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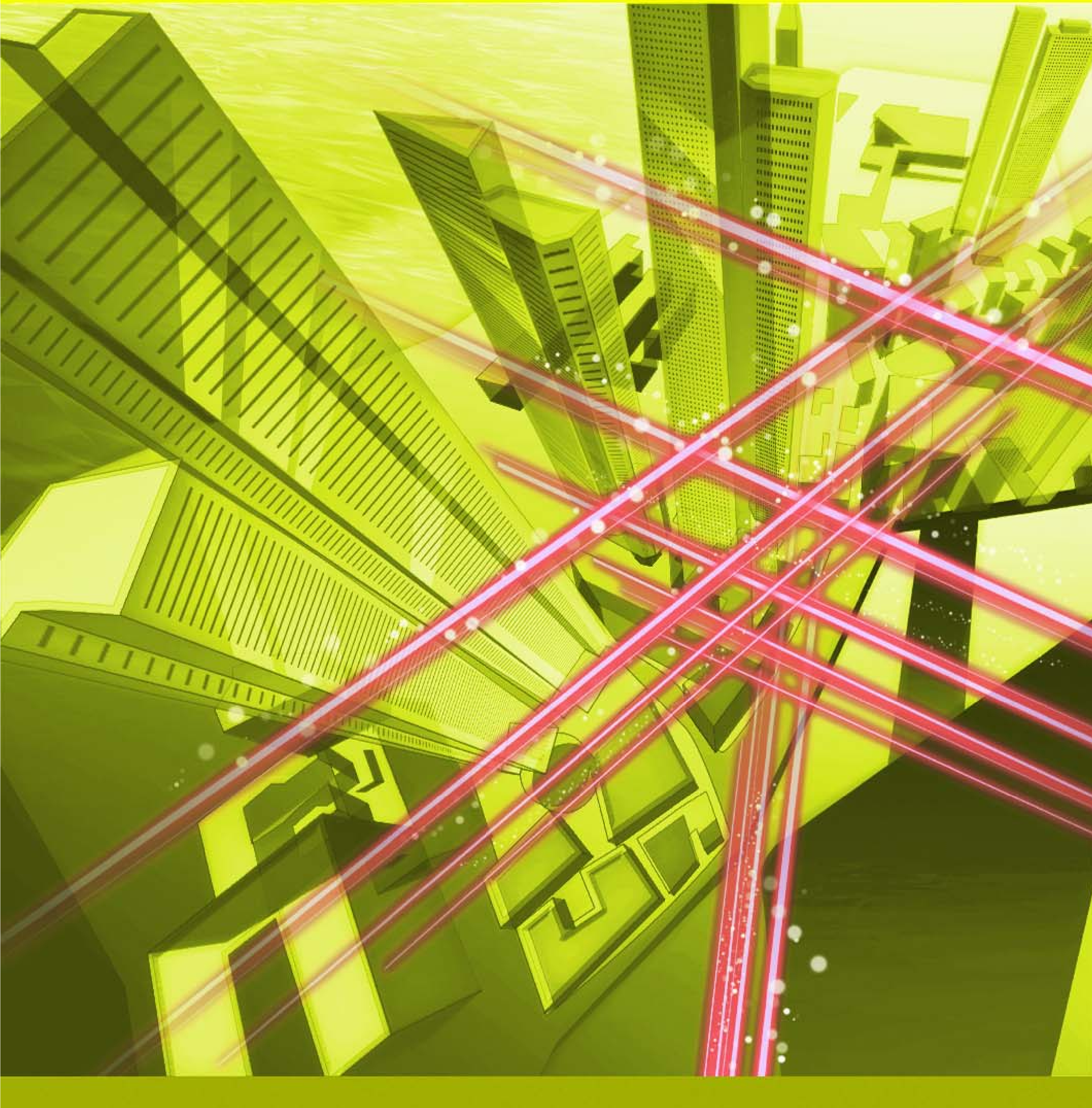

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Feature Articles: The Internet of Things and New Value Creation

Regular Articles

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Research and Development Initiatives on the Internet of Things at NTT

Ryutaro Kawamura and Shuichi Yoshino

Abstract

The Internet of Things (IoT) holds great promise for creation of new value in society, and this age of utilizing IoT represents a third era, which could be called the *driving era*, with great changes in the role of telecommunication networks and their requirements. This article introduces network and information processing requirements for realizing this new IoT era and describes a reference architecture for this functionality. It also introduces IoT related initiatives at NTT.

Keywords: Internet of Things, sensing, data exchange, social prediction

1. Introduction

The term Internet of Things (IoT) has been appearing in the newspapers every day recently, and there is much anticipation of the value that it will bring society. Telecommunication networks have made great advances over the years. The first generation had the role of *connecting*, mainly providing communication between people, and the second generation had the role of *understanding*, which refers to gathering knowledge and information from around the world (**Fig. 1**).

In contrast, the idea of connecting *things* to the network and somehow controlling them has been around for a long time; examples include infrastructure monitoring using sensors, and home security technology. This basic concept is also represented in proposed developments such as ubiquitous computing. However, there are several reasons why IoT has become the large-scale initiative it is today. One is that the spread of networks and computing functionality has surpassed a threshold, and the number and types of things connected to networks is growing explosively [1]. Another is that in synergy with the rapid collection of knowledge brought by the second generation, the potential for new value is becoming apparent.

For example, through the development of low-power wide-area wireless technology able to send and receive information using extremely low energy, it is becoming possible for objects with minimal capabilities to connect to networks over long periods of time. Technologies to collect huge amounts of data on the cloud, and data analysis technologies such as machine learning and artificial intelligence (AI) to analyze it, are also being developed, and every day the knowledge available on the network is being consolidated further.

IoT is being used to visualize, optimize, and control the activities of physical things and society in this way; that is, it is *driving* them. Therefore, this third generation could be called the driving era, which involves great changes in the role of telecommunication networks. Second-generation communication has required the involvement of people, who also made all final decisions in most cases. In the IoT era, however, actions occur without human intervention, automatically and at very high speeds, and the real, physical world that we can touch is controlled by cyberspace, which is integrated with the real world. Thus, it is inevitable that the requirements for telecommunication networks will be different than they have been until now. The Feature Articles in this issue introduce key new technologies for realizing this IoT era, along with some of their applications in society.

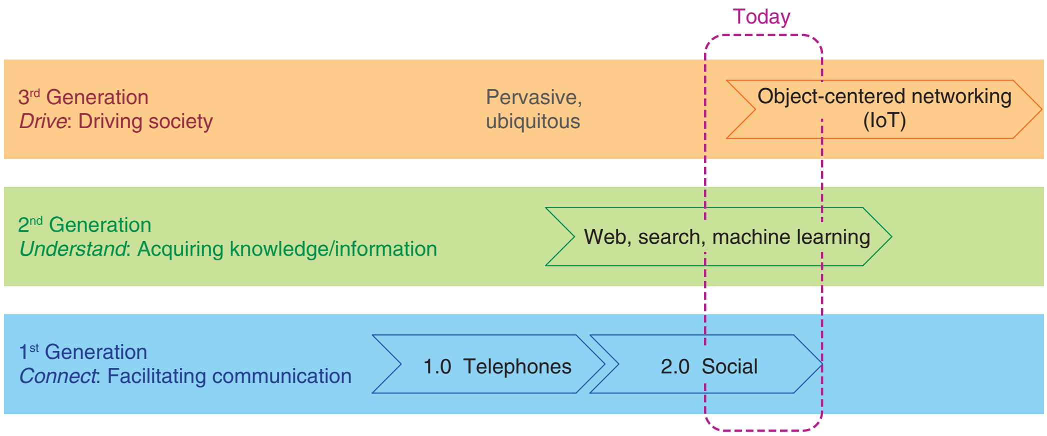

Fig. 1. Third-generation telecommunications: *driving* society.

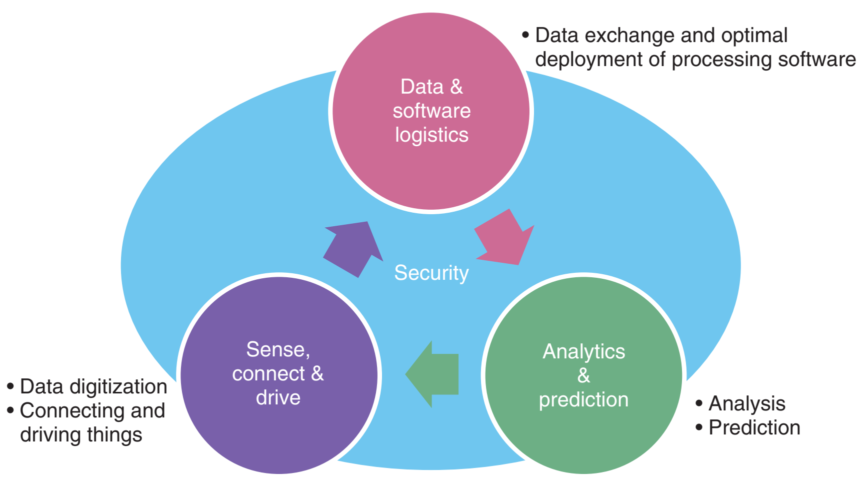

Fig. 2. Four roles and technologies in IoT.

2. The four roles and technologies of IoT

Four essential roles and technologies for the development of IoT are shown in **Fig. 2**.

2.1 Sense, connect & drive

Sense, connect & drive refers to the processes of digitizing the information of physical things into a form that computing devices can handle and connecting them to a network through some type of access method. In other words, it is the interface function between the real world and cyberspace. The number and variety of connected things is directly related to the value produced with IoT, so this role is extremely important. In order to drive society, communication requirements such as reliability and real-time performance must also be satisfied, more than ever before.

2.2 Data & software logistics

Data & software logistics refers to moving the data from connected things to a location suitable for processing and utilizing the data, and to deployment of the software that will perform this processing and utilization. IoT holds promise for creating new value by combining diverse data spanning different types of industries. However, development has advanced independently in the past, in different industries and different regions around the world, and this has resulted in a flood of different data models and protocols in the market and made interoperability among

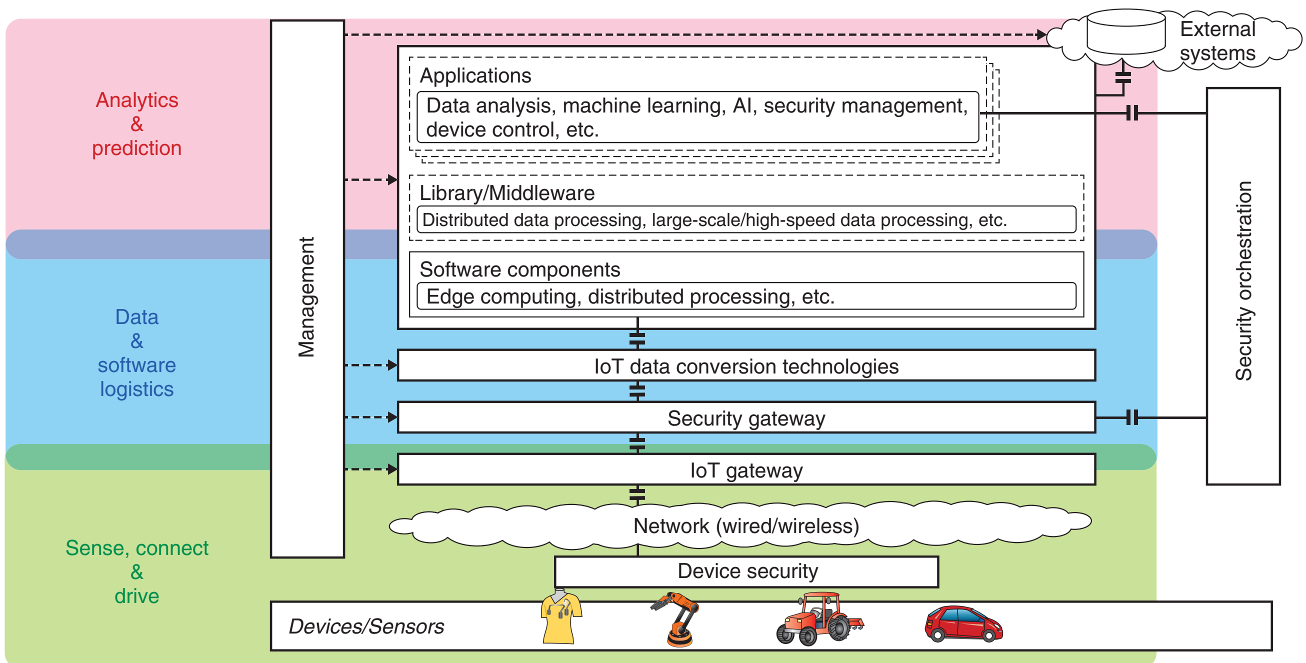

Fig. 3. Reference architecture.

them very difficult in their current condition.

For example, field networks for production management in factories, networks for building management, and networks for device control in automobiles each have their own de facto standards and regulations in their respective industries.

One important aspect of this function is to absorb these differences in a practical way to enable exchange and interoperability of data. Another function is related to how the physical location where data are processed is increasingly significant with IoT. A major recent development is that most data processing applications operate in two locations: the *cloud*, where servers are located, and the *end device*, but IoT is expected to bring great changes in this state of affairs. Due to the local nature of IoT data, the need for real-time control, and the large amounts of data produced by the many devices such as high-definition cameras, it is more appropriate to perform processing closer to the objects—at the network edge—rather than at a distant location on the cloud in an increasing number of cases. Since data processing locations are dispersing in this way, functions to select appropriate processing locations and to deploy processing algorithms are becoming increasingly important.

2.3 Analytics & prediction

Analytics & prediction refers to the creation of value from data. Big data analysis technologies such as machine learning and AI, which have grown rapidly in recent years, are used to create value by processing the IoT data being collected and circulated, understanding conditions, and predicting faults and other events that could happen in the future.

2.4 Security

The last element is security. With IoT driving real society, security risks such as cyber-attacks are a greater concern than ever [2]. There is also a greater range of IoT devices and the types of software used with them than with personal computers and smartphones, so safety must be maintained using different principles than have been used thus far.

To build IoT systems using these four functions, we have created the reference architecture shown in **Fig. 3**. The devices and data in the lower layers are gathered and circulated for higher layers, and applications in the top layer analyze the data and create value, and the results are fed back to control devices and to drive society.

3. IoT initiatives at NTT

We introduce in this issue recent IoT initiatives at NTT, namely the following.

3.1 Promoting partnerships to create new business

NTT's management strategy is focused on a B2B2X (business-to-business-to-X) business model, and business in the IoT domain is a typical example. In the third generation of telecommunication networks, we are aiming for an approach that expands collaboration with the owners of objects and information and the various stakeholders that derive value from them. With this in mind, the NTT Group is building partnerships from the early stages of developing technologies and working to create value through IoT. In the article "NTT Group Initiatives to Create New Internet of Things Business" [3] in this issue, we introduce some of the many initiatives already started, which are undergoing field trials and demonstrations or that are in technical development in collaboration with partners, as well as efforts to promote these initiatives.

3.2 New initiatives in sensing and its applications

One promising IoT initiative is creating value in healthcare using data from the human body. Devices such as smart watches are being used as sensors, but devices that can be used as sensors by simply wearing them like clothing, without any other special implements, are also coming into use. The NTT Group, in collaboration with Toray Industries, Inc., has developed a functional material called "hitoe" and is working on sensing applications for industries and uses not possible earlier. The article "Natural Sensing with 'hitoe' Functional Material and Initiatives towards Its Applications" [4] introduces the use of "hitoe" in the medical and safety management fields and the development of middleware technology that will expand the range of possible applications.

3.3 Initiatives promoting data exchange in society

As explained earlier, data models and their protocols have been developed within their business and/or regional domains (referred to as *silos*), which becomes a significant barrier of data exchange among various domains. However, to further increase the value created through IoT, it is essential to combine and use diverse data, and the promise of achieving IoT data exchanges in society so that data that span services can be circulated and utilized, is increasing. Industry 4.0 in Germany is an example of this. The article, "Data Exchange Technology Providing Real-time Data Processing and Scalability" [5] introduces NTT Group initiatives to promote this sort of IoT data exchange in society, including IoT data exchange technologies that deliver data reliably from devices to applications, and edge computing technology that realizes real-time performance by processing the IoT data being exchanged at an optimal location in the network.

3.4 Initiatives to make predictions in society using data

The NTT laboratories are advancing research and development (R&D) on spatio-temporal multidimensional collective data analysis technology able to model spatial and temporal relationships among the broad and diverse data and predict the place and time frame when phenomena will occur [6]. This is one technology able to create value from the large amount of diverse data being gathered and stored, from the real world and cyberspace, using sensing technology and data exchange.

We have recently developed this technology further using data on the flow of people and vehicles in urban areas to predict the immediate congestion risk, and we are conducting R&D on technology to give optimized guidance to groups in advance to avoid that congestion. The article, "Optimal Crowd Navigation via Spatio-temporal Multidimensional Collective Data Analysis" [7] introduces R&D initiatives on technology combining machine learning and simulation that is derived from optimized group guidance.

4. Future prospects

The number of *things* connected to networks is expected to continue to increase, so we hope to support society by further expanding and developing our range of IoT applications in order to promote development of a society where there is cooperation among people and things. The NTT Group will continue to collaborate with our partners in diverse fields and to promote R&D that creates new value.

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NTT Group Initiatives to Create New Internet of Things Business

Shinji Sugimoto, Shuichi Yoshino, Tsutomu Horioka, Naoto Abe, and Daiki Endo

Abstract

The NTT Group is promoting initiatives to solve societal issues and bring lifestyle innovation using a business-to-business-to-X (B2B2X) model through collaboration with partner companies in a wide range of industries such as manufacturing, agriculture, and transportation. We are developing businesses that use the Internet of Things to provide new added value to end users, represented by the X in B2B2X. The NTT Group is also supporting promotional activities such as trade shows to distribute information about new business initiatives.

Keywords: Internet of Things, B2B2X, collaboration

1. NTT Group Internet of Things initiatives

The NTT Group is promoting initiatives to solve societal issues and bring lifestyle innovation using a business-to-business-to-X (B2B2X) model through collaboration with partners in a wide range of industries. In order for service providers—the second B—to be able to provide new added value to the end users (X), innovation in both the NTT Group and its partner companies in other business areas is important, and we are working to expand such business, including in the field of the Internet of Things (IoT), which is highly anticipated for its wide-ranging potential (**Fig. 1**).

Moving from trials and proof of concept to business is a very important task when creating business using IoT. Accomplishing this task requires more than simply *visualizing* the data gathered by sensors and other IoT devices. Data analysis must be used to solve end-user problems or to create new value, and there are many possible forms of second B service for each industrial field and many different problems and types of value for end users. As such, domain knowledge and experience are necessary to use data in this way. The NTT Group is therefore promoting collaboration with various partner companies having their own domain knowledge and experience in order to create new business using IoT in a broad range of fields including manufacturing, agriculture, transport, smart cities, and healthcare (**Fig. 2**).

For example, in manufacturing, IoT could be used to centrally manage equipment such as machine tools on the production floor (factory), and to operate them more efficiently and with less waste, thereby increasing productivity. The NTT Group is working in collaboration with FANUC CORPORATION, a global supplier in factory automation, to gather and analyze data in factories in real time on the operation of industrial robots and large machine tools [1]. This is used to increase productivity by tuning the equipment, detecting any signs of malfunction or faults in the machinery early, and reducing overall factory down time. As part of this, the NTT Group is using edge computing research and development (R&D) technologies, data analysis, and cloud services to implement real-time data gathering and analysis.

In agriculture, producers are continuing to age, and workers are in demand, so automating work and using smart machinery to save on labor are key issues, along with optimizing harvesting methods to stabilize and increase the harvest [2].

