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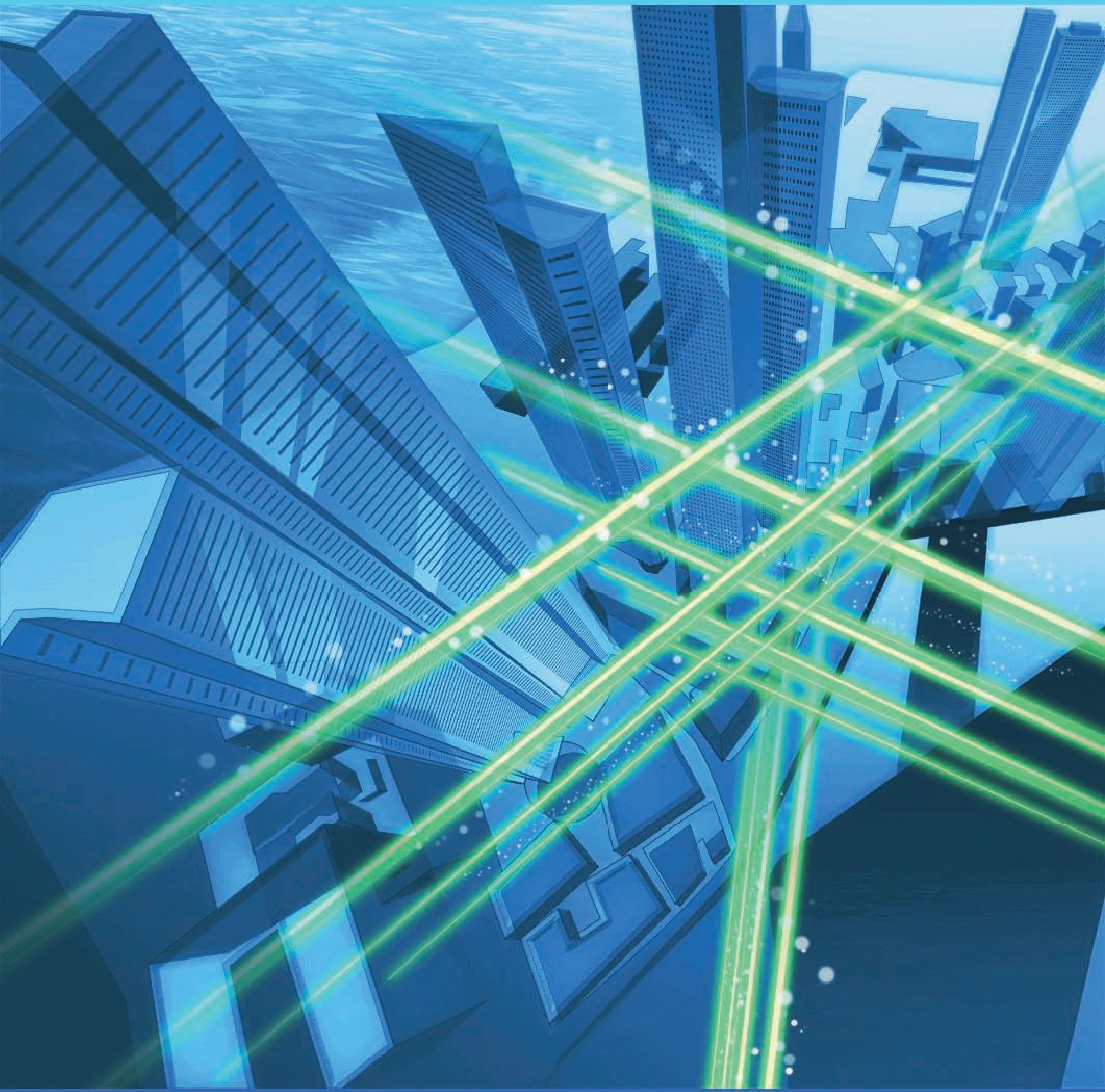

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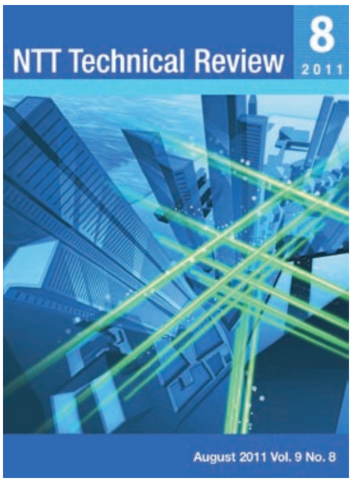

Regular Articles

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Toward Well-timed Application of Advanced Technology

Yutaka Miyamoto
Senior Distinguished Researcher
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Ultrahigh-capacity digital coherent optical transmission technology for communication networks of the broadband era builds upon past results and successful implementations in the optical communications field. With this technology, Senior Distinguished Researcher Yutaka Miyamoto aims to achieve transmission in excess of 100 Tbit/s over one strand of optical fiber. We asked him about his past experiences in this field and the key transitions that he has seen in optical communications.

Optical communications technology: increasing capacity by more than 10,000 times over the last thirty years

—Mr. Miyamoto, what kinds of technical transitions have you seen in optical communications research to date?

First of all, let me point out that NTT has constructed a highly reliable and economical communications network that multiplexes and accommodates customer information from an access network like the telephone or fiber-to-the-home (FTTH) system, transmits this information via a high-capacity optical metro-core network using artery-like optical fibers, and distributes the information to specific areas, again by an access network. Since entering NTT, I have been engaged in the research and development (R&D) of ultrahigh-speed optical communications technology for high-capacity optical trunk-transport networks analogous to the *shinkansen* (bullet train) portions of the Japanese railway system.

In Japan, full-scale research on optical fiber as a transmission medium for optical communications began in the mid-1970s. At that time, progress in increasing the bitrate of the optical transmission system was made through optical fiber and electrical time division multiplexing (ETDM) based on integrated semiconductor circuits, and the first 32-Mbit/s commercial system was deployed in 1981.

I entered NTT in 1988, and about ten years later, the first single-mode optical fiber route along the length of Japan was completed and the first gigabit-class system, featuring a bitrate of 1.6 Gbit/s over a single optical fiber, was deployed. R&D of a next-generation 10-Gbit/s transmission system then commenced at NTT Laboratories and I was assigned to that project. Up to that time, optical communications had been progressing mainly as system technology for highly reliable and economical transmission of voice calls. This was an intensity-modulated direct-detection system that achieved high-capacity communications by high-speed on/off modulation of optical intensity using one wavelength (color). Here, a capacity of 10 Gbit/s was equal to about 130,000 telephone lines or the information requirements of one Japanese rural prefecture at that time, and this capacity was expected to be sufficient to meet future demands.

However, with the coming of the Internet in the latter half of the 1990s, the situation changed radically:

it was recognized that data communications would become the dominant form of traffic on the network and that a dramatic increase in transmission capacity would be needed. Since then, optical communications R&D at NTT has brought forth a number of amazing system technologies, and today, transmission in excess of 1 Tbit/s over a single optical fiber can be achieved, which represents an increase from early bitrates of about 10,000 times.

—What is the reason for this dramatic increase in communication capacity?

Let me provide some background first. The intensity of an optical signal traveling through a transmission fiber is significantly attenuated after 100 km to as much as 1/100 to 1/1000 of the original level owing to optical-fiber loss. Thus, to maintain signal quality and achieve long-distance transmission, it was initially necessary to use optical repeaters, which convert light to electrical signals every 100 km as elements of repeater systems. However, to achieve even higher speeds with a practical intensity-modulated direct-detection system, determining how to significantly lower noise in this optical repeater became a major technical issue. In this regard, the development of the optical fiber amplifier in 1989 proved to be an epoch-making event.

The optical fiber amplifier amplifies light by using optical fiber with a core doped with rare-earth elements as an amplification medium. Despite its extremely simple structure, it can amplify input light with high efficiency, and since the amplification medium itself is optical fiber, it is highly compatible with optical fiber in the transmission path.

The erbium-doped optical fiber amplifier (EDFA) in particular can amplify light in the wavelength band where optical-fiber transmission loss is minimum (in the neighborhood of 1.55 μm). Furthermore, exciting it with short-wavelength light rather than signal light can cause energy to accumulate in the erbium, enabling the signal intensity to be increased very effectively. The EDFA can also transmit up to 100 channels (wavelengths) of information on a single optical fiber compared with only one wavelength in earlier optical communications systems. In short, the EDFA constitutes a wavelength-multiplexing system that can amplify multiple waves in a batch, enabling high-capacity transmission with very good efficiency.

The EDFA was first shown to be an effective device in 1989 and was first deployed about six years later. Its use suddenly lifted the transmission capacity of optical fiber into the 10-Gbit/s/wavelength region. Since then, systems using EDFA have undergone dramatic increases in transmission capacity as wavelength-division-multiplexing (WDM) systems that transmit information using multiple wavelengths. At present, EDFA systems with a transmission capacity of 1.6 Tbit/s per optical fiber are being put to practical use. This capacity corresponds to about 40 Gbit/s/wavelength, which is sufficient to transfer a two-hour DVD (digital versatile disc) movie in only 1 s.

As a key device that revolutionized information-communication networks, the EDFA—together with the Internet—has brought dramatic changes to the world. If EDFAs had never been developed, the advances that we have seen in broadband communications would probably have never materialized. This one innovative technology has not only altered research trends but also profoundly revolutionized the organizational structures of research laboratories around the world and the approach to system development (**Fig. 1**).

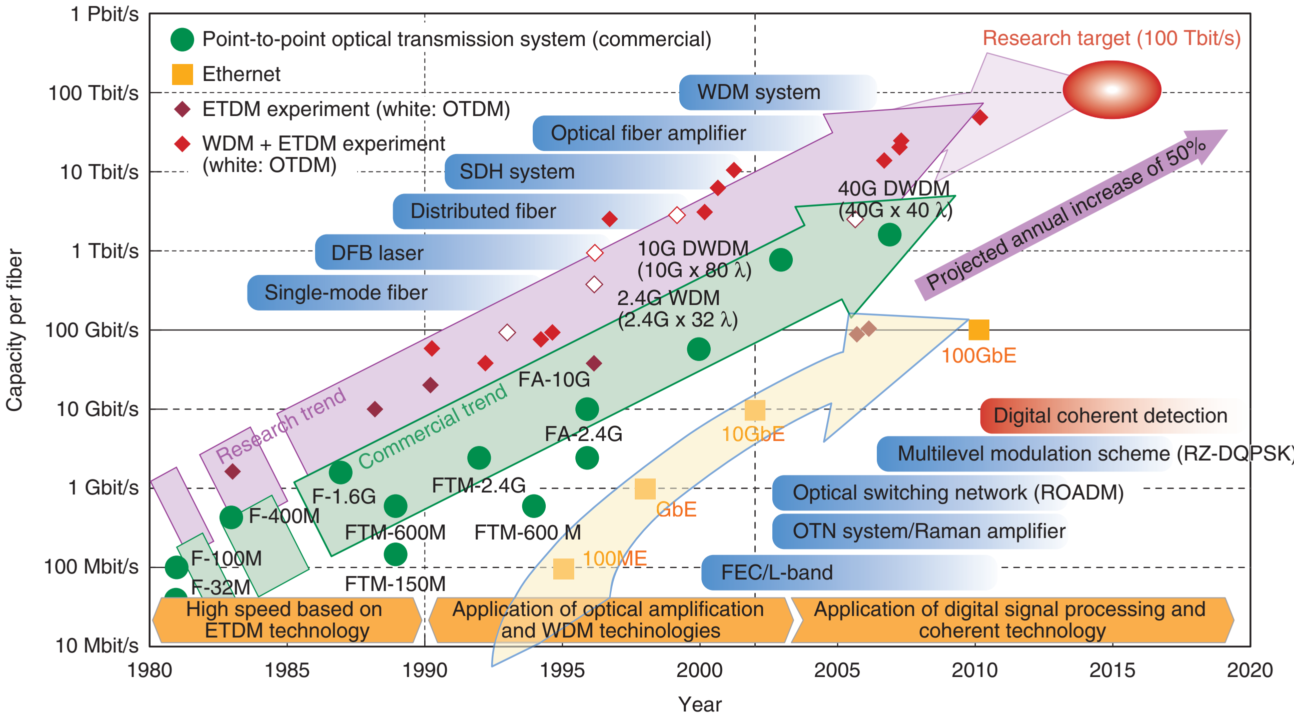
I witnessed this historical transformation brought about by the optical fiber amplifier only one year after joining NTT, and it was a revelation to me that a single technology could lead to such radical changes. Looking back, I was truly fortunate in being assigned to a project where NTT researchers worked diligently to research and develop innovative technologies and apply them to practical systems in a well-timed manner to bring something useful to society. This was a precious experience for me.

Ultrahigh-capacity digital coherent optical transmission technology: toward the 100-Tbit/s class

—Please tell us about your current research efforts.

If the current growth in data traffic continues unabated, a transmission capacity of the 100-Tbit/s class—or 100 times the current level—will be needed ten years from now. With this in mind, I'm looking to develop optical communications system technologies to support this new era in communications. This will require the development of new technologies in addition to enhancing the performance of existing technologies. In this regard, I have high expectations for ultrahigh-capacity digital coherent optical transmission technology.

Digital coherent optical transmission technology combines optical coherent transmission technology and digital signal processing. Coherent technology



100ME: 100-Mbit/s Ethernet
DFB: distributed feedback
DWDM: dense wavelength division multiplexing
F, FTM, and FA are the names of NTT systems.
FEC: forward error correction
G: Gbit/s
GbE: Gigabit (Gbit/s) Ethernet
λ: wavelengths
M: Mbit/s
ME: Megabit (Mbit/s) Ethernet
OTDM: optical time division reflectometry
OTN: Optical Transport Network
ROADM: reconfigurable optical add/drop multiplexer
RZ-DQPSK: return-to-zero differential quadrature phase key shifting
SDH: synchronous digital hierarchy
WDM: wavelength division multiplexing

Fig. 1. Trends in optical transport technologies.

achieves high-capacity transmission by using not only the intensity but also the frequency, phase, and polarization of the carrier wave used to transmit information. As in wireless technologies like mobile communications and wireless local area networks, combining coherent technology with digital signal processing can produce a jump in transmission speed and capacity.

The current high-capacity optical communications system has a transmission capacity of more than 1 Tbit/s on a single optical fiber using multiple wavelengths. Nevertheless, the range of wavelengths that an optical amplifier or repeater can handle at one time is limited and is currently equal to a bandwidth of about 4 THz. Thus, to achieve even higher capacities, we need technology that can pack even more signals into a single optical fiber. The answer is digital coherent transmission technology, which applies and expands upon signal-processing techniques used in wireless communications to raise the transmission capacity. Specifically, this technology simultaneously modulates optical intensity and phase to increase transmission capacity per wavelength in a limited frequency band and therefore improve spectrum efficiency.

In the beginning, it was thought that the application of digital coherent transmission technology could increase transmission capacity by 10 to 100 times that of current levels. This would require, however, that the throughput of the semiconductors (LSIs) used for signal processing be greater than 1 Tbit/s. Achieving such ultrahigh-speed signal processing has traditionally been difficult, but recent advances in semiconductor technology are now making it possible. At present, digital coherent transmission technology can be used to achieve stable transmission at a capacity of 100 Gbit/s per wavelength and an overall transmission capacity of about 10 Tbit/s per optical fiber. This

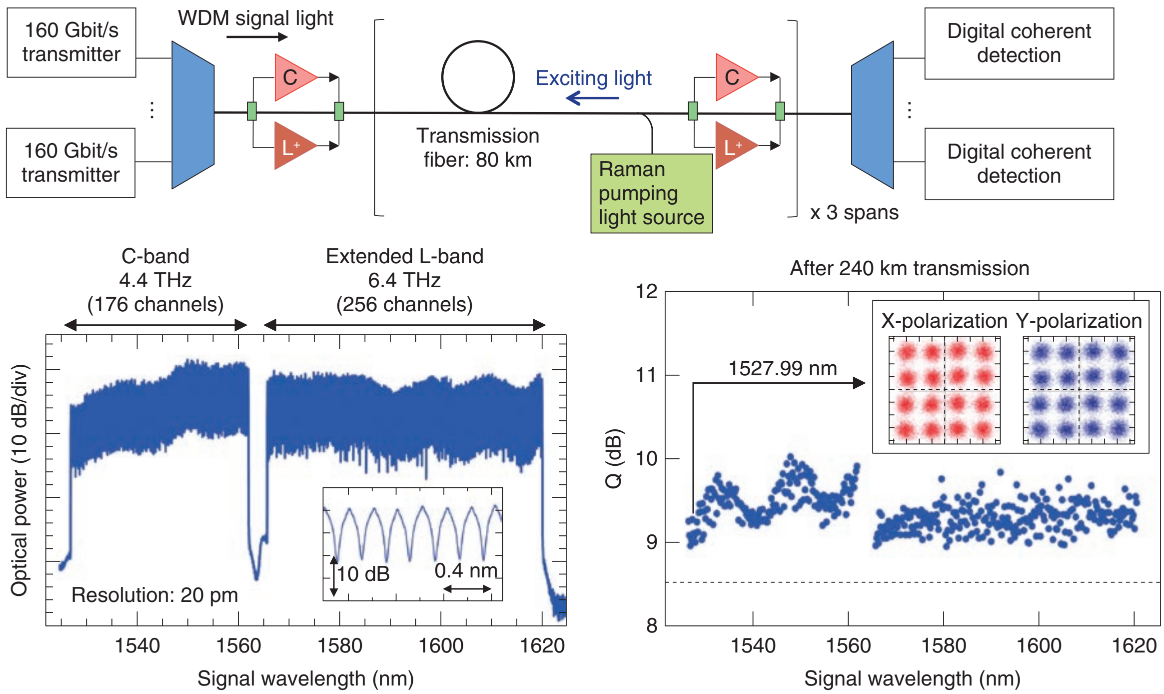


Fig. 2. 69.1-Tbit/s optical transmission experiment using polarization-division-multiplexing 16QAM (quadrature amplitude modulation) digital coherent optical modulation/demodulation technology [1].

technology is therefore maturing and approaching a practical level.

