is used to design the structures of various industrial products as 3D models. Using CAD makes it possible to check interferences between objects and measure strain using physical simulation before manufacturing an actual product. For manufacturing real objects, the technology is excellent at representing a microscopic perspective due to its extremely high accuracy. However, the data format differs across various industrial fields and is not standardized.

Photogrammetry technology [3] (**Fig. 2**), which estimates feature points from moving images of objects and creates 3D models from these points, and shape-extraction technology by radar measurement have been proposed [4]. While there is an advantage in that all objects can be modeled in 3D from images, the extraction accuracy depends on the state of the environment, such as lighting level, and there are still many challenges with real-time extraction of moving objects in video processing.



Input image
(More than 100 images with different positions/directions)

Extracted 3D model
(Parts with strong specular reflection have not been extracted.)

Fig. 2. Example of extracting a 3D model by using a tool (Meshroom) implemented with photogrammetry technology.

3. Challenges towards digital-twin creation technology for reproducing the real world

Digital Twin Computing (DTC) technologies will make it possible for a real person to interact in a virtual space with various objects in the real world by digitizing all real objects. An interaction in a virtual space is considered to have meanings ranging from, for example, feedback from the senses (e.g., feeling a sensation when touching something) to acquiring information (such as seeing the usage history when touching something). For the 3D-modeling technology mentioned above, attributes are defined according to the usage in each industrial field. However, they are not defined under the assumption that digitized objects interact with real people.

To create a digital-twin space in which digitized objects can move dynamically in real time, the digitized objects must be managed in an integrated manner. For example, objects digitized by a third party can be placed in a virtual space where buildings are geographically spread out like a city and many people can touch them at the same time. To do this, different attributes (3D coordinate system, accuracy, data format, etc.) created in various industrial fields must be standardized. We aim to form—as one framework—(i) attributes that enable people to interact with digital twins of things and (ii) interface conditions for handling digitized objects generated in multiple industrial fields in a virtual space.

4. Large-scale real-time simulation technology

Large-scale real-time simulation technology, namely, simulation using digital twins constituting a digitized city space, aims to enable real-time optimal control of city-wide activities (such as people flow, traffic flow, logistics, and energy flow) and mid- to long-term planning and decision-making in cities and governments. The key features of this DTC simulation is that it manipulates wide areas and achieves high accuracy. The challenges and efforts concerning each key feature are described below.

4.1 Wide-area simulation

Simulation of a city includes simulation of people living in the city and their activities, transportation (cars, etc.), and environment (weather, etc.). Tokyo is taken as an example city. Central Tokyo has a population of over 13 million and over 3.5 million vehicles on its streets [5, 6]. Since it is not realistic to conduct these simulations on a single computer, it is possible to, for example, divide Tokyo into several areas, and subject each area to parallel distributed processing. However, in this case, it is necessary to consider people and vehicles moving across these areas of parallel distributed processing (**Fig. 3**). We are researching wide-area simulation with which movement across such areas is assumed.

4.2 Highly accurate simulation

When simulations are used for real-time optimal control of activities of an entire city and for planning

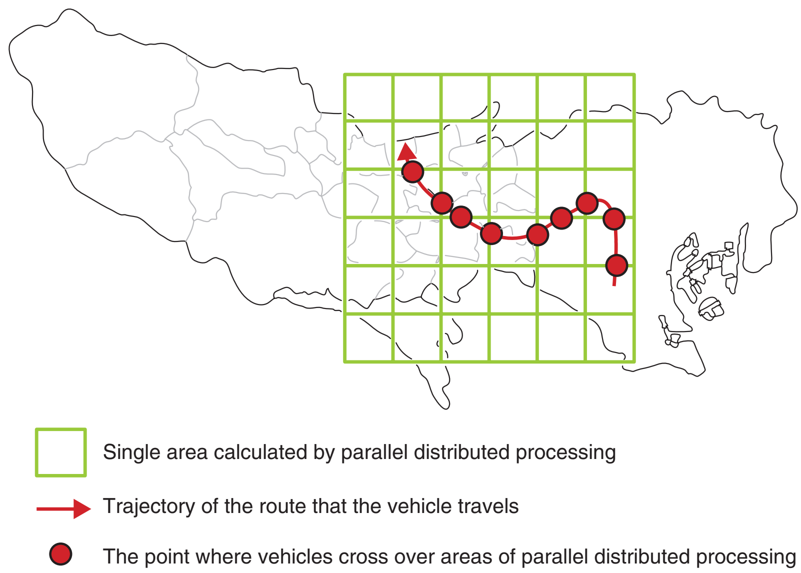


Fig. 3. Example of a vehicle moving across areas of parallel distributed processing.

and decision-making by cities and governments, it is essential to improve the accuracy of the simulation results. Therefore, it is possible to improve simulation accuracy by including computational elements that have not been considered in the simulation thus far, for example, wind flow passing between buildings, a building's exposure to sunlight, activity of each citizen, and movement of each car. However, if the number of such calculation elements is simply increased, the calculation amount will increase exponentially; therefore, we are clarifying which calculation elements have a significant effect on the simulation results and studying how to incorporate them into the simulation.

It is also necessary to consider fluctuations in simulation results caused by uncertain phenomena that cannot be easily predicted from past events, such as traffic accidents and heavy rain. To execute a simulation considering these uncertain events, it is necessary to not only execute numerical analysis on a computer but also reflect the events that occurred in the real world in the simulation calculation in real time to bring the calculation results closer to the events in the real world. We are currently researching technology to satisfy these requirements (**Fig. 4**). Through these efforts, we aim to enable large-scale, high-resolution, and highly accurate city simulations, which will be useful for optimizing city activities and human decision-making.

5. Future prospects

We will continue researching and developing (i) digital-twin creation technology for reproducing the real world that enables objects and spaces to interact and (ii) technology that simulates the future in a digital space and feeds the prediction results back to the real world. While pursuing these efforts, we will also focus on implementing the 4D digital platform™ [7]. To achieve DTC, we will also promote a partnering strategy with various companies across industries.

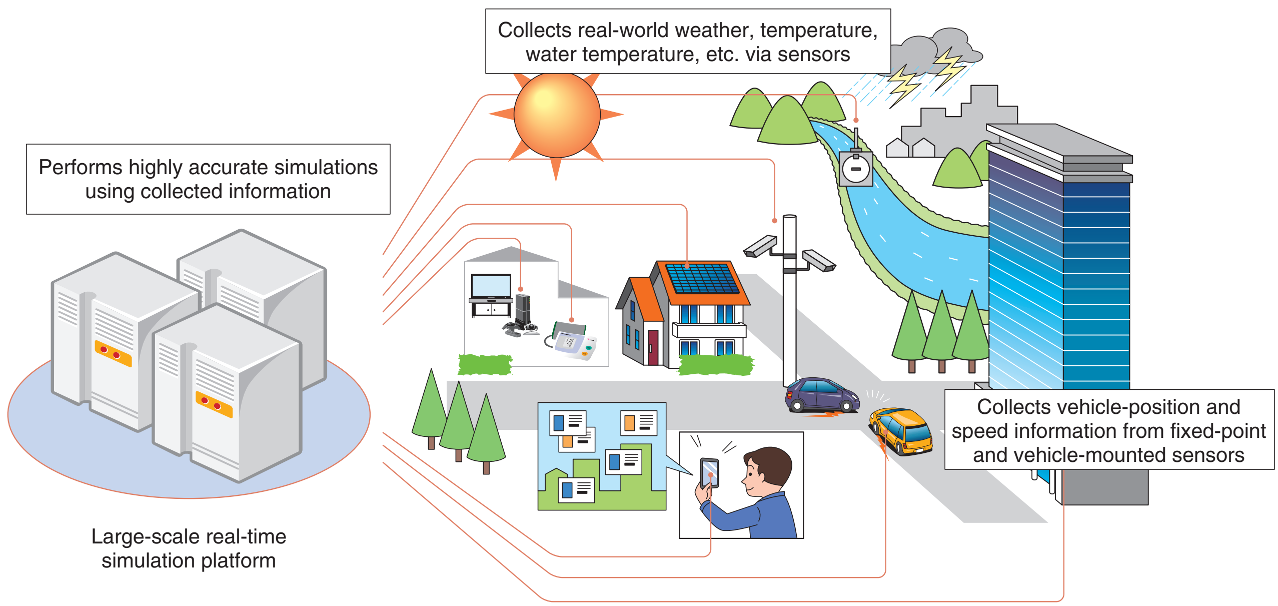


Fig. 4. Simulation using phenomena in the real world.

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Masahiro Maruyoshi

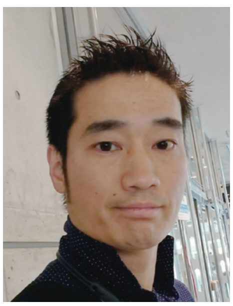
Senior Research Engineer, NTT Digital Twin Computing Research Center, NTT Media Intelligence Laboratories.

He received a B.E. and M.S. in information engineering from Nagoya University, Aichi, in 2000 and 2002. He joined NTT in 2002 and was engaged in research and development of software defined network technologies. Since 2020, he has been in charge of research for Digital Twin Computing at NTT Digital Twin Computing Research Center.

Koya Mori

Senior Research Engineer, NTT Digital Twin Computing Research Center.

Since joining NTT in 2004, he has been involved in the research and development of an IoT application based on software technologies, such as OSGi, OpenStack, and Edge Computing. Since 2020, he has been in charge of research for Digital Twin Computing at NTT Digital Twin Computing Research Center.



Muneyuki Kawatani

Senior Research Engineer, NTT Digital Twin Computing Research Center, NTT Media Intelligence Laboratories.

He received a B.E. and M.E. from Kobe University in 2004 and 2006. He joined NTT in 2006 and was engaged in research and development of application platform systems for open source software. Since 2020, he has been engaged in the Digital Twin Computing project, specifically developing the simulation technology described in this article. He also worked at NTT DOCOMO from 2011 to 2016 and developed a network system for smartphones.

Approaches to Cyber-physical Interactions Linking the Real World and Cyberspace

Yukio Koike, Tatsushi Matsubayashi, and Shigekuni Kondo

Abstract

From among the technologies incorporated in the cyber-physical interaction layer connecting the real world and cyberspace towards achieving Digital Twin Computing, this article introduces biological-signal-decoding and feedback technologies to extend motor-function capabilities by feeding the results of operations done with a person's digital twin back to him/herself and zero latency media technology that enables operations that do not feel uncomfortable by feeding back a prediction presentation that eliminates delay and overcoming the physical distance of the real world and human perception of time.

Keywords: cyber-physical interaction, zero latency, biological signal decoding and feedback

1. Cyber-physical interactions linking the real world and cyberspace

NTT laboratories are aiming to actualize Digital Twin Computing (DTC) to create diverse virtual societies through interactions between various objects and humans at a higher level beyond the constraints of the real world and to expand the scope and potential of human activities by fusing virtual societies with the real world. From among the technologies incorporated in the cyber-physical interaction layer connecting the real world and cyberspace, this article introduces biological-signal-decoding and feedback technologies to extend motor-function capabilities by feeding the results of operations done with a person's digital twin back to him/herself and zero latency media technology to have these operations be discomfort-free through feedback of near-future prediction results (**Fig. 1**).

2. Biological-signal-decoding and feedback technologies to make DTC possible

One aspect of a human digital twin in DTC is that it is an interface for one's real-world self to interact with various digital twins in cyberspace or interact with other real-world humans. Specifically, a digital twin enables experiences in cyberspace to be conveyed to one's real-world self via a human-machine interface (HMI). Thus, an HMI plays an important role in the interactions between digital twins and the real world [1]. Digital twins of humans are not just human reproductions but also expand capabilities through *exchange and fusion* in cyberspace, which are key digital twin operations [1]. An HMI also plays an important role in enabling a human to demonstrate such capabilities in the real world.