NTT Group companies are collaborating with Kubota Corporation, an agricultural machinery manufacturer, in studying ways to combine advanced

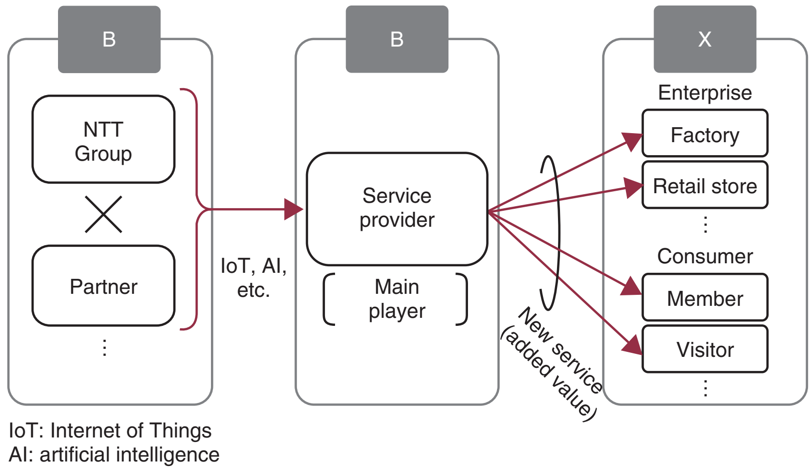

Fig. 1. B2B2X model initiative.

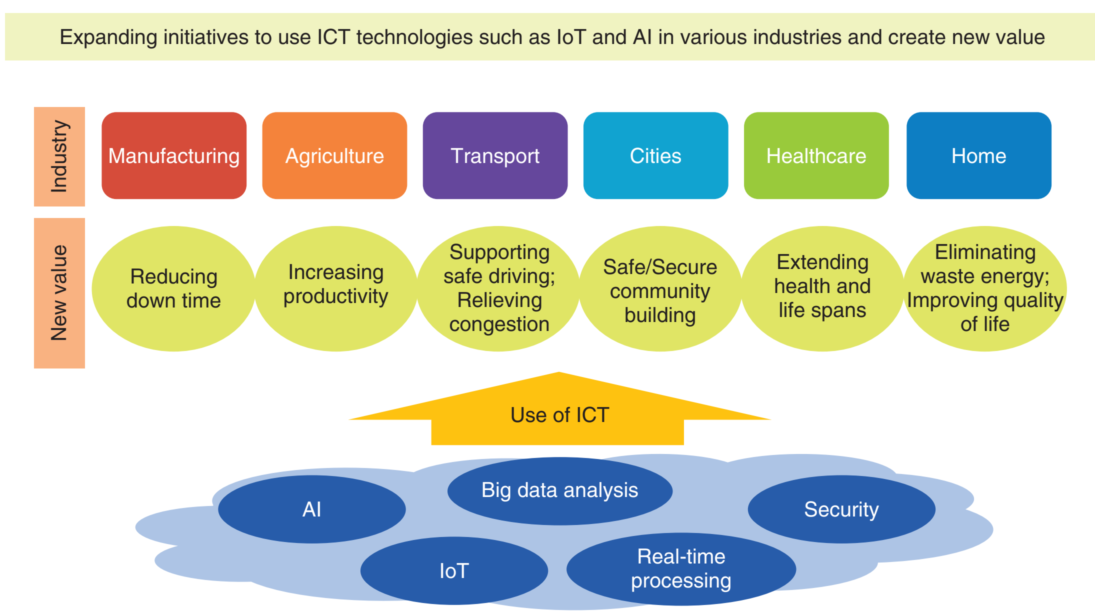

Fig. 2. IoT initiatives in wide-ranging fields.

information and communication technology (ICT) services such as wireless technology and weather information and map information, with advancing R&D technologies such as artificial intelligence and IoT, to build optimized systems for gathering data efficiently in farming environments under various conditions. The data are then used to create value in the agricultural field. We are collaborating with partners to advance the agricultural machinery and agriculture support systems provided by our partners. This is expected to achieve high-quality agriculture through visualization, automation, and improved efficiency of agriculture management [3].

In the transport field, we are working to use vital data in bus operation systems to support safe operation and improve administrative efficiency [4].

As described above, the NTT Group is undertaking initiatives to create new value through IoT by collaborating with partners in various fields.

Photo 1. NTT Group display at CEATEC JAPAN 2016.

Photo 2. NTT Group display at CeBIT 2017.

2. Promotion through trade shows

To disseminate information on NTT Group IoT business initiatives, we are promoting them through exhibits at the NTT R&D Forum and external events such as trade shows.

The NTT Group appeared at CEATEC JAPAN 2016, held October 4–7, 2016 at Makuhari Messe Convention Center, presenting NTT Group IoT business initiatives to the many attendees. Five group companies (NTT EAST, NTT WEST, NTT Communications, NTT DOCOMO, and NTT DATA) exhibited 19 solutions in six fields: manufacturing, logistics/retail, cities, healthcare, agriculture, and home, and also introduced each solution on the presentation stage (**Photo 1**).

We also appeared at CeBIT 2017, held in Hanover, Germany on March 20–24, 2017 (**Photo 2**). CeBIT is the largest information technology trade show in the world, with approximately 3300 companies and organizations from 70 countries around the world exhibiting, and over 200,000 attendees over the five days. In total, 118 Japanese companies and organizations exhibited their products and technologies in the Japan Pavilion. The NTT Group exhibited videos of advanced B2B2X business using ICT, including collaborations using IoT in the fields of manufacturing, agriculture, and transportation [5].

The NTT booth had over 5000 visitors in the five days, including many high-ranking and well-known people, and politicians such as Japanese Prime Minister Shinzo Abe and German Chancellor Angela Merkel. It was covered by 26 television and newspaper media companies (20 from outside Japan), resulting in NTT Group initiatives being introduced to the world.

The IoT business continues to advance daily, and we will continue to carry out promotional activities such as these as a valuable opportunity to understand customer needs and respond to markets so that we can create new business in a timely manner.

3. Future prospects

Going forward, the NTT Group as a whole will collaborate with top-tier partners to develop markets and create new value using the advanced technologies from Group R&D efforts. We will also identify technologies that can be applied across different fields through collaboration in various industrial fields, and work to expand our business range utilizing IoT.

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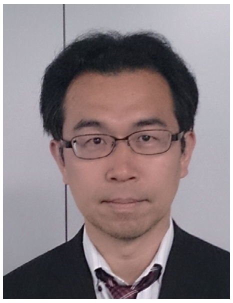

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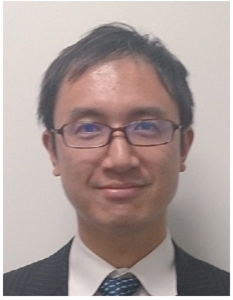

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Natural Sensing with “hitoe” Functional Material and Initiatives towards Its Applications

Toshihiko Kondo, Yoji Yamato, Makoto Nakayama, Akihiro Chiba, Ken Sakaguchi, Takahiro Nishiguchi, Tomoaki Masuda, and Tokutaro Yoshida

Abstract

This article introduces initiatives to expand the range of applications for “hitoe” wear, clothing that can sense biological data when the user wears it, including services for monitoring rehabilitation patients and bus drivers. It also describes a data collection technology that accommodates the sensors and middleware for storing and analyzing the data, which is called the Fast and Distributed IoT Processing Platform.

Keywords: “hitoe” functional material, rehabilitation, driver management

1. Introduction

The material known as “hitoe” is a new functional material arising from a cross-industry collaboration between NTT and fiber manufacturer Toray Industries, Inc. [1]. It was created using conductive fiber technology developed by NTT by applying a special conductive polymer coating to one of Toray’s latest products, a nanofiber material [2] (**Fig. 1**). This resulted in a new material that can be used to detect vital data with high sensitivity, even though it is non-metallic. When “hitoe” is worn next to the skin, it can measure vital data such as heart rate and electrocardiographic waveforms, and the level of relaxation can be estimated from R-wave intervals.

Furthermore, “hitoe” does not contain metal, so it is easy on the skin, highly hydrophilic, and durable against sweat and moisture. Thus, it feels like ordinary clothing and can sense vital data very naturally. The nanofibers are finer than fibers generally used for clothing, so they have better adhesion and more contact area with the skin, which enables stable sensing of vital data. The conductive polymer also adheres well, so it is also very durable when washed.

In an effort to expand the range of uses for “hitoe,” NTT is working to find practical applications for it in various fields through collaboration between NTT Group companies and external partners. Beyond simply gathering data, it is also important to study how that data can be processed, analyzed, and interpreted to produce high-added-value information.

In this case, we have focused on the medical and safety management fields with applications that make use of the strengths of “hitoe,” namely, (1) the ability to obtain stable data even when the subject is perspiring and thus achieve comfortable monitoring over long periods, and (2) enabling more accurate bodily information to be obtained based on electrocardiographic waveforms.

This article introduces initiatives to develop applications in rehabilitation patient monitoring and a bus driver management service. We also describe technologies supporting these applications, including data gathering technology that accommodates the sensors and the Fast and Distributed IoT Processing Platform.

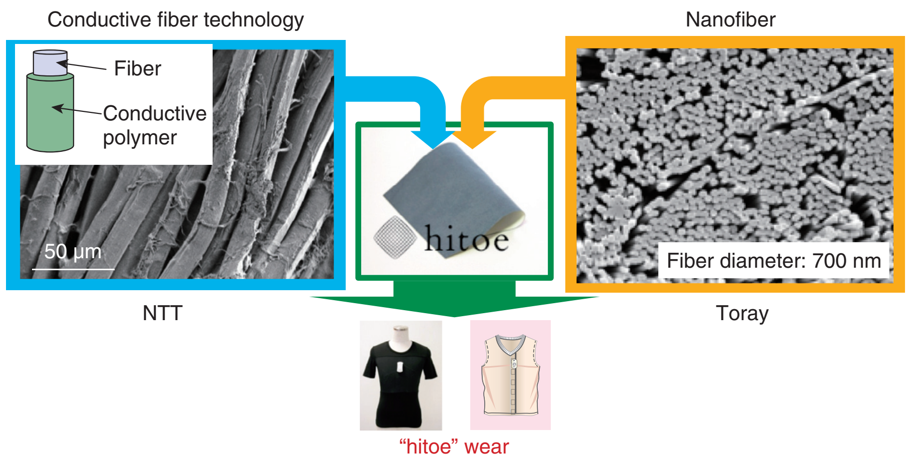

Fig. 1. Cross-industry collaboration with Toray to develop "hitoe."

Table 1. Roles of participating organizations in collaborative experiments.

	Role
Fujita Health University	Study use of "hitoe" in a rehabilitation hospital environment.
Toray	Study "hitoe" wear for rehabilitation.
NTT	Study systems supporting "hitoe" for rehabilitation that can obtain a stable heart rate and collect/display data used to estimate activity.
NTT DOCOMO	Study commercialization of the rehabilitation patient monitoring system.

2. Rehabilitation patient monitoring and data collection technology

The goal in monitoring rehabilitation patients is to measure the effects of rehabilitation objectively and contribute to more suitable interventions and faster recovery through 24-hour monitoring of the patient's heart rate and activity information. Rehabilitation costs in Japan are expected to increase as the population continues to age, and many hospitals are demanding improved rehabilitation quality and effectiveness.

On February 7, 2017, NTT, in collaboration with Fujita Health University, Toray, and NTT DOCOMO, began testing to demonstrate the effectiveness of a rehabilitation patient monitoring system using "hitoe" [3]. Fujita Health University Hospital has the largest rehabilitation department in Japan. The purpose of this testing is to investigate the effectiveness and potential of "hitoe" for 24-hour monitoring of patient heart rate and conditions (activity level, position data) and the potential use of such quantitative diagnostic data in the field of rehabilitation. The roles of the university and the participating companies are listed in **Table 1**.

We first describe here the rehabilitation patient monitoring system used in these tests. Activity data output from the "hitoe" transmitter are sent via a Bluetooth[*1] Low Energy link to a smartphone or other receiver module and collected on a data gathering and management server through the network (**Fig. 2**). Doctors and therapists can refer to the activity data stored on this server at any time, 24 hours a day, using a viewer connected to the network. The gathered data could also be used to study rehabilitation programs based on the type or seriousness of the ailment.

The "hitoe" transmitter has functions to output the heart rate from the electrocardiographic waveform obtained continuously from the "hitoe" wear and to output data such as slope and vibrations from the built-in three-axis accelerometer. The output of a stable heart rate and calculation of activity level is enabled through the use of NTT's noise cancellation technology. NTT's acceleration analysis technology

*1 Bluetooth is a registered trademark of Bluetooth SIG Inc.

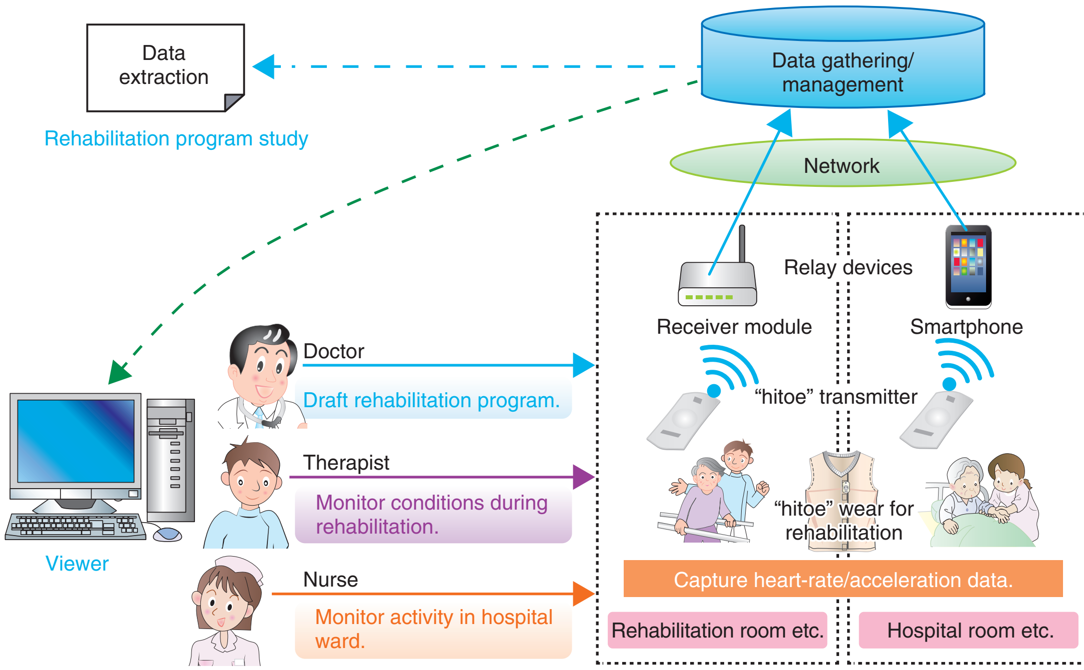

Fig. 2. Overview of rehabilitation patient monitoring system.

Fig. 3. Screenshot of viewer.

can also be used to estimate the cadence or type of movement. The use of a smartphone in hospital rooms and hallways makes it possible to gather data while patients carry out their normal activities. In the rehabilitation room, data can be obtained and sent through a receiver module without a smartphone simply by having patients wear "hitoe" clothing, so rehabilitation activities are not inhibited.

Until now, separate devices to monitor heart rate have been necessary in the rehabilitation room and in hospital rooms, and no device was able to record heart-rate conditions continuously. With this new system, the latest data from rehabilitation patients' activity are always displayed on the viewer (**Fig. 3**). Results for aggregate heart rates, number of steps, and calories burned can be displayed, with units of days or weeks selected on the calendar. History data can be displayed by graphing daily data and selecting heart rate, cadence, resting/walking/running categories, standing/sitting/lying-down categories, or exercise intensity.

In these experiments, we can visualize the activity data in a composite form and study whether it can contribute to designing rehabilitation programs. Specifically, our scheme consists of the following three steps.

2.1 Step 1: Preliminary study with healthy subjects

Healthy subjects were asked to exercise while wearing "hitoe" wear, and heart rate data were recorded while exhaled air was analyzed and SpO_2*2 was estimated. We also measured speed and distance while the subjects were walking. We then checked whether the data obtained from "hitoe" reflected the exercise load.

2.2 Step 2: Study rehabilitation improvement effects

We had in-patients and out-patients undergoing rehabilitation at the Fujita Health University Hospital Rehabilitation Center wear "hitoe" wear for rehabilitation. We collected the heart rate and activity data (data indicating active or resting, standing or lying down, etc.) while they were in rehabilitation. The collected data were used to check whether the exercise load of the training was appropriate. Also, the viewer can be used to check changes in heart rate or activity during a rehabilitation session or the progress of heart rate and activity in past rehabilitation sessions, so it should be useful for doctors in creating highly effective rehabilitation programs. In these experiments, we are studying what effects the use of "hitoe" can have on creating and conducting rehabilitation programs and on patient recovery.

2.3 Step 3: Evaluating rehabilitation effects with 24-hour monitoring, including life in the hospital ward

When patients in the rehabilitation department wear "hitoe" wear, their activity in the hospital 24 hours a day can be transmitted. Thus, changes in patient activity could be used to detect activities with a higher risk of falling, and patients prone to becoming bedridden can be encouraged to exercise. We are evaluating the connection between using "hitoe" and early detection of dangerous patient activity, and also promoting activity within hospital wards.

Through these studies, we are able to check and verify the effectiveness of "hitoe" in the rehabilitation field. We will work to create services utilizing "hitoe" in this field in the future.

3. Driver management service based on Fast and Distributed IoT Processing Platform

Bus travel is a common means of transportation in Japan, so there is a great need for safety for both passengers and drivers. We describe here a system we developed to improve the safety of bus travel.

3.1 Driver management service

A driver management service is a safety management service that analyzes drivers' vital data and detects transportation risks. A serious bus accident occurred in Japan in 2016, and since then, the demand for transportation safety management has increased. We developed this service for safety management of bus drivers. An outline of the service is shown in **Fig. 4**. This service collects vital data, vehicle data, and environment data on a cloud, then visualizes and analyzes the data and takes appropriate actions. Vital data include electrocardiographic waveforms and acceleration of the driver acquired by "hitoe" wear; vehicle data include abrupt handling actions and tire pressure; and environment data include weather, traffic, and vehicle location. For example, the driver management service first visualizes changes in the fatigue level of drivers, then analyzes the correlation of fatigue level and abrupt handling actions or other factors, and finally, it recommends actions such as suggesting the driver take a break based on fatigue level changes.

Our driver management service was developed through collaboration between NTT and SAP SE, the enterprise software company. Heartbeat data acquired by "hitoe" wear are analyzed on the Fast and Distributed IoT Processing Platform (described below) in the NTT cloud to estimate the fatigue of the central nervous system (brain and spinal cord) when the driver is driving, and the fatigue data are then output.

Coordination between the NTT cloud and SAP cloud is achieved with a representational state transfer (REST) application programming interface (API), and vital information such as fatigue data are provided to the SAP cloud via this and other APIs. The vehicle and environment data are collected in the SAP cloud, and all of the information, including the fatigue data, is visualized using a web graphical user

*2 SpO_2: The proportion of hemoglobin in arterial blood that is oxygenated, expressed as a percentage.

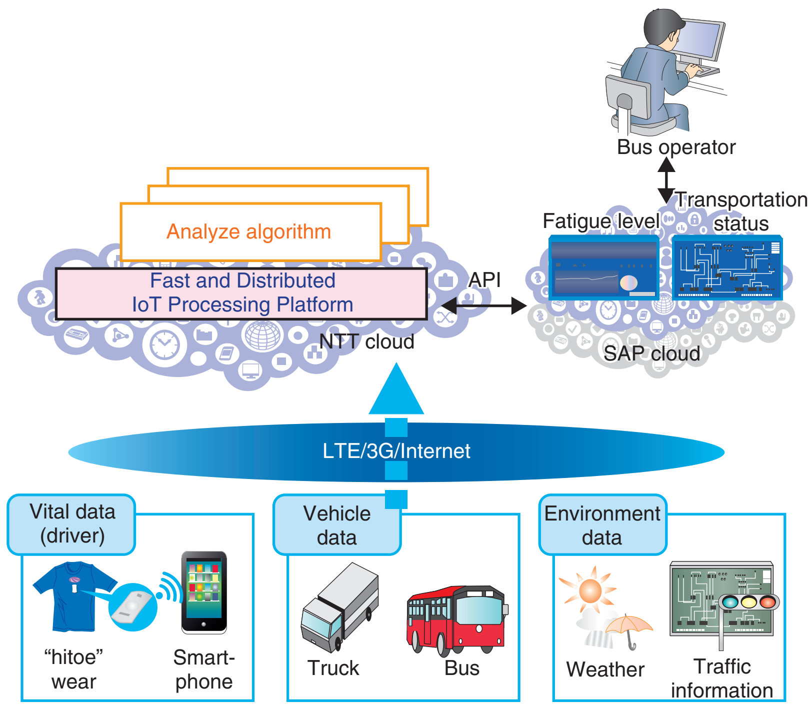

Fig. 4. Outline of driver management service.

interface (GUI). Then, appropriate actions are taken using service coordination technologies, for example, as in the work described in a published study [4]. Operators in bus companies can confirm the total information of bus location, driver fatigue, and other data by checking the web GUI.