In addition, it appears that the recent development of a new technology has increased the above transmission speed by ten times in laboratory experiments, thereby bringing transmission capacity up to the 100-Tbit/s class. At NTT Laboratories, it has been about five years since we began R&D on 100-Gbit/s-class system technology, and throughout this time, our papers have regularly been selected at leading international conferences in post-deadline sessions where the latest research results compete with each other. In this way, we have been developing technology by competing head-on with other top transmission performance results (**Fig. 2**). Competition of this kind at international forums has helped us to accelerate our R&D efforts while making sure that our technology is always moving in the right direction in terms of global trends in communications system development.

Pampered generation of Japan: the electronics nation

—Your original research target was semiconductors, wasn't it? What led you to research optical fiber?

I entered NTT at the height of Japan's economic bubble, and during that time, people of my age group were called the *pampered generation*. But this pampering could not go on forever, and in time, the bubble burst, bringing an economic slowdown to Japan centered on the financial industry. Many of my fellow university students had planned to look for work in the financial industry, and several of my friends had a hard time because of this drastic change in the economy. I myself liked to make things from an early age, and as I wanted to pursue hardware-related work, I majored in fundamental semiconductor research at university. Then, seeking a field useful to society that would apply semiconductors and challenge me at the same time, I entered NTT. At that time, Japan, which was taking the world by storm with semiconductor technologies, was often called the *electronics nation,* and it was naturally expected that it would continue to develop in that direction. During that era, many NTT researchers were doing excellent work in the field of ultrahigh-speed semiconductors, and that was also a factor in my entering NTT.

At NTT Laboratories, I was assigned not to a

Photo 1. Mr. Miyamoto performs a field trial on a 10-Gbit/s optical amplifier system that originated in Tokyo not long after he joined NTT.

department that researched semiconductors themselves but to one that researched high-capacity optical communications systems making use of semiconductors. Although I had first heard about the field of optical communications systems from lectures in graduate school and found it somewhat interesting, semiconductors was still the only field I knew anything about up to then. In other words, the field of optical communications systems was a completely unknown world to me at that time. To make matters worse, my knowledge of light and optics was minimal upon entering the company, and I really wondered whether I could survive in this field. This was such a source of anxiety for me that I sometimes thought about quitting (*laughs*).

However, not long after I entered NTT, the revolutionary EDFA technology that I mentioned earlier began to recast the world of peripheral platform technologies and optical communications systems, and I was fortunate to become part of this process. Looking back to that time, I remember getting a circuit that I designed myself to run in a stable manner, enabling me to contribute, even if only slightly, to the R&D process. This experience and the feeling of accomplishment that it engendered provided me with an important foundation for my future R&D work (**Photo 1**). Later, during difficult times, I was able to continue with my research without giving up, perhaps because I also had a number of experiences of being part of a wave of major technical innovations at that time. I am also happy to see that today's digital coherent technology is also unfolding in conjunction with semiconductor technology.

—Mr. Miyamoto, could you leave us with some advice for young researchers?

I would be happy to. First, in research fields involved in systems R&D, it is very important that researchers pursue their work while imagining scenes in which technology provides something useful for society. The R&D work that we are currently pursuing ranks as an advanced field in optical communications, but it is important to achieve a balance here between fundamental and applied research so that this field does not simply become research for its own sake but produces technology with practical applications. If it shows absolutely no affinity with existing technologies, even a long-awaited technology may be unable to demonstrate its value. With this in mind, I believe that the ideal way of researching advanced technologies is to keep involved with technical issues in the real world. This is the first step toward well-timed application of advanced technology. I believe that making a contribution to society through research results that can be used in practice cannot help but make researchers feel that their work has been worthwhile.

Second, I would like young researchers to keep in mind that today's research achievements build upon the proven results achieved by our predecessors and benefit from the development of peripheral technologies. Of course, results achieved through individual efforts are also essential, but not all advanced technologies will make it simply by virtue of being advanced. In this industry, going from nothing at all to a highly competitive product is a most difficult task.

In fact, a coherent detection scheme for configuring a digital coherent system was being vigorously researched twenty years before I arrived at NTT, and this coherent detection technology was slated to be an alternative to the intensity-modulated (on/off) direct-detection system used at that time and the next big thing in optical communications technology toward ultrahigh-speed, high-capacity transmission. However, the appearance of the EDFA in 1989 dramatically raised the performance of intensity-modulated (on/off) direct detection, and the coherent technology that had been progressing up until then was put on the back-burner where it has been for about twenty years. Now, however, developments in digital signal processing technology are helping coherent technology to make a strong comeback after more than twenty years, though in a somewhat different form.

If there had been no research foundation left to us by our seniors who developed this coherent detection system, it would no doubt have been difficult for us to achieve the present WDM transmission system and the recent digital coherent system. Furthermore, these systems depend on basic technologies like high-performance semiconductor lasers and optical passive devices, and if those technologies had not been established, today's advanced results might have been difficult to obtain. What this all means is that we engage in R&D in a rich, privileged environment founded on past achievements. I would therefore like young researchers to be aware of this and appreciate it and use this knowledge to good effect in future research.

These things, however, are difficult to understand simply on the basis of a verbal explanation. Thus, as I once learned from my superiors, I would like to impress upon young researchers the importance of creating an environment that can provide hints toward the next phase of R&D. This can be accomplished by identifying the technical problems involved in the practical application of technology and participating in the process of solving those problems.

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Yutaka Miyamoto

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He received the B.E. and M.E. degrees in electrical engineering from Waseda University, Tokyo, in 1986 and 1988, respectively. In 1988, he joined NTT Transmission Systems Laboratories, Yokosuka, where he engaged in R&D of 10-Gbit/s terrestrial optical communications systems with EDFAs. His current research interests include high-capacity optical transport networks with advanced modulation formats and digital signal processing. He is a member of IEEE and a Fellow of the Institute of Electronics, Information and Communication Engineers (IEICE). He received the Best Paper Award from the IEICE Communication Society in 2003, the 23rd Kenjiro Sakurai Memorial Prize from the Optoelectronics Industry and Technology Development Association in 2007, the Achievement Award from IEICE in 2010, and the 56th Maejima Award from the Teishin Association in 2011. He became an NTT Senior Distinguished Researcher in 2011.

Ultrahigh-speed Ultrahigh-capacity Transport Network Technology for Cost-effective Core and Metro Networks

Shinji Matsuoka†

Abstract

This article introduces cost-effective highly functional ultrahigh-speed ultrahigh-capacity optical transport network technologies that use optical paths to provide safe and secure diverse services cost-effectively.

1. Introduction

The diffusion of the Internet, the penetration rate of mobile phones and smartphones, and all the services that utilize networks—such as video distribution services like YouTube, terrestrial digital television (TV), three-dimensional TV, online shopping, and e-government—have exceeded expectations for communication network services and continue to grow. These types of broadband services are supported by terrestrial and wireless communication networks: fiber to the home (FTTH) has brought the optical era to peoples homes, with subscriber contracts in Japan exceeding 20 million as of March 2011, and LTE (Long Term Evolution) enables wireless communication speeds in excess of 70 Mbit/s (as of Dec. 2010). High-speed high-capacity transport technology has contributed greatly in the configuration of these communication networks by cost-effectively accommodating the vigorous 1.5-fold annual increase in traffic. The technological trends in transport technologies to date are shown in **Fig. 1**.

Transport networks are generally classified into three types: core networks connect major cities throughout the country, metro networks connect major areas within prefectures, and access networks provide connections to subscribers. In particular, there is a need to connect core and metro networks using high-speed signals, and we have constructed cost-effective transport networks based on cutting-edge optical transport network technology such as high-speed transmission technology. At present, there are cost-effective low-power consuming systems such as the 1.6-Tbit/s dense wavelength division multiplexer (DWDM)*1 transmission system [1] that multiplexes 40 wavelengths each carrying a 40-Gbit/s signal and the 800-Gbit/s (10 Gbit/s × 80 wavelengths) reconfigurable optical add/drop multiplexer (ROADM)*2 transmission system that is used to construct 10-Gbit/s optical signal add/drop optical ring networks. However, as shown in **Fig. 2**, even these systems will have difficulty in the future in dealing with the boom in traffic volume, so even-more-cost-effective low-power-consuming optical transport network technology will be in demand. NTT Innovation Laboratories is vigorously pursuing the research

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*1 DWDM: One type of communication technology that uses optical fiber. This scheme achieves multiplexing in an optical fiber by simultaneously using multiple optical signals that have different wavelengths.

*2 ROADM: A combination of a wavelength multiplexing scheme and path management technology that is applied for efficient utilization of ultrahigh-speed high-capacity transmission networks.

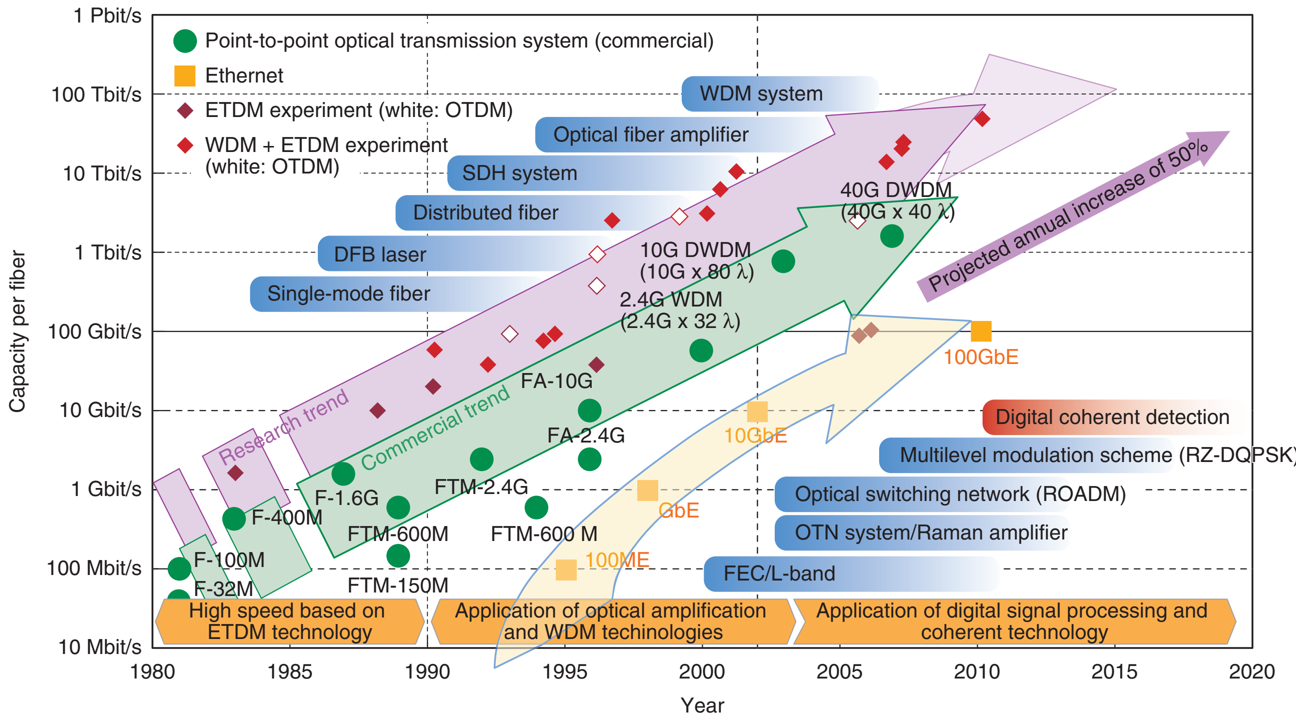

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Fig. 1. Trends in optical transport technologies.

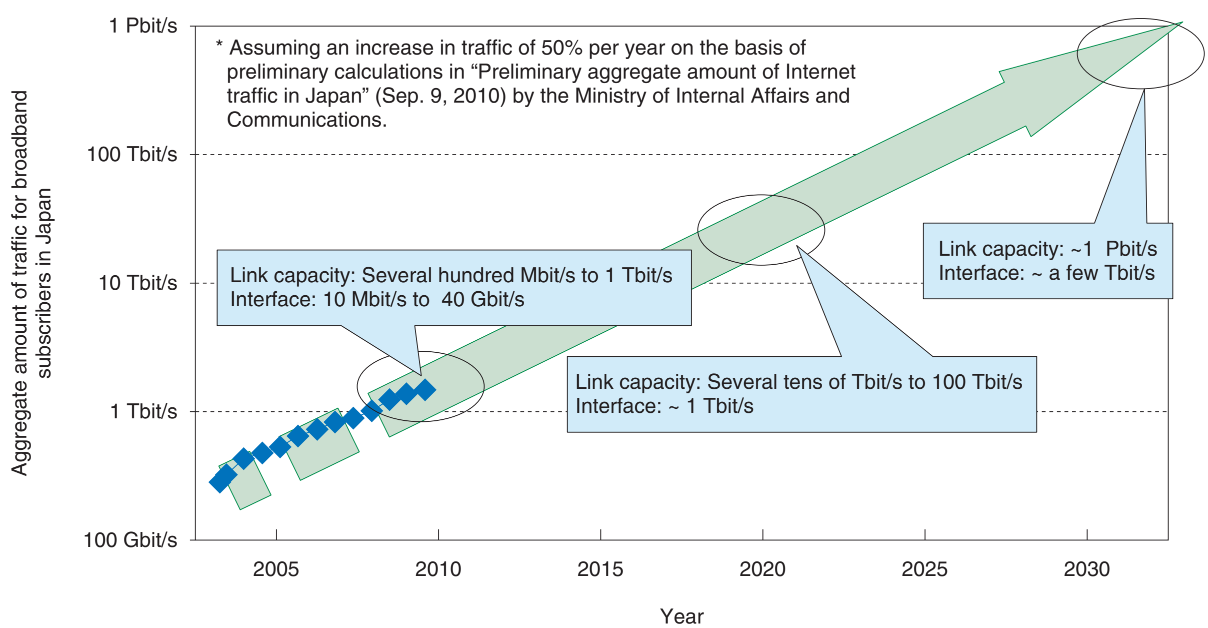

Fig. 2. Current and predicted traffic demands.

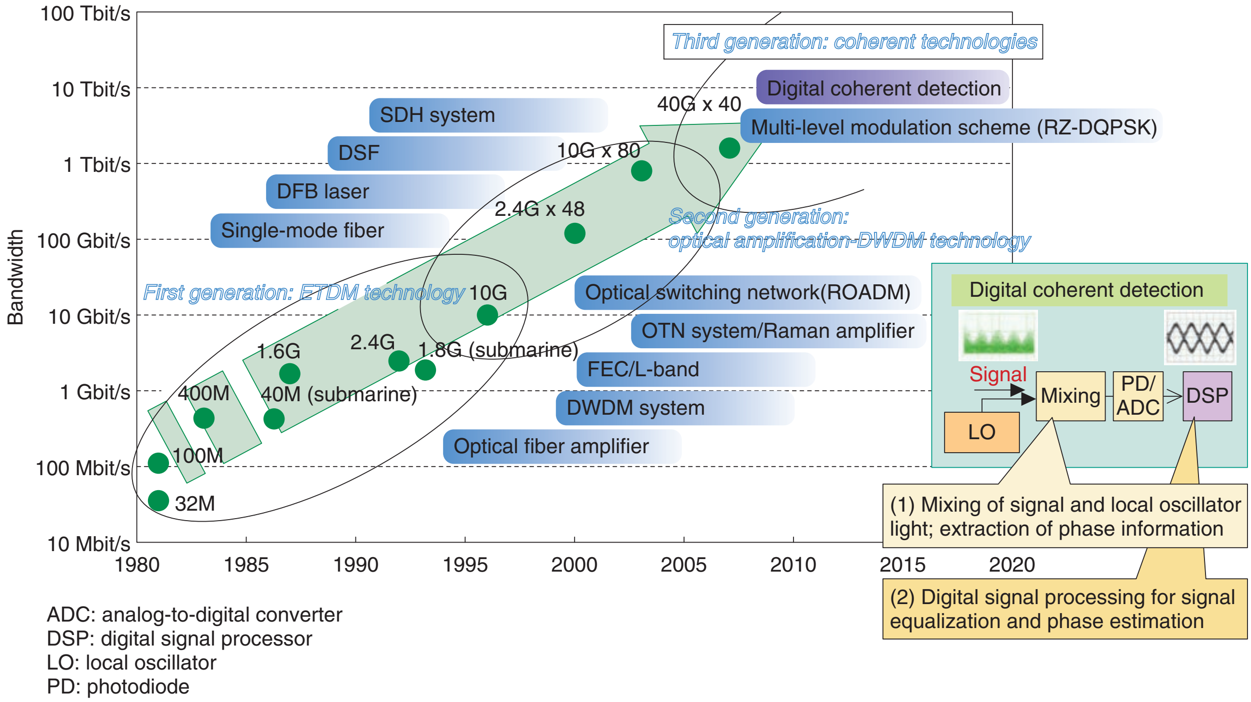

Fig. 3. Evolution of main technologies for photonic systems.

and development (R&D) of optical transport networks with the goal of making cost-effective core and metro networks [2].