Therefore, we have embarked on HMI-technology (biological-signal-decoding* and feedback technologies) initiatives to achieve this from the perspective of expanded motor-function capabilities, which are particularly important elements of expanded human capabilities in both cyberspace and the real world.

In general, motor control in the human body results when stimulation received by a sensory organ is

* Decoding: Analysis and understanding of biological signals (sensory reproduction from brain waves, etc.).

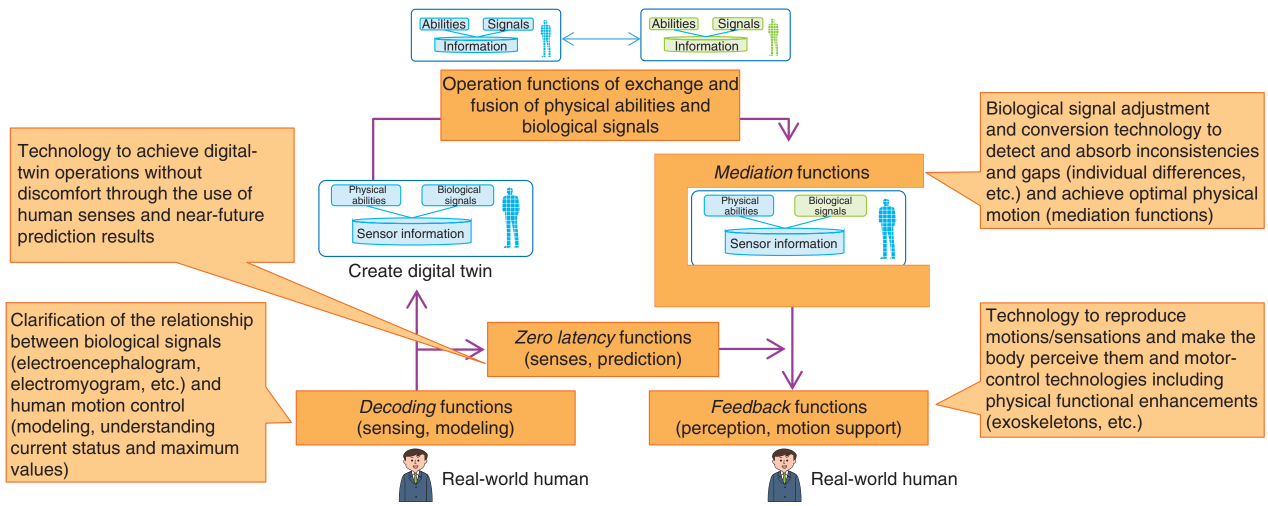


Fig. 1. Technology supporting the cyber-physical interaction layer.

perceived by the brain via the nervous system, cognitive activity such as planning for action occurs in the brain, and commands for the movements to be executed are transmitted via the nervous system to the musculoskeletal system where the muscles that received the signals contract [2]. The exchange and fusion between digital twins regarding sensory functions, nervous functions, musculoskeletal functions, the biological signals transmitted between these functions, and feedback of the results of these to humans in the real world to enhance functionality and signal distribution is our objective for enhanced motor-function capabilities. This initiative will make it possible for humans in the real world to acquire enhanced motor-function capabilities through physical support or training in which the motor-control functions and biological signals of a skilled person are projected onto a trainee.

To feed expanded motor-function capabilities back to humans in the real world to enhance human motor functions, we believe the following biological-signal-decoding and feedback technologies are important.

- Biological-signal-decoding technology: Clarifying and digitizing the relationships between biological signals (electroencephalogram, electromyogram, etc.) and movements between the functional elements of human motor control (digital informatization through decoding and extraction and patterning of time-space feature values for highly reproducible sense and movement signals)
- Feedback technology: Technology to reproduce movements and sensations and make the body perceive them and motor-control technologies including expanded physical functionality (for use and control of exoskeletons)
- Mediation technology (related to feedback technology): Biological signal adjustment and conversion technology (*mediation* functions) to detect and absorb inconsistencies to optimize body movements based on decoded information

In particular, we consider the role of the mediation functions to be important in expanding capabilities through the digital twin operations of exchange and fusion. Exchanging and fusing the functions and signals of human motor control between digital twins will not only involve simple feedback to the real world but will also require detection and adjustment for inconsistencies between the real world and digital twin information expected to occur with such feedback. More specifically, it will be necessary to absorb the individual differences in functionality and signaling and the differences in the states of digital twins and humans in the real world. For example, if biological signals from a skilled athlete are fed back to someone who is unskilled, the unskilled person might not be able to move as originally expected due to their muscle strength, limited range of movement of their joints, or their current posture. There are also safety issues that may lead to ruptured muscle fibers, joint injuries, etc. Therefore, we are aiming to develop HMI technology that includes mediation functions in which the strength of signals to be fed back are adjusted or converted for movement more suitable to the human to create a world in which people with extended capabilities move as if with their own body.

We are proceeding with research and development of these biological-signal-decoding and feedback technologies to apply exchange and fusion, which are central to DTC, and extend human capabilities.

3. Zero latency media technology for DTC

In the real world, the concepts of space and time can be considered closely linked as individual people and objects are defined by unique spatial coordinates and the time axis. Information exchanges are carried out at the speed of light for visual information or the speed of sound for auditory information. Therefore, information transmission cannot physically exceed the speed of light. For this reason, delays occur when operating something remotely, which means physical constraints must be transcended to recognize the object being operated as being in the same space. Humans also experience cognitive delays with information transmission when signals are sent to the brain from sensory organs. Recognition and judgment are then carried out, leading to movement, etc. For this reason, the cognitive constraints of human recognition and judgment must be surpassed, even for events that take place in the same space. By focusing on physical latency that occurs with communications, etc. when operating objects and latency due to human cognition through DTC, we have embarked on the zero latency media technology initiative with a focus on the perspectives of *distant-independent expanded capabilities* that transcend the constraints of spatial distance and *individual-independent expanded capabilities* that step into the world of cognition not dependent on personal abilities. Below, we give an overview of these expanded capabilities and introduce the direction in which we would like to take them.

3.1 Distant-independent expanded capabilities

In DTC, in which people and objects are fused and coordinated when providing feedback to the real world through the cyber-physical interaction layer, the concept of space-time must be defined in the cyberspace framework instead of the simple synchronous time progression in the digital-world presentation layer. There is always a physical communications delay when providing feedback to the real world, which can cause problems with a range of applications. Examples include discomfort due to lip-sync deviation with video streaming [3] or video motion sickness that occurs due to delays in system processing with virtual reality and augmented reality [4, 5]. These issues manifest as discomforts that occur when sense-organ information different from the information expected by the human is given [4], which is also a major problem with DTC.

As well as feedback to the real world, there are even greater delays in *human-to-thing* and *human-to-human* interactions between remote locations, which necessitate technology to align the two different time axes to be fused. For example, in principle, with signal processing to remotely operate a machine, predicting environmental changes occurring with respect to the input makes alignment to the same time axis in the same space-time in cyberspace possible. However, simple physical prediction alone does not lead to a world where people and objects are fused. It is known that perceptual discrepancies about operations occur when people manipulate objects, but these can be eliminated with training and experience. Taking the example of driving a car, different capabilities are used when driving at 50 km/h and when racing at 300 km/h to process the sensation of driving gained from handling the vehicle or the resistance between the tires and the road surface, and the cognitive sense of time is completely different.

Hence, we are conducting research into modeling how prediction is performed in the brain as well as prediction of environmental changes by matching the cognitive delays (called sensory delays) that arise with human body movements for manipulating objects with system problems that occur when operating objects and delays in remote communications (called physical delays). The aim is to expand capabilities to freely operate objects remotely by eliminating the discomfort that occurs due to these physical and sensory delays and overcoming, through cyberspace, the physical gaps in distance in the real world.

3.2 Individual-independent expanded capabilities

Cognitive-delay tolerances and predictive abilities that occur when humans manipulate objects vary greatly from person to person. For example, there are large differences in the abilities of skilled workers, such as surgeons, airplane pilots, car racers, or professional athletes, compared to those of untrained humans, and it is possible to eliminate such differences in cognitive ability by experience and training. Although acquiring some of these skills requires a great deal of training, providing a simulated experience of the world experienced by skilled workers is also an effective way to learn. For example, learning to pilot an aircraft or drive a racing car does not start out with maneuvering an actual machine but entails sufficient training with a flight or drive simulator. Similarly, training for competitive swimming is possible by having the experience of swimming fast by being pulled by a rope, or baseball training to raise one's ability to respond to fastballs can be done by practicing with high-speed balls from a pitching machine. There has also been research into expanded capabilities that involves providing people with the experience of improved reflexes by stimulating the muscles using electrical muscle stimulation [6], enabling responses faster than the human cognitive delay. This research showed that it is possible to vary the amount of stimulation to give participants the illusion that they are actually performing a behavior such as grabbing a falling stick or taking a picture of a flying ball.

In light of this, we will study the human ability to make predictions by researching both human physical-reflection mechanisms and prediction mechanisms by modeling the speculative decision-making that takes place in the brain. By making it possible to exchange these prediction capabilities, we also aim to expand individual-independent capabilities to make it possible to exceed one's limitations and those in human capabilities in general.

3.3 The world we aim for and its application

Through expanded distance-independent capabilities and individual-independent capabilities, we aim to achieve a world in which remote objects can be operated freely by manipulating space-time in cyberspace to overcome the physical distance in the real world. This could entail remotely operating a device such as a robot arm in space or on the other side of the world in real time with the sensations of grabbing, moving, or crafting with the human hand. We will also work on extended capability technologies in DTC by studying semi-autonomous control technologies required for the negative latency world beyond zero through prediction considering the interactions between people and objects in their surrounding remote environments.

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Yukio Koike

Senior Research Engineer, Cybernetic Intelligence Research Project, NTT Service Evolution Laboratories.

He received an M.S. from Nagoya University, Aichi, in 2004 and joined NTT the same year. His research interests include network technology for Internet-of-Things services and biological signal processing.

Shigekuni Kondo

Senior Research Engineer, Planning Section, NTT Service Evolution Laboratories.

He received a B.E. in applied physics and an M.S. in integrated design engineering from Keio University, Kanagawa in 2003 and 2005 and joined NTT in 2005. His research interests include software modularity, home networks, and user interfaces. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Tatsushi Matsubayashi

Distinguished Researcher, Cybernetic Intelligence Research Project, NTT Service Evolution Laboratories.

He received a Ph.D. in science from Tokyo Institute of Technology in 2006. He joined NTT in 2005 and developed information-visualization, big-data-analysis, and optimization technologies. He is currently engaged in human-machine interface and brain-machine interface technology.

Social Issues with Digital Twin Computing

Katsumi Takahashi

Abstract

This article introduces the social issues with Digital Twin Computing to bring about new digital societies—a fusion of the real and virtual. Issues are presented as those of the three elements of data, autonomous agents, and virtual societies from the perspectives of security/privacy and ethics/laws. Essentially, social issues entail the human quest to freely engage in activities in both the real and virtual to achieve more comfortable and affluent lifestyles.