We conducted a field trial of the driver management service with Keifuku Bus Co., Ltd. in Fukui Prefecture in October and November, 2016. About 15 drivers participated in the field trial. The drivers wore "hitoe" garments, enabling us to collect stable data. From the data, we were able to verify the validity of fatigue estimation and the feasibility of real-time fatigue estimation analysis. We also confirmed various business aspects such as the operational feasibility of this service and the effectiveness of the analyzed results. We discussed how to improve bus operations with Keifuku Bus based on the trial results (e.g., bus schedule changes). NTT Communications launched a commercial driver management service after the completion of this trial.

3.2 Fast and Distributed IoT Processing Platform

We explain here the Fast and Distributed IoT Processing Platform on which the driver management service runs. The Fast and Distributed IoT Processing Platform has been developed by the NTT Software Innovation Center and is a platform to collect, store, and analyze Internet of Things (IoT) data. This platform was built based on cloud technologies (e.g., that described by Yamato et al. [5]) and can use information obtained not only from "hitoe" wear but also from various sensor devices.

The Fast and Distributed IoT Processing Platform has a data storage function, a data analysis function, and a messaging function that connects the other functions. There are other IoT platforms such as Amazon AWS IoT*3 and Microsoft Azure IoT Suite*4. These platforms also have similar storage, analysis, and messaging functions. However, our platform has a lower price structure thanks to the use of open source software (OSS). It also has a flexible structure, with functions that can be customized for each project.

An outline of the Fast and Distributed IoT Processing Platform is shown in **Fig. 5**. Sensors such as "hitoe" wear continuously collect IoT data (also called *stream* data), and the IoT data are transferred

*3 Amazon and AWS are trademarks of Amazon.com, Inc. or its affiliates in the United States and/or other countries.

*4 Microsoft and Azure are registered trademarks of Microsoft Corporation in the United States and/or other countries.

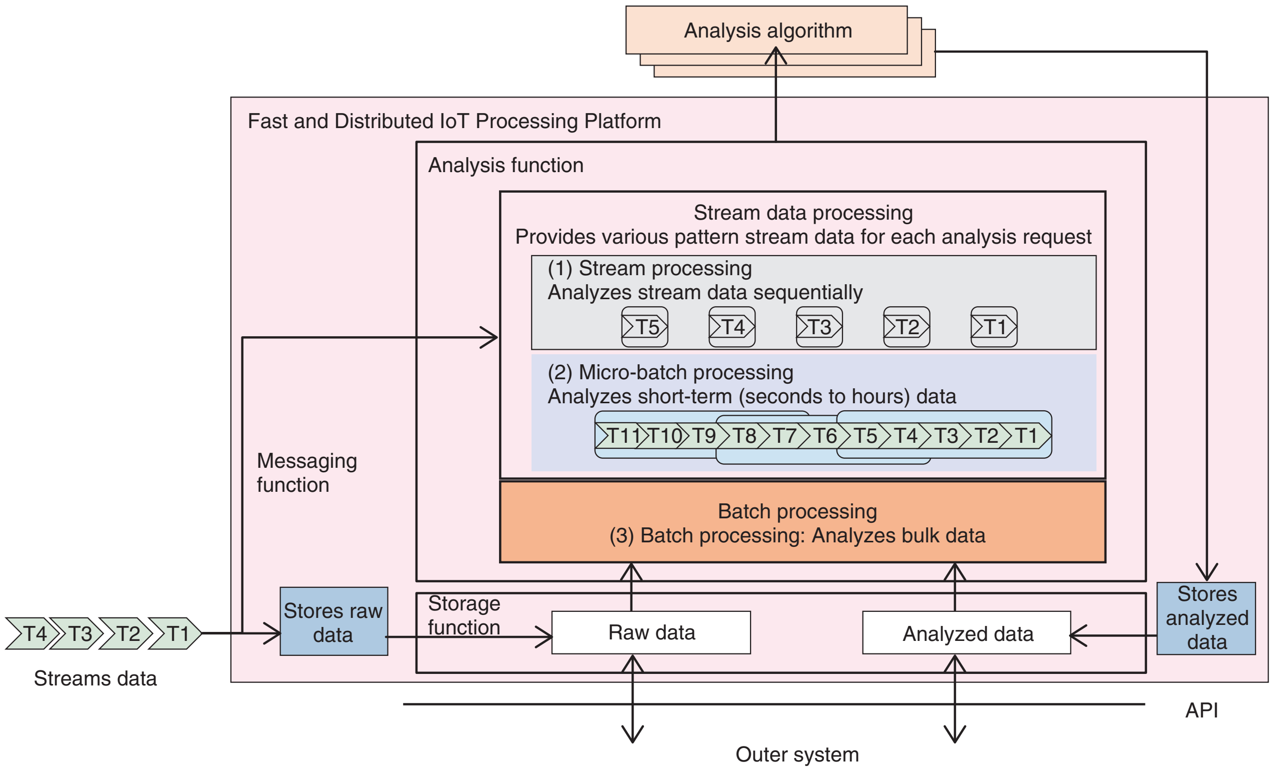

Fig. 5. Outline of Fast and Distributed IoT Processing Platform.

to a cloud by smartphones or other gateways. The data are delivered to the storage and analysis functions by the messaging function. The Fast and Distributed IoT Processing Platform uses Apache Kafka*5 for the messaging function, Apache HBase for the storage function, and Apache Spark for the analysis function.

In the driver management service, stream data of heartbeat and other vital information acquired by "hitoe" wear are transferred to the Fast and Distributed IoT Processing Platform by smartphones. Kafka delivers data to HBase for storing and Spark for analyzing. Spark processes the stream data through the micro-batch processing of Spark Streaming and estimates the fatigue level. Micro-batch processing is a kind of processing that analyzes short-term data (seconds to hours) and is an intermediate type of processing between batch processing and stream processing. Because fatigue is estimated based on fluctuation of heartbeat R-wave intervals, micro-batch processing is suitable for analyzing heartbeat data for particular periods. In the driver management service, one minute of heartbeat data is analyzed in a micro-batch.

We are now developing additional functions to select not only micro-batch processing of Spark Streaming but also batch processing and stream processing for the analysis function by agile software development based on previous OSS development experience. These analysis functions can be configured in various patterns for each project. For the analysis algorithm that runs on the analysis function, we can run not only the fatigue estimation algorithm*6 described above but other algorithms as well.

Analyzed data such as fatigue level and raw data are stored in the storage function. Stored data are utilized in periodic batch analyzing or outer system coordination via a REST or other API. In the driver management service, our system provides analyzed data to the SAP cloud at regular intervals and also when the analyzed data exceed certain threshold values.

*5 Apache, Apache Kafka, Apache HBase, and Apache Spark are either registered trademarks or trademarks of the Apache Software Foundation in the United States and/or other countries.

*6 The fatigue estimation algorithm for the trial was based on central fatigue estimation technology developed by NTT Service Evolution Laboratories [6].

4. Future prospects

In this article we introduced examples of two "hitoe" applications. In our initiatives towards rehabilitation patient monitoring, we will continue to promote research and development of our monitoring system so that it can collect data seamlessly, whether in the hospital, at home, or away from home, for both home rehabilitation and home medical care in the future. We also plan to utilize the Fast and Distributed IoT Processing Platform in rehabilitation applications.

We also introduced a bus driver management system and the Fast and Distributed IoT Processing Platform to support it. We will continue to use the Fast and Distributed IoT Processing Platform to analyze the data collected using "hitoe" wear and other sensors and will promote other projects using it in business.

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Data Exchange Technology Providing Real-time Data Processing and Scalability

Atsushi Terauchi, Kenichi Ooto, Noriyuki Takahashi, Kei Harada, and Ikuo Yamasaki

Abstract

The pervasive spread of the Internet of Things, or IoT, in recent years is remarkable, and NTT is working to incorporate IoT in industries showing the greatest promise for creating new value—manufacturing, the auto industry, agriculture, and other sectors. This article provides an overview of NTT's initiatives in IoT data exchange technology and edge computing technology, and reviews standardization trends pertaining to these technologies.

Keywords: IoT data exchange, edge computing, container-based virtualization

1. Data exchange technology: opening the way to real-time data processing and greater scalability

The pervasive spread of the Internet of Things (IoT) in recent years has been truly remarkable, and NTT is working to incorporate IoT in industries showing the greatest potential for creating new value—manufacturing, the auto industry (automatic driving support), agriculture, and other sectors. IoT really comes together in the form of services that connect sensors that gather data, and applications that leverage the gathered data. This involves a vast number and range of devices, and an equally diverse variety of applications. The true value that IoT creates is derived from leveraging new combinations of data gathered by sensors, and today we see growing demand from both the public and private sectors for an IoT data exchange society that supports leveraging and delivery of IoT data across services. This requires IoT data exchange technology that acquires IoT data from a wide variety of devices, then precisely scales the data for delivery to a wide range of applications.

However, the ability of certain manufacturing sectors to exploit the IoT has lagged behind as a result of growing network loads, processing speed delays, and the inability to meet the exacting requirements of robotic real-time control, self-driving support in vehicles, and other stringent requirements. NTT is now working to address this challenge by applying edge computing technology to IoT. Edge computing optimizes cloud computing systems by locating computer resources at the edges of the network and thus carrying out data processing near the source of the data. It is apparent that in order to leverage the limited computer resources deployed at the edge of the network, technology for dynamically configuring a software component at the edge of the network is also critically important.

This article provides an overview of NTT's recent work in IoT data exchange technology and edge computing technology and also reviews standardization trends pertaining to these technologies.

2. IoT data exchange technology

In this section, we explain aspects of IoT data exchange technology, focusing on current trends, research and development (R&D), and standardization.

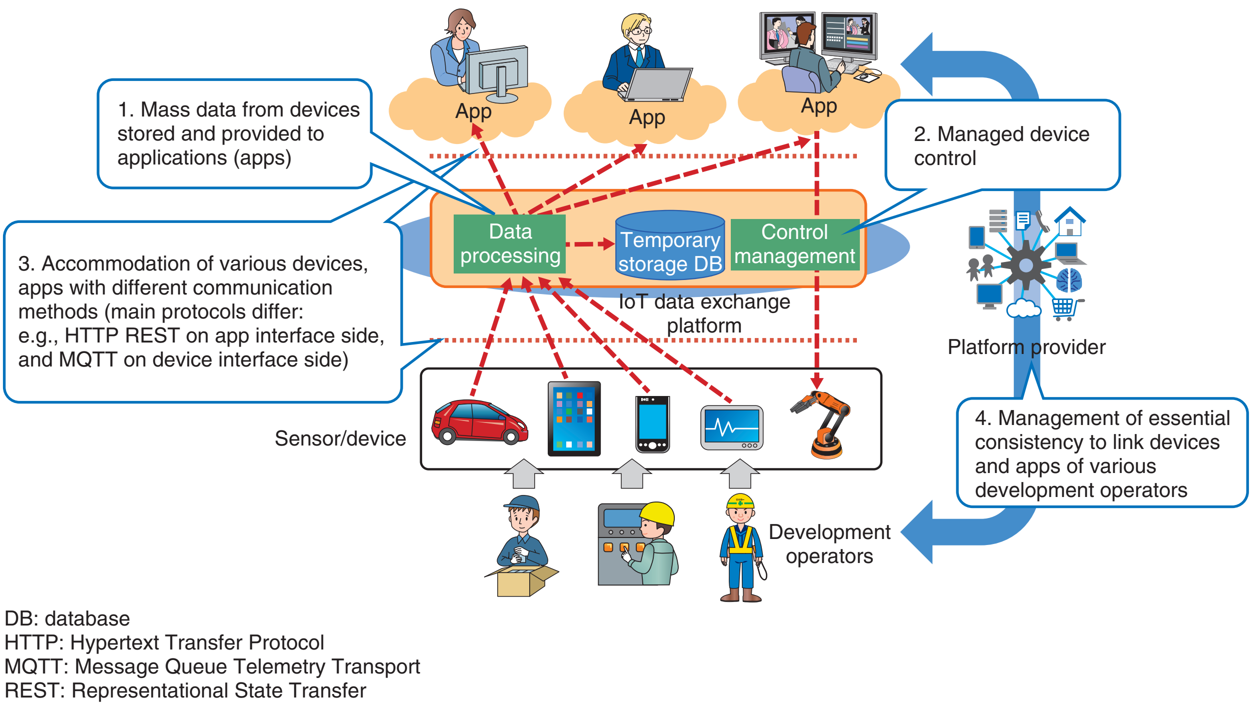

Fig. 1. IoT data exchange platform.

2.1 Technology trends and R&D

Until now, most schemes for gathering IoT related data have been implemented as standalone systems, so IoT data collected from devices are confined to a single system based on a *vertically* integrated IoT architecture. However, today we are shifting away from this model with rapidly growing demand for IoT systems based on a *horizontally* integrated IoT architecture built around a software infrastructure that is not dependent on vendor-specific applications and devices, that provides shared capabilities, and that supports a range of different IoT services and mutual distribution and utilization of IoT data. Horizontal integration has a number of significant advantages over vertical integration [1, 2]:

(1) Sharply reduced system development costs made possible by using shared functions and capabilities on the platform

(2) Support for a far greater range of connections made possible by abstracting connections between IoT devices and applications

(3) More efficient utilization of gathered data among many services

In order to create a robust data exchange society capable of creating value by incorporating IoT across diverse industrial sectors and sharing IoT data, we must first build a viable platform—*an IoT data exchange platform*—that mediates the exchange of IoT data between applications and devices, and NTT is making solid progress in establishing the core IoT data exchange technologies to achieve this objective. We have already compiled considerable knowledge by studying IoT system use cases for particular industries, which has enabled us to define the requirements of the IoT data exchange platform and come up with a platform design that meets these requirements (**Fig. 1**). NTT has now moved on to the development phase and plans to unveil a practical IoT data exchange platform in the near future.

2.2 Associated standardization trends

In order to actually implement a horizontally integrated IoT data exchange platform, it would be preferable to base the interfaces between the platform and applications, and between the platform and devices, on an international standard and not simply use an in-house proprietary solution. One promising standard initiative that would meet these requirements is oneM2M™*1 [3]. To prevent the proliferation of excessive standards, oneM2M was launched in July

*1 oneM2M: oneM2M is a trademark of oneM2M Partner Type 1.

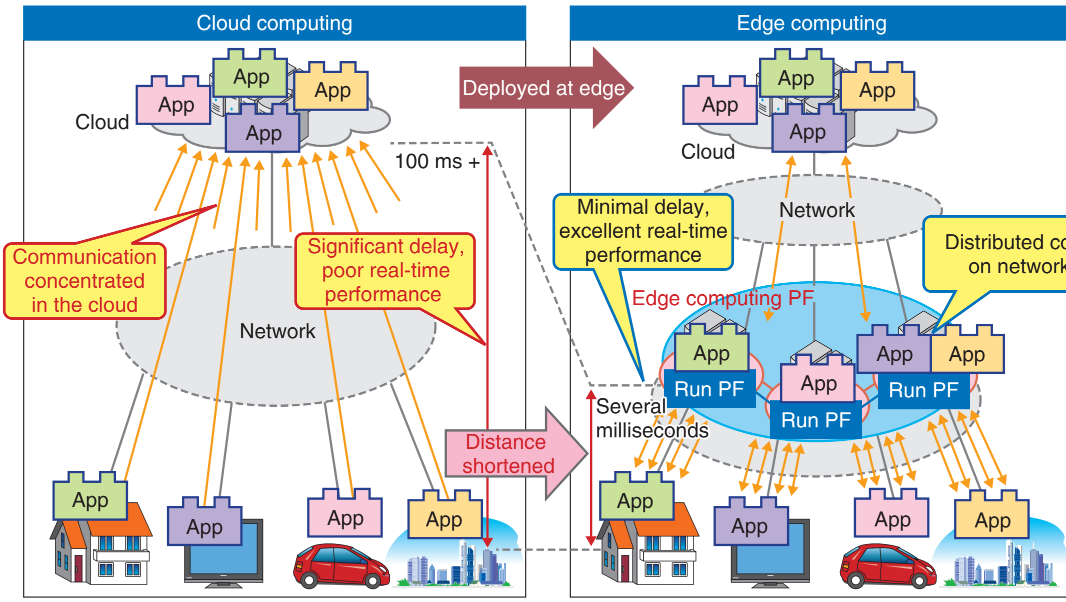

Fig. 2. Comparison of cloud computing and edge computing.

2012 as a global organization involving the world's preeminent standards development organizations*2 that collaborated to develop the requirements and specifications for machine-to-machine (M2M) and IoT technologies. The ultimate goal of oneM2M is to draft standards for a horizontal platform architecture that can be shared by many different industries and services; oneM2M currently has more than 200 participating partners and members, including NTT.

Release 1 of the oneM2M standard was issued in February 2015, followed by Release 2 in August 2016, and many companies and organizations have already implemented IoT data exchange platforms in compliance with the standard. One key aspect of oneM2M is interoperability and compliance with other relevant standards—OMA (Open Mobile Alliance), 3GPP (Third Generation Partnership Project), and so on—and considerable work has been done to verify and test the consistency and interconnectivity of oneM2M with other standards. While collaborating with other organizations on standards initiatives, NTT is convinced that oneM2M will be critically important in the deployment of IoT data exchange and is moving boldly to implement an IoT data exchange platform based on the oneM2M standard.

3. Edge computing technology

Another important area of focus is edge computing technology. We describe key aspects of this technology in this section.

3.1 Technology trends and R&D

NTT is breaking fresh R&D ground in pursuit of edge computing that drastically shrinks communication delay from users by deploying edge servers that provide computational resources at the edge of the network in close proximity to user terminals and IoT devices [4, 5]. Offloading the terminal-side processing to the edge server opens the way to markedly enhanced performance: large-capacity application processing at very high throughput unconstrained by computational performance of the terminal. Edge computing is also well adapted for applications requiring real-time response or big data processing that involves frequent communication or large-volume communication with the server.

A side-by-side comparison of cloud computing and edge computing is shown in **Fig. 2**. Cloud computing provides access to shared computer processing

*2 Japan's participants in oneM2M are the Telecommunication Technology Committee and the Association of Radio Industries and Businesses.