This article introduces the next-generation optical transport network technology, summarizing component technologies, discussing standardization trends, and clarifying R&D targets. It also introduces some future optical transport technologies for ten to twenty years ahead.

2. Latest technological trends in ultrahigh-speed high-capacity optical transport

Optical technology has been part of communication networks for nearly thirty years, and during this time there have been striking advances in optical network technology such as a 10^4-times increase in transmission capacity and an over-10^6-times increase in the product of signal bandwidth and transmission distance, which are transmission technology indicators. There have been several important eras or generations for these pioneering technologies. The first generation focused on electrical time division multiplexing (ETDM)*3 technology, the second focused on optical amplification technology such as the erbium-doped fiber amplifier (EDFA)*4 and DWDM technology, and the third (current) generation focuses on coherent detection technology, which utilizes wave properties and is widely utilized in wireless networks (**Fig. 3**). In particular, the fusion of digital signal processing technology and coherent detection technology will be a primary approach to supporting optical communications in the future, and R&D of this is being eagerly promoted by major research organizations. This transport technology achieves a higher signal-to-noise ratio (SNR)*5 than existing technologies, uses multilevel modulation such as quadrature phase shift keying (QPSK)*6 in the optical phase, quadrature amplitude modulation (QAM)*7, and polarization-division multiplexing in ultrahigh-capacity transmission that has not been available up to now. Furthermore,

*3 ETDM: A digital multiplexing technology that bundles multiple lines into one shared line.

*4 EDFA: An optical amplifier in which erbium ions are added to the optical fiber core. It is mainly used for DWDM optical amplification.

*5 SNR: Represents the ratio of the signal level to the noise level. If the SNR is high, then the influence of the transmission noise is low.

*6 QPSK: A multilevel modulation scheme in which two bits are transmitted per symbol and the phases of four carrier waves are made to correspond to four values.

*7 QAM: A digital modulation scheme used in wireless communications.

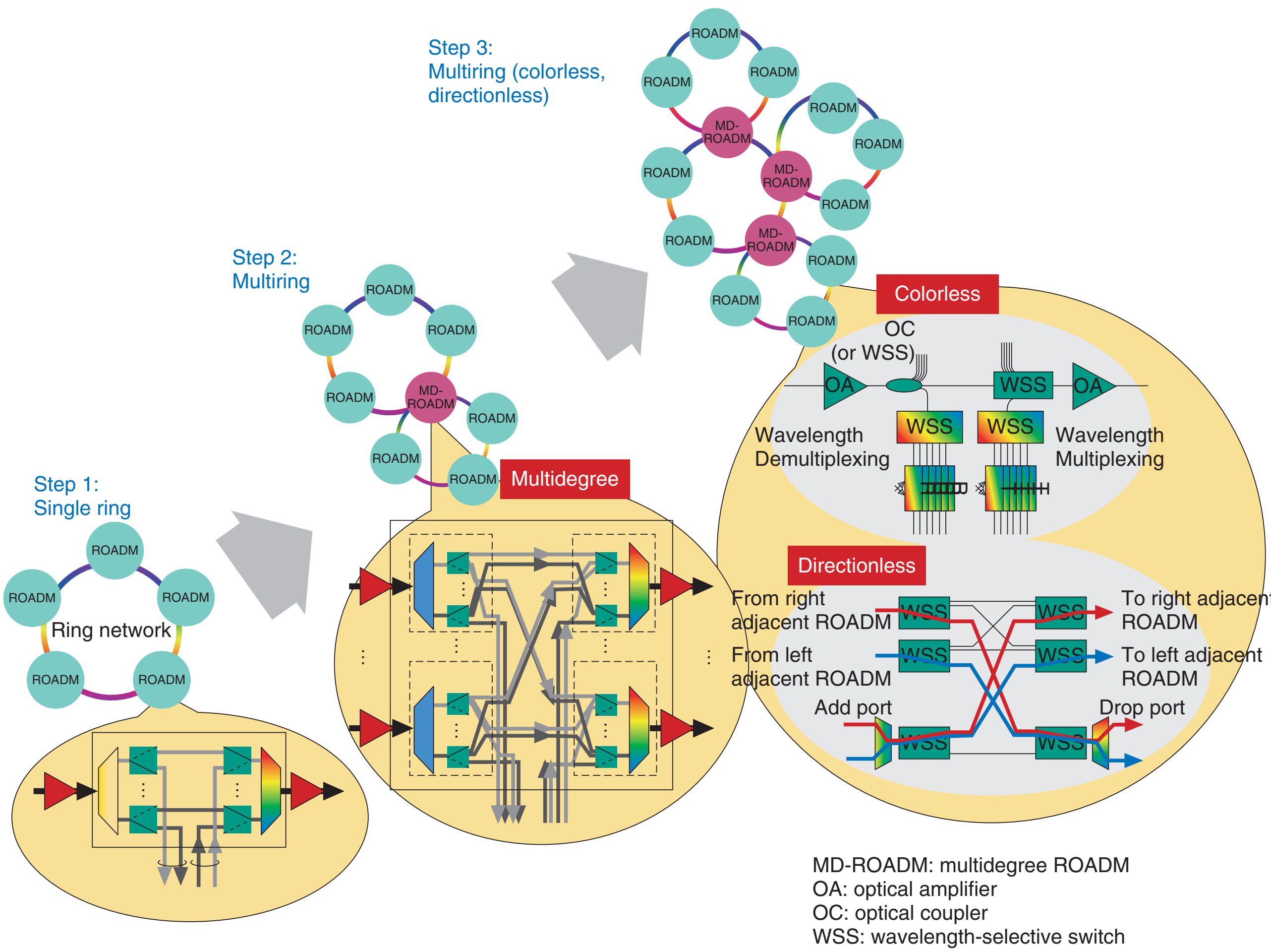

Fig. 4. Development of optical ring system.

the linear distortion created by chromatic dispersion and polarization-mode dispersion generated from optical fibers in the transmission path can be compensated for. Other major advantages are that it makes possible long-distance transmission and eliminates the need for the additional optical dispersion compensation fiber used for dispersion compensation between links; instead, compensation can be performed on the receiver side even when the transmission path is changed drastically. The NTT Science and Core Technology Laboratory Group, together with major domestic vendors, has conducted studies in a project supported by the Ministry of Internal Affairs and Communications to accelerate R&D of digital coherent technology in particular [3].

3. Optical transport network node technology and high-efficiency networking

With the progress in digital coherent detection technology and other technologies, improved long-distance transmission of ultrahigh-speed signals is possible and as the optical domain widens, efficient design and operation at the optical level will become important. The progress in the optical transport network architecture is shown in **Fig. 4**. In the ring networks that form the foundation of the metro and core domains, the current ROADM transmission systems are mainly based on a single optical ring system. The expansion of the ROADM optical switch scale enables multiple rings to be connected at the optical level, and optical signal transmission without optical-electrical-optical regeneration can be achieved cost-effectively (**Fig. 5**). In addition, by devising optical

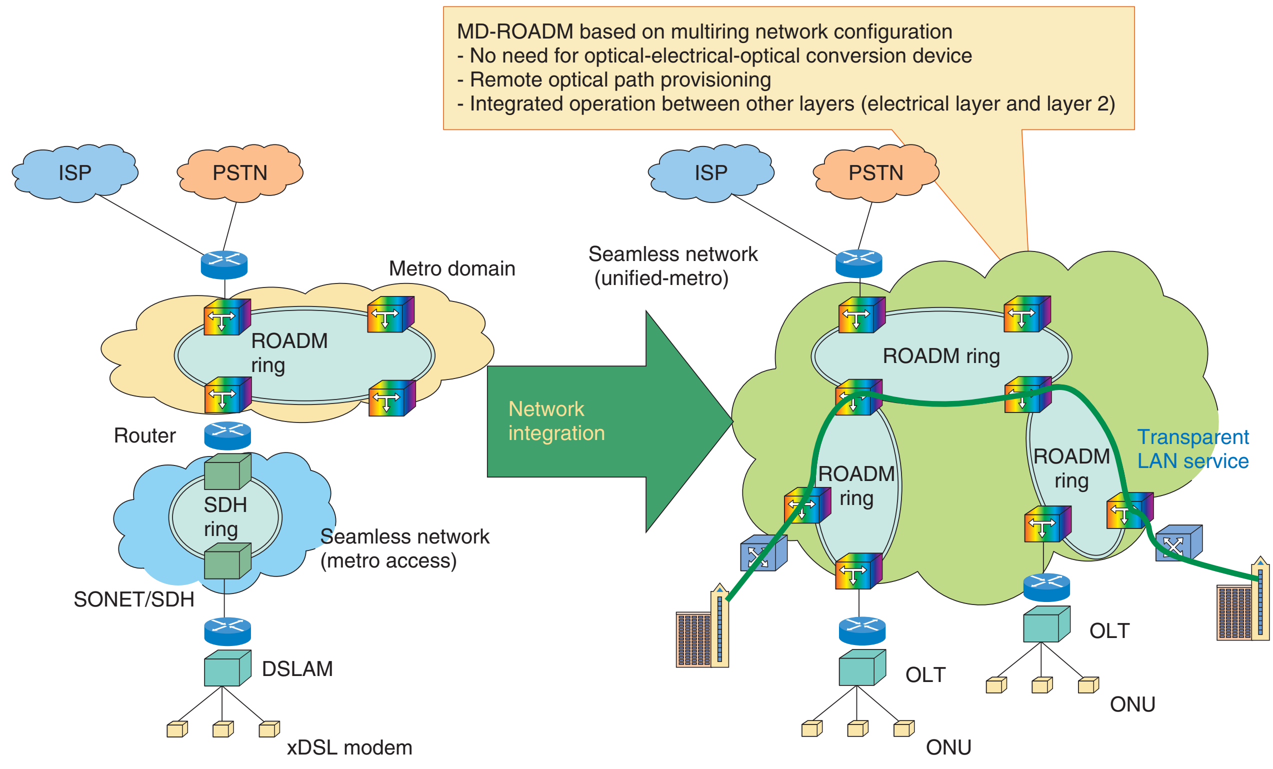

Fig. 5. Ring-based seamless network based on optical networking.

switches such as wavelength selective switches, we can achieve colorless and directionless capabilities that remove the need for us to be concerned with color (wavelength). Optical networking enhancement at the optical level can be advanced as shown in Fig. 5.

Strengthening of the relationship between optical and electrical paths will become important in enhancing transport networking overall as the optical domain expands. There is demand for transport networks to be improved and diversified to handle datacenters that support ultrahigh-speed services in major metropolitan areas, ultrahigh-speed mobile backhaul for LTE etc., aggregation of low-to-medium-scale traffic in rural areas, and migration of the current telephone networks, etc. For this reason, by making appropriate use (integration between layers) of the three transport layers (i.e., the optical path layer incorporating multidirectional paths, the high-capacity electrical optical-channel data unit (ODU) path layer in the Optical Transport Network (OTN), and the MPLS-TP*8 (multiprotocol label switching transport profile) path layer), according to the network scale, we can expect to create highly cost-effective transport networks. Furthermore, the role of transport networking in future progress for the base network for cloud networking will be beneficial.

4. Role of standardization toward actualizing optical transport networks

In the progress of globalization in the field of optical communications, standardization for the global market is essential for the construction of cost-effective systems as well as for technological innovations. Standardization bodies such as ITU-T (International

*8 MPLS-TP: Part of the functionality of MPLS that was diversified and added as an optimization of requirements to actualize the quality level required by telecommunications carriers.

Telecommunication Union, Telecommunication Standardization Sector), IEEE, and OIF (Optical Internetworking Forum) need to discuss actively and popularize optical transport network technologies such as OTN technology, which efficiently conveys broadband services and various information data uniformly accommodated in optical channels, high-speed Ethernet technology that supports high-speed IP (Internet protocol) network services, and representative network control technologies such as GMPLS (generalized multiprotocol label switching)*9, which utilizes the network efficiently.

5. Future optical transport network technology

At the practical stage, we currently have 10-Tbit/s-per-fiber-class systems utilizing 100-Gbit/s signal processing technology, but at the research level, studies on 100-Tbit/s/fiber-class systems are fruitful. In March 2010, a world record was established for 69.1-Tbit/s transmission per fiber using multilevel modulation and polarization multiplexing [4]. Within ten years, we may expect to see a practical 100-Tbit/s/fiber-class system utilizing existing optical fiber. However, to achieve even higher speeds and capacities, we will need innovative optical transport network technology to overcome the limitations on existing technologies, namely the Shannon limit*10, noise figure limit, shot noise limit*11, and power limits (both optical and electrical). The amount of power injected into a fiber should be limited for safe transmission in legacy optical fiber already installed around the world, so a total per-fiber capacity of more than 100 Tbit/s, in the case of long-distance transmission, is probably impossible to achieve for some time. Research on innovative forms of optical fiber, such as multimode fibers and multicore fibers in which the nonlinear effect can be controlled even when the optical input power is high, will accelerate [5] along with research on multiplexing and modulation technologies.

On the other hand, in pursuit of a transport technology that can support the explosive growth in traffic demand, we are starting a new investigation initiative to fully utilize the efficiency of the optical spectral resources in optical fibers in transport networks. Until recently, the bandwidth of optical fiber was thought to be practically infinite, and the transmitted signal is allocated at specified locations (frequency grid). However, research has begun on an *elastic optical path network* [6] in which the required amount of optical spectral resources is assigned at the time they are needed. By using an OFDM (orthogonal frequency division multiplexing)*12 bandwidth-variable transponder and a switch that flexibly modifies the bandwidth, we can assign the required and minimum optical spectral resources to transmit data and achieve much more cost-effective transport networks.

6. Summary

Optical transport networks should be significantly changed from existing telephone-based networks because of the rapid establishment of broadband service following the spread of the Internet and the appearance of high-speed mobile communications such as LTE. NTT is supporting these changes through digital coherent technology, which is representative of new optical transmission technologies, optical transparent network node technology of optical multiring systems, multilayer management control technology that extends over multiple layers, and the standardization needed for economization. Furthermore, transport networking will play a beneficial role in future advancement of the trunk network for cloud networking.

This set of five Feature Articles introduces ultrahigh-speed ultrahigh-capacity optical transport network technologies that will lead to future cost-effective ultrahigh-capacity networks. The other four articles cover ultrahigh-capacity digital coherent optical transmission technology, optical transparent network node technology, highly efficient photonic networking technology, international standardization and implementation technology for optical transport networks, and future innovative optical transport network technology.

We expect the development of these system technologies and photonic device technologies to lead to the construction of safer, more secure, and more

*9 GMPLS: A generalized form of MPLS defined to support data transmission based on packet-layer labels. The label concept for GMPLS is generalized and expanded to make it applicable to the time-division multiplexing layer, optical path layer, and lower layers.

*10 Shannon limit: The maximum transmission capacity beyond which data transmission speed cannot be increased. It is determined by the SNR and frequency bandwidth of a communications channel.

*11 Shot noise limit: A type of electrical circuit noise. The shot noise limit is expressed as the average values of light intensity and electrical current, which increase in proportion to each other.

*12 OFDM: A digital modulation scheme used in wireless communications.

pleasant communication networks.

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Ultrahigh-capacity Digital Coherent Optical Transmission Technology

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Abstract

In this article, we introduce the current progress in ultrahigh-capacity digital coherent optical transmission technology that will support future broadband networks. It enables great improvements in optical transmission performance through the use of ultrahigh-speed digital signal processing and will lead to capacities exceeding 10 Tbit/s per optical fiber.

1. Introduction

Digital coherent optical transmission technology is a key technology that can greatly improve the transmission performance of optical fiber by incorporating ultrahigh-speed digital signal processing (DSP) into optical communications. In the Optical Transport Network (OTN), various client signals such as those of 40G and 100G Ethernet (40GbE and 100GbE; G denotes Gbit/s) are accommodated in an ultrahigh-speed optical channel at the line rate of 112 Gbit/s per wavelength. As a result, highly reliable long-distance high-capacity transmission is achieved.

2. High-capacity optical networks based on ultrahigh-speed channel transmission technology

In the future OTN, 10-Tbit/s-class optical networks will be achieved using 100G optical channels with a frequency spacing of 50 GHz [1] (**Fig. 1**). Furthermore, by using optical switches having multidegree reconfigurable optical add/drop multiplexers (ROADMs) in intermediate optical nodes, it is possible to enhance the scalability of optical networks significantly. In 2006, we successfully conducted a 14-Tbit/s wavelength division multiplexing (WDM) transmission experiment that demonstrated for the first time the feasibility of a 10-Tbit/s-class OTN, in which 100-Gbit/s-class optical channels can transparently transport 100GE signals. We used polarization-division-multiplexed return-to-zero differential-quadrature-phase-shift-keying direct detection (PDM-RZ-DQPSK-DD) systems [2]. In order to achieve highly reliable 100-Gbit/s-channel-based high-capacity systems having backward compatibility with existing systems, the following technological issues must be resolved.