Keywords: security, privacy, ethics

1. What are the social issues with Digital Twin Computing?

NTT laboratories are conducting research and development of Digital Twin Computing (DTC) to achieve new digital societies that fuse the real and virtual. Social issues with DTC entail ensuring human activities are not hindered in either the real or virtual or discovering such hindrances in advance. Humans now live in both real and virtual societies. We, NTT laboratories, believe a stress-free combination of activities in both these societies will expand human activities and bring about more comfortable and affluent lifestyles. If there are inconsistencies between the real and virtual, for example, activities in the virtual that are not recognized in the real or activities in the virtual that become uncontrollable and destroy real activities, etc., such inconsistencies could become sources of stress and anxiety for individuals and society. The essence of social issues with DTC is how these inconsistencies (which we call *disconnected parallel worlds*) can be foreseen. We believe that the DTC vision we have put forth will become socially stable by developing technologies to prevent such inconsistencies or limit the damage they cause.

2. Components of DTC

To achieve new digital societies with DTC, we adopted the concept of digital twins. A digital twin is "a mapping process that accurately represents in cyberspace the shape, state, function, etc. of a real-world object (thing)" [1]. Virtual societies are created by gathering digital twins. To address the social issues with DTC, we perceive DTC as having three elements (**Fig. 1**).

- Data
- Autonomous agents consisting of data and interaction functions
- Virtual societies consisting of collections of digital twins

Data express people and objects. In contrast to conventional digital twins that have been developed for objects, DTC focuses on digital twins of humans. We believe that digital twins must be used for general purpose as well as express complex content because we expect each digital twin to work in a broader social context rather than just as a solution to a problem. The goal of this idea is expressed as *reproducing human internalities* in our DTC vision.

We presume that digital twins are autonomous agents, in other words, systems that operate autonomously. This is because we assume that digital twins will represent and strengthen human activities in virtual societies. We believe that digital twins will need

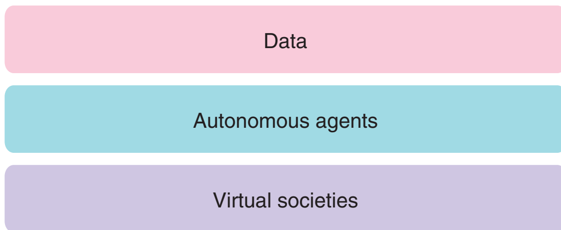

Fig. 1. Elements of DTC.

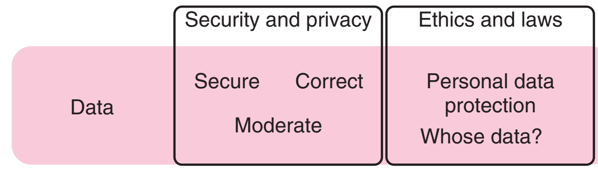

Fig. 2. Data of digital twins with DTC.

to be able to interact with each other (using functions called *operations*) and, at least in part, will inevitably need to be able to interact autonomously. Digital twins will also carry out simulations and other calculations and actively feed the results back to the real targets. Therefore, they will bridge the gap between the real and virtual. Not only can digital twins be viewed as autonomous agents but also as part of cyber-physical systems when viewed together with real humans or objects that have received feedback. We are also studying the generation of digital twins with properties that do not exist (called *derivative digital twins*) by other digital twins. This is a challenge.

A collection of digital twins and their activities is called a *virtual society*. DTC will provide environments where digital twins can be placed and operate. Digital twins are autonomous agents that hold data for people and objects internally, thus can form some kind of society. This will not just entail the aforementioned digital twin interactions. We believe that by giving the operating environments of digital twins or derivative digital twins high level functionality or even linking them with external applications, it will be possible to create various virtual societies.

3. Considerations of social issues

As explained above, the goal of DTC is to create new digital societies that combine the real and virtual and avoiding the creation of inconsistencies between these two domains, in other words *solving parallel-world problems*, is a social issue.

What are the approaches for solving parallel-world problems? There should be approaches for monitoring and controlling all digital twin activities in the environment provided by DTC. We do not deny that these approaches could be used in dedicated and closed services that use digital twins, but we will not take these approaches. Instead, we believe that each element of DTC will follow conventional data processing and computing rules and that by harmonizing the whole, we can avoid creating disconnected parallel worlds.

Accordingly, we will study each DTC element—data, autonomous agents, and virtual societies—as issues to debate. We will attempt analysis from the technical (security/privacy) and rule (ethics/laws) perspectives. Although, the technical perspective focuses on information security [2] and privacy frameworks [3], we will address broader concepts. Obviously, the rule perspective must follow current laws; however, we will also address ethics and laws without making strong distinctions between them.

4. Data issues

The data for digital twins assumed with DTC will have the following properties (**Fig. 2**).

- Data will express humans and objects
- Personal data will be included
- A wide scope will be described to address general problems
- Details will be described to address complex problems
- Sensors will be used proactively
- Data from a variety of sources will be integrated
- Data may also be generated from other digital twins

A digital twin is a *lump* of data. Because we are proactively thinking about digital twins of humans with DTC, a large amount of personal data will be included. Moreover, because we want to achieve more advanced computing with digital twins, we aim to make digital twins be general-purpose as well as be able to express complex content. When expressing human internalities, digital twins will consist of sensitive personal data that must be handled carefully.

We also take a proactive approach to generate data in DTC. We are studying fusing and using sensor and capture data, measurement data from wearable devices, and behavioral data from the Internet from the real world. We are also studying not only the simple accumulation of data but also data generation (derivative digital twins) by other digital twins.

From the above, we assume the following issues.

4.1 Security and privacy issues

As mentioned above, a digital twin is a lump of data, thus requiring information security. Of course, this will entail discussions about the basics of security—confidentiality (free of information leaks) and availability (available when required). Therefore, how will the integrity of a digital twin be perceived? If we simply think of it as data integrity (accurate and without omissions), then solutions are easy, but digital twin integrity becomes an interesting issue when thinking of it as the integrity of objects and humans in digital space; a little beyond the scope of information security. Ultimately, the question of integrity is whether all the data required to solve a problem is described with a digital twin. Another idea recommended in the context of data privacy is called data minimization, which is the pursuit of moderation in the handling of data. The goal is to simultaneously pursue moderation and precise collection of data.

4.2 Ethics and law issues

Since digital twin data are also personal data, it will be necessary to comply with privacy and data protection regulations, and consistency will be required even if these personal data are not subject to regulation. The main point of this issue is the nature of the design objectives, i.e., regarding how and to what extent the person (subject) of the digital twin can understand the generation of the digital twin and its purpose.

Such digital twin data can be generated from sensors installed by other people or data from other digital twins, which would make the digital twin a collaborative work so to speak. Thus, the issue here is whose data are they?

5. Issues with autonomous agents

Digital twins assumed with DTC are autonomous agents and will have the following properties (**Fig. 3**).

- Digital twins are systems that operate autonomously
- They have functions called operations and interact with other digital twins
- They can generate new digital twins (derivative digital twins)
- They comprise virtual societies
- Unified with the real, they become part of cyber-physical systems

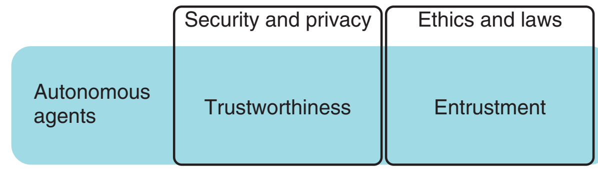

Fig. 3. Autonomous agents with DTC.

A digital twin is also a software system that expresses a target human or object as data. This software has functions called operations and operates autonomously by interacting with other twins. The range of autonomy will gradually be implemented from here on, although one currently planned capability is the generation of digital twins with properties that do not exist (derivative digital twins). Digital twins will form virtual societies. They will also feed data back to real entities and become part of cyber-physical systems through unification with the real.

From the above, we assume the following issues.

5.1 Security and privacy issues

As with many other systems, we believe the expectation for autonomous agents will be their trustworthiness. Naturally, this means operating as expected (or enough to believe it so) at any time. Trustworthiness is a concept that includes a number of requirements that is not discussed in detail here, however, in this case it is characterized by authentication and authorization (information security), artificial intelligence (AI) malfunction, physical safety (cyber-physical systems), etc.

5.2 Ethics and law issues

The first issue is to entrust work to a digital twin. The presence of objective judgments is a clue to this. This is likely to involve transparency and explainability often discussed in the context of AI ethics. The second issue is the social framework of entrustment. This involves considering whether the autonomous agent is a tool, representative of a human, the self of a human, etc., and delving deeper into the relationship between the autonomous agent and the law. A derivative argument of this issue is whether it is even ethical to use a digital twin. This problem is like that of being allowed to use your smartphone to study at home but not in an examination room. The third issue is of whether the work is one that a twin must not be made to do, aside from breaking the law. For example, in the case of derivative digital twins, if another person creates a digital twin of someone else, how will it be interpreted? Are there digital twins that are appropriate to create or those that should not be created (including the data-related issue of who owns the data that are created)?

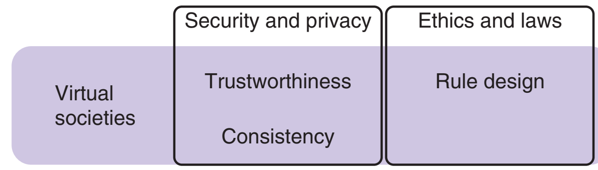

Fig. 4. Virtual societies with DTC.

6. Issues with virtual societies

Virtual societies conceived with DTC are collections of digital twins and their activities, as discussed above. Virtual societies may be achieved through linkages with external applications or be thought of as cyber-physical systems through linkages with actual humans. Although there are conceivably many variations of virtual societies and many subjects responsible for them, the following two general issues (**Fig. 4**) are discussed in detail.

6.1 Security and privacy issues

With virtual societies, trustworthiness is typically expected to be the same as with autonomous agents, but cybersecurity measures are more important. A major additional issue is that of ensuring consistency. Consistency means that there are no contradictions between the state of a digital twin and that of its subject. Since there can be more than one digital twin, this also includes consistency between digital twins. For example, if twin A sells a belonging of a subject, and at the same time twin B has it destroyed, consistency will cease to exist (transaction management). The first question in a virtual society is to what extent transaction management is required and is key to solving parallel-world problems.

6.2 Ethics and law issues

An important issue with a virtual society consisting of autonomous agents is the design of the rules of the society. This is the problem of how to constrain the free behavior of agents. Examples of this could include distribution of limited resources (ensuring fairness) or the necessity of basic prohibitions (e.g., the elimination of discrimination). There is also the issue of whether to allow rules to override individual protections when it is in the public interest, for example, to respond to disasters or pandemics.

7. Future developments

This article described the aims of DTC and discussed the social issues that should be addressed to achieve those aims as those of the three elements of data, autonomous agents, and virtual societies, and described them from the perspectives of security/privacy and ethics/laws. By continuing to think about these issues, we believe new digital societies that combine the real with the virtual are achievable.

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Katsumi Takahashi
Executive Research Scientist, Senior Manager of Planning Section, NTT Secure Platform Laboratories.
He received a B.S. in mathematics from Tokyo Institute of Technology in 1988 and a Ph.D. in information science and technology from the University of Tokyo in 2006. He joined NTT in 1988 and has studied information processing technologies including security and privacy.

Spatio-temporal Equalization Technology for High-capacity Underwater Acoustic Communication

Hiroyuki Fukumoto, Yosuke Fujino, Kazumitsu Sakamoto, Marina Nakano, and Toshimitsu Tsubaki

Abstract

We are currently researching and developing Mbit/s-class underwater acoustic communication technology enabling high-definition video and other large data transmission. This article proposes a spatio-temporal equalization technology, which is key for achieving high-speed underwater transmission.