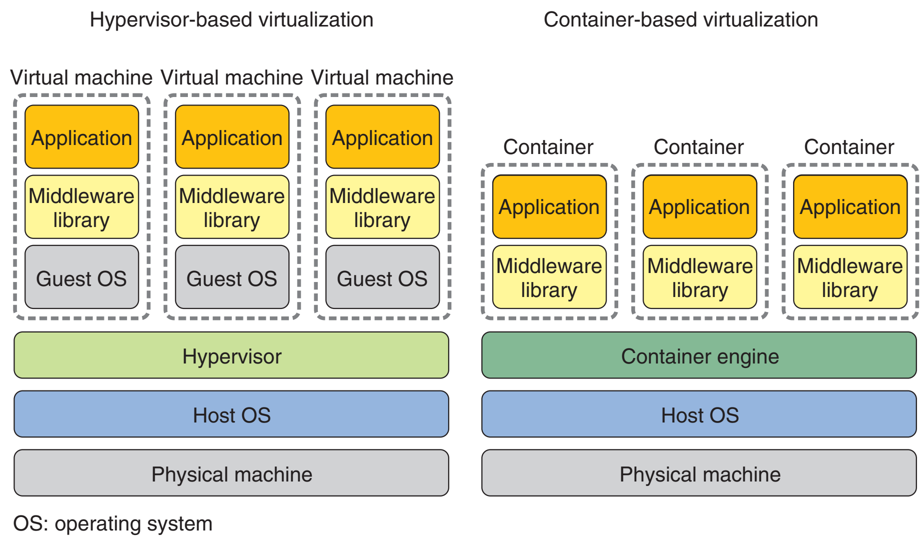

Fig. 3.   Schematic of hypervisor-based virtualization and container-based virtualization.

resources on the Internet, and the typical round-trip delay time (RTD) between terminals is less than 100 ms domestically, 100 ms between Japan and the United States, and 200 ms between Japan and Europe.

In the case of edge computing, multiple edge servers are deployed on the periphery of a carrier's access network. The edge server can be regarded as a small-scale cloud datacenter in close proximity to the user that has arithmetic processing functions and storage capabilities, and that can run application programs and store data content.

The user terminal communicates directly with an edge server, and the RTD can be slashed to just a few milliseconds. Moreover, when an edge server is used to perform regional processing, the computational and communication resources used can be localized. For example, by tallying a large number of sensor readings on an edge server instead of delivering the readings one at a time to a central server (in the cloud), and by sending just the key statistical parameters (such as averages and deviations) and noteworthy outliers, the overwhelming bulk of communication can be localized just between the sensors and the edge server, and traffic on the network backbone can be drastically reduced.

3.2 Container-based virtualization edge server architecture

Edge servers for IoT might be implemented in a number of different ways, but at NTT, we assume rather tight constraints on the server's computer resources (the CPU (central processing unit), memory, and disk I/O (input and output)), so our efforts have focused on a container-based virtualization edge server architecture. Container-based virtualization is an operating system-level virtualization method for running multiple isolated resource systems called *containers* on a computer. Compared to the older hypervisor-based virtualization method, container-based virtualization uses far fewer resources for processing and also ensures application portability between different equipment. A schematic overview of hypervisor- versus container-based virtualization is shown in **Fig. 3**.

Adopting this type of containerized virtualization while incorporating an IoT data exchange platform and various applications onto an edge server would enable us to tailor the amount of computer resources for each process according to priority, which would significantly upgrade resource utilization efficiency. A schematic of how this would work is illustrated in **Fig. 4**.

Another well-known platform for container-based virtualization is the open-source container management software Docker [6]. We are currently evaluating this software for distributing and managing containerized applications. Docker is able to deliver and exercise executive control over applications based on containerized virtualization. Therefore, by adapting Docker to connect edge servers in development and commercial environments, one can build an environment that seamlessly covers the entire sequence from

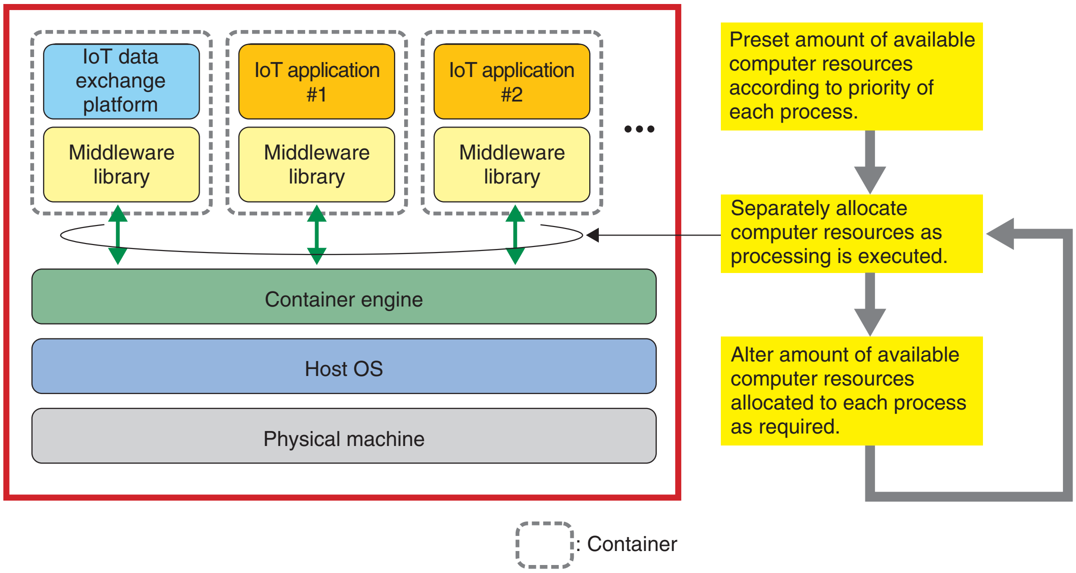

Fig. 4. Schematic of edge server using container-based virtualization.

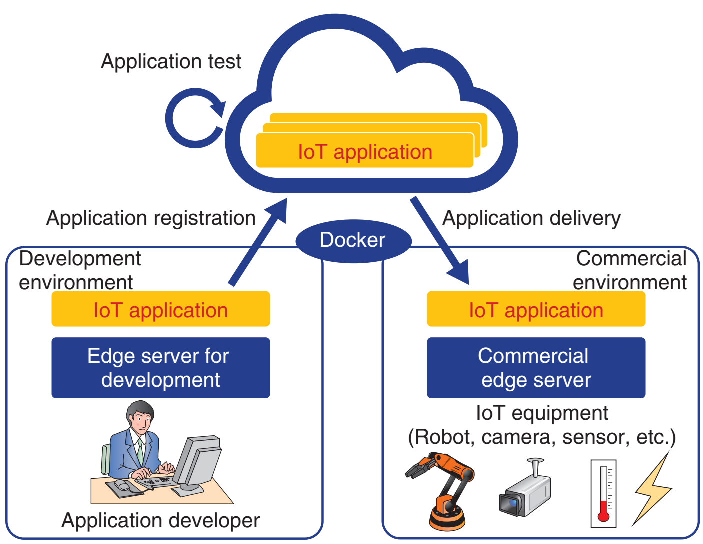

Fig. 5. Schematic of development, delivery, and management of IoT application based on Docker.

application development and testing to distribution and monitoring (**Fig. 5**). This strategy will contribute to the rapid uptake of IoT by creating an environment that promotes rapid development of applications and proliferation of edge servers by application service providers, equipment vendors, users, and other players.

3.3 Associated standardization trends

Edge computing has attracted a great deal of interest as a promising new approach for opening the way to application areas that are currently not covered by conventional cloud computing, and much standardization work has already been completed. The Industry Specification Group (ISG) of ETSI (European Telecommunication Standards Institute) has been especially active since 2014 in pursuing work on

MEC (which initially stood for Mobile Edge Computing, but was later changed to Multi-access Edge Computing) [7].

NTT and NTT DOCOMO have been involved in work on MEC since ISG was first organized. We have carefully considered technical requirements of edge servers for a variety of different use cases and have drawn up function-level architectures and basic API (application programming interface) specifications.

In a related development, the Open Edge Computing Initiative organized by Carnegie Mellon University has set up a city-scale testbed that consists of a number of edge servers and wireless base stations to conduct field trials of this architecture [8].

4. Future development

A good portion of the technology described in this article is now being applied as a first use case in manufacturing and is now being incorporated in the IoT platform *FIELD system*[*3] [9] for manufacturing, which is under development by FANUC CORPORATION, an industry leader in robotics. Building on work done so far, we will of course further consider these technologies as manufacturing use cases, but at the same time will continue to pursue R&D on IoT data exchange technology and edge computing technology with the goal of applying this work to other sectors and opening a new era of the IoT data exchange society.

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*3 FIELD system: FANUC Intelligent Edge Link and Drive system

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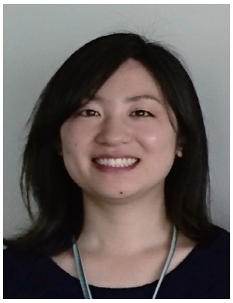

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Optimal Crowd Navigation via Spatio-temporal Multidimensional Collective Data Analysis

Futoshi Naya, Masaru Miyamoto, and Naonori Ueda

Abstract

We introduce technology for predicting the risk of congestion in the near future from real-time observational data of people or automobile flows and for automatically deriving an optimal crowd navigation plan online to avoid that risk. This technology can deal with unforeseen situations by performing simulations based on machine learning. Our aim in establishing this technology is to help construct a safe and secure and more comfortable social infrastructure.

Keywords: spatio-temporal data analysis, congestion risk prediction, collective navigation

1. Introduction

Thanks to improvements in sensing technology and the rapid spread of smartphone applications and devices making up the Internet of Things (IoT), it is becoming possible to measure diverse types of data such as the movement of vehicles and things, human behavior, and environmental changes from just about anywhere. However, it is extremely difficult to extract and appropriately apply significant and useful information lying latent in combinations of such diverse and massive amounts of data collected and stored in the above way.

NTT is researching and developing Ambient-AI as an artificial intelligence (AI) technology targeting IoT [1]. The idea behind this technology is to obtain information on everything under the sun (things, people, the environment) from diverse types of data collected and stored in real space and cyber space, perform instantaneous event detection, analysis, and prediction based on that information, and feed the results back to the real world.

A key technology supporting Ambient-AI is spatio-temporal multidimensional collective data analysis, which has come to be constructed in order to model the spatio-temporal relationships among multidimensional data having multiple attributes and to predict the place and time of a future event [2, 3]. This technology considers time, space, multidimensionality, and collectivity as four elements of data to foresee and gain insight on near-future events. Here, the idea behind collectivity is to estimate the spatio-temporal flow of people or vehicles only from aggregate data, as in the number of people or vehicles per cell, in which individual persons or cars cannot be identified.

In this article, we introduce our latest research and development (R&D) efforts in extending this technology. Starting with real-space information on people or vehicles collected from real-time observations, we input this information online into a simulation environment in cyber space, model the spatio-temporal features of that information, instantaneously predict immediate congestion risk, and preemptively and optimally navigate the crowd to avoid that risk [4].

2. Learning multi-agent simulation

Multi-agent simulation (MAS) is becoming increasingly popular as a technique for modeling the individual behavior of autonomously acting entities (= agents) such as people, cars, animals, and insects, modeling the micro-interaction of those agents with the surrounding environment, and analyzing and predicting macro-phenomena uncovered from the

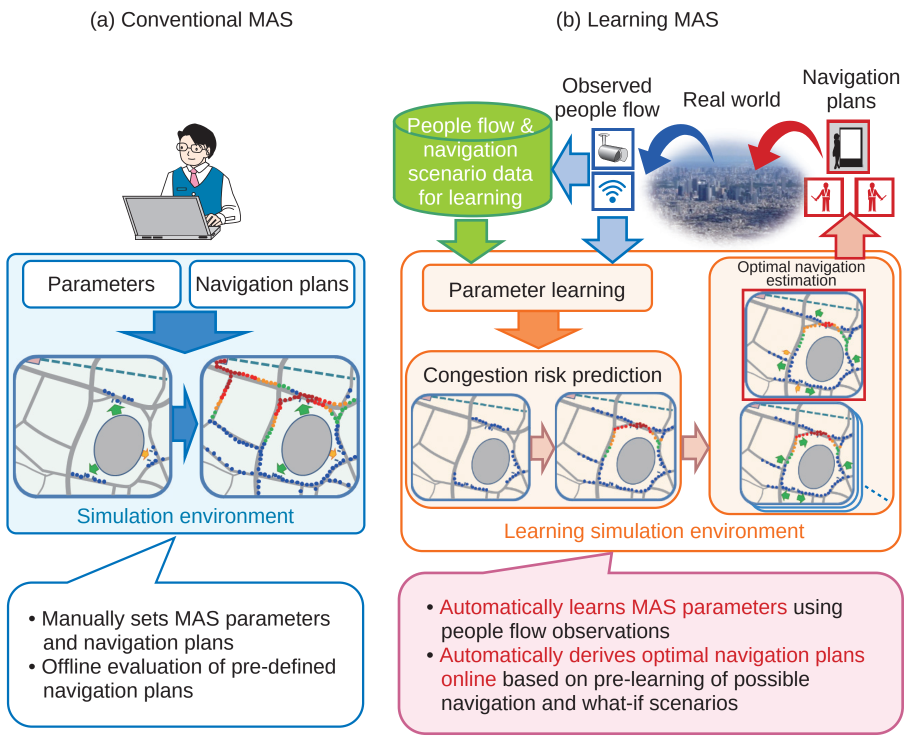


Fig. 1. Differences between conventional and learning MAS.

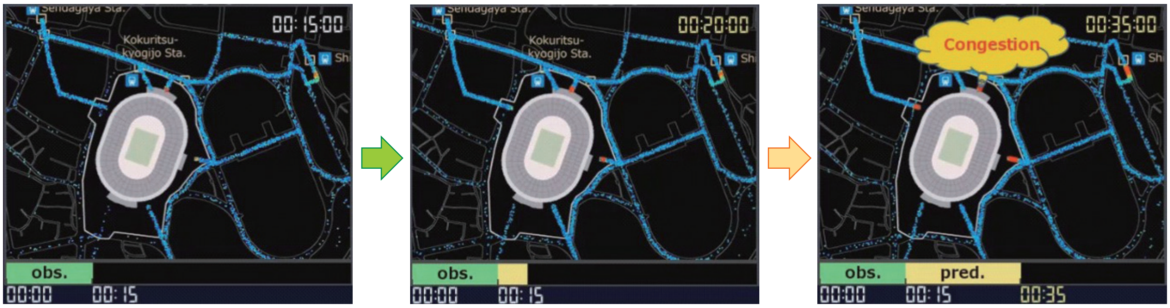
interaction among multiple agents and their interaction with the environment. In fields commonly referred to as complex systems, it may be possible to understand and describe individual micro-behavior, say of the people making up a society, neurons making up the neural network of a brain, and molecules, atoms, and other elements in the atmosphere giving rise to various types of weather phenomena.

However, analysis techniques using MAS have come to be widely researched for analyzing large-scale systems in which the overall macro-behavior of things such as social activities, brain activities, and weather phenomena cannot be broken down into the behavior of individual elements. These techniques have recently found use in sensor networks, smart grids, and intelligent transport systems and in evacuation guidance simulations for disaster preparedness.

To give a specific example, we consider the navigation of tens of thousands of spectators exiting a stadium. In this case, individual spectators are agents who leave the stadium from their current locations via exits and move toward train stations as their destinations. In spectator movement, a commonly used model considers an average walking speed (e.g., 4 km/h) related to the attributes of individual spectators such as age and gender and the attenuation of that walking speed on traversed roads in a manner proportional to congestion conditions (crowd density). Crowd control manuals [5] state that passing becomes difficult and walking speed begins to drop at a crowd density of 1.2 persons/m^2 and that movement comes to a halt at 4 persons/m^2. Crowd density is also called *service level* [6], and the road width, space, and flow rate in pedestrian lanes that maintain a certain service level satisfying safety standards can be computed.

In conventional analysis methods using MAS, it is common to manually set parameters such as walking speed and navigation plans such as pedestrian paths and flow rate and to conduct simulations to evaluate beforehand the effects of those plans. Such methods have been applied when actually implementing crowd control (**Fig. 1(a)**). However, these parameters and navigation plans are limited to a small number of combinations decided beforehand and do not necessarily match actual human movements or observed results based on navigation operations.

Today, however, rapid progress in IoT and sensing technologies means that local people flow and congestion conditions in the real world can be measured in real time using a variety of positioning means such



(a) Observed people flow in the past 15 min

(b) Prediction after 5 min

(c) Prediction after 20 min

Fig. 2. Example of immediate congestion risk prediction.

as surveillance cameras, GPS (global positioning system), Wi-Fi*, and beacons. With this in mind, the NTT laboratories are moving forward on the development of a learning MAS system that transfers events in real space such as people flow observed in real time to a simulation environment in cyber space, automatically learns modeled parameters based on observations, and predicts the spatio-temporal unfolding of events (**Fig. 1(b)**).

The aim here is to establish technology based on the learning MAS to predict immediate congestion risk, automatically derive an optimal navigation plan online at any time to avoid that risk, and support navigation through crowd handlers and other personnel.

3. Prediction of immediate congestion risk and automatic derivation of an optimal navigation plan

An example of an immediate prediction of congestion risk is shown in **Fig. 2**. First, people-flow data are obtained from real-time observations and input into a simulation environment. The prediction process takes some of that data, say from the immediately preceding 15 minutes, to simulate subsequent spatio-temporal behavior. That is, in combination with the spatio-temporal multidimensional collective data analysis described above, it predicts with high accuracy spatio-temporal congestion risk into the immediate future, that is, 5 minutes, 10 minutes, and 20 minutes later. In an example of the flow of spectators moving toward a stadium from nearby train stations, the process predicts that congestion will occur 20 minutes later, particularly near the entrance on the north side of the stadium (Fig. 2). The next step is to automatically generate potential navigation plans by computer to eliminate this congestion risk and to search for an optimal navigation plan (**Fig. 3**).

In this example, one navigation plan is to temporarily close one of the six stadium entrances and direct spectators toward the other entrances (Plan B in the figure). However, a huge number of combinations is possible when considering which entrances to close and when and for how long to close each one, or whether to completely or partially close a particular entrance. This process therefore efficiently prunes the massive number of candidate navigation plans and discards those that would have no effect on navigation, those that cannot actually be put into operation at the site, and those that may generate confusion, and then immediately searches for an optimal navigation plan.

Various criteria can be considered here for optimality such as the shortest time required for all spectators to get inside the stadium or the minimum time or area in which spectators are held up due to congestion. However, it is difficult to directly evaluate which navigation plan has an optimal criterion value, and it is unrealistic to perform an exhaustive search of this massive search space.

To solve this problem, we use a machine learning technique called Bayesian optimization that efficiently searches for promising candidates from a small number of search results to derive an optimal navigation plan. For example, with the search results of Fig. 3, this technique derives a navigation plan that closes two of the stadium entrances at the 25-minute point (**Fig. 4**). This plan can be presented to crowd handlers to help them navigate arriving spectators.

* Wi-Fi is a registered trademark of Wi-Fi Alliance.

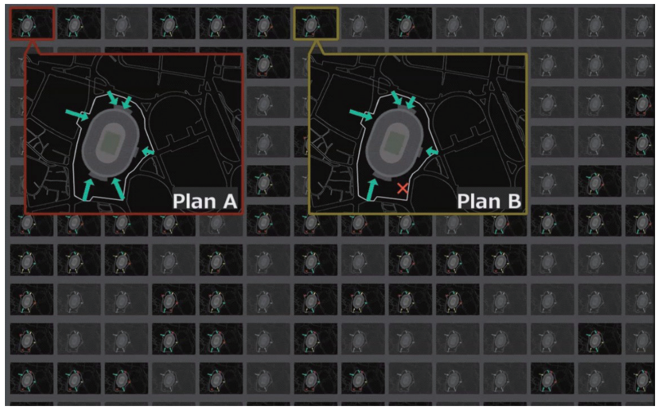


Fig. 3. Automatic generation of candidate navigation plans and searching for optimal plan.

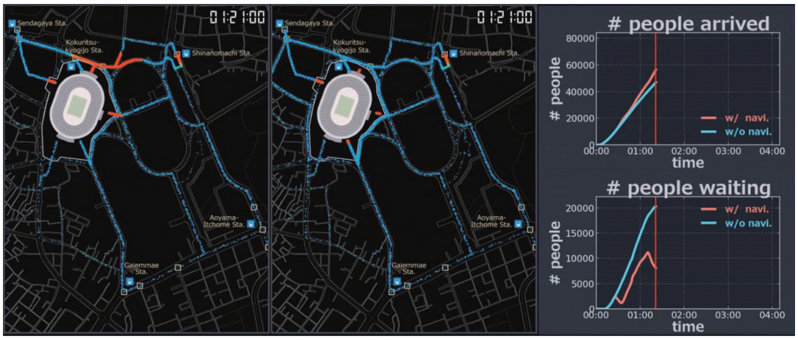
Fig. 4. Automatically derived optimal plan.