- Improve the signal-to-noise ratio (SNR) and spectral efficiency (SE)
- Improve chromatic dispersion (CD) tolerance and polarization mode dispersion (PMD) tolerance
- Improve the tolerance to spectral filtering induced by the optical nodes
- Improve optical fiber nonlinear tolerance

For increased transmission capacity, multilevel modulation formats are attractive for enhancing the SE, the same as in wireless communications. However, when considering a multilevel format with the number of levels m equal to or higher than 4, as shown in **Fig. 2**, we must increase the total system SNR to achieve the same regenerative repeater spacing. This is because the required SNR of a higher-level multilevel format (m>4) is higher than that of QPSK (m=4). For this purpose, it is promising to combine new multiplexing/demultiplexing schemes such as PDM and OFDM (orthogonal frequency division multiplexing) with a multilevel format to enhance both the SNR and SE simultaneously.

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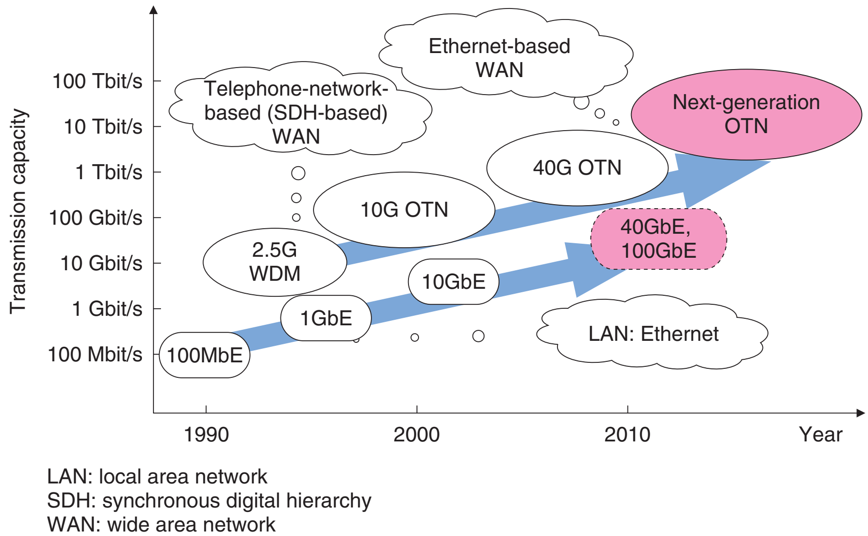

Fig. 1. Progress in optical networks.

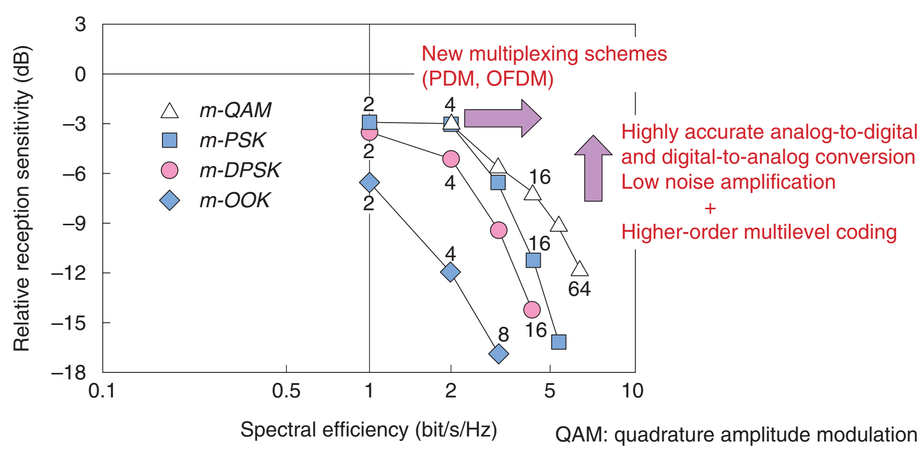

Fig. 2. Tradeoff for multilevel coding.

3. Digital coherent optical transmission technology: overview and advantages

Introducing digital signal processing to optical communications provides three main advantages.

(1) Coherent detection enables a high-sensitivity receiver that utilizes the frequency and phase of an optical carrier signal. Long-haul transmission can be achieved, since a 3-dB improvement in the SNR can be achieved compared with conventional intensity modulation direct detection.

(2) Powerful digital equalization of the linear waveform distortion caused by CD and PMD has been achieved by using DSP; such strong equalization cannot be used in conventional receivers. This feature greatly simplifies the operation and configuration of optical amplifier repeater systems.

(3) DSP-aided highly reliable PDM can be introduced into high-capacity optical transmission systems, and the SE can be improved by more than two fold compared with conventional systems.

The relationship between the optical signal trans-

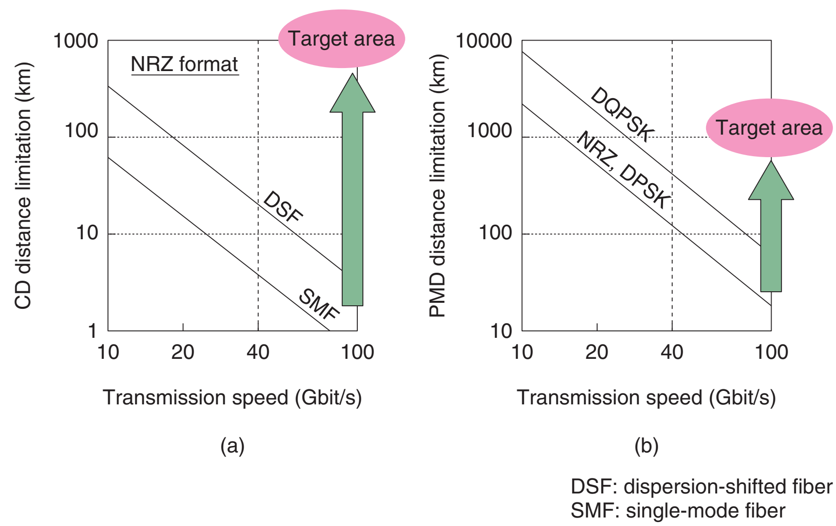

Fig. 3. Digital coherent technology based on mitigating the CD and PMD transmission distance limitations.

mission speed and the transmission distance limited by CD and PMD is shown in **Fig. 3**. The CD limit is caused by waveform distortion originating from the group velocity dispersion of the optical frequency, and the achievable transmission distance decreases in inverse proportion to the square of the data bitrate. For example, as shown in Fig. 3(a), in the case of the typical binary non-return-to-zero (NRZ) intensity modulation format, the transmission distance is limited to less than 10 km at a data rate of 100 Gbit/s. PMD is closely related to the birefringence caused by the anisotropy of the core diameter during the manufacturing process and the stress imposed during the installation and operation of fiber cables. There are two independent states of signal polarization in the fiber in the presence of PMD. Their signal propagation delays (differential group delays (DGDs)) are slightly different from each other and they vary with time. Therefore, owing to the fluctuation of the incident signal polarization and DGD, the waveform distortion has dynamic characteristics. Such dynamic waveform distortion is dominant at transmission speeds higher than 40 Gbit/s. To mitigate these issues, RZ-DQPSK-DD was used in a 40-Gbit/s-channel WDM system, where the PMD tolerance was enhanced and the SE was improved to 0.4 bit/s/Hz compared with that for binary code. A 1.6-Tbit/s-per-fiber transmission system with a regenerative repeater spacing of more than 500 km has been implemented [3].

At data rates over 100 Gbit/s, however, the PMD-limited transmission distance is less than 100 km, even if RZ-DQPSK-DD is used, as shown in Fig. 3(b). As a promising candidate for overcoming this limitation, DSP-aided coherent detection systems (i.e., digital coherent systems) have recently attracted much attention. Digital coherent systems fully utilize previously unused properties of the optical signal, such as phase, frequency, and polarization. By adaptively mitigating waveform distortions caused by CD and PMD, a regenerative repeater spacing of greater than 1000 km is expected in long-distance transmission with capacities higher than 10 Tbit/s per fiber core.

The basic configuration is shown in **Fig. 4**. In the coherent optical communications scheme, wireless homodyne detection*1 and heterodyne detection*2 are performed similarly, and a local oscillator (LO) is provided in the receiver. The received optical signal and its beat signal are converted into baseband or intermediate-frequency-band electrical signals and the received equalized waveform is regenerated. Since these detection schemes enable highly sensitive detection and large CD/PMD compensation in an

*1 Homodyne detection: A high-sensitivity coherent detection scheme based on using the interference generated when the optical carrier wave frequency and local light frequency are equal.

*2 Heterodyne detection: A high-sensitivity coherent detection scheme that allows the signal light to interfere with local light of a different optical frequency from the signal light and then converts the optical signal and its beat signal into intermediate-frequency-band electrical signals.

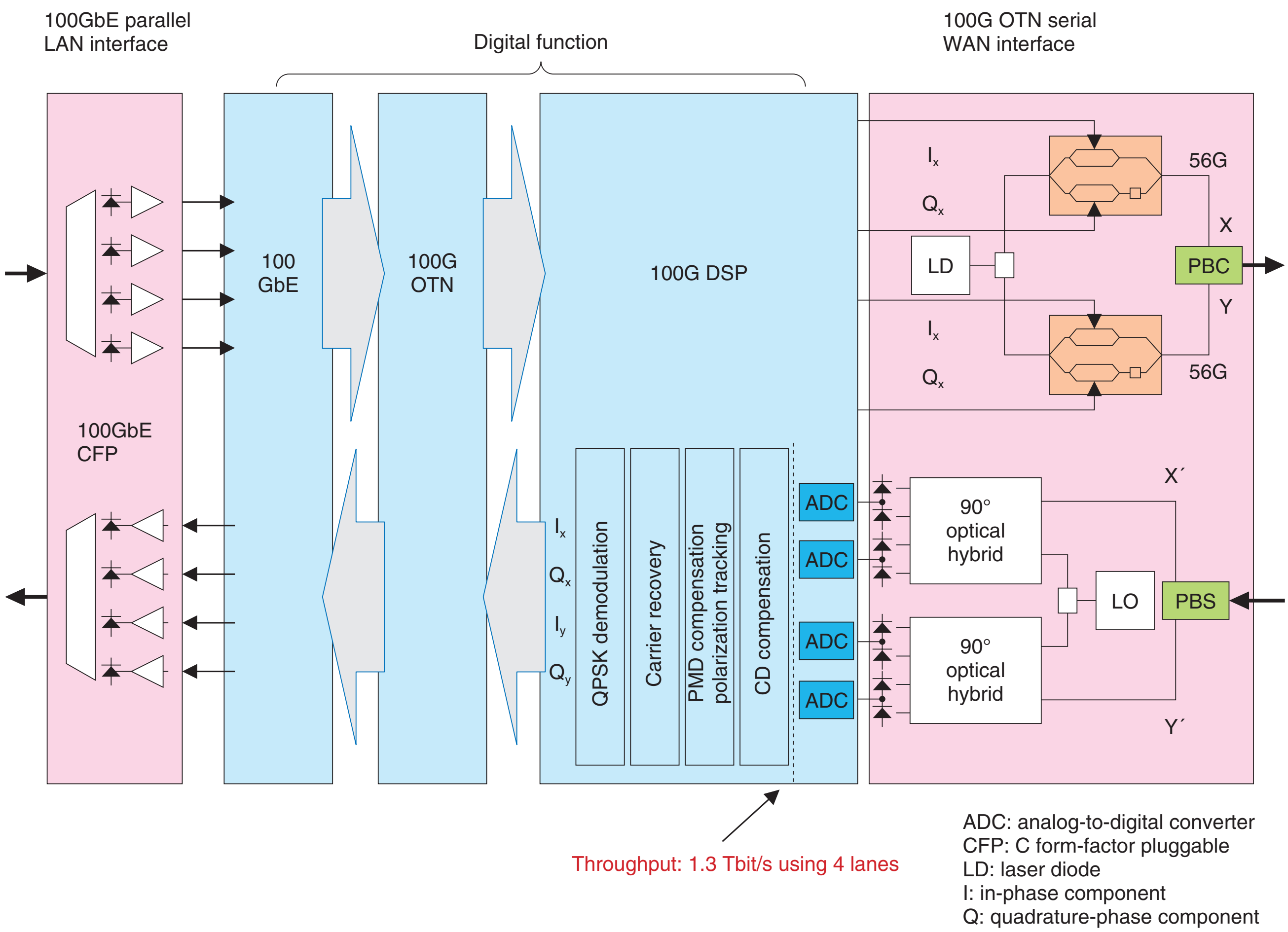

Fig. 4. Configuration example of digital coherent optical transmission technology using repeater configuration.

electrical intermediate frequency band, these technologies were actively investigated up to approximately twenty years ago. However, at that time, there were significant issues with the conventional coherent optical communications systems: (1) the physical synchronization of the frequency and phase between the received signal and LO light and (2) the polarization tracking at the optical level. The introduction of a digital signal processor (DSP) at the coherent receiver enables high-speed electrical synchronization between the receiver signal and the LO, so high-speed polarization tracking can be performed in real time in the digital domain. Since the adaptive digital filter in the DSP compensates for the dynamic waveform distortion due to CD and PMD through the optical fiber, we can greatly improve the distance limit in ultrahigh-speed signal transmission at a data rate of 100 Gbit/s.

4. Component technologies for digital coherent optical transmission

One critical issue in achieving the abovementioned digital coherent transmission is achieving DSP with high-speed analog-to-digital (A/D) and digital-to-analog conversion. Let us consider the PDM-QPSK format as an example for a 112-Gbit/s digital coherent system. The 112-Gbit/s PDM-QPSK signal consists of two polarization components, on the X and Y axes, and each polarization signal is independently modulated by 56-Gbit/s QPSK by using a nested Mach-Zehnder modulator (MZM). As a result, the symbol rate is 28 Gsymbol/s.

At the transmitter, the signal is transmitted as a QPSK optical signal, which uses the same modulator configuration as in the DQPSK-DD system. Independently modulated 56-Gbit/s QPSK signals are polarization multiplexed using a polarization beam

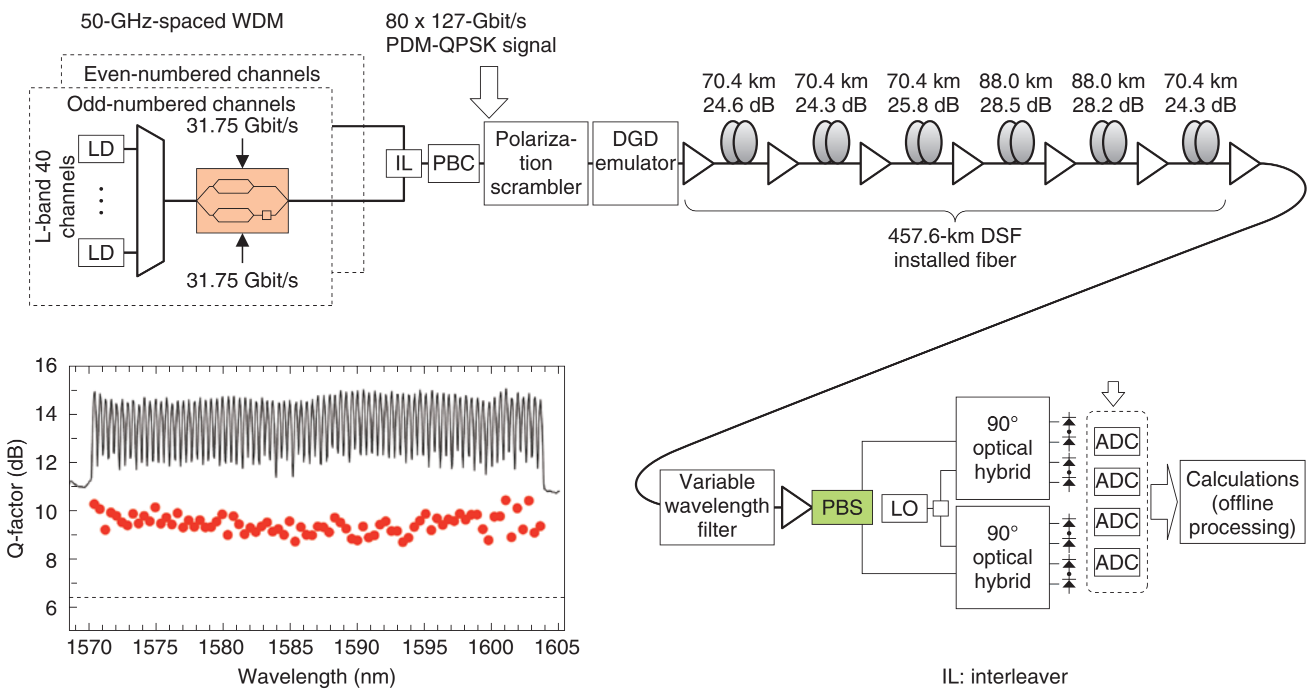

Fig. 5. 8-Tbit/s WDM field experiment.

combiner (PBC) to form a 112-Gbit/s PDM-QPSK optical signal. In optical fiber transmission, the polarization states are not maintained after transmission because of temperature changes in the fiber cable and physical contact with the fiber by an operator.

At the receiver, the PDM QPSK signal is separated into X' and Y' polarization components at the polarization beam splitter (PBS). These signals pass through a 90° optical hybrid and differently polarized signals are separated into in-phase and quadrature-phase components by coupling them with the LO signal, for each polarization axis (X', Y'). A/D converters convert the 112-Gbit/s received signal into 4-lane 28-Gsymbol/s electrical digital signals. In the DSP part, after synchronization between the received signal light and the LO signal, CD compensation, polarization demultiplexing, PMD compensation, and carrier phase recovery are conducted to demodulate the original 112-Gbit/s PDM-QPSK signal in the digital domain.