Keywords: underwater acoustic communication, spatio-temporal equalization, distortion compensation in double selective channel

1. Introduction

Acoustic waves have long been used by humans as a transmission medium underwater, similar to how dolphins use them. With the advantages of long communication range and not being affected by water turbidity and ambient light, acoustic communication has been applied for underwater image transmission and communication between deep-sea exploration vessels and offshore support vessels [1]. However, the communication rate with current commercial modems is only tens of kbit/s (bits per second); hence, a large amount of data, such as high-definition video, cannot be transmitted in real time [2]. Against this, we are currently researching and developing high-capacity Mbit/s-class underwater acoustic communication technologies by utilizing our expertise in wave-propagation and signal-processing technologies that have been applied to terrestrial radio wireless communication. Our technologies make it possible to transmit high-definition video and other large data, allowing full wireless remote control of undersea equipment such as remotely operated vehicles (ROVs), as shown in **Fig. 1**.

As a key technology to accelerate the transmission rate, this article proposes a spatio-temporal equalization technology that can provide stable distortion compensation regardless of transceiver movement or degree of double selectivity in broadband acoustic communication.

2. Underwater channel characteristics and issues regarding high-speed transmission

The underwater acoustic channel has double selectivity, in other words, the channel impulse response varies with time. The cause is that the multipath waves generated by reflection from the sea surface, sea bottom, and underwater structures arrive at the receiver accompanied with Doppler shift due to the movement of the transceiver and fluctuation of sea surfaces, as shown in **Fig. 2** [3]. Since the propagation speed of sound waves in the sea (about 1500 m/sec) is about 200,000 times slower than that of radio waves (about 3×10^8 m/sec), both degree of delay spread and that of Doppler spread of underwater channels, which are key parameters representing double selectivity, are much larger than those of land

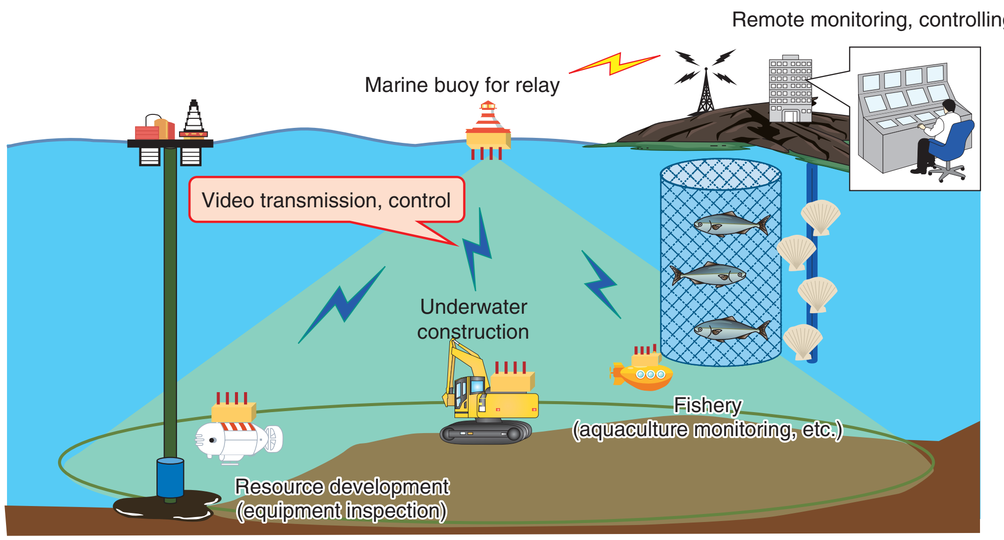


Fig. 1. Our vision.

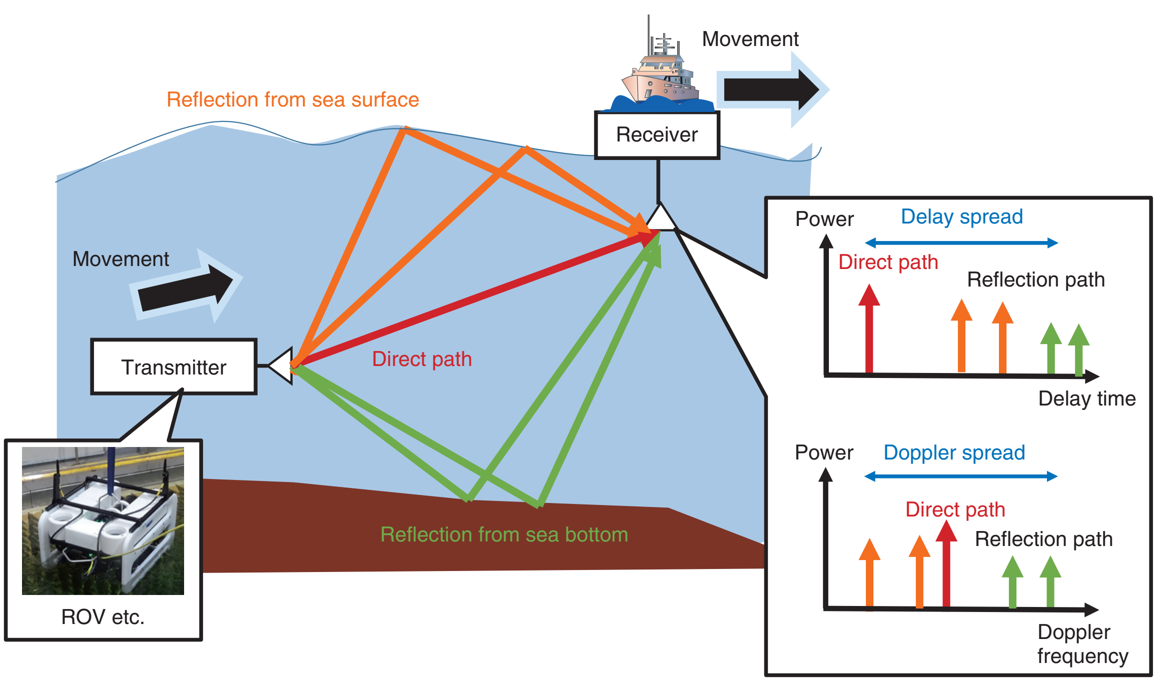


Fig. 2. Acoustic propagation through underwater channels.

mobile radio channels. Thus, adaptive signal processing is essential for tracking time variations.

To accelerate transmission speed, we are now considering broadband acoustic transmission using a high carrier frequency of 100 kHz or more, which is rarely used in current commercial systems. Since Doppler spread increases in proportion to the carrier frequency from the viewpoint of sound propagation theory, broadband transmission, which must use a high carrier frequency, makes time selectivity stronger than that with conventional narrowband transmission systems. Thus, the state of a channel response

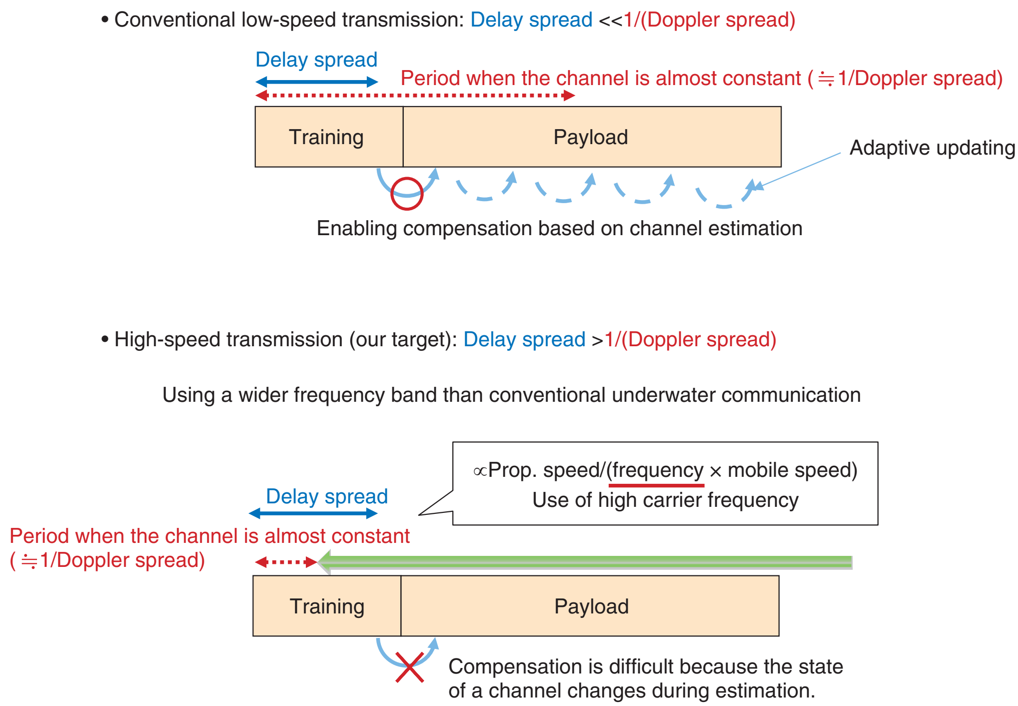


Fig. 3. Issues regarding high-speed transmission.

rapidly and drastically varies even during a training period. Conventional adaptive equalization technologies, such as decision-feedback equalization [4], for estimating the inverse characteristics of the underwater channel cannot keep up with channel variation if the delay spread is less than the reciprocal of Doppler spread, as shown in **Fig. 3**. Therefore, there is a need for technology that can provide stable compensation regardless of transceiver movement, or degree of double selectivity, to accelerate the data transmission rate.

3. Our spatio-temporal equalization technology

The essential diffculty with distortion compensation is estimating and tracking overall channel responses in the time or frequency domain. Thus, equalization technologies that are based on prior knowledge of the channel do not work well. The key with our spatio-temporal equalization technology is to shorten delay spread and Doppler spread by eliminating some of the delayed waves in the spatial domain before carrying out equalization in the time domain. By doing so, both delay spread and Doppler spread of the multipath channel can be made substantially smaller than those of actual channel response, as shown in **Fig. 4**, and this makes it possible to equalize acoustic signals through multipath channels regardless of double selectivity.