Here, we can expect spectator behavior to generally change due to such navigation, but not all spectators will necessarily comply with that navigation. Accordingly, this technique takes into account continuous observations and predictions of new congestion risks to repeatedly search for an optimal navigation plan and perform actual crowd control in the same way as above through a feedback loop.

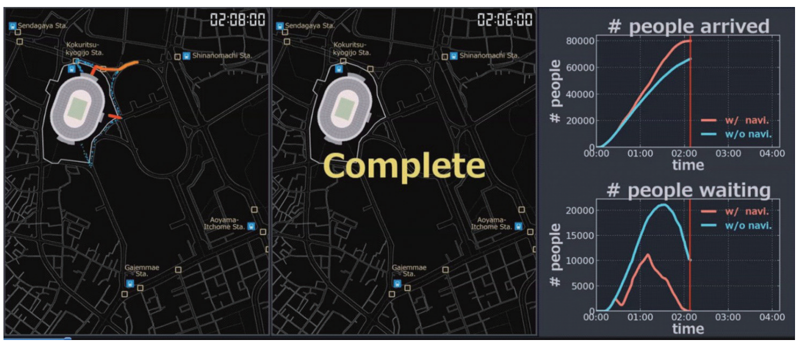
4. Examples of application to entering/exiting stadium

The results of simulations for a scene with 80,000 spectators entering a stadium with and without optimal navigation are shown in **Fig. 5** for comparison purposes. The people flow at the point 1 hour and 20 minutes after spectators begin to arrive at the station and make their way toward the stadium is shown in Fig. 5(a). For the case without navigation shown at the left of the figure, the concentration of nearby train stations on the north side of the stadium results in congestion at the entrances near those stations and the appearance on public roads of queues of spectators that are held up and cannot move forward.

In contrast, for the case with navigation shown in the center of the figure, crowding at particular entrances is avoided by blocking access to north-side entrances at key locations, thereby minimizing the generation of queues on public paths. With the navigation plan, all spectators were able to arrive and be inside the stadium at about the two-hour point, as shown in the center of Fig. 5(b).



(a) 1 hour and 20 min later



(b) 2 hours later

Fig. 5. Simulation results with optimal navigation plans for entering stadium.

However, without navigation (left side of Fig. 5(b)), time is needed to naturally clear congestion, and it would be about another hour until all spectators were inside the stadium. A graph with the vertical axis representing the number of people waiting and the horizontal axis representing time is shown at the lower right of Fig. 5(a) and 5(b). It can be seen that with navigation, the number of people waiting is kept low. Therefore, determining how to minimize the number of people waiting is an important issue, particularly for events held during the hot summer months. The proposed technique is expected to be effective in this regard.

Next, we consider a scene of 80,000 spectators exiting a stadium and making their way toward nearby stations. We examine, in particular, a scenario in which unforeseen situations (e.g., accidents) not envisioned in prior studies in conventional navigation planning occur in rapid succession at four locations within 20 minutes after spectators begin to exit (**Fig. 6**). It is assumed here that the flow of people walking toward the stations and the flow of people coming out of the stations become intertwined, that the widths of some roads are reduced (path narrowed) due, for example, to the arrival of emergency vehicles (locations A, B, and D in the figure), and that a road is closed (path closed) due to an accident (location C).

The results of simulations performed to determine whether the proposed technique can derive an optimal navigation plan even under such unforeseen conditions is shown in **Fig. 7**. First, simulation results are shown in Fig. 7(a) for the point 20 minutes after people begin exiting the stadium, when accidents at four locations occur. At this time, the flow of people is the same with or without navigation, but a red congestion location starts to appear due to the effects of the path closure in the upper right portion of the map.

Next, simulation results at 30 minutes are shown in Fig. 7(b). With navigation, the proposed technique clears congestion by directing people to a detour to avoid the congestion caused by the above path closure. It can be seen from the results for the point 2 hours later in Fig. 7(d) that all spectators have arrived at their target stations. With no navigation, however, congestion occurs at various locations 1 hour and 20

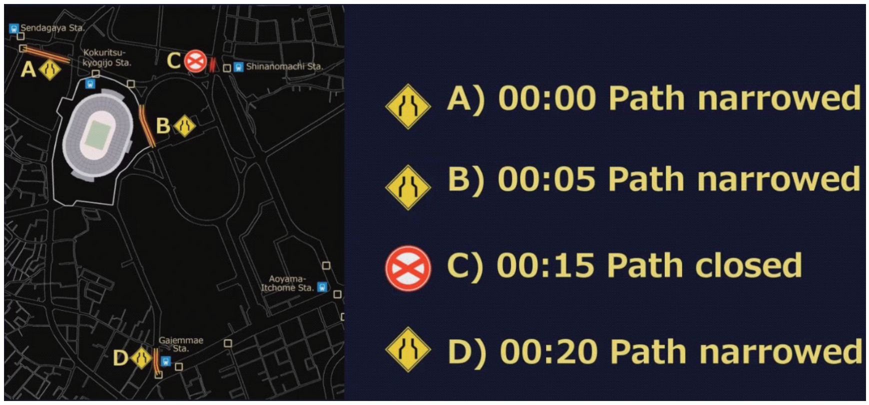
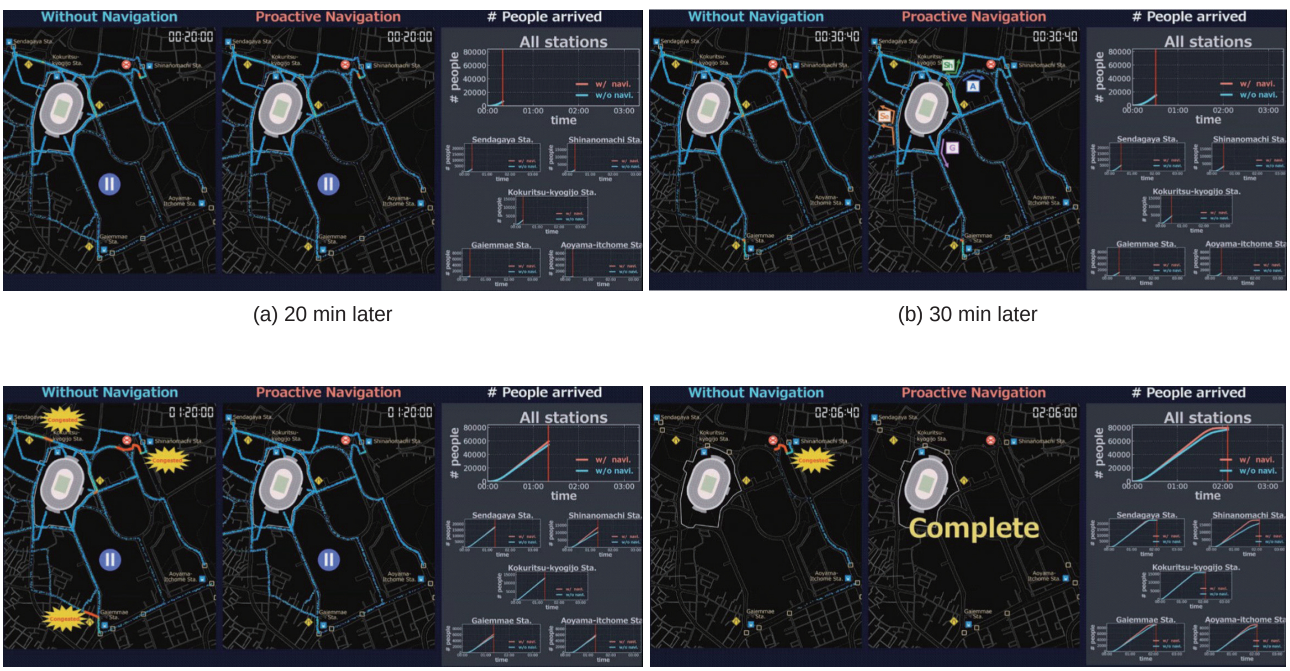


Fig. 6. What-if scenarios for exiting stadium.



(a) 20 min later

(b) 30 min later

(c) 1 hour and 20 min later

(d) 2 hours later

Fig. 7. Simulation results with optimal navigation plans for exiting stadium.

minutes later, as shown in Fig. 7(c). Even at 2 hours later as shown in Fig. 7(d), congestion has yet to be cleared, and compared with the results with navigation, many people have to wait for 30 minutes or longer. In this way, the proposed technology is not limited to the occurrence of accidents envisioned beforehand; it can also predict immediate congestion for the multiple and ongoing occurrence of unforeseen situations and automatically derive an optimal navigation plan at any time.

5. Future outlook

People-flow simulation introduced in this article has been based for the most part on pseudo data generated from statistics on past numbers of train station users and other information. NTT, however, is developing a learning-oriented simulation environment based on actual measurements of people flow at actual event venues and stadiums. We expect the application of this technology to extend beyond people flow to include risk prediction and optimal infrastructure control for flows in various types of social infrastructures such as traffic flow, logistics, and even communications traffic. As we look forward to 2020, we will continue to measure flow in peripheral areas including large-scale event venues, train stations, and road networks and will work on making simulations increasingly detailed. Our aim through these R&D efforts is to achieve optimal crowd navigation technology that can deal with unforeseen situations.

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Orbital Angular Momentum Multiplexing Technology towards the Realization of Tbit/s Wireless Transmission

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Abstract

We explore the potential of orbital angular momentum (OAM) multiplexing towards enabling high-speed wireless transmission. OAM is a physical property of electromagnetic waves that are characterized by a helical phase front in the propagation direction. This characteristic can be exploited to create multiple orthogonal channels, and thus, wireless transmission using OAM can enhance the wireless transmission rate. We clarify two major issues in OAM multiplexing: beam divergence and mode-dependent performance degradation. To address these issues, we present a simple but practical receiver antenna design method. Because there are specific location sets with phase differences of 90 or 180 degrees, the method allows each OAM mode to be received at its high signal-to-noise ratio region. We confirm the feasibility of OAM multiplexing in a proof of concept experiment at 5.2 GHz. Finally, we briefly introduce the future directions of this work.

Keywords: orbital angular momentum multiplexing, uniform circular array, 5G, millimeter wave

1. Introduction

Significant progress has been made in wireless communication technologies in recent decades. In particular, the utilization of higher frequency bands (e.g., the millimeter-wave (mm-wave) band), where several gigahertz of bandwidth is available, has played a key role in achieving such progress. Recent research efforts have shown the feasibility and possibility of utilizing mm-wave technologies to provide transmission at up to several tens of gigabits per second [1].

Despite such achievements, providing high-order data-rate transmission is expected to be necessary to satisfy the ever-increasing demand for such transmission in the coming decade. We have also observed from history that the transmission rate of wireless communication has increased 100 times every 10 years, as shown in **Fig. 1**. Considering this trend and the current mature status of mm-wave technologies [1], we consider it is high time to discuss the candidates for wireless transmission technologies to provide up to 1-Tbit/s transmission.

The orbital angular momentum (OAM) multiplexing method is an emerging wireless transmission technology that exploits a physical property of electromagnetic waves characterized by a helical phase front in the propagation direction [2]. The propagating beams with a distinct number of phase rotations, that is, OAM modes, are orthogonal to one another and create multiple orthogonal channels. From a wireless communication perspective, the beauty of OAM multiplexing is that it generates multiple orthogonal channels in a line-of-sight channel

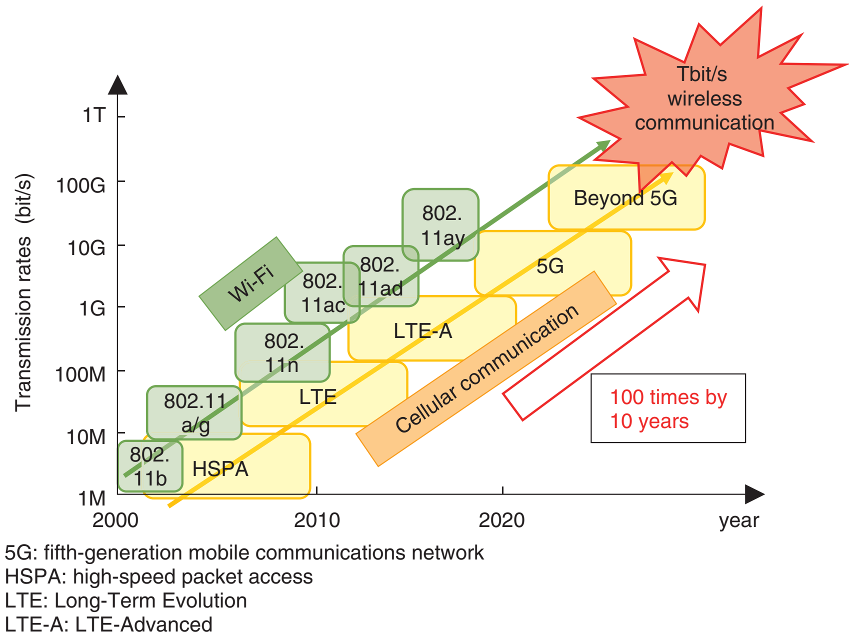


Fig. 1. Evolution trend of wireless communication technologies and transmission rates.

environment without complex signal processing such as channel diagonalization.

We investigated the performance of wireless communications using OAM multiplexing and clarified the most significant challenges that hinder the potential of OAM multiplexing, which are beam divergence and mode dependency of the performance. The higher the OAM mode, the more severe the beam divergence becomes. This results in the need for larger receiver (Rx) antennas or reduced Rx signal-to-noise ratio (SNR).

We discuss here how we are addressing these issues with our practical and novel Rx antenna design and corresponding signal separation methods [2]. We also describe how we confirmed the feasibility of OAM multiplexing in a proof of concept experiment at 5.2 GHz. Finally, we briefly introduce the future directions of this work.

2. Background and challenges

Several challenges arise with OAM multiplexing, which we describe in this section. First, we review the background of this technology.

2.1 History of OAM multiplexing

Research on electromagnetic waves carrying OAM modes goes back a long way. Some work in this field dates from the early 1900s. In the 1980s, the multiplexing concept using OAM modes was suggested by researchers studying circular array antennas. From the late 1990s to the 2000s, similar concepts were studied in various fields, including radio astronomy, photonics, and free-space wireless communication. From the early 2010s, interest was drawn again to the wireless communication field, influenced by maturing technologies using mm-wave band communications.

Studies related to OAM multiplexing in the wireless communication field are categorized into those focusing on antenna design and beam generation [3–5], proof of concept experiments [4, 6, 7], signal processing methods [8], and system studies such as those concerning capacity analysis and link budget [9].

Much work has been done on antenna design and beam generation since the renewal of interest in the early 2010s. Various antenna designs using helicoidally deformed parabolic antennas [3], spiral phase plates (SPPs) [4, 6, 7], holographic plates (HPs) [4], and elaborately tuned planar SPPs [5] have been reported. Despite some reports of successful transmissions, it seems to be difficult to perform multiplexing in a practical manner using such antennas since each OAM mode needs a differently located antenna. However, a uniform circular array (UCA)

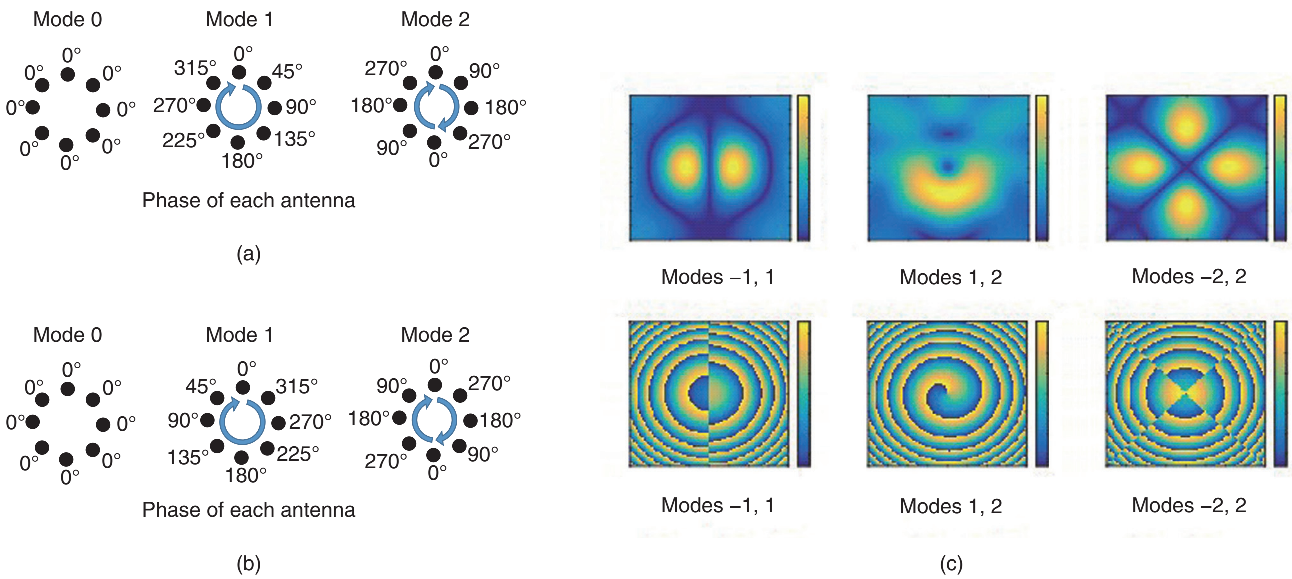


Fig. 2. (a) Generation of OAM modes with a UCA, (b) separation of OAM modes with a UCA, and (c) intensity distribution (above) and phase distribution (below) of combined OAM modes.

and/or multiple UCAs [2, 8] are considered to be suitable for OAM multiplexing because they can transmit coaxially aligned multiple streams simultaneously.

The feasibility of OAM multiplexing has been validated in many different experiments [4, 6, 7]. Yan et al. successfully demonstrated 32-Gbit/s OAM multiplexing over a 60-GHz mm-wave band with four concurrent OAM modes (Modes = –3, –1, 1, and 3) with 16-quadrature amplitude modulation (QAM) [7]. The transmission distance was 2.5 m, and four SPPs were used for multiplexing with a 4-to-1 combiner. Mahmouli et al. conducted 4-Gbit/s uncompressed video transmission over a 60-GHz mm-wave band using HPs and SPPs [4]. However, as of yet, no Gbit/s-level transmission experiments over 10 m have been reported.

2.2 OAM beam generation and separation

To generate the beam carrying the OAM mode n (L = n), antenna elements are connected with phase shifters that make $n \times 360$ degrees of rotation. Examples of beam generations of OAM modes 0, 1, and 2 using UCAs consisting of eight antenna elements are shown in **Fig. 2(a)**. Note that it is possible to use either a single UCA or multiple UCAs for multiple OAM mode generation. In the former case, superposed beams are transmitted by a single UCA. In the latter case, concentric multiple UCAs are used.

The separation of beams carrying OAM modes can be done in a way similar to that for generation using antenna elements connected with phase shifters that make opposite rotation directions. As long as the number of antenna elements is larger than $2n$, rotations of $n \times 360$ degrees are orthogonal to one another. Therefore, each OAM mode can be separated from mixed OAM mode signals without aliasing. An example of each antenna element phase corresponding to the example above is shown in **Fig. 2(b)**. Such beam separation can also be done by using a single UCA or multiple UCAs as in the beam generation. Note that a divider is fitted between antenna elements and phase shifters in the former case.