DSP throughput greater than 1.3 Tbit/s is required for 112-Gbit/s digital coherent systems (e.g., for each lane with a 28-Gsymbol/s received waveform, six quantizing bits, and a sampling rate of 2 samples/symbol, the throughput per lane is 336 Gbit/s; thus, for all four lanes, 1.344-Tbit/s digital signal processing is required). In recent years, several developments have advanced realtime DSP technology, leading to innovations in 100-Gbit/s class transmission performance and we anticipate further progress in the future. We will accelerate our research efforts for realtime digital coherent optical transmission technology; the key concept of the DSP architecture has been studied under the Universal Link Project supported by the National Institute of Information and Communication Technology (NICT) of Japan [4]. Proof-of-concept studies for 100-Gbit/s-class digital signal processing are also being conducted in a project supported by the Ministry of Internal Affairs and Communications of Japan [5].

5. Field trials of 100-Gbit/s digital coherent scheme

To confirm the feasibility of this scheme, we conducted a 8-Tbit/s field experiment using 80 × 100-Gbit/s DWDM (dense WDM) test signals over an installed dispersion shifted fiber (DSF) [6].

The experimental setup is shown in **Fig. 5**. In this experiment, the line rate was set to 127 Gbit/s to improve the optical SNR by introducing strong forward error correction (Ultra FEC (UFEC)) with 20%

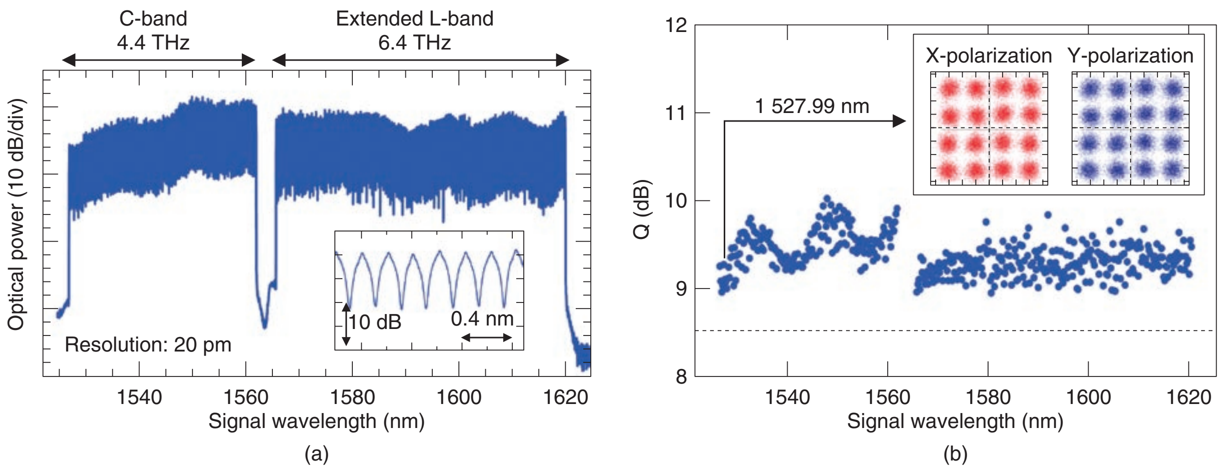

Fig. 6. 69.1-Tbit/s transmission experiment.

redundancy. An 8-Tbit/s test signal was generated to wavelength-division-multiplex 80 channels of 127-Gbit/s PDM-QPSK signals with a 50-GHz spacing. A polarization scrambler and a DGD emulator were arranged at the transmitter output to simulate various polarization conditions and PMD.

The transmission line used in the experiment comprises an 8.8-km 100-core slotted-core DSF cable with dozens of connectors constructed between NTT Yokosuka R&D Center and NTT EAST's Yokosuka office. The test wavelengths were from 1570.4 nm to 1603.6 nm in the L band. The 457.6-km line with L-band erbium-doped fiber amplifier (EDFA) inline repeaters has four spans of 70.4 km and two spans of 88.0 km. Its CD coefficient ranged from 1.4 to 4.2 ps/nm/km, the PMD coefficient was less than 0.2 ps/km$^{0.5}$, and the loss in each span ranged from 24.3 to 28.5 dB.

A tunable wavelength light source with a line width of 100 kHz was used as an LO in the digital coherent receiver. For digital signal processing, offline processing was performed using a computer and a real-time oscilloscope. The CD and PMD in the transmission line were completely compensated for by digital signal processing in the receiver, and inline dispersion compensation at each optical amplification repeater was not used.

The 8-Tbit/s (127 Gbit/s × 80 channels) WDM spectra and the error rate for all channels (Q factor) after 457.6-km transmission are shown in Fig. 5. For all the channels, Q factors of more than 8.5 dB were obtained; that is, they were all above the UFEC limit of 6.4 dB. Thus, we confirmed the feasibility of transmitting a stable 8-Tbit/s signal over an installed DSF.

6. Challenges toward achieving higher capacities

We investigated the feasibility of much higher capacities with higher SE of more than 2 bit/s/Hz by using enhanced DSP based on higher-order multi-level quadrature amplitude modulation (QAM) formats. We successfully achieved 69-Tbit/s DWDM transmission over a distance of 240 km by using 171-Gbit/s PDM-16QAM [7]. This advanced DSP scheme enhances the phase noise tolerance required in order to use PDM-16QAM. The test results are shown in **Fig. 6**. In this experiment, we used hybrid EDFA/Raman optical amplification in three 80-km spans of ultralow pure-silica core fiber with fiber loss of 0.16 dB/km. As a result, we achieved low-noise signal transmission with bandwidth of more than 10.8 THz covering the C band (1527.22–1562.03 nm) and an expanded L band (1565.91–1619.84 nm) that compensated for the reduction in optical SNR tolerance caused by using the 16QAM format. The redundancy of the enhanced FEC (E-FEC) was 7%. As a result, we successfully achieved ultrahigh-capacity transmission of more than 10 Tbit/s with a high SE of 6.4 bit/s/Hz.

7. Summary

In this article, we introduced the latest technical trends in ultrahigh-capacity digital coherent transmission technologies for future optical transport networks that support broadband network evolution. We will continue research and development of a practical 10-Tbit/s-class OTN.

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Photonic Network Node Technology for Transparent Path Accommodation

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Abstract

In this article, we introduce research and development trends related to optical-electrical hybrid nodes. Meeting the demands for higher channel capacities, by for example wavelength division multiplexing at 100 Gbit/s per wavelength, will require not only optical switching of optical paths at photonic nodes, but also sub-lambda (electrical path) technology for multiplexing/demultiplexing and switching 1–10 Gbit/s medium-sized electrical paths.

1. Introduction

The photonic network can provide high-quality delivery of user traffic via optical paths over long transmission distances. This is achieved by assigning wavelength-based identifiers to the optical paths. In this article, we describe three main trends concerning new requirements related to photonic nodes.

1.1 High-capacity optical paths

The use of advanced digital signal processing enables a spectral efficiency of 2 bit/s/Hz to be achieved, enabling long-distance transmission with a capacity of 10 Tbit/s (100 Gbit/s × 100 wavelengths) [1]. On the other hand, the input-output signals of client nodes, which contain user traffic multiplexed at edge routers, are expected to still be at the 10-Gbit/s level (10-Gbit/s Ethernet (10GbE)) in the mainstream in the near future. Therefore, the photonic nodes for these signals will need functions not only for optical multiplexing/switching of large optical paths, but also for electrical multiplexing/switching of medium-sized electrical paths, where the medium-sized electrical paths are aggregated into a large optical path. In other words, we need a multilayer processing function that can handle both optical and electrical paths in one node. The conceptual scheme for the optical-electrical hybrid node, with reference to the international standard for the Optical Transport Network (OTN), is shown in **Fig. 1**. The optical channels (wavelengths) conform to a digital frame format called an optical-channel transport unit (OTU) containing optical-channel data units (ODUs) [1]. An important point is that a client signal is wrapped into ODUs transparently, without any overwriting of the client overhead. NTT was the first in the world to achieve optical and electrical transparent-multiplexing technology for the OTN and has been leading the world in international standardization.

In this simple example in Fig. 1, four wavelengths are multiplexed in a single fiber. The first wavelength (λ1) contains an OTU4, which accommodates 10 × 10G electrical paths (ODU2), where the ODU2s are demultiplexed from a single ODU4 after optical-to-electrical (O/E) conversion and connected to the electrical (ODU) switching fabric (G: denotes Gbit/s). In the ODU switching fabric, each ODU's route is provisioned, either to drop into a tributary port*1 or to continue into the express port. The express ODU2s are then multiplexed into a single OTU4 again, and converted (by optical-to-electrical (E/O) conversion) into a single optical path of wavelength λ1. The

*1 Tributary port: After demultiplexing, it is the exit port of the equipment (e.g., a dense wavelength division multiplexing (DWDM) system) that outputs the signal and is connected to the client equipment (e.g., a router) in the building. It is also the input port for the equipment (e.g., DWDM system) in the reverse direction.

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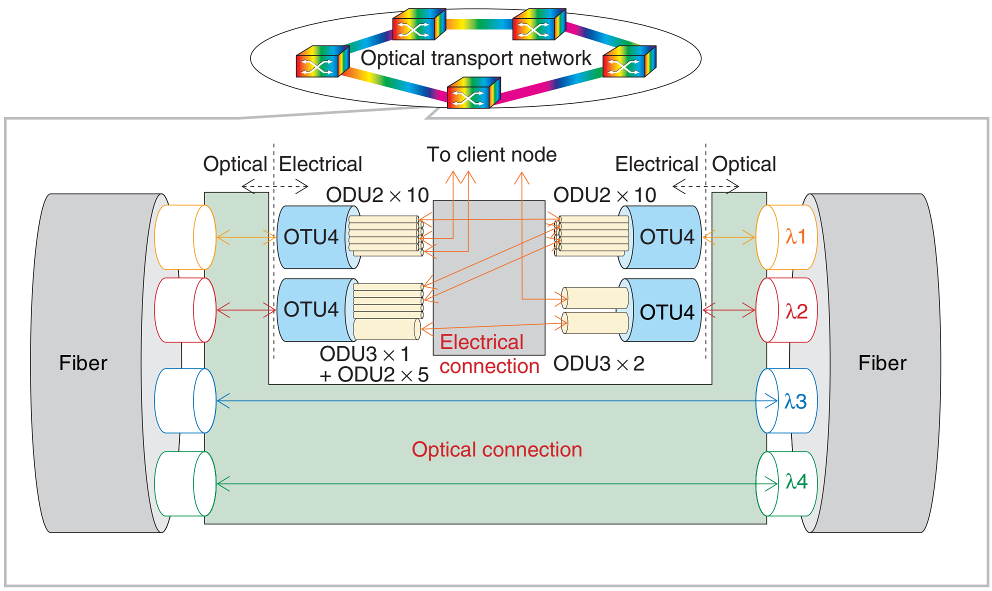

Fig. 1. Concept behind OTN node.

second wavelength (λ2) contains 2 × 40G electrical paths (ODU3), and they are connected to the ODU switching fabric. The third and fourth wavelengths (λ3 and λ4) are connected to the optical switch without O/E/O conversion.

1.2 IP traffic off-loading by cut-through in photonic node

The photonic network deployed to date has the simple role of connecting Internet protocol (IP) core routers. In all core networks, each IP core router has a multihop configuration, and the photonic networks are segmented sub-networks that are finely divided into small domains in a core network. With the target of low cost of overall networks, if we analyze the contents of core router processing, we begin to understand that it is often the case, in core routers, that traffic at the input port is simply forwarded to a fixed output port by means of a Layer-3 function. By providing cut-through technology at relatively low layers (optical and electrical paths), these simple functions can efficiently decrease the cost and power consumption.

1.3 Multidegree photonic nodes

Unlike ordinary telephone traffic, IP (Internet) traffic has a tendency to be concentrated in large cities such as Tokyo and Osaka (and beyond Tokyo, there are many instances of connection to international circuits). To a certain extent, establishing multiple sets of equipment in different locations around a large city is known to be an effective decentralization method. The problems facing this configuration are that, since traffic increases are becoming unpredictable as a result of recent Internet characteristics, it is difficult to give a precise design target for the path capacities to be handled at each node. Therefore, we need flexibility in handling paths, e.g., some spare bandwidth and a mechanism for sharing it among nodes at different locations. If the traffic increases and exceeds the spare bandwidth prepared at a particular node, it will be even more necessary to disperse the traffic to other nodes at different locations while minimizing the difference in latency. The existing reconfigurable optical add/drop multiplexers (ROADMs) that support a node degree of 2 may be insufficient. A photonic node that supports multidegree switching would let us deal flexibly with this type of unpredictable demand.

Another need is the ability to deal with disaster recovery. If we consider the effect of calamities such as earthquakes on the social infrastructure, e.g., on Internet commerce, it is not enough to have only two routes, i.e., the currently used working route and one backup protection route. We need to reserve a third route. For this purpose, photonic nodes that support multidegree switching are important.

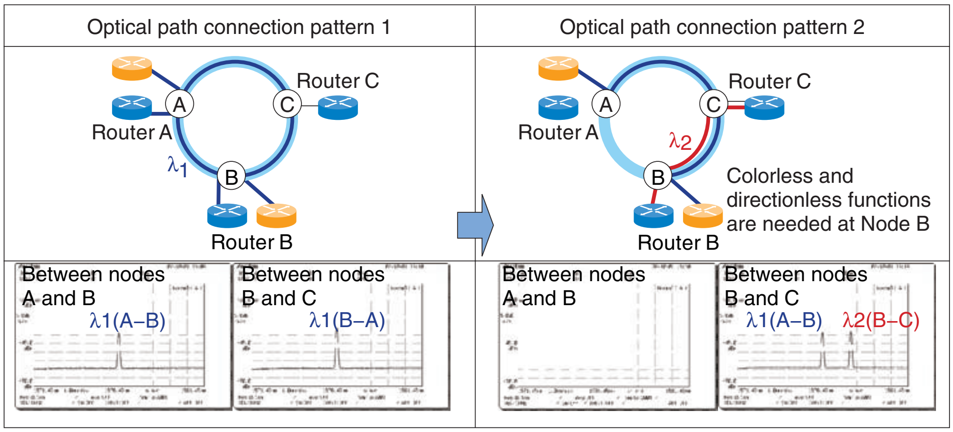

Fig. 2. Demonstration of colorless and directionless node.

2. Optical layer switching technology

Here, we introduce a function that meets the need for optical layer switching that arises from the new demand mentioned above and technology that enables the function. In photonic nodes, a multilayer configuration, i.e., with both optical and electrical switches, means that hybrid operation is needed, and an important issue is designing the electrical switch capacity because it represents a large proportion of the cost and power. One important point is what percent of the total transmission capacity of the fiber to allocate to electrical switching. In a practical design, we should carefully consider the traffic pattern etc., but from a functional perspective at least an arbitrary wavelength of an add/drop optical path should be connected to an arbitrary port of an electrical switch. As mentioned earlier, not only are existing ROADMs limited to a node degree of 2, but also the relationship between the add/drop wavelengths and tributary ports is fixed. In other words, when provisioning an optical path, after determining the established wavelength, operators must physically go to the add/drop equipment and insert the interface board in the port assigned to that wavelength. At an optical electrical hybrid node, the interface between the add/drop optical path and electrical switch port is inside the equipment, and operators generally do not touch the intraconnections once initial construction has been completed because of the vendor-dependent node configuration (the risk of misconnection might increase in different ways as a result of manual setting depending on the vendors).

The technology that enables connections from a remote site, among arbitrary wavelength add/drop optical paths and arbitrary tributary ports, is called *colorless*. A similar function that deals with an add/drop optical path from an arbitrary express direction is referred to as *directionless*. Furthermore, in order to achieve directionlessness in the optical layer, there is a special methodology that avoids interference in a device among optical paths of the same wavelength called *contentionless*. An overview of the colorless-directionless demonstration conducted at NTT is shown in **Fig. 2** [2]. A bidirectional ring network was used in the demonstration. As the initial operating state, optical path λ1 was established between node A and node B along the shorter route, and a different optical path was established between nodes B and A along the longer route with the same wavelength as λ1 (pattern 1). Although both optical paths had the same wavelength, the first path was protected from interference by the second path. In the optical spectra at the bottom of the figure, the wavelength in each route is active. In the next phase of the demonstration (pattern 2), the optical path between nodes A and B in the shorter route became unnecessary: instead, it was assumed that a demand for connection from node B to node C arose. Since λ1 was already active in this B-to-C route, wavelength λ1 could not be used. A different wavelength had to be used (λ2). Through the colorless directionless optical switch used in this demonstration, we showed remote resetting of the wavelength to meet new demands without physical replacement of the interface board. In pattern 2, two wavelengths were active in one route. A more detailed example of a colorless node configuration is shown in **Fig. 3**. The wavelength selective switch (WSS) shown

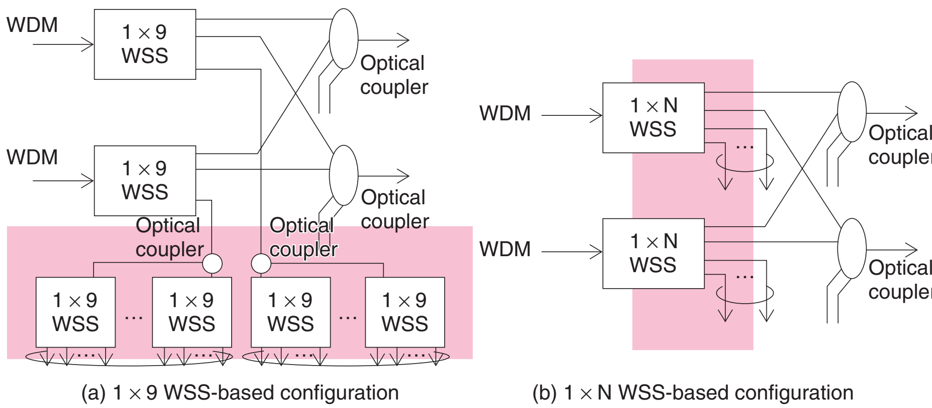

Fig. 3. Example of optical part in optical node.

in the figure is a device that enables switching of an arbitrary combination of WDM input signals to any combination of WDM output signals. To date, the 1 × 9 type WSS module has typically been used. To achieve the colorless function (Fig. 3(a)) by using the combination 1 × 9 WSS modules, the upper WSS establishes an optical path connection from an express-port to another express-port or from an express-port to an add/drop port connection. The lower WSS is for a path connection from an add/drop port to a tributary port. In this configuration, the number of modules is increased and each module incurs optical loss. Therefore, an optical amplifier is needed to compensate for the loss. A multiport (1 × N) WSS is currently under development; its configuration is shown in Fig. 3(b). This simple configuration will have fewer modules and a lower cost. We are verifying the principle of a 1 × 43 WSS and conducting verification experiments on the colorless function.