We now briefly describe the proposed spatio-temporal equalization technology. **Figure 5** shows a block diagram of our technology. All the finite impulse response (FIR) filter coeffcients cascaded to each input channel are adaptively updated using adaptive algorithms, such as the recursive least squares algorithm, to minimize the square error between the desired and equalized signals. It is similar to the design of adaptive equalization [5], except for the length of the feed forward FIR filter. From the operational comparison on the left of **Fig. 6**, the proposed technology uses FIR filters, the filter length of which is much shorter than the actual delay spread. In this case, the signal components of the indirect path, the delays of which are longer than the length of a FIR filter, do not correlate with the desired signal. Hence, they are suppressed in the spatial domain by FIR-filter-operation updating with an adaptive algorithm. On the other hand, the signal components, the arrival delay of which is less than the length of a FIR filter, correlate with the desired signal, therefore they are equalized in the time domain, as shown at the bottom right of Fig. 6. Long-delay waves are thus

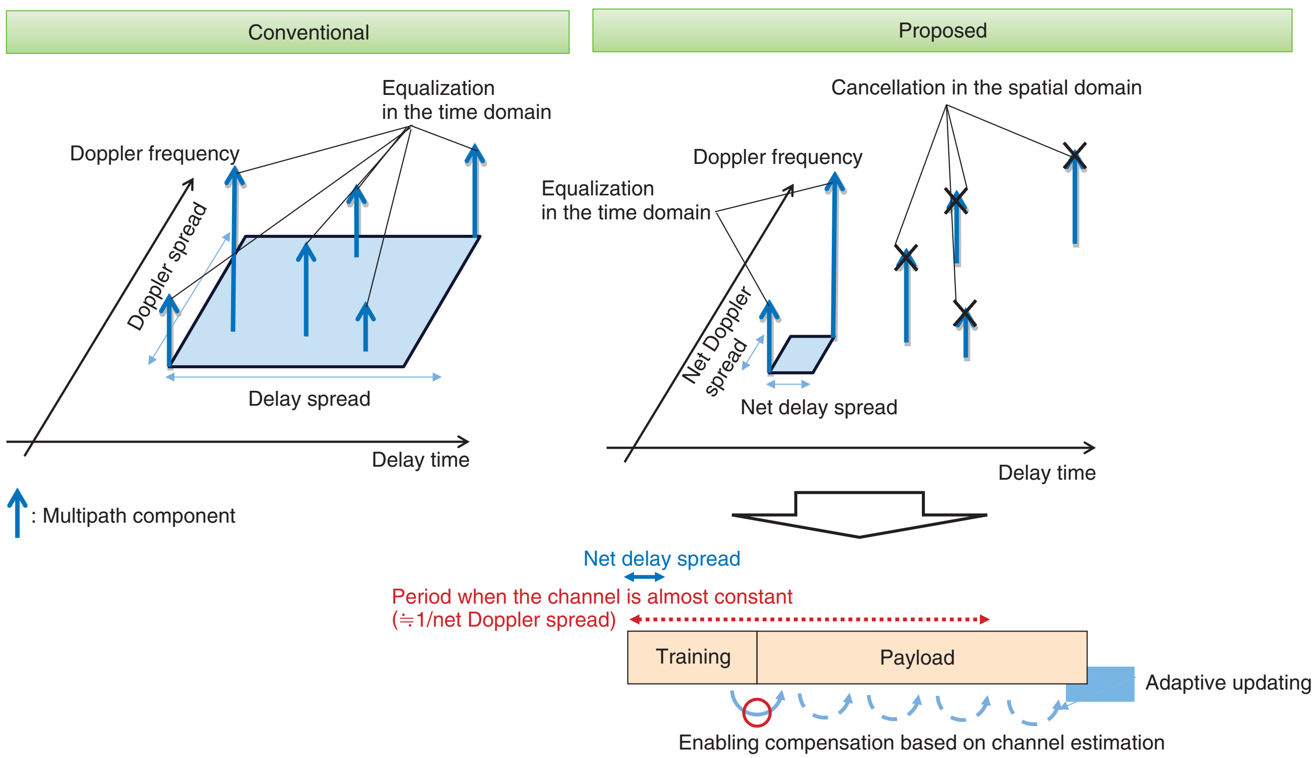


Fig. 4. Comparison with conventional equalization and proposed spatio-temporal equalization technologies.

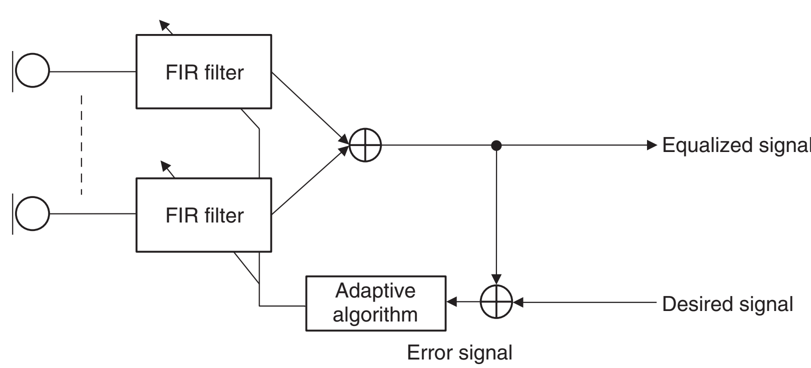


Fig. 5. Practical implementation of our spatio-temporal equalization technology.

cancelled in the spatial domain while equalizing residual paths in the time domain. Such a path-selective receiving structure makes stable compensation of underwater acoustic channels possible.

4. Field experiments

To verify the effectiveness of the proposed spatio-temporal equalization technology, we conducted two transmission experiments using offline signal processing on a measurement barge moored in Suruga Bay off of Shizuoka Prefecture, Japan. We experimentally evaluated the bit error rate (BER) with respect to the speed of the vertically moving transmitter and confirmed that a stable BER can be achieved regardless of this speed or strength of double selectivity. The experimental system is shown in **Fig. 7**, experimental environment for both experiments

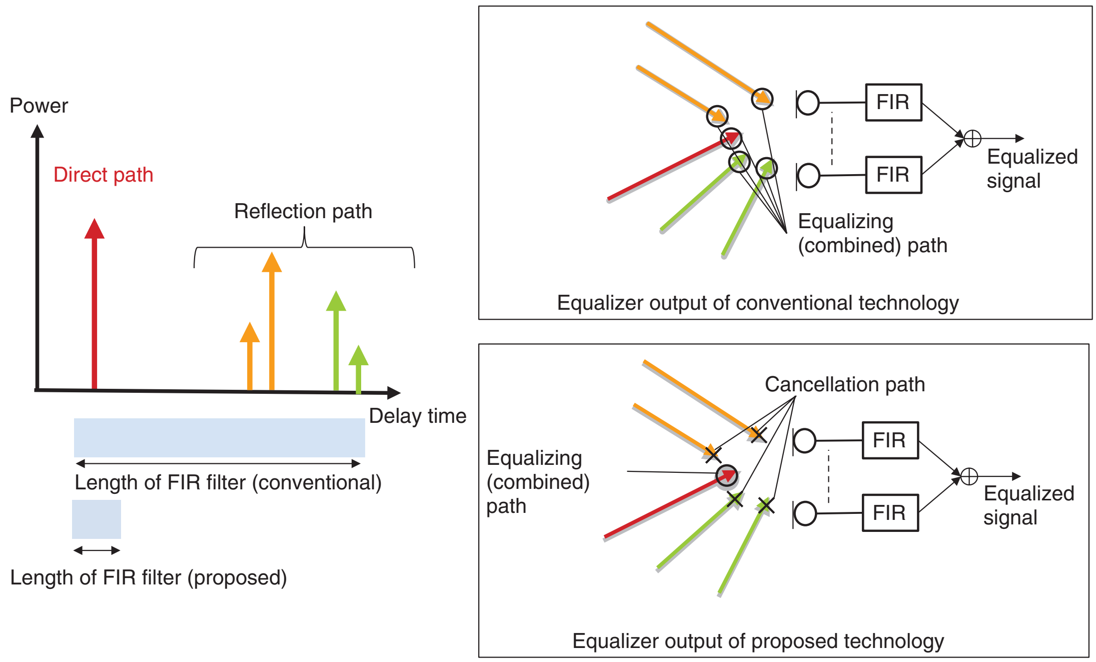


Fig. 6. Operation of our spatio-temporal equalization technology.

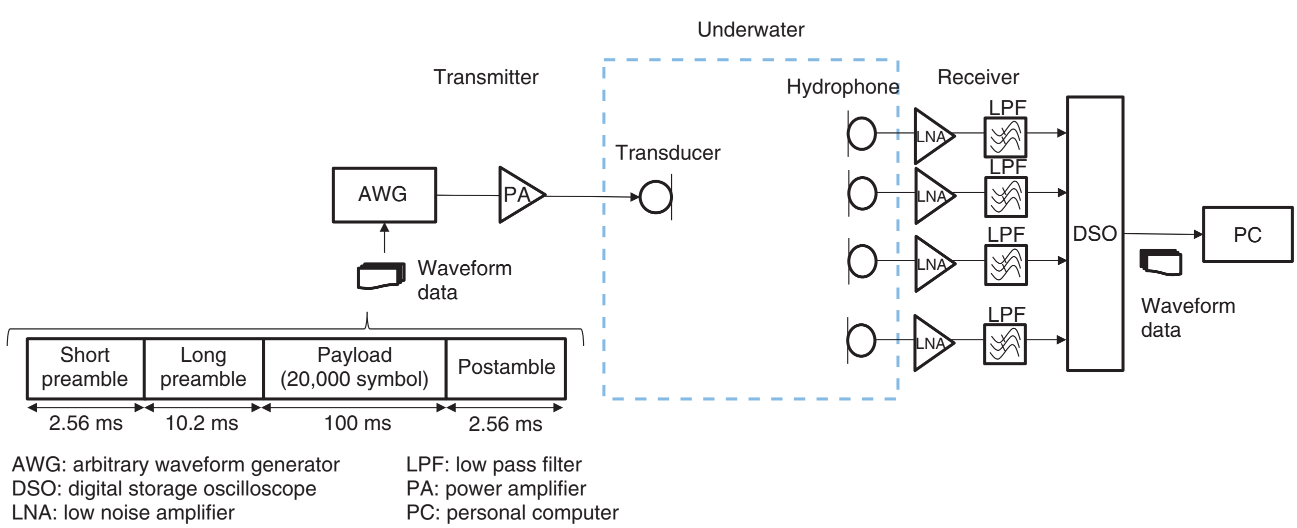
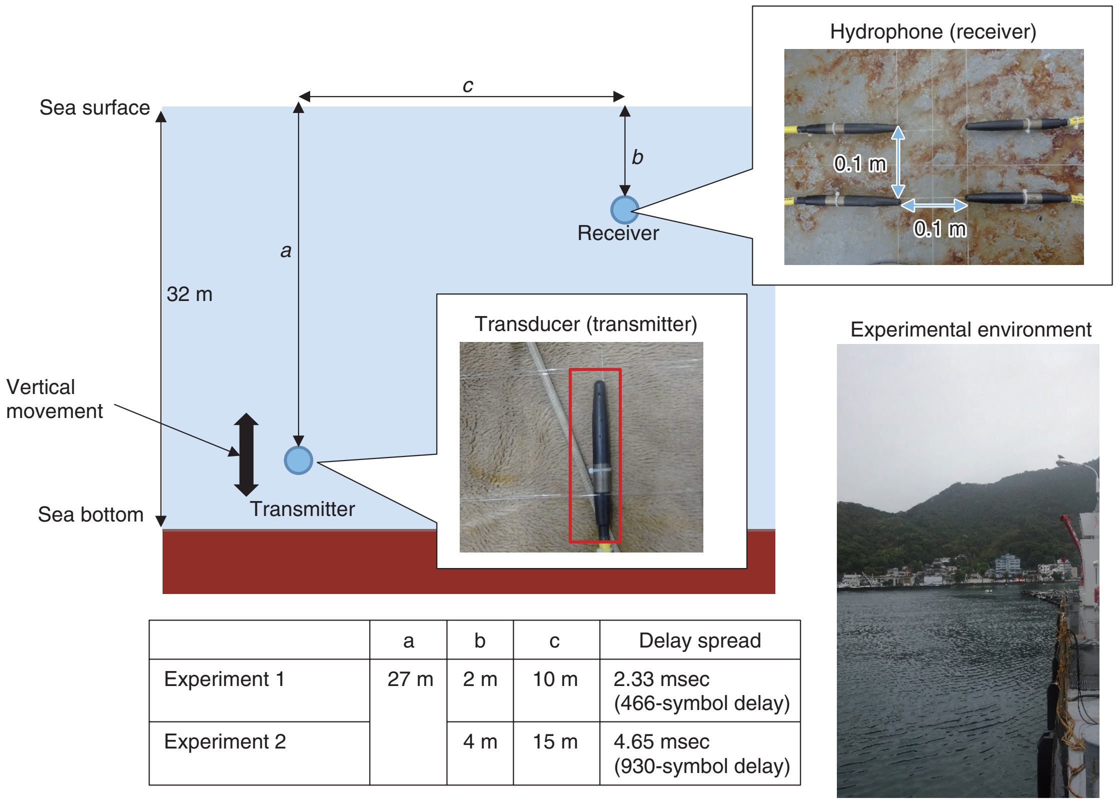


Fig. 7. Experimental system.