2.3 Properties of OAM beams

Some examples of intensity and phase distributions of beams carrying multiple OAM modes generated by a single UCA are shown in **Fig. 2(c)**. At the Rx antenna, the diffraction pattern generated by a single transmitting UCA is calculated by the summation of the electric field generated from each antenna element. Since the diffraction pattern of the UCA can be approximated as a Bessel beam, the electric field distribution of the beam carrying OAM mode L is often expressed by the Bessel beam's equation as below.

$$v_L(r,\theta,z) = \frac{\lambda \exp[(2\pi i/\lambda)\sqrt{r^2+z^2}\,]}{4\pi\sqrt{r^2+z^2}} \cdot i^{-L} \exp[iL\theta] \cdot J_L\left(\frac{2\pi r D}{\lambda\sqrt{r^2+z^2}}\right), \quad (1)$$

where $J_L(\cdot)$, λ, and D respectively denote the L^{th} order Bessel function of the first kind, the wavelength of the carrier frequency, and the radius of the transmitting UCA. Equation (1) is represented in cylindrical coordinates, where r and θ are respectively the radius and azimuthal angle at the Rx plane that is vertical to the beam propagation direction, and z is the distance between the centers of the transmitter (Tx) and Rx UCAs.

Under the free-space propagation or AWGN (additive white Gaussian noise) channel, the intensity and phase of the received signals at a certain location can be analytically obtained by Eq. (1) with parameters consisting of the radius (D) of the Tx UCA, wavelength (λ), and the L^{th} order Bessel function of the first kind ($J_L(\cdot)$).

2.4 Challenges

This subsection highlights three major issues that have to be resolved in order to fully exploit the potential of OAM multiplexing. These issues are as follows.

(1) Beam divergence

Beams carrying OAM modes diverge along with their propagation as shown in **Fig. 3**. Other than OAM mode 0, the locations of the first Rx peak intensities of OAM modes diverge as the propagation distance increases. It may be considered that various beam-forming technologies can generate a sharp non-OAM carrying beam of which the divergence is not significant. However, the divergence of OAM carrying beams is determined by the Tx UCA radius and wavelength. It is therefore necessary to increase the physical size of the Tx UCA or to use a higher frequency in order to reduce the divergence of OAM carrying beams. Since both the Tx antenna size and frequency band are usually not tunable design factors, we leave this issue as an open problem while suggesting that the Tx antenna size be set as large as the physical environment allows.

(2) Mode-dependent performance degradation

The beam that carries different OAM modes yields different locations of the peak intensities. This non-identical peak Rx intensity results in mode-dependent performance degradation in accordance with the location of the Rx antenna. In addition, the required Rx antenna size to capture the peak Rx power becomes larger as the number of OAM modes increases. If the Rx antenna size is limited to a certain size, some OAM modes might not have the peak Rx power. Correspondingly, the performance degradation for higher OAM modes becomes more severe.

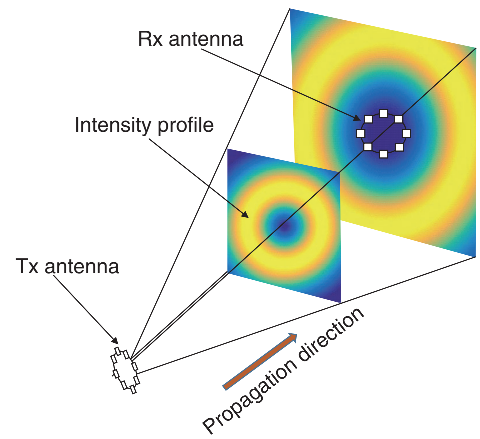


Fig. 3. Conceptual drawing of OAM beam divergence.

We propose a novel Rx antenna design to resolve the issues above.

3. Proposed Rx antenna design and OAM beam separation

In this section, we introduce the proposed antenna design and discuss the issue of beam separation.

3.1 Rx antenna design

In view of the distinct beam propagation and divergence among OAM modes, it may be a good approach to put the Rx antenna for each OAM mode at its optimum or near-optimum location. For example, the use of many concentric Rx UCAs that capture OAM modes at their high Rx SNR region may lessen the beam divergence problem and mode-dependent performance degradation. In such concentric Rx UCA cases, the outer UCA is generally used for the reception of a higher OAM mode. Since the UCA antenna radius increases by the power of two in such cases, a spacious antenna is necessary to capture the higher OAM mode signals in this approach.

To provide a practical solution that allows higher OAM mode signals to be received at a high Rx SNR while maintaining a reasonable antenna size, we present a simple but practical Rx antenna design and

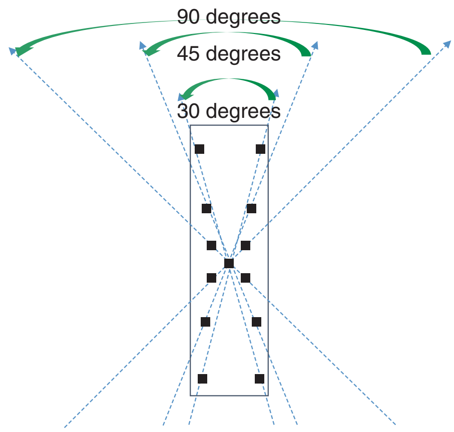


Fig. 4. Proposed Rx antenna.

corresponding beam separation method. Our idea is based on the fact that there are specific location sets of which phase differences are 90 or 180 degrees. Since such specific location sets depend not on the Euclidean distance but on the angle conditions that will be explained later, these specific location sets are invariant in terms of the distance between Tx and Rx. This provides the flexibility in the system design.

The concept of the proposed Rx antenna for concurrent transmission of seven OAM modes, including OAM modes –3, –2, –1, 0, 1, 2, and 3, is illustrated in **Fig. 4**. We use a four-antenna-element set to receive a pair of OAM modes of which the absolute values are identical and the signs differ from each other, for example, OAM modes 1 and –1. We also use an antenna at the center for OAM mode 0. In Fig. 4, the outermost, middle, and innermost four-antenna-element sets are respectively for OAM modes 3 and –3, 2 and –2, and 1 and –1. Four antenna elements in each set are located equidistant from the center and form an 'X' type configuration. The angles of the two upper antenna elements of each set are respectively 30, 45, and 90 degrees. The angles of the two lower antenna elements of each set are the same as those of the upper ones. Note that such angles become narrower as the number of OAM modes increases. Therefore, in contrast to the UCA case, the necessary area to capture the higher OAM modes does not increase by the power of two in its radius.

3.2 OAM beam separation

With the presented Rx antenna configuration, OAM beams are separated by analog cancellation followed by digital cancellation. We explain the details on the beam separation, which consist of the following three steps, referring to **Fig. 5**.

(1) Step 1) analog separation of odd and even OAM modes

Diagonally located antenna elements in each four-antenna-element set are combined by either an equal-phase or a reverse-phase combination using 2-to-1 analog combiners. Before these combinations, in the four-antenna-element sets installed for odd OAM modes, the two antenna elements at the bottom are first inserted into the 180-degree phase shifters as shown in Fig. 5. With these equal-phase or reverse-phase combinations, the combined outputs can only bear either an odd or even OAM mode.

(2) Step 2) analog extraction of each OAM mode

In this step, we begin by explaining an example of the extraction of OAM modes –3 and 3. A conceptual example to extract OAM mode 3 is shown in **Fig. 6**. Two reverse-phase combined outputs from the outermost four-antenna-element set contain only odd OAM modes (i.e., OAM mode –3, –1, 1, and 3) while even OAM mode signals are canceled out.

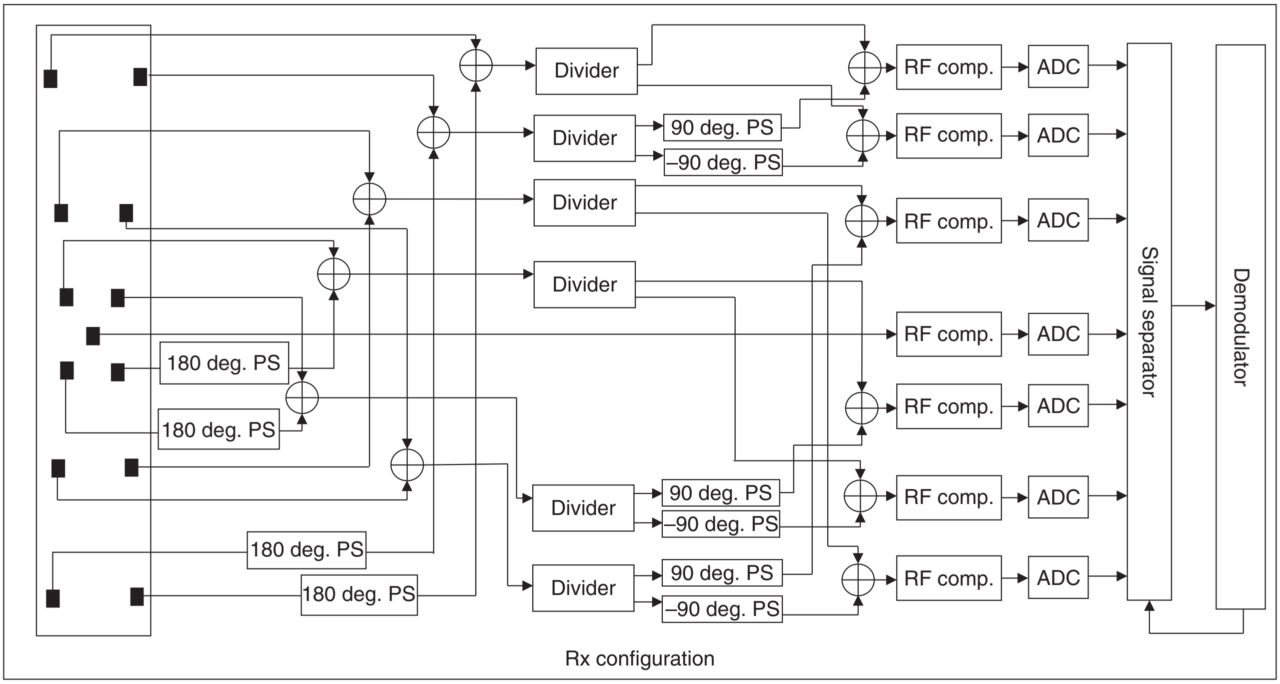
Each of the two combined outputs is again divided into two signals by a 1-to-2 divider. One output of the two dividers is inserted into the 90 and –90 degree phase shifters. The outputs of these phase shifters are respectively combined again with the outputs of the other two dividers. These combined signals respectively yield OAM modes –3 and 3 containing some interference from OAM modes –1 and 1. The interference is resolved by digital processing in step 3. OAM modes –1 and 1, and –2 and 2 are similarly extracted using two equal-phase combined outputs from the middle and innermost four-antenna-element sets. Extraction of OAM mode 0 is directly obtained from the antenna element at the center since all OAM modes disappear other than OAM mode 0 at the center.

(3) Step 3) digital pruning of each OAM mode

Each of the OAM mode signals extracted in the previous step is further pruned by digital signal processing such as successive interference cancellation or multiple-input multiple-output equalization. This step can be skipped when the residual interference after step 2 is negligible, or it can be intentionally skipped to reduce the complexity.

4. Evaluation: Proof of concept experiments

We conducted proof of concept experiments to examine the feasibility of OAM multiplexing. First, beams carrying OAM modes were generated using an



ADC: analog-to-digital converter
RF comp.: radio frequency components
PS: phase shifter

Fig. 5. Configuration of Rx device using proposed Rx antenna.

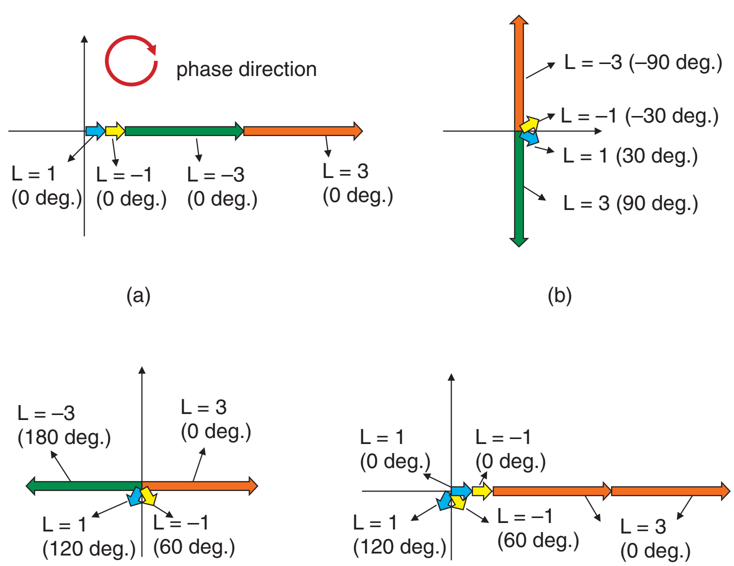
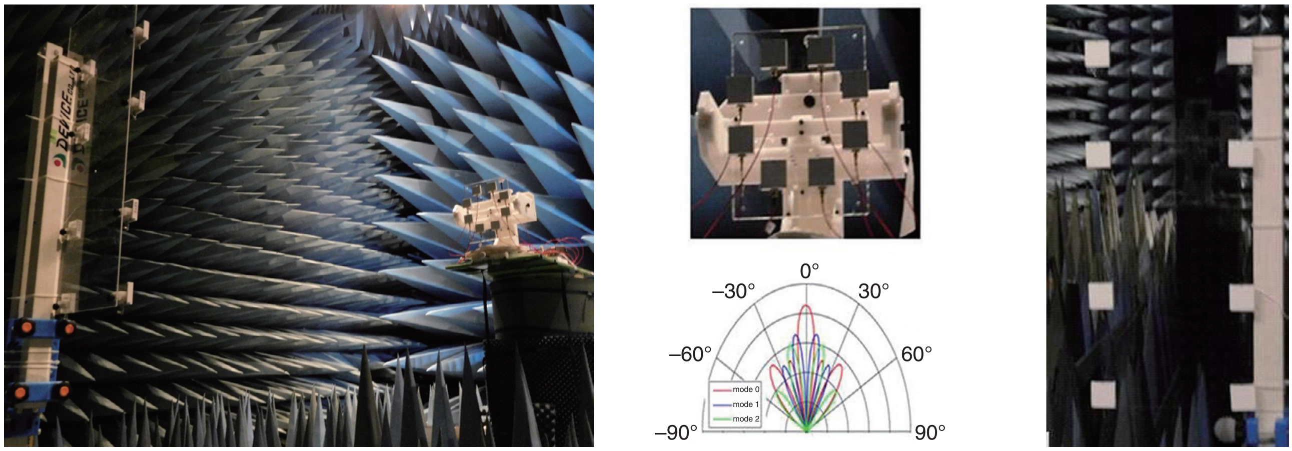
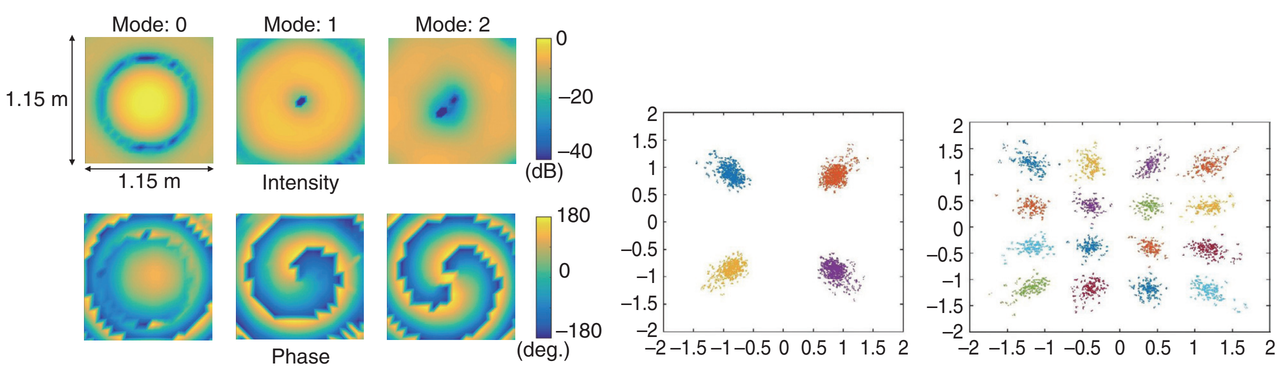


Fig. 6. Conceptual example of OAM signal separation (OAM mode 3). (a) One output of the reverse-phase combination using two antenna elements among the outermost four-antenna-element set; (b) output of 90-degree phase shifter using another output of the reverse-phase combination using remaining antenna elements among the outermost four-antenna-element set; (c) output of –90-degree phase shifter using another output of the reverse-phase combination using remaining antenna elements among the outermost four-antenna-element set; and (d) combined signal of (b) and (c) (OAM mode 3 is extracted).



(a) Experiment environment (b) Tx antenna and radiation pattern (c) Rx antenna

Fig. 7. Experimental setups.



(a) Intensity and phase distributions (OAM modes 0, 1, and 2) (b) QPSK (c) 16 QAM

Fig. 8. Experimental results.

unmodulated signal at 5.2 GHz. Their propagation was also investigated. Second, wireless communication experiments using quadrature phase shift keying (QPSK) and 16-QAM modulated signals at the same frequency band were conducted using our proposed antenna. Our experimental environment, Tx antenna and its radiation pattern, and the proposed Rx antenna are shown in **Fig. 7**.

4.1 OAM beam generation and propagation experiments

Three beams respectively carrying OAM modes 0, 1, and 2 were generated using a single Tx UCA at different times. The results of measuring intensity and phase distributions are shown in **Fig. 8(a)**. The figure shows the average intensity distribution normalized to the peak intensity of OAM mode 0 and the phase distribution in terms of the distance from the Rx antenna center. We confirmed from the measurement results that the experimental generated OAM beam propagation patterns were in good agreement with theory.

Precisely, an unmodulated signal at 5.2 GHz was generated and fed into a 1-to-8 divider. The divider's eight outputs were then respectively connected to eight tunable phase shifters. Each tunable phase shifter was connected to the antenna elements of the Tx UCA. We set the phases of the tunable phase shifters in order to independently generate beams carrying OAM modes. For example, we set the phases from

0 degrees to 315 degrees by increasing them in 45-degree increments to generate OAM mode 1. This yielded 360 degrees of phase rotation. To capture the intensity and phase distributions at the Rx plane, we used a horn Rx antenna and a moving positioner. While transmitting the generated OAM beam, we recorded the intensity and phase distribution at two-dimensional grids of the Rx plane.

Our experimental setup in the shielding room is shown in Fig. 7(a), and the Tx UCA (top) and its radiation pattern (bottom) are in Fig. 7(b). Note that we conducted these experiments using a horn Rx antenna and a moving positioner. The distance between the Tx UCA and the Rx horn antenna was around 235 cm (40.7 λ), and the diameter of the Tx UCA was around 11.54 cm (2 λ). The positioner was moved over a 21 × 21 square grid. One span of the grid was 5.77 cm (1 λ), and the measured area at the Rx plane covered around 115.38 cm × 115.38 cm. The center of the grid was set to be the peak intensity spot for OAM mode 0, while it was set to be the null points for OAM modes 1 and 2.

4.2 Modulated signal transmission using OAM beams

Here, we describe the results obtained in a wireless communication experiment using modulated signals. Except for the Rx antenna, the experimental environment was the same as that used in previous experiments. Instead of using a horn antenna, we used our proposed antenna shown in Fig. 7(c). The width and height of the Rx antenna were respectively 29 cm and 70 cm. QPSK and 16-QAM modulations were used for both uncoded and coded (1/2 rate low-density parity check (LDPC)) cases. Orthogonal frequency division multiplexing was carried out with 64 subcarriers over a 20-MHz signal bandwidth. Of the 64 subcarriers, 16 were used. Due to the practical limitations of the experimental setup, this experiment was conducted using a single stream while varying the OAM modes among –2, –1, 0, 1, and 2. The OAM multiplexing was evaluated by combining these single stream signals by offline processing.

The constellation maps of QPSK and 16-QAM signals obtained from a single stream are shown respectively in **Figs. 8(b)** and **(c)**. Their error vector magnitude values were respectively 14.18% and 13.5% with OAM mode 1, and 14.3% and 15.65% with OAM mode 2. Through off-line combining of the received signals of three single streams (OAM modes 0, 1, and 2) that were obtained by analog extraction, we confirmed that a bit error rate less than 0.001 is feasible with LDPC coding (rate 1/2). More enhanced performance is expected when digital pruning is further applied. These results validate the feasibility of wireless transmission by OAM multiplexing.