3. Electrical layer switching technology

Attention to electrical switch technology in the OTN is currently focused on Layer-1 technology and also packet-oriented Layer-2 (sometimes referred to as Layer-1.5) technologies using, for example, multiprotocol label switching transport profile (MPLS-TP)*2 or provider backbone bridge traffic engineering (PBB-TE)*3. There is high affinity between OTN and the synchronous digital hierarchy (SDH)*4 in terms of Layer 1 and also between MPLS-TP (PBB-TE) and asynchronous transfer mode (ATM)*5 in terms of Layer 2 (or 1.5), where carriers have the benefit of familiar network operation in practical use. Here, we introduce electrical-layer (Layer-1) switching and the hitless protection switching technique, which is important to NTT's networks.

The OTN frame is constructed with reference to the digital-frame format stipulated in ITU-T Recommendation G.709 (ITU-T: International Telecommunication Union, Telecommunication Standardization Sector). This digital frame is a widely used format and is already becoming established in worldwide de jure and de facto standards. NTT previously developed an OTN framer LSI (large-scale integrated circuit) that could handle 40 Gbit/s [3], and the LSI took a large share of the world market after its commercialization. For the OTN, a multiplexing hierarchy is defined, and the ODU, which is a path in an OTN, is multiplexed/demultiplexed in fixed byte units. Therefore, an ODU switch should be of the circuit-switching type such as SDH. On the other hand, unlike SDH, the clock domain is sometimes not synchronized in frequency, and a device configuration that uses a frame buffer memory (first-in, first-out (FIFO)) is frequently used. This was triggered by the recent

*2 MPLS-TP: Part of the functionality of MPLS. It is characterized as optimization according to the quality level requirements by telecommunications carriers such as manageable connections. New features are added according to the detailed operations, administration, and maintenance (OAM) requirements.

*3 PBB-TE: A scheme for configuring a point-to-point relay path in a PBB network as stipulated in IEEE802.1ah.

*4 SDH: Standardized by ITU-T for multiplexing. During multiplexing from a lower-order tributary to a higher-order signal, byte-interleaving based on precise integer multiplication of the clock rate is used.

*5 ATM: A multiplexing scheme based on a 53-byte cell; the timeslot is not predetermined and a connection is established prior to the communication.

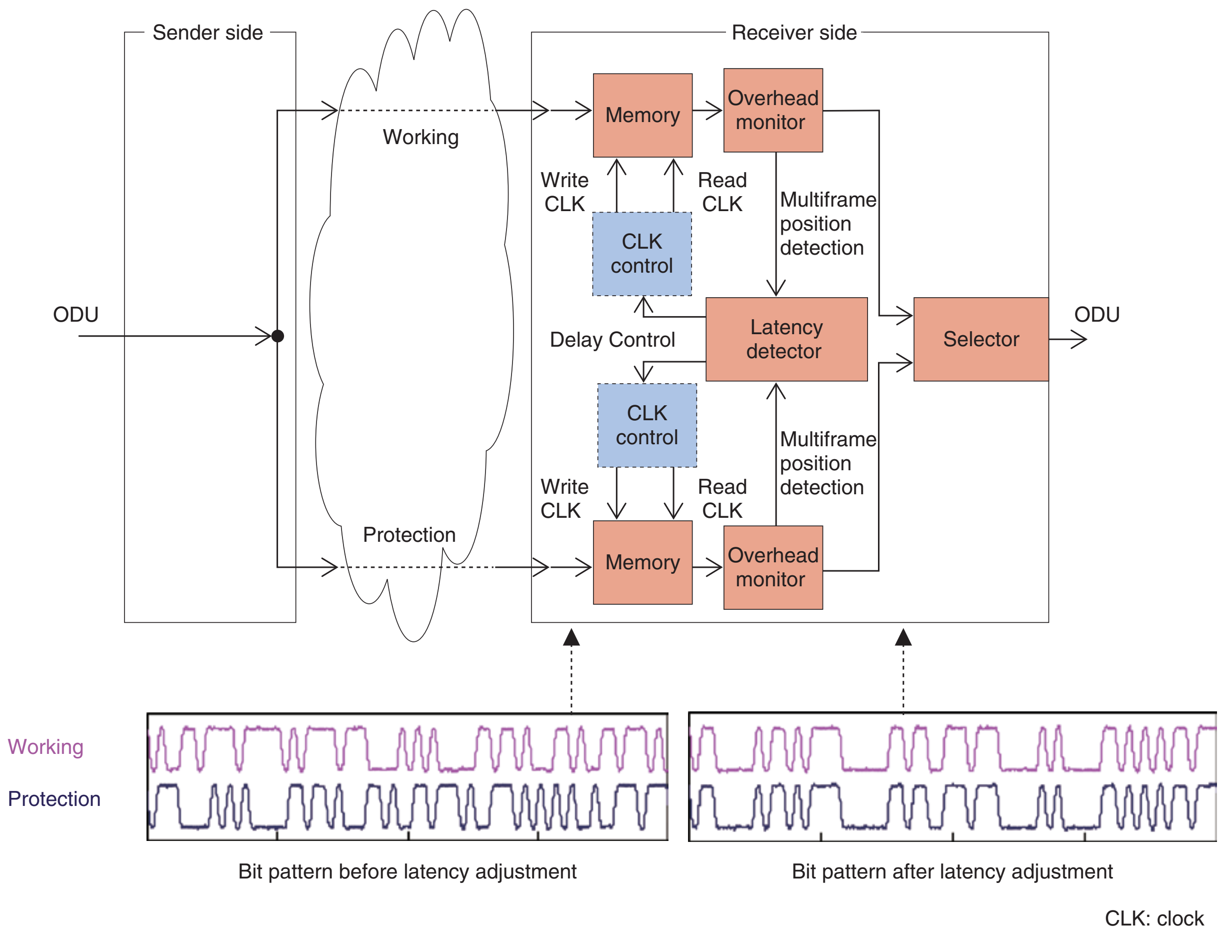

Fig. 4. Verification of hitless protection switching operation in OTN layer.

proliferation of personal computers leading to the availability of low-cost compact memory. Accordingly, there are two proposed ways to configure the ODU switch: the first is a circuit switching fabric whose capacity is extended from the ordinary one, and the second uses a packet switching fabric to achieve the ODU circuit switching function. In the latter case, the purpose of using the packet switching fabric is to take advantage of the lower cost of ICs achieved by the large production volumes shared with local area network (LAN) application. No conclusion had been reached yet on which way is better.

Fault restoration and rerouting can be handled in the OTN layer, and at NTT Innovation Laboratories, we are investigating hitless protection switching technology, which is important to NTT's networks. An overview of the hitless protection switching scheme is shown in **Fig. 4**. Basically, the same types of technologies as used in SDH can be applied to it. Namely, a multiframe is constructed by gathering digital ODU frames. This scheme achieves switching without any bit loss by detecting the difference in latency between the working and protection routes from the headers of these multiframes and by absorbing the latency difference in the buffer memory. In the ordinary hitless protection scheme, the protection route is predetermined, and switching should be based on 1+1 protection. On the other hand, we are extending the hitless protection scheme from the ordinary version to one in which an arbitrary non-predetermined protection route is possible (and the latency is not known in advance), which would be suitable for multidegree nodes because it provides multiple candidates for the protection route. By shifting the working clock frequency in a very slight range (sub-parts-per-million (ppm) order) while maintaining compliance to the standard ±20 ppm for the frequency shift, this scheme changes the phase (latency) of the current data. The configuration of a demonstration of this technology is shown in Fig. 4 together with the relationship between the working path data phase and the protection path data phase before and after latency adjustment. Here, the blue blocks represent the new scheme and the brown blocks represent the existing scheme to which the OTN frame is applied. After latency adjustment, the data phases are synchronized, and in the experiment, we verified that there was no bit loss during the switching.

4. Summary

As a new direction in photonic nodes, this article described new technological trends in optical-electrical hybrid nodes that are the focus of research and development trends in our group in NTT Network Innovation Laboratories. Besides the technologies described here, we are also conducting research on efficient resource (bandwidth) usage based on control over multiple layers and on a transmission node that enables bitrate and bandwidth flexibility. Our activities are continuing to put into practice long-term research and development to achieve an economical flexible network configuration in the future.

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Highly Efficient Photonic Networking Technology

Osamu Ishida, Akira Hirano, Yoshiaki Sone, Akihiro Kadohata, and Atsushi Watanabe

Abstract

This article introduces a networking management control technology that achieves *highly efficient photonic networking* by having λ paths (wavelength paths) and sub λ paths function cooperatively to increase the efficiency of user traffic accommodation.

1. Introduction

Photonic transport networking in core networks conveys accumulated user traffic that is collected and distributed through access networks. The transport of traffic uses wavelength division multiplexing (WDM) transmission and optical path-switching. The requirements are shown in **Fig. 1**. In recent years, with the proliferation of broadband service through the penetration of fiber-to-the-home (FTTH) and expanding use of information and communications technology (ICT) in enterprise networks, increasingly higher-capacity path provisioning has been in demand for transport networking. In light of this, NTT Network Innovation Laboratories has been conducting research and development of 100-Gbit/s-class transmission technology and node technology [1]–[3]. Moreover, as the number of various high-capacity services increases such as datacenters and video delivery service, transport network flexibility will become important in addition to rapid path establishment. This is because long-term estimation of the traffic demand for these new services is difficult. Furthermore, considering severe price competition, further economization of transport networks is essential. On the other hand, to deal with the shrinking work force, from a network application perspective, operational cost reduction is also important. In regard to this, countermeasures such as utilizing remote control to decrease the number of service calls, automation, and simplified applications are necessary.

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2. Network architecture

To deal with these requirements, the photonic network architecture is progressing along with optical transmission technology.

2.1 Transparency

In the current optical transmission system, by using wavelength division multiplexing (WDM) technology, we have reached nearly 100 wavelengths per optical fiber. By using an optical fiber amplifier, we can amplify a large multiplexed optical signal of this type all at once. However, repeated optical amplification leads to the accumulation of noise. Moreover, optical fiber group velocity dispersion*1 and a nonlinear effect*2 occur owing to the physical characteristics of the optical fiber and they cause the optical signal waveform to distort during propagation. The distortion per wavelength becomes a serious problem as the transmission capacity becomes high. For this reason, before the distortion limit is exceeded, the optical signal must be converted into an electrical signal, the

*1 Group velocity dispersion: The wave speed (group velocity) fluctuates depending on the optical frequency. It is one source of performance degradation of optical signals.

*2 Nonlinear effect: A general term for optical nonlinear phenomena in which the refractive index of an optical fiber changes depending on the optical intensity. It is a source of optical signal performance degradation.

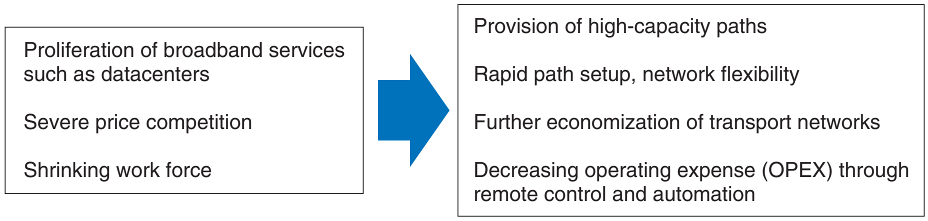

Fig. 1. Photonic transport network requirements.

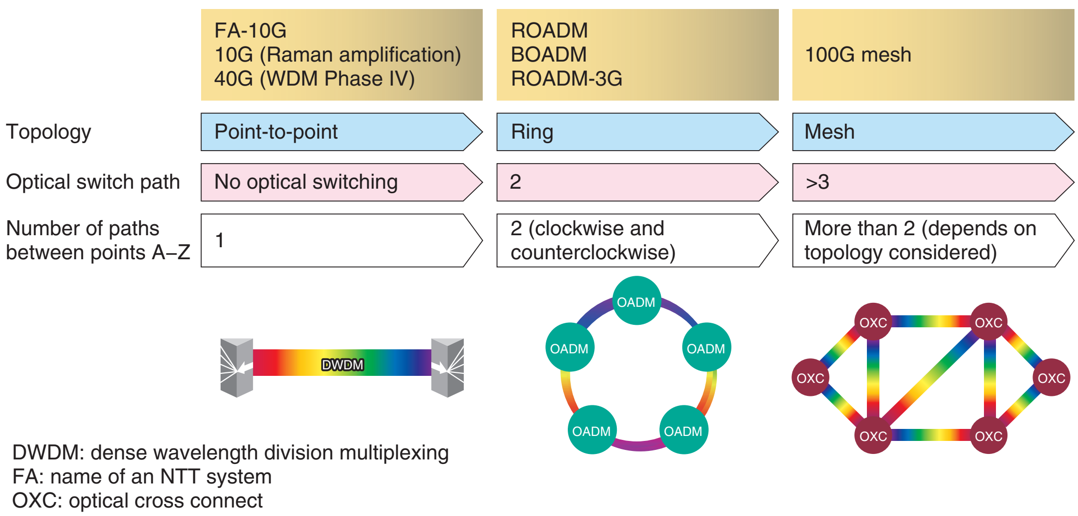

Fig. 2. Progress in photonic transport network.

waveform reshaped, and electrical regeneration processing performed. Since this process must be performed for each wavelength, there are equipment cost, power consumption, space, and maintenance issues.

In recent years, optical transmission technology has progressed and this type of discrete electrical regeneration processing is no longer used. The transmission distance and transmission capacity of optical transmission without electrical regeneration have increased rapidly, contributing significantly to the economization of transport networks. In other words, the reach of optical signals without electrical regeneration, i.e., the *transparent* domain of optical signals, has expanded rapidly. This is called the transparency of the photonic network.

2.2 Evolution of network topology (mesh networks)

From the photonic networking topology viewpoint (**Fig. 2**), a high-capacity optical transmission system for long-distance spans, such as the Tokyo-Nagoya-Osaka link, is installed as a point-to-point system linking two points by using WDM technology. In this case, path changes require optical-to-electrical signal conversion electrical regeneration, as mentioned earlier, which involve incur cost and power issues.

However, recent progress in optical transmission and switching technologies has enabled conversion-free optical path switching. In current metropolitan areas, optical switches have been put into practical use as reconfigurable optical add/drop multiplexers (ROADMs) that perform conversion-free optical path switching in ring networks. In ROADM ring networks, additional equipment and application costs can be reduced since operations such as path switching can now be accomplished from a remote location.

We are currently further increasing the number of degrees of freedom for routing to produce multidegree

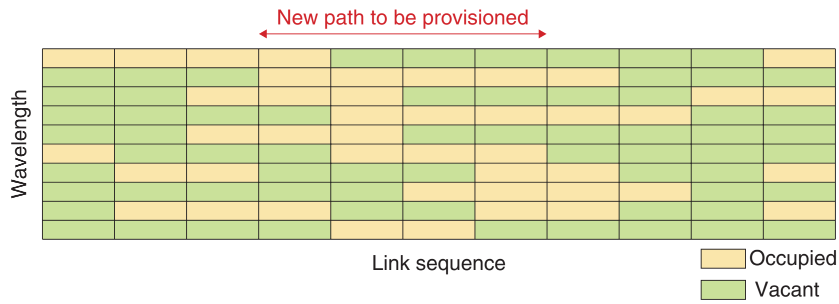

Fig. 3. Wavelength collision.

ROADMs. In an ROADM ring network, there are only two choices for routing candidates, i.e., clockwise rotation or counterclockwise rotation, and these choices are referred to as degrees. For multidegree ROADMs, the maximum is three or more. This type of multidegree choice enables more degrees of freedom for optical routing without conversion or electrical processing. It allows us to configure an economical network. Furthermore, the network topology has evolved from a ring to a mesh.

2.3 Multilayer transport

The diversification in transport technologies has led to multiple alternatives for transmitting the same volume of traffic. For example, in the case of transmitting user traffic with a bandwidth of 10 Gbit/s, there are many technologically feasible ways to transmit a signal besides a direct 10G (G: Gigabit/s) optical wavelength (λ path), such as transmitting using a 10G electrical path and optical-channel data unit 2 (ODU2) as a sub λ path, using time division multiplexing (TDM) to multiplex 40G and 100G wavelength transmissions, or using pseudo-wire technology[*3] based on multiprotocol label switching transport profile (MPLS-TP) packet processing. The electrical technology has higher functionality than optical technology, and packet multiplexing (Layer 2) has higher functionality than TDM (Layer 1). On the other hand, the electrical and packet processing have higher cost and power requirements, so their scalability to supporting future demands for high-capacity traffic will be an issue. For this reason, it is economical to use a lower layer for a given transmission function.