(experiments 1 and 2) is shown in **Fig. 8**, and experimental specifications are presented in **Table 1**. Waveform data were recorded while the transmitter was continuously moving in the vertical direction, and the recorded data were analyzed. The mooring rope was manually moved vertically so that various speed patterns would be generated.

The observed BERs are shown in **Figs. 9** and **10** for experiments 1 and 2, respectively. The horizontal axis is the speed of the vertically moving transmitter estimated using the known signal of the frame, and the vertical axis is the BERs calculated from the frame demodulation results. The BERs fluctuated regardless of the speed. This is because the level ratio of the



	a	b	c	Delay spread
Experiment 1	27 m	2 m	10 m	2.33 msec (466-symbol delay)
Experiment 2		4 m	15 m	4.65 msec (930-symbol delay)

Fig. 8. Experimental environment.

Table 1. Experimental specifications.

Parameter	Value
Carrier frequency	300 kHz
Bandwidth	200 kHz
Modulation	Quadrature phase-shift keying
Transmission system	Single carrier transmission
Transmission rate	400 kbit/s (payload only)
Equalization technology	Spatio-temporal equalization
Number of taps	54 tap/ch
Transducer and hydrophone arrangement	TX: 1, RX: 4 (2 x 2 rectangular array)

direct wave and sea-surface reflected wave varied greatly from frame to frame due to changes on the sea surface. All the BERs were below the forward error correction (FEC) limit of 7% [6]. Also, the correlation coeffcient between speed and BER was 0.21, and there was almost no causal relationship between the deterioration in BER with respect to speed or double selectivity of the channel. Through these experiments, we confirmed the possibility of high-speed broadband acoustic transmission under actual sea conditions.

5. Conclusion

In this article, we presented our future vision for an underwater wireless communication system. Channel characteristics and issues with broadband acoustic transmission were also presented. To obtain stable

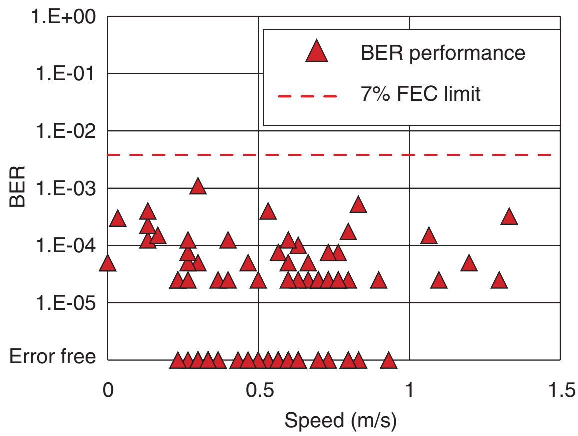


Fig. 9. BERs observed in experiment 1.

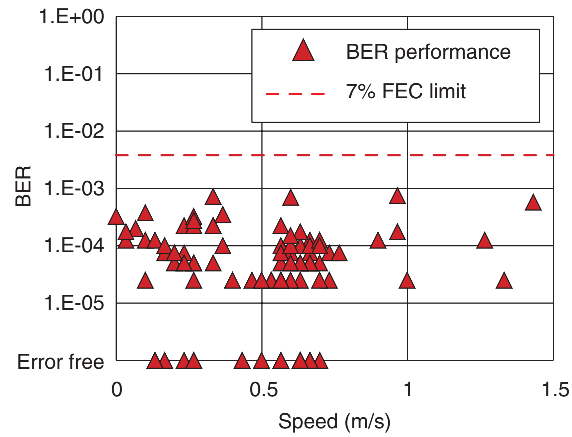


Fig. 10. BERs observed in experiment 2.

compensation regardless of double selectivity, we proposed a spatio-temporal equalization technology and presented experiments conducted at sea and the results, which indicate that stable communication can be achieved regardless of speed. We also confirmed the possibility of broadband underwater communication.

We mainly considered a single-input multiple-output transmission system in this article. However, multiple-input multiple-output (MIMO) extension is easy to implement thanks to the fact that our equalization technology eliminates uncorrelated interference signals simultaneously. With this property, we successfully transmitted 5.12 Mbit/s signals over 18 m using 8 × 16 MIMO transmission with offline signal processing, demonstrating the achievability of Mbit/s-class transmission. See our paper to be published [7] for a detailed description of a field experiment and a method of extending MIMO transmission.

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Hiroyuki Fukumoto
Researcher, Wave Propagation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. in engineering from Kobe University, Hyogo, in 2013, and an M.E. in informatics from Kyoto University in 2015. He has been with NTT Network Innovation Laboratories since 2015. His research interest includes adaptive signal processing, information theory, and space division multiplexing technologies. His current research is on architecture design and implementation for high-speed underwater acoustic communication modems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Yosuke Fujino
Senior Research Engineer, Wave Propagation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in electrical and electronic engineering from Shizuoka University in 2002 and 2004. He joined NTT Network Innovation Laboratories in 2004 and engaged in research on physical layer signal design and transceiver architecture for Internet of Things (IoT) wireless systems. The current focus of his research is wireless communication technology for frontier areas such as underwater, underground, and space.

Kazumitsu Sakamoto
Research Engineer, Wave Propagation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in electrical engineering from Kyushu University, Fukuoka, in 2008 and 2010. In 2010, he joined NTT Network Innovation Laboratories and has been engaged in research on MIMO communication systems, millimeter-wave high-speed wireless systems, and IoT and machine-to-machine (M2M) wireless access systems. He received the Young Engineers Award and the Communications Society Best Letter Award from IEICE in 2015. He is a member of IEICE.

Marina Nakano
Researcher, Wave Propagation Laboratory, NTT Network Innovation Laboratories.

She received a B.E. and M.E. from Miyazaki University in 2015 and 2017. She joined NTT Network Innovation Laboratories in 2017 and is currently engaged in research and development of IoT/M2M wireless systems. She is a member of IEICE.

Toshimitsu Tsubaki
Senior Research Engineer, Wave Propagation Laboratory, NTT Network Innovation Laboratories.

He received a B.S. and M.S. in geophysics from Tohoku University, Miyagi, in 1994 and 1996. He joined NTT in 1996 and has been engaged in research and development of media access control for broadband wireless access systems, radio frequency identification tagging systems, non-contact high-speed transmission systems, and network assistance technologies for IoT services. His current research interest is in underwater high-speed ultrasonic communication systems. He is a member of IEICE.

Meeting Report on ITU-T FG-AI4EE—ICT Applications Using Artificial Intelligence in Climate Change Countermeasures and Their Standardization Trends

Xiaoxi Zhang, Kazuhiro Takaya, Yoshihiro Kondo, and Yoshinori Sugimoto

Abstract

Although emerging technologies, such as artificial intelligence (AI) and blockchain, are expected to improve service availability and work efficiency in various fields, they consume a large amount of energy during data collection from many sensors, learning, and data analysis. Therefore, it is necessary to evaluate the environmental impact as well as other effects of introducing such technologies. A short-term focus group in the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T), Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies (FG-AI4EE), was established in May 2019 to conduct a preliminary study of the environmental efficiency of AI and other emerging technologies and held its first meeting in December 2019. This article describes not only what FG-AI4EE is and what was discussed at its first meeting but also how NTT has been working on environmental issues based on the Innovative Optical and Wireless Network (IOWN), including the response to crises such as the current COVID-19 pandemic.

Keywords: environmental efficiency, AI and emerging technologies, focus group, ITU-T SG5

1. Environmental impact of artificial intelligence and emerging technologies

Society 5.0 [1] proposed by the Japanese Cabinet Office aims to achieve economic growth and solve social issues in parallel by using a system that closely integrates cyberspace and physical space. Information distribution using artificial intelligence (AI), Internet of Things (IoT), big data, etc., is intended to enable a high quality of life. Natural disasters due to climate change have also been causing substantial damage worldwide, so it is necessary to develop effective methods for environmental protection using information and communications technology (ICT). In particular, AI and other emerging technologies, such as blockchain, edge/cloud computing, and fifth-generation mobile communication systems (5G), are expected to help solve such environmental problems by enabling near-future environmental prediction and visualization of meteorological phenomena. However, the energy consumption of AI and other emerging technologies is also expected to have an environmental impact due to the increase in the size of applications and amount of calculation, which is similar to that of current services and applications. Furthermore, AI consumes a large amount of energy not only when analyzing a large amount of data collected from sensors and system logs but also during pre-learning and tuning. Therefore, to minimize the environmental impact of using ICT, a method is required for evaluating and measuring the environmental efficiencies with respect to both ICT performance and environmental impact, which have not been defined by existing international standards and/or guidelines in the environmental field.

2. Purpose of establishing FG-AI4EE

Within the International Telecommunication Union (ITU) under the United Nations (UN), telecommunications carriers and ICT vendors are developing ITU-T Recommendations for guidance to solve various environmental issues regarding ICT in Study Group 5 (SG5) of the Telecommunication Standardization Sector (ITU-T). The methodology for assessing the environmental impact of the ICT sector has been completed as Recommendation ITU-T L.1450. In addition, Recommendation ITU-T L.1451, which was developed in 2019 with contributions from NTT, defines the method of assessing the aggregated positive environmental impact of ICT in other sectors. Since the quantitative evaluation of ICT's potential contribution to environmental protection has progressed, a short-term Focus Group on Environmental Efficiency for AI and other Emerging Technologies (FG-AI4EE) was established in May 2019 to conduct a preliminary study called "Environmental Efficiency for AI and other Emerging Technologies." FG-AI4EE started its activities to promote a global dialogue on the environmental efficiency of AI and other emerging technologies.

Emerging technologies are expected to improve work efficiency and expand potential applications in various fields but consume a large amount of energy during installation and operation and increase environmental impact. To achieve the UN Sustainable Development Goals (SDGs), methods and global evaluation standards are needed to evaluate and measure the environmental impact of solutions that use emerging technologies. FG-AI4EE is expected to function as a platform for clarifying the standardization requirements for achieving the SDGs.

3. Overview of the first FG-AI4EE meeting

The first FG-AI4EE meeting was held in Vienna (Austria) from December 11 to 13, 2019. A workshop of the AI4EE Forum and a meeting of the U4SSC (United for Smart Sustainable City) index thematic group were held in conjunction with the FG-AI4EE meeting. Unlike the ITU-T SG5 meeting, the FG-AI4EE meeting involved not only telecommunications-related parties but also other entities: international organizations such as UN and government-affiliated organizations, and academic institutions such as universities and think tanks. About 30 participants attended the meetings in person, including two of the authors (Mr. Kondo and Mr. Sugimoto), and about 15 attended remotely from around the world.

There were two sessions in the AI4EE Forum. The first session was held to explore the possible environmental impact of AI, and the second was devoted to discussing use cases for assessing such impact. During the forum, the necessity of AI and the goal of FG-AI4EE were shared among all participants. At the FG-AI4EE meeting, there were discussions regarding 1) management team, 2) working group (WG) structure, 3) terms of reference (ToR), and 4) FG deliverables to be developed.

3.1 Management team

The FG chairpersons are Dr. Paolo Gemma (Huawei), who also chairs Working Party 2 of ITU-T SG5, and Dr. Neil Sahota (IBM & University of California). Professors and experts in the fields of finance/economics and environment/energy are among those named as vice-chairpersons. **Table 1** shows the chairpersons and vice-chairpersons agreed at this meeting.