5. Conclusion and future directions

We introduced ways of achieving high order wireless transmission using OAM multiplexing. We also reviewed the current literature on this topic and identified two major issues. To resolve these issues, we proposed a simple but novel Rx antenna and corresponding mode separation methods. We validated the effectiveness of the proposed methods through proof of concept experiments.

Many issues still remain to be addressed. For example, although in our work we did not explicitly utilize the fact that nulls of each OAM mode appear at different locations, this gives rise to other possibilities to be explored such as OAM specific spatial channel coding. Considering various aspects, from the vision of future wireless technologies to practical configurations, we are making efforts to achieve our goals that enable Tbit/s wireless transmission.

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ITU-R Study Group 3 Activities towards Use of High Frequency Bands for 5G and Other Wireless Communication Systems

Motoharu Sasaki, Minoru Inomata, Wataru Yamada, and Yasushi Takatori

Abstract

Before frequencies are allocated to new wireless communication systems, it is important to investigate frequency sharing to avoid interference with existing systems. The International Telecommunication Union Radiocommunication Sector Study Group 3 (ITU-R SG 3) supports activities of other SGs by developing and maintaining recommendations for radiowave propagation characteristics and prediction models necessary for frequency sharing studies. This article introduces the activities of ITU-R SG 3 focused on the use of high frequency bands in new wireless communication systems such as the fifth-generation mobile communication system (5G).

Keywords: propagation, 5G, high frequency band

1. Introduction

This section explains the roles of the International Telecommunication Union Radiocommunication Sector Study Group 3 (ITU-R SG 3) pertaining to the fifth-generation mobile communication system (5G).

1.1 Structure and roles of ITU-R and ITU-R SG 3

In discussions on frequency allocation to new wireless communication systems, it is important to study frequency sharing to avoid interference with existing systems and to achieve co-existence with such systems. The scope of ITU-R SG 3 concerns propagation of radiowaves in ionized and non-ionized media and the characteristics of radio noise for the purpose of improving radiocommunication systems, as established in Resolution ITU-R 4-7 [1]. ITU-R SG 3 supports the activities of other SGs by developing and maintaining recommendations for radiowave propagation characteristics and prediction models necessary for frequency sharing studies. The structure of the ITU-R SGs is shown in **Fig. 1**. The SGs are organized from SG 1 to SG 7 (except for SG 2, which does not exist). The Radio Regulations (RR) will be revised at World Radiocommunication Conferences (WRCs) based on the study results of each SG.

SG 3 supports studies underway in other SGs by providing recommendations for radio propagation characteristics. That is to say, with the results obtained by SG 3 in examining radio propagation characteristics, the other SGs conduct frequency sharing studies, and their results lead to discussions in WRCs and revision of RR. Because the results of revising the RR affect the usage of worldwide wireless communications and may also affect domestic laws such as the Radio Act, the examination of radio propagation characteristics in SG 3 is a significant activity supporting all SGs.

As shown in Fig. 1, ITU-R SG 3 is composed of four Working Parties (WPs) that address issues

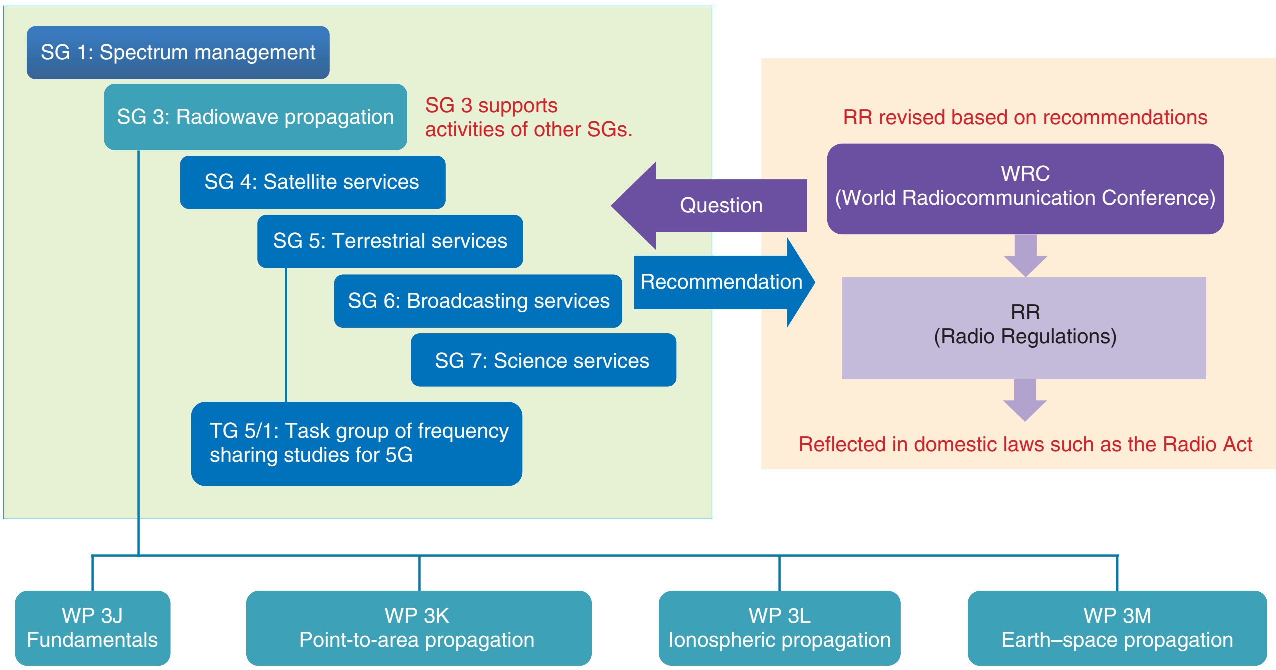


Fig. 1. Structure of ITU-R Study Groups.

concerning fundamental propagation such as rainfall effects and diffraction theory, ionosphere propagation, noise characteristics, terrestrial propagation, and satellite propagation. Although SG 3 deals only with radio propagation characteristics, its scope of study is diverse.

1.2 5G related discussion in ITU-R SG 3

ITU-R SG 3 has addressed numerous issues, but in recent years, attention has focused primarily on topics related to 5G. In discussions on the frequency allocation for 5G in WRC-19, the candidate frequency bands for the 5G era are those from 24 GHz to 86 GHz, as set in WRC-15. To study frequency sharing with existing wireless systems, Task Group 5/1 (TG 5/1) was newly established under SG 5, which is a temporary research group whose task is to identify the frequency bands to be used for 5G [2]. SG 3 received a request to provide propagation models at the relevant frequency bands that can be used for frequency sharing studies in TG 5/1, and March 31, 2017 was set as the deadline according to the activity plan of TG 5/1. Although SG 3 meetings are generally held once a year, additional meetings were scheduled to be held after the above deadline to accelerate the development of recommendations.

2. Development of recommendations for frequency sharing studies for 5G

At the additional meeting held in March 2017, the number of contribution documents from each country, the number of participants, and the number of conference sessions increased because of the importance of this meeting. With the input of information to TG 5/1, whose deadline had been set on March 31, 2017, two main topics were discussed: the development of recommendations considered to be significant in the study of frequency sharing between 5G and existing systems, and the liaison statement to be sent to TG 5/1 that summarizes the related recommendations.

In considering the frequency sharing study (interference examination) between 5G and existing systems, the participants discussed recommendations taking into account the interference with satellite stations and terrestrial stations existing in the distance, and obstruction by buildings (clutter) surrounding 5G radio stations (base stations and terminal stations).

These recommendations are depicted in **Fig. 2**. There are six main recommendations: (i) ITU-R P.[CLUTTER]: propagation loss (attenuation of radiowaves) due to clutter, which is obstruction of radiowaves by the buildings around a radio station;

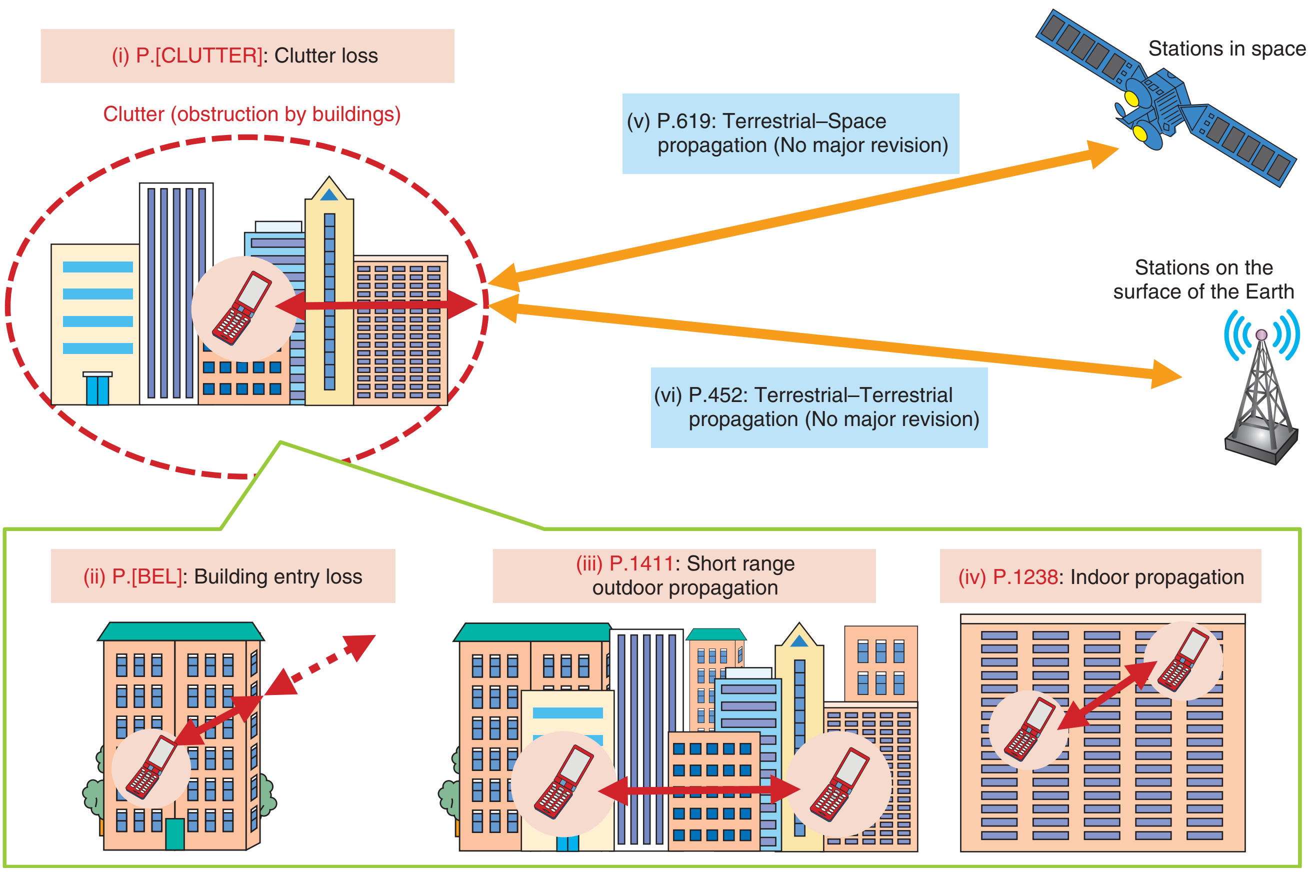


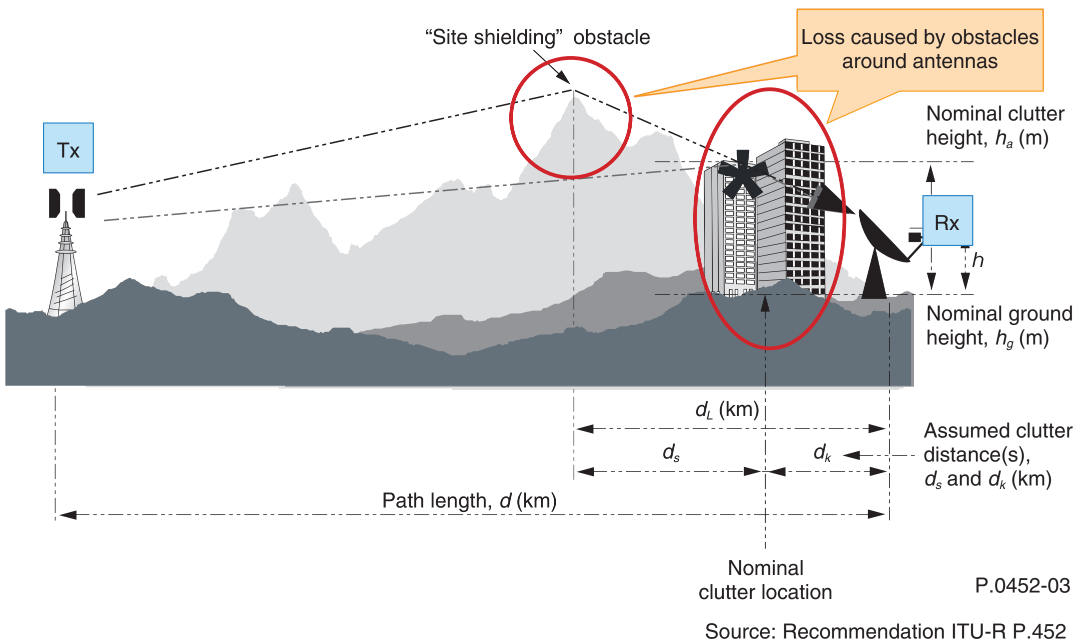
Fig. 2. ITU-R Recommendations in the liaison statement to TG 5/1 related to frequency sharing studies for 5G.

(ii) ITU-R P.[BEL]: building entry loss when radiowaves enter a building (equivalent to indoor-to-outdoor path); (iii) ITU-R P.1411: outdoor short range propagation characteristics (up to 1 km) assuming both the transmitting and receiving stations are located in nearby buildings; (iv) ITU-R P. 1238: indoor propagation characteristics assuming the case when both the transmitting and receiving stations are present in the same building; (v) ITU-R P.619: propagation characteristics between a terrestrial station and a space station; and (vi) ITU-R P.452: propagation models for predicting propagation loss between terrestrial stations.

The recommendations in (ii)–(iv) are thought to be useful for the situations where both the transmitting and receiving stations are surrounded by buildings, defined as clutter in (i). The development of recommendations (i) and (ii) progressed significantly at this meeting and were approved as new recommendations. Additionally, recommendations (iii) and (iv) were revised to cover as wide a frequency range as possible up to the 86-GHz band, which is the highest candidate frequency band for the 5G era, and the revisions were approved. There were no major revisions for (v) and (vi) from the existing recommendations. Finally, the liaison statement summarizing the details of these recommendations was approved for provision to TG 5/1. In this article, we outline the new ITU-R Recommendations (i) ITU-R P.[CLUTTER] and (ii) ITU-R P.[BEL], which were regarded as particularly important in this meeting.

2.1 New Recommendation ITU-R P.[CLUTTER]

Several ITU-R Recommendations on terrestrial radio propagation describe prediction methods that incorporate the type of propagation loss called clutter loss. Clutter loss is propagation loss caused by reflection or scattering due to terrain profiles including the presence of buildings around the antennas, as shown in **Fig. 3**. Clutter loss is a factor in many recommendations that address long range propagation such as ITU-R P.452. To evaluate the interference between



Tx: transmitter
Rx: receiver

Fig. 3. Definition of clutter loss in Recommendation ITU-R P.452.

other systems, it is necessary to consider radio stations in the distance. Therefore, it is important to utilize a prediction method that incorporates clutter loss in long range propagation. However, since the prediction methods that use clutter loss have been utilized with relatively low frequency bands such as the VHF/UHF (very high frequency and ultrahigh frequency) bands, it was unclear whether it could be expanded to the high frequency band. Therefore, it was decided to study expansion into a high frequency band and to summarize the prediction methods using clutter loss as a new Recommendation ITU-R P.[CLUTTER].

An example of clutter loss calculation in the new recommendation is shown in **Fig. 4**. The graph shows the median values of clutter loss (Y-axis) at each frequency with respect to the distance between the transmitter and receiver (X-axis); the calculation example is assumed for clutter loss between terrestrial stations. It is clear that in a short distance, the clutter losses decrease because the incident angle for the obstructing buildings becomes small. As the distance becomes longer, the incident angle can be considered constant, so the clutter losses are also a fixed value.

Such variation with respect to distance is based on the measurement results in an urban area, which were obtained by NTT Access Network Service Systems Laboratories (**Fig. 5**). The X-axis represents the path loss (propagation loss) values at each frequency, and the Y-axis is the distance between transceivers. Incidentally, the measurement results of multiple frequencies, including the high frequency bands up to 66.5 GHz and long distances up to 1 km, are a significant contribution and are the only data without reporting examples from other countries. The measurement results in Fig. 5 are also reflected in Recommendation ITU-R P.1411 (outdoor short range propagation) shown in Fig. 2, and reliable prediction formulas based on the measurements have been adopted for each recommendation.

2.2 New Recommendation ITU-R P.[BEL]

Building entry loss (BEL) is propagation loss that occurs when radiowaves enter from outside a building into the building (and also can be applied to inside-to-outside). SG 3 has been studying BEL for quite some time. Although the definition and the examples of measurement results have been summarized in ITU-R P.2040 (effects of building materials and structures) and ITU-R P.2346 (measurement data of BEL), the prediction methods (propagation models) had not yet been defined. Therefore, the urgent

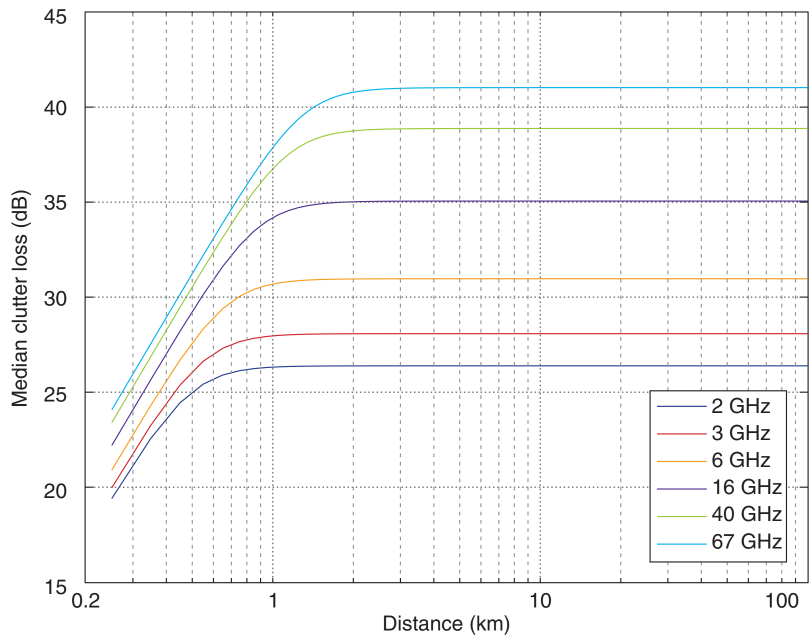


Fig. 4. Example of clutter loss calculation result in new Recommendation ITU-R P.[CLUTTER].