2.4 Routing complications and wavelength collision

Mesh networks using multidegree ROADMs have more paths connecting a pair of points than ring networks, so path determination is more complex. Moreover, since no electrical processing is performed in the relay nodes along the path connecting the two points, the same wavelength must be used in the optical path between the starting and end nodes. For this reason, if we use randomly unoccupied wavelengths, some wavelengths cannot be assigned despite the existence of unoccupied wavelengths in each span. This is called wavelength collision and is shown in **Fig. 3**. Here, the span indicated in red is the new path to be established. If we look at each link span, it appears as if the unoccupied wavelengths indicated in green can all be guaranteed in the path. However, upon closer inspection, we see that it is impossible to guarantee the same desired wavelength for all the links in the path. For this reason, the wavelength exclusion process prevents path establishment despite the fact that there are available wavelengths. This reduces the overall utilization efficiency.

3. Network management control technology

3.1 Multigranular accommodation design technology

To resolve the abovementioned types of routing complications and wavelength collisions and ensure that economical transparent mesh networks are reliable, NTT Network Innovation Laboratories is investigating multigranularity accommodation design technology. For example, the basic function considering the hierarchy of the λ path and the electrical ODU path (sub λ path) is shown in **Fig. 4**. This function selects the path and wavelength for traffic having various bandwidths without squandering resources

*3 Pseudo-wire technology: Based on MPLS-TP, it achieves stable quality through the use of packet processing devices.

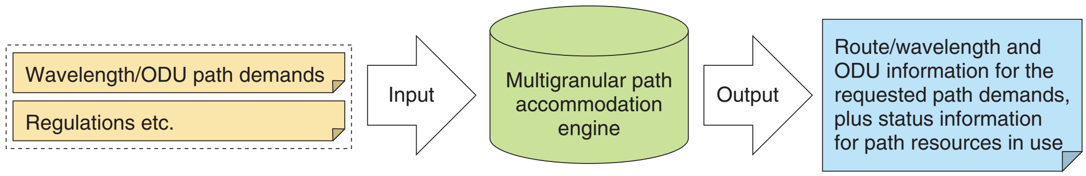

Fig. 4. Multigranular path accommodation design.

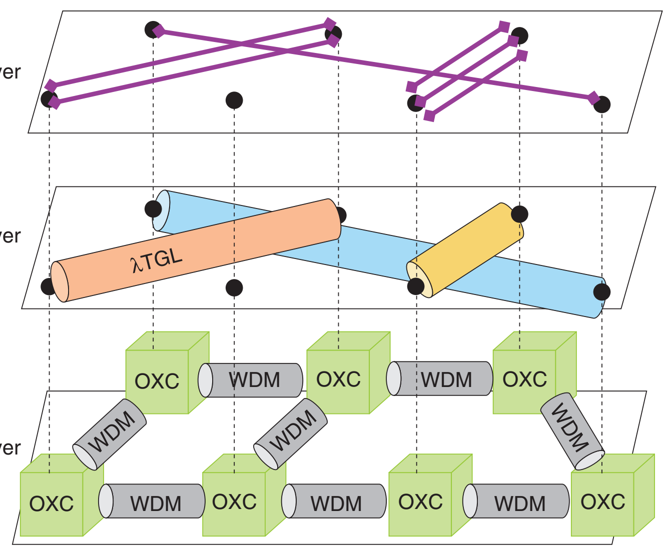

Fig. 5. λ TGL layer.

by considering wavelength collision and the advantages and disadvantages of each layer. The function displays the wavelength working conditions for each link. Furthermore, various constraints such as path arrangement, cable construction conditions, and actual network conditions are considered.

In a transparent network, in addition to routing complications and wavelength collisions, the limit on the reachable distance for conversion-free optical transmission must be considered. Although the number of selectable routes is much higher in a transparent network, we must also determine whether optical transmission can be performed without conversion for each path. Moreover, even if we know the unused wavelengths for each optical fiber, we must comprehensively consider and judge the path, wavelength, and distance that the optical signal can be transmitted without conversion. To resolve these issues, we are investigating transparent network control technology that uses wavelength-grouped transmission-guaranteed link (λTGL) technology [4]. As shown in **Fig. 5**, the λTGL layer is defined for the estimated demand on the basis of a path designed in advance, considering the distance that the optical signal can be transmitted without conversion or wavelength collisions. The prepared λTGL establishes a virtual path whose path group capacity corresponds to the estimated demand. By specifying λTGL beforehand, we can reserve the required number of paths from the desired λTGL peers. Furthermore, since we can virtualize the supply of wavelength units, understanding what resources remain becomes simple. In this way, once we have established individual λ paths we do not need to consider the constraints on the transparent network characteristics, so we can expect a reduction in operating costs by simplifying the application and achieving economization through efficient usage of the transport equipment.

Through initiatives of this type, the network resources can be optimized on the basis of the estimated demand and we can aim to economize the transport network. In the future, the appearance of various high-capacity services such as datacenters and image/video transfer services will lead to a higher proportion of high-volume traffic, for which fluctuation estimation is difficult. Therefore, transport networks will also need to have the flexibility to absorb fluctuations. To overcome these various issues and utilize to the maximum the merits of transparent network economization, we are further advancing multigranularity accommodation design technology and component technology investigations.

3.2 Transport network virtualization

In future transport networks, we will have to cope with two traffic types: traffic with easy-to-estimate fluctuations and traffic with difficult-to-estimate fluctuations. If separate networks are configured for these requirements, then overall resources will be squandered. In order to provide economical transport services, we need a common transport foundation that can flexibly handle different types of demands. We are also investigating virtualization technology that provides transport services that satisfy different requirements and constraints on the same foundation as if the services were provided through separately configured dedicated networks. We expect that this type of transport network virtualization will be supported at the lowest level by a variety of virtualization technologies that are currently under investigation for cloud services.

4. Future expansion

With the aim of achieving further economization and application-cost reduction in photonic transport networks, we are advancing related standardization and collaborative research and development on higher-layer cooperation, flexible implementation to deal with demand fluctuations, and transport network virtualization.

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International Standardization and Implementation Technologies for Optical Transport Networks

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Abstract

This article introduces recent trends in international standardization related to optical transport networks and NTT's standardization activities. We also present standardization activities related to optical transmission with 100 Gbit/s per wavelength, which have drawn attention recently. Furthermore, as an example of applying the standardization results up to now to devices, we introduce two types of large-scale integrated circuits for optical transmission equipment.

1. Introduction

There has been much progress in various international standards related to transport networks. We can see the benefits of international standardization all around us in our daily lives. There are countless examples such as telephones, faxes, personal computer interfaces, and the TV broadcast system. The significance of such standardization can be recognized through 1) compatibility and interoperability, 2) encouragement of competition and market expansion based on the opening of specifications, 3) reductions in cost due to mass production, and 4) a high level of technology achieved through specialization within an industry. The field of optical communications is no exception. We have gained many benefits through standardization.

For NTT, international standardization means that the results produced by its laboratories enable technologies attractive to operating companies to be introduced quickly as international standards. Moreover, it subsequently enables cost reduction and economization to be achieved through mass production, and the global spread and competition of products can be improved through the application of standardized technology by our group companies.

There are a number of standardization bodies, forums, and industrial groups in the field of optical communications. The International Telecommunication Union, Telecommunication Standardization Sector (ITU-T), the Institute of Electrical and Electronics Engineers (IEEE), and the International Electrotechnical Commission (IEC) officially establish standards (de jure standards), and industrial groups such as the Optical Internetworking Forum (OIF) decide on practical standards (de facto standards). These standardization bodies have recently compartmentalized the technical areas and are advancing standardization on the basis of a collaborative relationship (**Fig. 1**). For the extremely high level of technology that is used in optical communication technologies, based on complementary specialization, efficient and fast technological progress can be targeted in the pertinent areas.

2. Standardization activities

NTT is actively participating in standardization related to optical transport networks. One topic related to optical transport networks that has recently been drawing much attention in international

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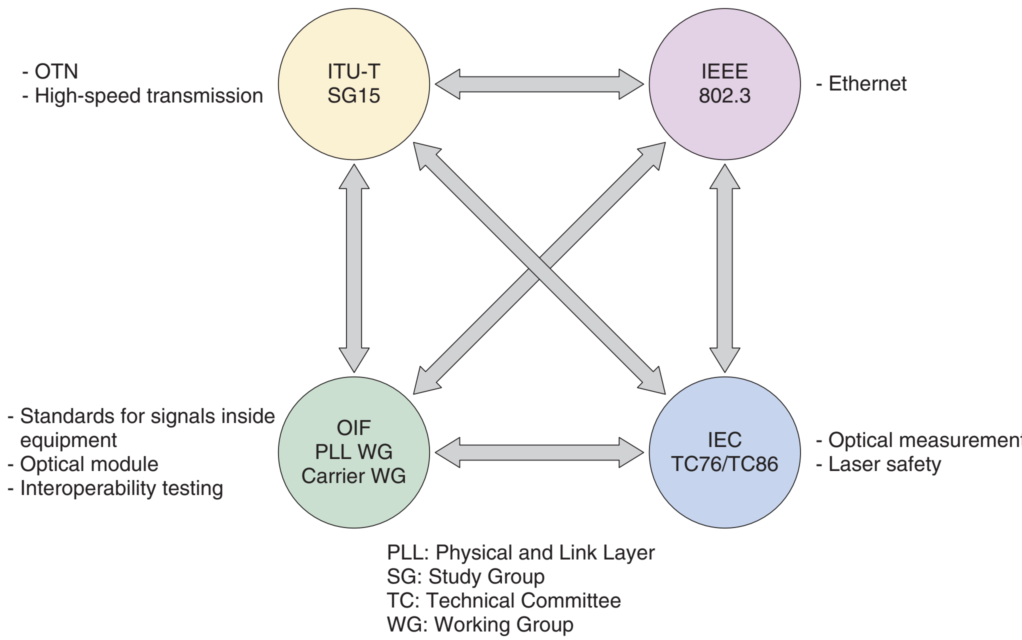


Fig. 1. Standardization bodies related to optical transport network.

standardization is the increase in transmission capacity achieved by using a speed of 100 Gbit/s per wavelength. Below, we note the 40- and 100-Gbit/s-related activities of each standardization body to date.

ITU-T is an international standardization organization subordinate to the UN that focuses on telecommunication standardization. It produces various standards (ITU-T Recommendations). For example, synchronous digital hierarchy (SDH)*1 is a well-known signal multiplexing method that is an international standard for telecommunication systems. Furthermore, wavelength multiplexing technology has been introduced and the Optical Transport Network (OTN) standardized. In recent years, a highly reliable transmission method for new high-capacity client signals such as 40-Gbit/s Ethernet (40GbE) and 100-Gbit/s Ethernet (100GbE) [1] and interface specifications [2] to achieve high-speed optical transmission have been standardized. A series of proposals regarding transport of Ethernet over OTN were submitted by NTT and many of them were accepted.

IEEE is a standardization body that is mainly an American scientific society. Familiar examples of its standards are Ethernet (IEEE 802.3) and wireless local area networks (IEEE 802.11). In recent years, it has standardized 40GbE and 100GbE, known as IEEE 802.3ba. In IEEE, NTT has been promoting not only discussion from a telecommunication standard viewpoint, but also support for the telecommunication standard OTN.

IEC is an organization that focuses on international standards related to the widespread field of electrical technology. Its purpose is to promote international cooperation and understanding related to standardization and the evaluation of compatibility to those standards in the field of electrical and electronic technologies. To date, as the base, we have fostered knowledge of NTT's high-speed transmission technologies and have contributed toward standardization of a 100-Gbit/s modulation format and evaluation techniques.

OIF is an industry group that cooperates in the fields of data communications and optical communications [3]. It deals with industry-standard Implementation Agreements (IAs). In recent years, it has advanced discussion of various specifications related to 100-Gbit/s transmission and produced IAs for optical modules (MSA: Multi-Source Agreement)*2, integrated optical transmitters, and integrated optical

*1 SDH: Lower-bitrate signals are multiplexed to a higher-bitrate signal.

*2 MSA: A scheme for establishing a stable product supply through the collaboration of multiple vendors regarding product specifications for package size, pin arrangement, etc.

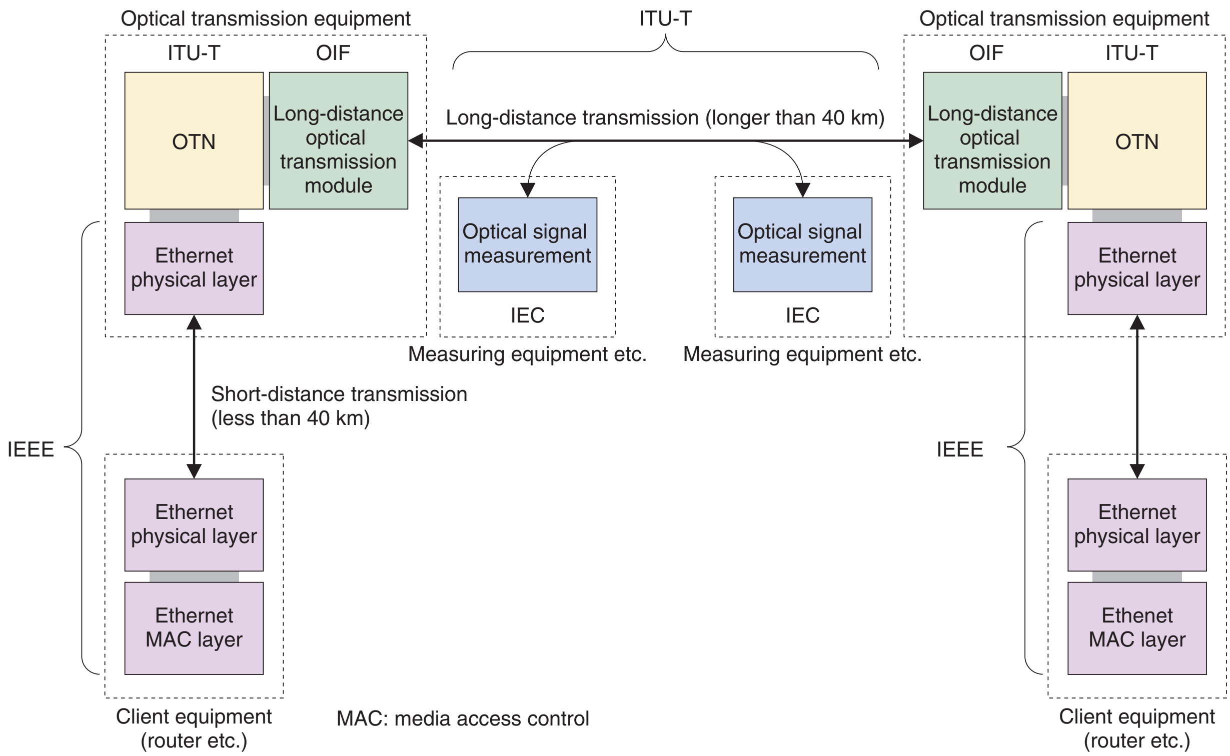


Fig. 2. Relationships among standardization bodies.

receivers. On the basis of the technology trends of other standardization bodies, NTT has made proposals that took account of technological feasibility and has contributed to decisions about IAs.

As an example of specialization in a technology area among the standardization bodies, we describe high-speed transmission technology. As shown in **Fig. 2**, optical transmission equipment uses a combination of IEEE-specified Ethernet standards, ITU-T-specified OTN recommendations, and OIF-specified optical module IAs. Since multiple specifications are involved in the configuration of one set of equipment, the standardization bodies that produced them arrange to share information among themselves from time to time to improve the integrity of the specifications.

With regard to these standardization bodies, NTT is advancing standardization activities related its own technologies, furthering the understanding of technological trends, and bolstering the framework for cooperative relations among the other organizations involved in standardization.

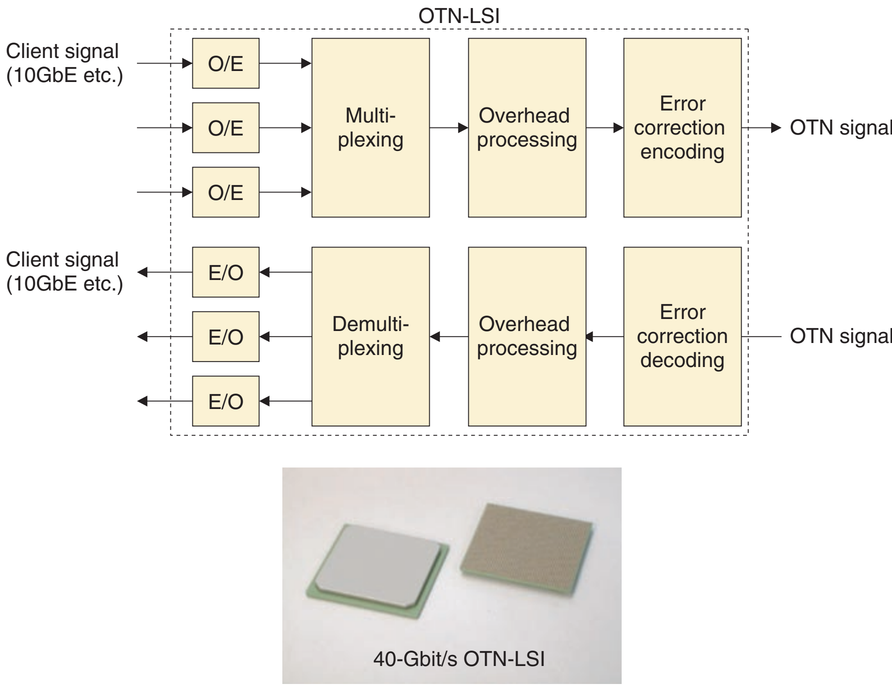
3. Application of standardization results to actual devices

Next, we describe standardization activities to date and standardization results and give a few specific examples of devices in which the standardized technologies are applied.