3.2 WG structure

It was agreed that the three newly established WGs shown in **Table 2** would carry out detailed studies.

(1) WG1: Requirements of AI and other Emerging Technologies to Ensure Environmental Efficiency

WG1 studies the requirements for improving environmental efficiency when introducing AI and other emerging technologies. In various use cases, introducing an emerging technology that fulfills these requirements would be expected to result in reduced energy consumption, which would reduce environmental impact. For example, key performance indicators (KPIs) such as bandwidth usage are collected from an optical line termination and optical network termination in a passive optical network (PON) system, then root-cause analysis using AI is carried out. This analysis would identify minimum required resources that satisfy the service-level agreement, which would in turn reduce the power consumption of the PON system and the number of on-site calls.

(2) WG2: Assessment and Measurement of the

Table 1. FG-AI4EE management team.

Co-Chairpersons
• Paolo Gemma (Huawei, China)
• Neil Sahota (IBM & University of California)
Vice-Chairpersons
• Barbara Kolm (Austrian Economics Center & Austrian National Bank)
• Kari Eik (Organization for International Economic Relations (OiER))
• Joel Alexander Mills (AugmentCity AS)
• Mats Pellbäck Scharp (Ericsson)
• Alice Charles (World Economic Forum (WEF))
• Claudio Bianco (Telecom Italia)
• Peter Ulanga (Universal Communications Service Access Fund, United Republic of Tanzania)
• Stefano Nativi (European Commission - Joint Research Centre)
• Mandar Deshpande (Ministry of Communications, India)
• UN-Environment Programme

Table 2. FG-AI4EE WG structure.

WG	Title
WG1	**Requirements** of AI and other Emerging Technologies to Ensure Environmental Efficiency
WG2	**Assessment and Measurement** of the Environmental Efficiency of AI and Emerging Technologies
WG3	**Implementation Guidelines** of AI and Emerging Technologies for Environmental Efficiency

Environmental Efficiency of AI and Emerging Technologies

WG2 studies environmental efficiency assessment and measurement methods that help carriers and related stakeholders introduce AI and other emerging technologies. It would be expected that the outcome for achieving the SDGs can be attained by using the evaluation and measurement methods studied in WG2 to improve the quality of these technologies while considering their operational efficiency and environmental impact.

(3) WG3: Implementation Guidelines of AI and Emerging Technologies for Environmental Efficiency

WG3 studies implementation guidelines to improve the environmental efficiency of AI and other emerging technologies. Regarding blockchain, which supports crypto-currencies, the guidelines on how to improve environmental efficiency and the principle of environmental efficiency by the transition from “proof of work” (allowing more computationally intensive users to work more favorably) to “proof of stake” (not wastefully consuming energy even when competing with others) will be provided.

3.3 ToR

FG-AI4EE will develop technical reports and technical specifications to address the environmental efficiency as well as water and energy consumption of emerging technologies to meet the SDGs. Specifically, the key objectives of the FG include the following.

- Identify and analyze the environmental impact of deploying and implementing AI and other emerging technologies
- Provide a platform for facilitating global dialogue and raising awareness on the environmental impact of AI and other emerging technologies
- Assist relevant stakeholders in minimizing the global environmental impact of operating AI and other emerging technologies
- Develop a framework and standardization approach to adopting AI and other emerging technologies in an environmentally sound manner

Table 3. Deliverables to be developed.

WG	Title	Source
WG2	Technical Report on Energy Efficiency Assessment and Metrics	University of Thessaly
WG3	Technical Report on Visions of Best Practices on Artificial Intelligence and Blockchain in 2025	Austrian Economics Centre
WG2	Technical Report on Methodology for Supporting the Implementation of Artificial Intelligence and Blockchain Solutions at the Government Level	
	Computer Processing, Data management and Energy Perspective	European Commission - Joint Research Centre
WG1	Guidelines Assessing Eco-Friendliness of Requirements	University of California
WG2	List of KPIs/Metrics	
WG3	Eco-friendly Build/Implement Guidelines	
WG1	Study on How AI Is Essential in Currently Deployed Network and Future Evolutions to Optimize Resource Utilization and to Reduce Call Out and Related Energy Dissipation	Huawei
WG2	Technical Report on “Guidelines on the Environmental Efficiency of 5G Usage in Smart Water Management”	
WG1 /WG2 /WG3	Requirements of AI and Other Emerging Technologies to Ensure Environmental Efficiency: Simulation Conference: Case Study of Environmental Impact of AI or Blockchain, Which Will Include the Visualization of the KPIs	AugmentCity
WG2	Establishment of 5G Energy Efficiency Assessment Model Based on AI and Big Data Analysis	China Telecom
WG3	Application of AI Technology in Improving Energy Efficiency of IDC Infrastructure	

IDC: Internet datacenter

- Describe strategic directions for future standardization efforts in tackling the environmental impact of these technologies

3.4 Deliverables to be developed

At the first FG-AI4EE meeting, participants agreed to develop 28 deliverables. **Table 3** lists some of these deliverables. Governmental and academic organizations that emphasize effective measures against climate change proposed evaluation metrics for the energy efficiency of AI and blockchain technologies. As a telecommunications carrier, China Telecom proposed developing methodologies for measuring and evaluating the energy efficiency of 5G networks using AI and big data analysis and writing up implementation guidelines.

The following deliverables were also proposed: 1) implementation and design requirements of assessment methodologies for environmental impact by visualizing measurement data of relevant KPIs using *digital twin* technology, 2) reporting templates for environmental-friendliness assessment and measurements, and 3) implementation guidance of network-operation management using AI and machine learning.

Since a WG that handles the deliverables shown in Table 3 has not been agreed upon, the deliverables are based on the proposal in the relevant contribution. The WG responsible for handling each deliverable will be decided from future discussions in the FG.

4. Changes in social environment after the first FG meeting

Social systems worldwide have had to adapt to the global spread of COVID-19. Changes include the increase in communication traffic caused by the transition to telework and online education, promotion of telemedicine, increase in online shopping and home deliveries, and increase in food disposal due to the closure of restaurants and schools. These changes will result in not only benefits but also considerable disadvantages in terms of environmental impact. To create a sustainable smart city, sustainable economic activities must be maintained while reducing greenhouse gas emissions from using ICT.

The NTT Group has proposed the Innovative Optical and Wireless Network (IOWN) toward 2030 with multiple pillars of technological developments, one of which is “a dramatic improvement in energy efficiency in ICT infrastructure” [2, 3]. IOWN must be achieved so that the environmental impact of ICT can be minimized. IOWN should enable ICT to be used to avoid or minimize any damage caused by future global crises as well as the current COVID-19 pandemic.

For the sustainable development of enterprises worldwide, the environmental impact of ICT services will need to be evaluated accurately and appropriately and various social issues will need to be solved by using IOWN from the perspective of environment, society, and governance (ESG) management considering the environment and society.

5. Summary and future activities

Although emerging technologies such as AI are expected to improve work efficiency and expand business possibilities in various fields, they consume a large amount of energy during installation and operation, which in turn leads to increased environmental impact. To achieve the UN SDGs, it is essential to develop methodologies for evaluating and measuring environmental impact and international evaluation standards. Most proposals at the first FG-AI4EE meeting were for energy efficiency and climate change, and few proposals were for a circular economy including measures for e-waste (electrical and electronic waste). Since ICT plays an important role in contributing to the SDGs, FG's activity should make enterprises and organizations aware of ESG management, as well as share best practices worldwide and develop international guidelines. While continuing to investigate the activities of this FG so that IOWN can simultaneously help solve environmental problems and various social issues, NTT laboratories will continue to contribute to the international telecommunications community by sharing the results of its ICT and environmental research and developments through this FG activity.

References

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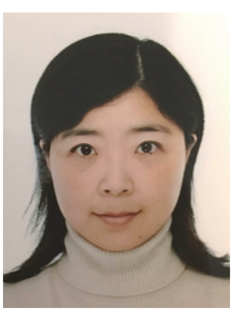

Xiaoxi Zhang

Senior Research Engineer, ESG Management Science Group, Resilient Environmental Adaptation Research Project, NTT Space Environment and Energy Laboratories.

She received a B.S. and M.S. in social engineering from Tokyo Institute of Technology in 2007 and 2009. Since joining NTT in 2009, she has been engaged in research on risk-based management of telecommunication infrastructures. She is currently researching methods of assessing the environmental and economic impact of ICT use. She won the Distinguished Service Award from the Telecommunication Technology Committee in 2020. She is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Kazuhiro Takaya

Senior Research Engineer, Supervisor, Zero Environmental Impact Research Project, NTT Space Environment and Energy Laboratories.

He received a B.E. and M.E. in electrical and electronic engineering from Okayama University in 1993 and 1995 and received a Ph.D. in electrical engineering from Kyoto University in 2019. He joined NTT Telecommunication Networks Laboratories in 1995. Since then, he has been engaged in the study of electromagnetic compatibility of communication systems. He received the Communication Society Activity Achievement Award in 2015 for his contributions as a secretary of IEICE Technical Committee on Electromagnetic Compatibility (EMCJ). He received the Encouragement Award in 2017 from the ITU Association of Japan for his contributions relating to ITU-T SG5. He is a Vice-chairman of ITU-T SG5. He is a member of IEICE.

Yoshihiro Kondo

Senior Expert Engineer, IOWN Business Development Business Unit, Network Innovation Business Headquarters, NTT Advanced Technology Corporation.

He received an M.S. and Ph.D. in electrical engineering from Northwestern University in Evanston, Illinoi, USA, in 1990 and 1994. After he worked for OKI Electric Industry Co., Ltd., where he developed optical access network systems, he joined NTT Advanced Technology in 2006. Since then, he has been working on standardization of multiple areas such as environmental and energy-efficiency-related issues, access network systems, and home network systems. He is a member of the Institute of Electrical and Electronics Engineers (IEEE).

Yoshinori Sugimoto

Engineer, IOWN Business Development Business Unit, Network Innovation Business Headquarters, NTT Advanced Technology Corporation.

He received a B.S. and M.S. in information and communication engineering from the University of Electro-Communications, Tokyo, in 2003 and 2005. Since joining NTT Advanced Technology in 2005, he has been engaged in research on high-speed data transmission in the Generalized Multiprotocol Label Switching network, and Service OAM (Operations, Administration, and Maintenance) in Metro Ethernet Forum, etc. He is currently researching the role of ICTs in tackling climate change. He is participating in ITU-T FG-AI4EE.

External Awards

DCASE 2019 Best Paper Award

Winners: Shota Ikawa, The University of Tokyo; Kunio Kashino, NTT Communication Science Laboratories
Date: October 25, 2019
Organization: The Workshop on Detection and Classification of Acoustic Scenes and Events (DCASE) Community

For "Neural Audio Captioning Based on Conditional Sequence-to-Sequence Model."
Published as: S. Ikawa and K. Kashino, "Neural Audio Captioning Based on Conditional Sequence-to-Sequence Model," Proc. of DCASE2019, pp. 99–103, NY, USA, Oct. 2019.

CHI 2020 Honorable Mention Award

Winner: Kentaro Yasu, NTT Communication Science Laboratories
Date: April 16, 2020
Organization: Association for Computing Machinery's Special Interest Group on Computer Human Interaction (ACM SIGCHI)

For "MagneLayer: Force Field Fabrication by Layered Magnetic Sheets."
Published as: K. Yasu, "MagneLayer: Force Field Fabrication by Layered Magnetic Sheets," Proc. of the 2020 CHI Conference on Human Factors in Computing Systems, Apr. 2020.