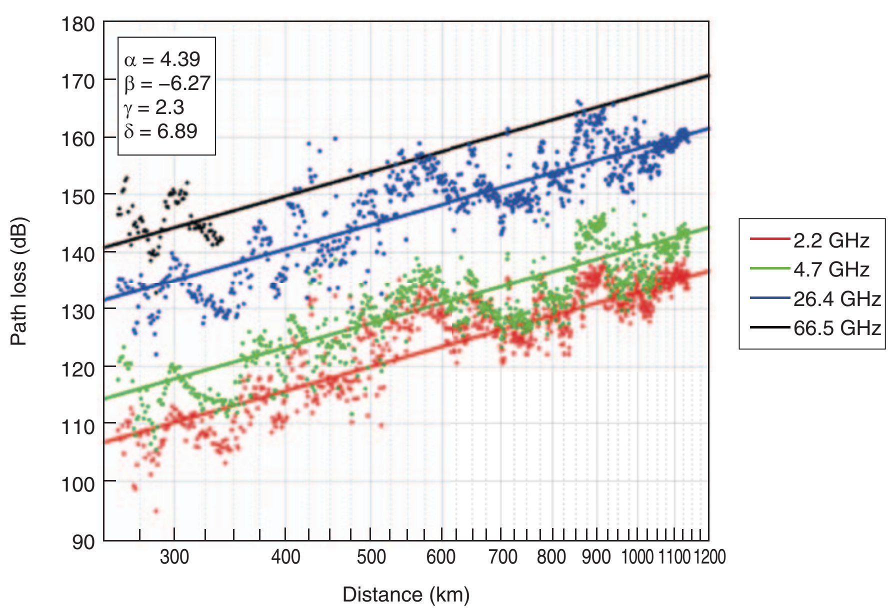


Fig. 5. Path loss measurement results from 2.2 GHz to 66.5 GHz in urban environment.

development of such a model was the goal of this meeting.

As a result, a prediction formula was summarized that considers the incident angle in the horizontal and vertical direction with respect to the building and that assumes interference with radio stations in space. BEL characteristics are greatly affected by the type of building material. For example, in modern buildings, the losses increase when windows have high thermal insulation properties. Therefore, the type of building

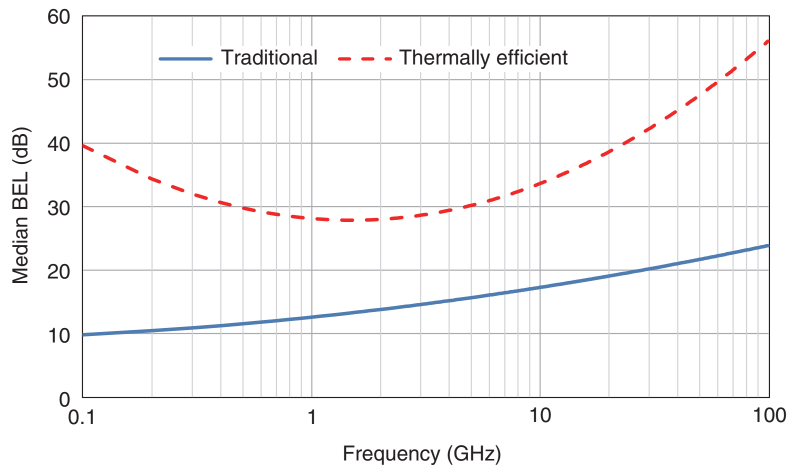


Fig. 6. BEL calculation result example in new Recommendation ITU-R P.[BEL].

was also taken into consideration in developing a propagation model.

An example of the BEL calculation results used in the new Recommendation ITU-R P.[BEL] is shown in **Fig. 6**. It shows the median values of BEL for two types of buildings (Y-axis) with respect to the frequency (X-axis). It can be seen that the loss characteristics differ greatly depending on the type of building (traditional or thermally efficient). Also, as the horizontal axis shows, the BEL values can be obtained for a wide frequency range up to 100 GHz. As with the case using clutter loss, this prediction formula was developed based on a large number of measurement results including measurement results in multiple frequency bands performed by NTT Access Network Service Systems Laboratories. The reliable results based on the measurements were adopted in the recommendation.

3. Future overview

ITU-R SG 3 studies various propagation characteristics, but the recent examinations of propagation characteristics were done mainly as part of the frequency sharing studies of candidate frequency bands for the 5G era carried out in TG 5/1. The authors contributed documents based on measurement data on a wide range of environments with multiple frequencies, including high frequency bands, and contributed to developing reliable recommendations. In addition, the authors' participation in various groups was key in promoting discussions on these topics. Dr. Wataru Yamada served as Vice-Chairperson of WP 3K and Chairman of SWG (Sub-Working Group) 3K-3, and Dr. Motoharu Sasaki served as Chairperson of DG (Drafting Group) 3K3B. To accelerate the development of various radio communication systems, including 5G, in the future, we intend to actively engage in the modeling of propagation phenomena and continue contributing to ITU-R SG 3 activities.

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Successful Field Trial of All-Raman Optical Amplification Technology for Multiband Large Capacity Transmission of 400-Gbit/s Signals in Installed Fiber—Double the Usable Bandwidth of Installed Fiber

1. Introduction

NTT recently announced that in conjunction with NTT WEST, it had successfully conducted a field trial on widely installed optical fiber cable. In this field trial, all-Raman optical amplification technology*1 was employed in transmission line repeaters, and 400-Gbit/s signals were transmitted in multiple bands at the same time. Furthermore, we confirmed through this field trial that it is possible to add signals in a new band without affecting the signals in the existing band.

The results of this field trial suggest the possibility of achieving ultralarge capacity transmission speeds of up 30 Tbit/s. These speeds, together with the ability to upgrade systems already in use, will be needed to satisfy the demands imposed by communication between datacenters. We are continuing to verify the ultimate performance limits as well as operational aspects, with the goal being to contribute to various fields that require ultralarge capacity transmission.

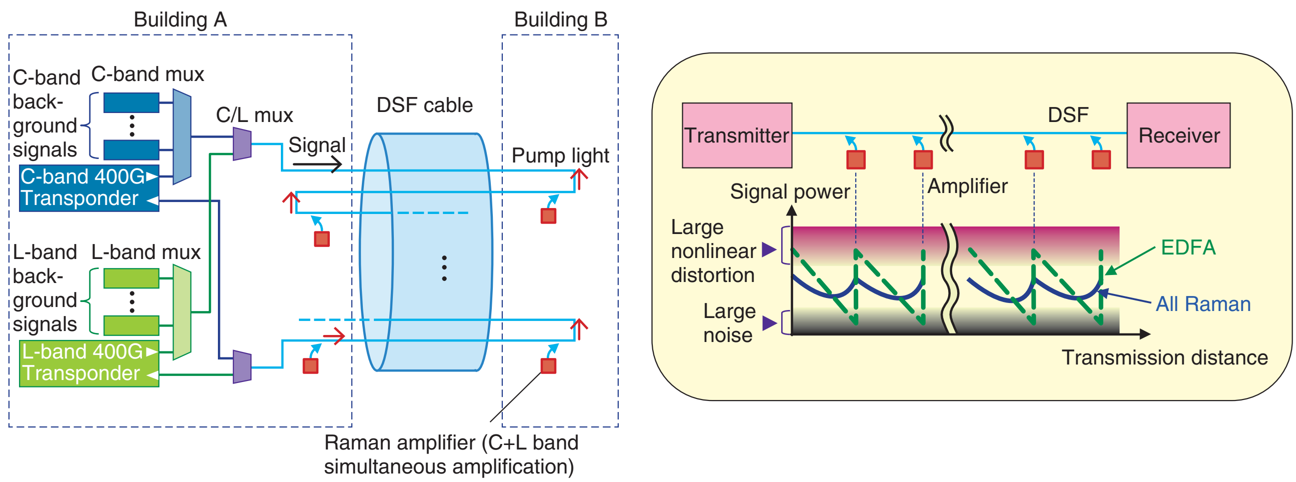
2. Background

Our vision of future communication traffic sees the widespread distribution of high-resolution images and video such as 4K/8K and full-scale popularization of machine-to-machine services. The obvious assumption is that capacity demands will skyrocket, so NTT has been actively pursuing a wide spectrum of studies into achieving ultralarge capacity transmission of signals exceeding 100 Gbit/s. Furthermore, with the recent increase in traffic between datacenters, greater capacity must be matched by greater cost savings.

Greater capacity is most directly achieved by using multiple bands (C band + L band etc.), which expands the usable bandwidth of the optical fiber. However, several problems arise if we attempt to transmit multiband signals by wavelength division multiplexing (WDM) over dispersion shifted optical fiber (DSF: dispersion shifted fiber) cable. The zero dispersion wavelength of DSF lies in the extended band (C band), and around this wavelength, the signal is degraded by nonlinear effects (especially four-wave mixing*2). The common solution, unequally spacing the signal wavelengths in the C band, degrades the wavelength utilization efficiency. This is a barrier to further capacity increases.

*1 All-Raman optical amplification technology: Raman amplifiers are a type of optical amplifier. They are based on a nonlinear effect of fiber called Raman scattering. Pump light that has a shorter wavelength than the wavelength band being used is injected into the fiber, which makes amplification in an arbitrary band possible. All-Raman optical amplification is the method of setting Raman amplifiers in all repeaters in the optical transmission line.

*2 Four-wave mixing: Four-wave mixing is a kind of nonlinear effect that occurs in optical fiber. When two or more different wavelengths of light transit a fiber, a new light with a wavelength different from any of the incident lights is generated. WDM optical transmission with equi-spaced wavelength intervals triggers four-wave mixing where the new light overlaps with the signal lights, which degrades signal quality.



Mux: multiplexer
EDFA: erbium-doped optical fiber amplifier

Fig. 1. Field trial configuration (left) and signal power image plot with all-Raman optical amplification (right).

3. Research results

Our approach involves applying all-Raman optical amplification technology in both the existing band (L band) and extended band (C band). This approach allowed us to transmit multiple 400-Gbit/s signals (each consisting of two 16-QAM (quadrature amplitude modulation) modulated signals) over 200 km of installed DSF cable with a sufficient transmission margin. The usable bandwidth is doubled by combining the existing band and the extended band (**Fig. 1**).

Because signal degradation due to four-wave mixing increases with the signal's optical power, low optical power levels are essential to suppress nonlinear effects. All-Raman optical amplifiers are superior to general EDFAs (erbium-doped optical fiber amplifiers), as they allow low signal transmission power to be used. Our approach also improves frequency utilization efficiency in the C band by equally spacing the wavelength intervals.

The use of Raman amplifiers raises safety issues because high power pump lights are used. Our field trials were designed to fully comply with IEC (International Electrotechnical Commission) standards. Furthermore, we confirmed that appropriately controlling the Raman amplifiers made it possible to add C band optical signals without altering the transmission quality of the L band signals. This confirms that capacity can be upgraded without disrupting L-band services already in use.

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External Awards

Research Award of Excellence

Winner: Muneaki Ogawa and Yoshikazu Takahashi, NTT Network Service Systems Laboratories
Date: March 2, 2017
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Information and Communication Technology for Safe and Secure Life (ICTSSL)

For "The Trends of Standardization on Emergency Communications and Future Technical Issues."
Published as: M. Ogawa and Y. Takahashi, "The Trends of Standardization on Emergency Communications and Future Technical Issues," IEICE Tech. Rep., Vol. 116, No. 92, ICTSSL2016-3, pp. 11–15, June 2016.

Achievement Award

Winner: Shoji Makino, University of Tsukuba; Hiroshi Saruwatari, The University of Tokyo; Hiroshi Sawada, NTT Communication Science Laboratories
Date: June 1, 2017
Organization: IEICE

For pioneering research on blind source separation of acoustic signals.

Achievement Award

Winner: Kunio Kashino, Hidehisa Nagano, and Takayuki Kurozumi, NTT Communication Science Laboratories
Date: June 1, 2017
Organization: IEICE

For research and development of extremely robust and fast media search technology.

ICSS Research Award

Winner: Hiroki Nakano, Yokohama National University; Fumihiro Kanei and Mitsuaki Akiyama, NTT Secure Platform Laboratories; Katsunari Yoshioka; Yokohama National University
Date: June 8, 2017
Organization: IEICE Technical Committee on Information and Communication System Security (ICSS)

For "Towards Finding Code Snippets on a Question and Answer Website Causing Mobile App Vulnerabilities."
Published as: H. Nakano, F. Kanei, M. Akiyama, and K. Yoshioka, "Towards Finding Code Snippets on a Question and Answer Website Causing Mobile App Vulnerabilities," IEICE Tech. Rep., Vol. 116, No. 522, ICSS2016-68, pp. 171–176, Mar. 2017.

Best Demo Award

Winner: Naoki Higo and Yoshiko Sueda; NTT Network Technology Laboratories; Arata Koike, Tokyo Kasei University
Date: June 13, 2017
Organization: IEEE International Symposium on Local and Metropolitan Area Networks (LANMAN) 2017

For "Cog: Overlay Network Functions Assisting Connected IoT Service Systems."
Published as: N. Higo, Y. Sueda, and A. Koike, "Cog: Overlay Network Functions Assisting Connected IoT Service Systems," Proc. of LANMAN 2017, Osaka, Japan, June 2017.

The Meritorious Award on Radio Presented by the Chairman of the Board of ARIB

Winner: Makoto Yaita, NTT Device Technology Laboratories; Yasuhiro Nakasha, Fujitsu Laboratories Ltd.; Akifumi Kasamatsu, National Institute of Information and Communications Technology
Date: June 15, 2017
Organization: Association of Radio Industries and Businesses (ARIB)

For research on terahertz wireless communications.

TTC Chairman's Prize

Winner: Kenichi Hiragi, NTT Network Service Systems Laboratories
Date: June 20, 2017
Organization: The Telecommunication Technology Committee (TTC)

For achievement of standardization progress concerning call control protocol from public switched telephone networks to IP interconnection.

Distinguished Service Award

Winner: Muneaki Ogawa, NTT Network Service Systems Laboratories
Date: June 20, 2017
Organization: TTC

For achievement of standardization progress concerning IP interconnection specifications for emergency notification systems.

Distinguished Service Award

Winner: Shoji Kimura, NTT Network Service Systems Laboratories
Date: June 20, 2017
Organization: TTC

For promoting standardization efforts concerning network operations management.

Excellent Presentation Award

Winner: Kana Eguchi, NTT Service Evolution Laboratories
Date: June 30, 2017
Organization: Information Processing Society of Japan (IPSJ) Multimedia, Distributed, Cooperative, and Mobile (DICOMO) 2017 Symposium

For "Missing R-R Interval Complement Method for Heart Rate Variability Analysis in Frequency Domain Using Wearable ECG Devices."
Published as: K. Eguchi, R. Aoki, K. Yoshida, and T. Yamada, "Missing R-R Interval Complement Method for Heart Rate Variability Analysis in Frequency Domain Using Wearable ECG Devices," Proc. of DICOMO 2017, 4G-5, pp. 888–897, Sapporo, Hokkaido, Japan, June 2017 (in Japanese).

Young Researcher Award

Winner: Asuka Nakajima, NTT Secure Platform Laboratories
Date: June 30, 2017

Organization: IPSJ DICOMO 2017 Symposium

For "Investigation of Method to Assist in Identification of Patched Part of Vulnerable Software Based on Patch Diffing."
Published as: A. Nakajima, R. Kimura, Y. Kawakoya, M. Iwamura, and T. Hariu, "Investigation of Method to Assist in Identification of Patched Part of Vulnerable Software Based on Patch Diffing," Proc. of DICOMO 2017, 4H-2, pp. 905–910, Sapporo, Hokkaido, Japan, June 2017 (in Japanese).

Young Researcher Award
Winner: Satoshi Hasegawa, NTT Secure Platform Laboratories
Date: June 30, 2017
Organization: IPSJ DICOMO 2017 Symposium

For "Implementation and Evaluation of Privacy Preserving Fisher's Exact Test for GWAS."
Published as: S. Hasegawa, K. Hamada, K. Chida, K. Misawa, S. Ogishima, and M. Nagasaki, "Implementation and Evaluation of Privacy Preserving Fisher's Exact Test for GWAS," Proc. of DICOMO 2017, 2H-3, pp. 430–437, Sapporo, Hokkaido, Japan, June 2017 (in Japanese).

Best Paper Award
Winner: Bo Sun, Waseda University; Xiapu Luo, The Hong Kong Polytechnic University; Mitsuaki Akiyama and Takuya Watanabe, NTT Secure Platform Laboratories; Tatsuya Mori, Waseda University
Date: July 6, 2017
Organization: The 2017 International Conference on Applications and Techniques in Information Security (ATIS)

For "Characterizing Promotional Attacks in Mobile App Store."
Published as: B. Sun, X. Luo, M. Akiyama, T. Watanabe, and T. Mori, "Characterizing Promotional Attacks in Mobile App Store," Applications and Techniques in Information Security—Proc. of ATIS 2017, Auckland, New Zealand, pp. 113–127, in Communications in Computer and Information Science Series, Vol. 719, Springer, 2017.

Papers Published in Technical Journals and Conference Proceedings

Topological Graph Layouts into a Triangular Prism

M. Miyauchi

Discrete and Computational Geometry and Graphs—18th Japan Conference, JCDCGG2015, Kyoto, Japan, September 14–16, 2015, Revised Selected Papers, pp. 241–246, in Lecture Notes in Computer Science, Vol. 9943, Springer, July 2016.

Prism layouts are special cases of track layouts of graphs. A triangular prism layout for graphs is a graph layout into a triangular prism that carries the vertices along the three crests between two triangles of the prism and the edges in the three rectangular surfaces such that no two edges cross in the interior of the surfaces. Also, a topological prism layout for graphs is defined so that edges are allowed to cross the crests. As for topological prism layouts, it is desirable to have good bounds on the number of edge-crossings over crests for various classes of graphs. This paper constructs two-color-edge topological triangular prism layouts for complete bipartite graphs with fewer edge-crossings over the crests than previous results.

(*d*, 3)-track Layouts of Bipartite Graph Subdivisions

M. Miyauchi

Proc. of FIT (Forum on Information Technology) 2016, Part 1, pp. 5–10, Toyama, Japan, September 2016.

A (d, k)-*track layout* of a graph G consists of a *k-track assignment* of G and an edge d-coloring of G with no monochromatic *X-crossing*. This paper studies the problem of $(d, 3)$-track layout of bipartite graph subdivisions. As for track layout, V. Dujmović and D. R. Wood showed that every graph G with n vertices has a $(d, 3)$-track subdivision of G with $2\lceil \log_d \mathrm{qn}(G)\rceil+1$ division vertices per edge, where $\mathrm{qn}(G)$ is the queue number of G. This paper improves their result for the case of bipartite graphs, and shows that for every integer $d \geq 2$, every bipartite graph $G_{m,n}$ has a $(d, 3)$-track subdivision of $G_{m,n}$ with $\lceil \log_d n\rceil-1$ division vertices per edge, where m and n are the numbers of vertices of the partite sets of $G_{m,n}$ with $m \geq n$.

Linear Predictive Coding without Yule-Walker Approximation for Transient Signal Analysis – Application to Switching Noise

F. Ishiyama, Y. Okugawa, and K. Takaya

Proc. of CSPA 2017 (13th IEEE International Colloquium on Signal Processing & its Applications), pp. 46–50, Penang, Malaysia, March 2017.

We are investigating countermeasure techniques against electric noise on telecommunication and related equipment. There are many types of electric noise, and we focus on the characterization of transient noise such as the switching noise of switching power supplies. We are developing a method of transient signal analysis based on linear predictive coding (LPC) for the purpose. Unfortunately, as standard LPC contains Yule-Walker (YW) approximation, which replaces a given time series with a periodic time series for simplification, it is not suitable for transient signal analysis. Therefore, our method of transient signal analysis does not contain YW approximation. Instead, we use the local linearization technique, which was developed in the field of quantum mechanics. Our method makes it possible to obtain instantaneous frequencies and instantaneous decay rates simultaneously with high precision from a small number of samples. We discuss our LPC method avoiding the use of YW approximation and using the local linearization technique and its application to repetitive ringing signals, which mimics the switching noise of a switching power supply, to show the efficiency of our method.

360-degree Screen-free Floating 3D Image in a Crystal Ball Using a Spatially Imaged Iris and Rotational Multiview DFD Technologies

T. Kawakami, M. Date, M. Sasai, and H. Takada

Applied Optics, Vol. 56, No. 22, pp. 6156–6167, August 2017.

A rotational multiview depth-fused 3D (DFD) display and 360-deg displaying optics using a spatially imaged iris method are proposed to realize a 360-deg 3D image. This method enables displaying clear floating images in a crystal ball. Its symmetric optics provide clear and natural 360-deg images with smooth motion parallax in horizontal and vertical directions using the directional selectivity of a spatially imaged iris method and natural 3D images of a rotational multiview DFD display.