IEEE SPS Young Author Best Paper Award

Winners: Daichi Kitamura, National Institute of Technology, Kagawa College; Nobutaka Ono, Tokyo Metropolitan University; Hiroshi Sawada, Hirokazu Kameoka, NTT Communication Science Laboratories; Hiroshi Saruwatari, The University of Tokyo
Date: May 5, 2020
Organization: IEEE Signal Processing Society

For "Determined Blind Source Separation Unifying Independent Vector Analysis and Nonnegative Matrix Factorization."
Published as: D. Kitamura, N. Ono, H. Sawada, H. Kameoka, and H. Saruwatari, "Determined Blind Source Separation Unifying Independent Vector Analysis and Nonnegative Matrix Factorization," IEEE/ACM Trans. Audio, Speech, Language Process., Vol. 24, No. 9, 2016.

AI2000 Most Influential Scholar Honorable Mention

Winner: Tomohiro Nakatani, NTT Communication Science Laboratories
Date: May 10, 2020
Organization: AMiner.org, Tsinghua University

For his outstanding contributions to the field of speech recognition between 2009 and 2019.

OSA Senior Member

Winner: Salah Ibrahim, NTT Device Technology Laboratories
Date: June 1, 2020
Organization: The Optical Society (OSA)

For his professional accomplishments with emphasis on optically switched networks and their enabling technologies.

DICOMO2020 Best Presentation Award

Winner: Keisuke Tsunoda, NTT Service Evolution Laboratories/NTT Smart Data Science Center
Date: June 26, 2020
Organization: Information Processing Society of Japan (IPSJ)

For "Estimation Number and Dwell Time of Visitors from CO_2 Concentration Based on Partial Modeling with Variable Time Window."
Published as: K. Tsunoda, N. Arai, and K. Obana, "Estimation Number and Dwell Time of Visitors from CO_2 Concentration Based on Partial Modeling with Variable Time Window," Proc. of the Multimedia, Distributed, Cooperative, and Mobile Symposium (DICOMO) 2020, pp. 259–266, June 2020.

Civil Engineering Informatics (CEI) Paper Award

Winners: Daisuke Uchibori, NTT Access Network Service Systems Laboratories; Sho Ashikaga, NTT EAST; Taishi Deguchi, Kazuhiro Nishimoto, NTT InfraNet Corporation; Hiroyuki Takahashi, Research and Development Planning Department, NTT; Masafumi Nakagawa, Kazuhiko Goto, NTT EAST; Shuichi Yanagi, NTT Device Technology Laboratories
Date: July 3, 2020
Organization: Japan Society of Civil Engineers

For "Development of a Manhole Cover with Pattern for Improved Durability and Visibility of Worn Condition."
Published as: D. Uchibori, S. Ashikaga, T. Deguchi, K. Nishimoto, H. Takahashi, M. Nakagawa, K. Goto, and S. Yanagi, "Development of a Manhole Cover with Pattern for Improved Durability and Visibility of Worn Condition," Journal of Japan Society of Civil Engineers F3 (Civil Engineering Informatics), Vol. 75, No. 1, pp. 1–12, 2019.

Papers Published in Technical Journals and Conference Proceedings

Classically Simulating Quantum Circuits with Local Depolarizing Noise

Y. Takahashi, Y. Takeuchi, and S. Tani

arXiv:2001.08373v1 [quant-ph], January 2020.

We studied the effect of noise on the classical simulatability of quantum circuits defined by computationally tractable (CT) states and efficiently computable sparse (ECS) operations. Examples of such circuits, which we call CT-ECS circuits, are instantaneous quantum polynomial-time (IQP), Clifford Magic, and conjugated Clifford circuits. This means that there exist various CT-ECS circuits such that their output probability distributions are anti-concentrated and not classically simulatable in a noise-free setting (under plausible assumptions). First, we consider a noise model where a depolarizing channel with an arbitrarily small constant rate is applied to each qubit at the end of computation. We show that, under this noise model, if an approximate value of the noise rate is known, any CT-ECS circuit with an anti-concentrated output probability distribution is classically simulatable. This indicates that the presence of small noise drastically affects the classical simulatability of CT-ECS circuits. Then, we consider an extension of the noise model where the noise rate can vary with each qubit and provide a similar sufficient condition for classically simulating CT-ECS circuits with anti-concentrated output probability distributions.

Si-nanowire-FET Sensor Detecting High-frequency Oscillation of a Multilayer-graphene MEMS by Means of Reflectometry Technique

K. Nishiguchi and A. Fujiwara

Proc. of the 67th Japan Society of Applied Physics Spring Meeting, 12p-D311-7, March 2020.

Using a field-effect transistor (FET)-based sensor composed of multiple Si nanowire channels, we demonstrated the detection of mechanical oscillations of a multilayer-graphene microelectromechanical system (MEMS). The multilayer graphene sheet is suspended above the FET's channels, which is driven by a high-frequency signal via microwave probes connected to double LC matching circuits. Such a reflectometry technique enables detection of graphene's mechanical oscillations at 240 MHz.

Control of Thermal Noise Originating from Single-electron Brownian Motion

K. Nishiguchi, K. Chida, and A. Fujiwara

Proc. of the 6th International Symposium toward the Future of Advanced Researches in Shizuoka University (ISFAR-SU 2020), pp. 24–25, March 2020.

The performance of a data-processing circuit composed of Si field-effect transistors (FETs) has been improved by the miniaturization of FETs. However, this FET miniaturization generates more noise, which degrades FET performance. Among various kinds of noises, thermal noise, which originates from the Brownian motion of electrons in electronic devices, is one of fundamental and unavoidable noises. This noise is also a main factor in providing the lowest limit of energy for one bit of information in data processing, which is known as Landauer's limit. Therefore, thermal noise is one of the most important topics that could provide insight into achieving low-power-consumption electric devices.

We introduce the microscopic analysis of thermal noise, i.e., counting statistics of single-electron Brownian motion, using Si FETs. Based on the analogy of Maxwell's demon controlling single-electron Brownian motion, we also discuss electric power generation from the Brownian motion.

Single-electron-resolution Noise Analysis and Application Using High-sensitivity Charge Sensor

K. Nishiguchi, K. Chida, and A. Fujiwara

AAPPS (Association of Asia Pacific Physical Societies) Bulletin, Vol. 29, No. 3, pp. 4–9, June 2020.

We introduce an analysis of thermal noise using a high-sensitivity charge sensor. Since the sensor is based on a Si field-effect transistor with a channel size of approximately 10 nm, it exhibits high sensitivity to detect single-electron motion even at room temperature. By connecting this sensor to a small capacitor composed of dynamic random-access memory, thermal noise in the capacitor can be monitored in real time with single-electron resolution. Such real-time monitoring reveals that when the capacitor is small enough that the charging energy for storing one electron in the capacitor is greater than the thermal energy, thermal noise is suppressed and enhanced. This represents a deviation from the law of energy equipartition. In addition to this noise analysis, we conducted an experiment on power generation using an analogy of Maxwell's demon that detects and manipulates single-electron motion, which should accelerate research in the field of thermodynamics. These experimental results indicate that the high-sensitivity charge sensor can function as a superior platform for microscopic analysis of noise, small electronic devices, and thermodynamics as well as a demonstration of theoretical expectation in basic research.

1-day, 2 Countries—A Study on Consumer IoT Device Vulnerability Disclosure and Patch Release in Japan and the United States

A. Nakajima, T. Watanabe, E. Shioji, M. Akiyama, and M. Woo

IEICE Transactions on Information and Systems, Vol. E103-D, No. 7, pp. 1524–1540, July 2020.

With our ever-increasing dependence on computers, many governments around the world have started to investigate strengthening the regulations on vulnerabilities and their lifecycle management. Although many previous works have studied this problem space for mainstream software packages and web applications, relatively few have studied this for consumer Internet of Things (IoT) devices. As the first step towards filling this void, this paper presents a pilot study on the vulnerability disclosures and patch releases of three prominent consumer IoT vendors in Japan and three in the United States. Our goals include (i) characterizing the trends and risks in the vulnerability lifecycle management of consumer IoT devices using accurate long-term data and (ii) identifying problems, challenges, and potential approaches for future studies of this problem space. To this end, we collected all published vulnerabilities and patches related to the consumer IoT products of these vendors between 2006 and 2017 then analyzed this dataset from multiple perspectives, such as the severity of the included vulnerabilities and timing of the included patch releases with respect to the corresponding disclosures and exploits. We uncovered several important findings that may inform future studies. These findings include (i) a stark contrast between how the vulnerabilities in this dataset were disclosed in the two markets, (ii) three alarming practices by the included vendors that may significantly increase the risk of 1-day exploits for customers, and (iii) challenges in data collection including crawling automation and long-term data availability. For each finding, we also provide discussions on its consequences and/or potential migrations or suggestions.

Experimental Demonstration of Secure Quantum Remote Sensing

P. Yin, Y. Takeuchi, W. Zhang, Z. Yin, Y. Matsuzaki, X. Peng, X. Xu, J. Xu, J. Tang, Z. Zhou, G. Chen, C. Li, and G. Guo

Physical Review Applied, Vol. 14, 014065, July 2020.

Quantum metrology aims to enhance the precision of various measurement tasks by taking advantage of quantum properties. In many scenarios, precision is not the sole target; the acquired information must be protected once it is generated in the sensing process. Considering a remote sensing scenario where a local site performs cooperative sensing with a remote site to collect sensitive information at that remote site, the loss of sensing data inevitably reveals sensitive information . Quantum key distribution is known to be a reliable solution for secure data transmission; however, it fails if an eavesdropper accesses the sensing data generated at a remote site. In this study, we demonstrated that, by sharing entanglement between local and remote sites, secure quantum remote sensing is possible, and the secure level is characterized by asymmetric Fisher information gain. Concretely, only the local site can acquire the estimated parameter accurately with Fisher information approaching 1. In contrast, the accessible Fisher information for an eavesdropper is nearly zero even if he or she obtains the raw sensing data at the remote site. This achievement is primarily due to the nonlocal calibration and control of the probe state at the remote site. Our results explore one significant advantage of "quantumness" and extend the notion of quantum metrology to the security realm.

Determination of Frequency Response of MEMS Microphone from Sound-field Measurements Using Optical Phase-shifting Interferometry Method

D. Hermawanto, K. Ishikawa, K. Yatabe, and Y. Oikawa

Applied Acoustics, Vol. 170, No. 15, 107523, July 2020.

Accurate determination of microphone sensitivity is important to build reliable acoustical instruments. Sensitivity is usually determined by calibration. However, because current microphone-calibration methods determine sensitivity from a mathematical model derived from the geometry of a conventional condenser microphone, they cannot be applied to the calibration of a microelectromechanical systems (MEMS) microphone straightforwardly. To compensate for this geometry difference with current calibration methods, some researchers proposed the development of adapters that fit the conventional calibration apparatus and modified the calibration procedure. In this paper, we propose a different approach to calibrate a MEMS microphone. Sensitivity is calculated directly from the measurement of the sound field applied to the MEMS microphone and its output voltage. The projection of the sound field is measured by parallel phase-shifting interferometry (PPSI), and sound pressure on the MEMS microphone is obtained by tomographic reconstruction. Experimental calibration of a MEMS microphone was conducted and validated using a microphone-substitution method to evaluate the discrepancies in the sensitivity results. It is shown that the proposed method can be used to determine the frequency response of a MEMS microphone in the frequency range of 1000 to 12000 Hz.