3.1 Standardization of 10GbE transport over OTN and OTN-LSI

Along with the increase in the volume of traffic, the enhancement of long-distance transmission is progressing. In particular, the growth in IP (Internet protocol) traffic has been remarkable recently, and the use of Ethernet as an interface has progressed rapidly. However, since the maximum transmission distance in the Ethernet standard is 40 km, it is insufficient for long-distance transmission between large cities. For this reason, ITU-T specifies the OTN as a long-distance transmission medium that achieves high reliability, and such optical transmission equipment is widely used.

However, a problem occurs in the transport of 10GbE over the OTN. Since the OTN assumed



E/O: electrical-to-optical conversion
O/E: optical-to-electrical conversion

Fig. 3. OTN-LSI.

10-Gbit/s SDH signals (STM-64) as client signals, this problem arose because the bitrate of 10GbE exceeds the maximum bitrate (payload capacity) of the client signal that can be accommodated in the OTN signal (ODU2). NTT continually advocated the importance of bit-transparent transport of 10GbE, and eventually a new OTN signal (ODU2e) suitable for 10GbE transport was standardized.

Concurrently with the ODU2e standardization, NTT developed a large-scale integrated circuit (OTN-LSI) for optical transmission equipment, and NTT Group companies have commercialized it. A photograph of the OTN-LSI and a schematic of its function blocks are shown in **Fig. 3**. The OTN-LSI accommodates 10GbE in an ODU2e and then multiplexes four ODU2e signals to form a 40-Gbit/s OTN signal OTU3e, which is suitable for long-distance transmission; it is a key device for 40-Gbit/s optical transmission equipment. The OTN-LSI is used by domestic transmission equipment vendors and has been introduced in the NTT operating companies. Furthermore, it has been promoted in the global market, and many system vendors in countries all over the world use it.

In this way, we have promoted technological development targeting commercialization concurrently with standardization and have been able to achieve quick deployment of the technologies to our operating companies. Furthermore, through the global promotion of products in our group companies, we are achieving price reductions through mass production and contributing to the economization of system deployment by our operating companies.

3.2 Standardization of 40GbE transport over OTN and mapping IC

The next standardized speeds after 10GbE are 40GbE and 100GbE. Since 100GbE is a new-bitrate client signal for the OTN, ITU-T SG15 (Study Group 15) revised the OTN standard to make it suitable for 100GbE. However, in the same way as in the above-mentioned 10GbE case, the bitrate of 40GbE exceeds the maximum bitrate (payload capacity) of the client signal that can be accommodated in the OTN signal (ODU3), which was assumed to be the 40-Gbit/s SDH signal (STM-256). At that point during the discussions on how to accommodate 40GbE in the OTN signal standardization, NTT searched for a way to accommodate 40GbE while maintaining the maximum

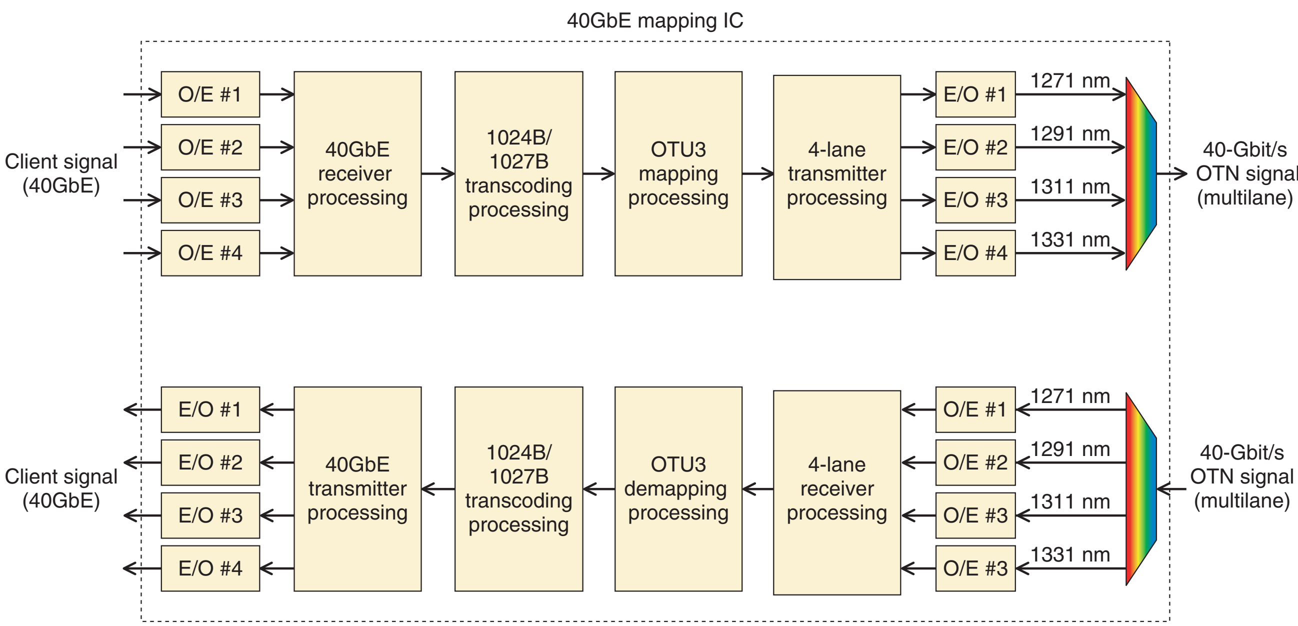


Fig. 4. Mapping IC.

transparency based on transcoding (rate compression), and our standardization proposals were adopted [1]. Specifically, we proposed replacing the 64B/66B code used for 40GbE by one with less redundancy, 1024B/1027B, and compressing the bitrate, which enable the existing 40-Gbit/s OTN signal (ODU3) to accommodate transcoded 40GbE.

Concurrently with this standard, NTT is developing a 40GbE mapping IC (integrated circuit) as an LSI for optical transmission equipment [4]. Its function blocks are shown schematically in **Fig. 4**. The mapping IC also contains multilane transmission technologies and other features. By using this mapping IC with existing transmission equipment for 40-Gbit/s SDH signals when developing optical transmission equipment for the new 40GbE, we can reduce the development cost.

In this way, NTT laboratories are effectively using previous development assets in equipment development that supports newly standardized technologies, considering ways to minimize the total development cost toward system deployment, and advancing device development.

4. Summary

NTT is advancing various international standardization activities related to optical transport networks in order to improve the business competitiveness of NTT Group companies by providing customers with attractive services and promoting NTT technologies in the global market. We are continuously promoting international standardization of technologies created in NTT laboratories and are progressing toward device applications.

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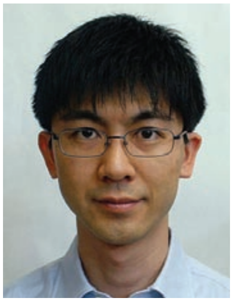

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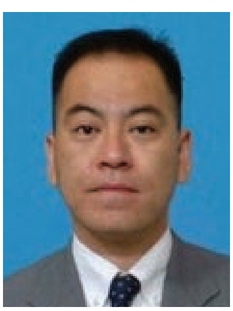

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Innovative Future Optical Transport Network Technologies

Toshio Morioka†*, Masahiko Jinno, Hidehiko Takara, and Hirokazu Kubota*

Abstract

This article introduces two initiatives by NTT—innovative optical transmission technology and elastic optical path networks—as ways to achieve rapid enhancement of the optical network in order to meet the demand for a thousand-fold increase in information volume and to fully utilize the potential of existing optical fiber.

1. Introduction

Traffic in core networks is increasing at several tens of percent per year, and we are searching for innovations in optical transmission technology for the long term that will enable the transmission of a thousand times as much information and innovations in optical networking technology for the mid-term that will lead to maximal utilization of the potential of existing optical fiber [1].

Optical transmission technology has developed rapidly over the past thirty years through three main technological innovations, as shown in **Fig. 1**: time division multiplexing (TDM) technology based on electrical multiplexing, optical amplification technology combined with wavelength division multiplexing (WDM) technology, and digital coherent technology, which is currently undergoing research and development. Although transmission technology research has reached a total capacity per fiber of 100 Tbit/s and progress is still being made, when we consider how to attain even higher capacities well above 1 Pbit/s, we find that optical fiber as a transmission medium and the existing multiplexing technologies such as TDM and WDM are facing their limits. Accordingly, to achieve a rapid increase in capacity beyond a 1000-fold, as indicated below, we need innovative optical transmission technology that will overcome the physical limits.

In the current optical networks based on WDM, optical signals are arranged on a fixed-spacing (e.g., 50-GHz) frequency grid standardized by ITU-T (International Telecommunication Union, Telecommunication Standardization Sector) and the same modulation technology has been used for optical signals of the same bitrate regardless of the transmission distance. So far, higher capacities per fiber have been achieved by improving the spectral efficiency (SE) by increasing the bitrate per channel while keeping or even narrowing the channel spacing. The abovementioned concern about approaching the capacity limit of conventional optical fibers has triggered recent vigorous efforts to investigate elastic optical path networks [1]–[3], where the required minimum spectral resources are allocated adaptively to an optical path according to the data volume and path length in order to improve the SE at the network level.

Optical transmission technology as a long-term initiative of NTT's R&D is introduced in section 2, and elastic optical path network technology as a mid-term initiative is introduced in section 3.

2. Optical transmission technology initiative

The first limiting factor facing existing optical transmission technology is the optical fiber signal input power. Optical fiber transmits an optical signal through a small core that has a diameter of approximately 10 μm. If the signal optical power exceeds a

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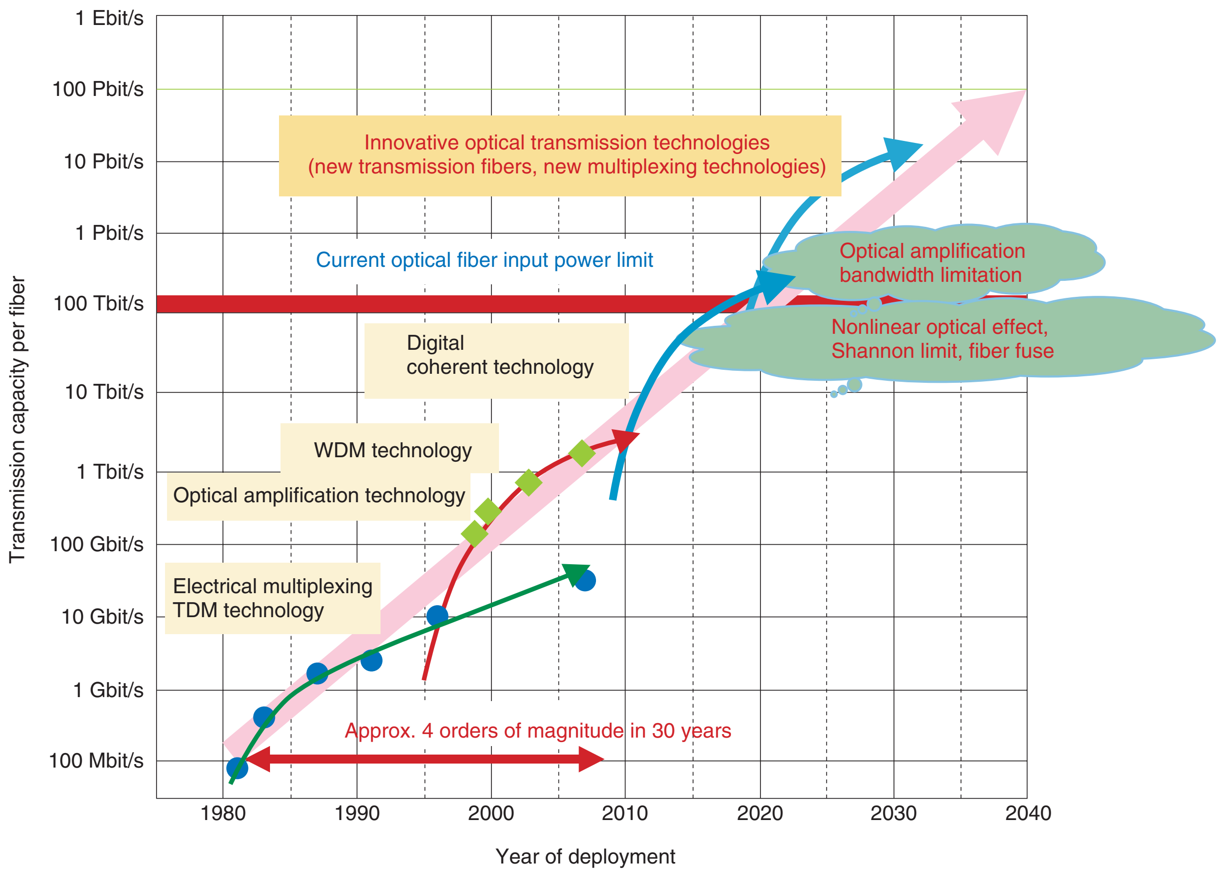

Fig. 1. Evolution in optical transmission technology.

certain level, and the temperature of the core suddenly increases for some reason, the core melts, and thermal destruction called fiber fuse occurs and propagates towards the light source [2], [4]. In current optical fibers, the fiber fuse transmission threshold power is 1.2–1.4 W, but we anticipate that in the future as the transmission capacity increases, the signal power will approach this threshold. On the basis of the latest optical transmission experiments, the relationship between the product of capacity per fiber and distance (Pbit/s • km) and the overall input signal power for an optical fiber is shown in **Fig. 2**, where the solid red line corresponds to 10 mW/(Pbit/s • km). The overall input power will gradually approach the abovementioned fiber fuse transmission threshold value. For example, achieving 1 Pbit/s over a distance of 1000 km (1000 Pbit/s • km) requires several watts of optical signal power. Accordingly, we need to develop an optical fiber that can withstand high power to overcome the fiber fuse and allow capacity expansion [5].

The second limiting factor is signal degradation due to the nonlinear optical effect in the optical fiber, whereby the optical signal phase and frequency are modulated depending on the signal intensity. If the signal power is increased in order to increase the communications capacity, WDM signal crosstalk is generated as a result of these effects, and the signal cannot be transmitted over a long distance. For this reason, we need to develop an optical fiber that suppresses the nonlinear optical effect.

The third limiting factor is the SE. The SE limit (communication capacity per unit bandwidth) for a fixed signal-to-noise-ratio (SNR) is given theoretically by the Shannon limit*1 and, depending on the abovementioned nonlinear optical effect, the fiber capacity is further limited. To improve the SE for a fixed input power, we need new multiplexing

*1 Shannon limit: The transmission capacity limit beyond which the data transmission speed cannot be increased. It is determined by the SNR and frequency bandwidth of a communications channel.

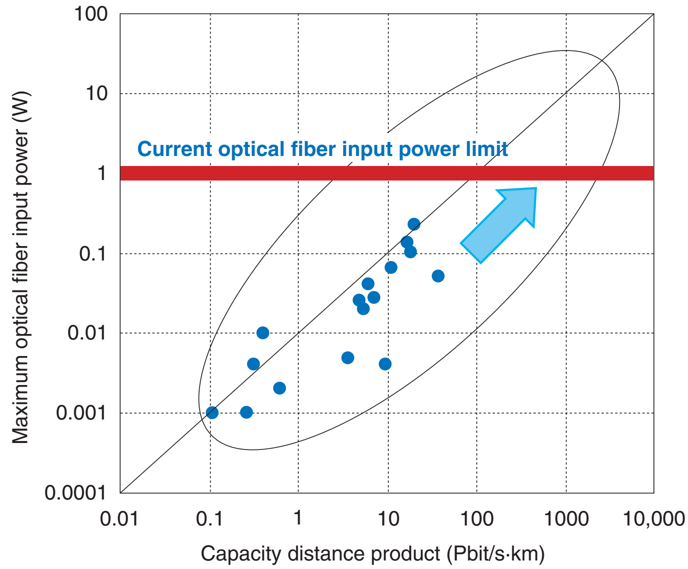

Fig. 2. Capacity-distance product versus optical fiber input power in recent optical transmission experiments.

technologies such as space division multiplexing.

The fourth limiting factor is the optical amplification bandwidth for the optical repeaters. The bandwidth for the 1.5-μm-band erbium-doped fiber amplifier used in linear repeaters is currently approximately 30–40 nm per band (L band or C band), so to increase the communication capacity, we must develop new wavelength bands for amplification. To resolve the abovementioned issues, we must research and develop new transmission media as well as new multiplexing technologies.

2.1 New transmission fibers

Toward transmission capacity expansion, we began research on a new optical fiber that has excellent power-tolerance characteristics and suppresses the nonlinear optical effect. For good power tolerance, new structures such as photonic crystal fiber and hole-assisted fiber are currently being investigated [2], [6]. Furthermore, we began investigation of a multicore fiber in which the power density per core is controlled to increase the overall transmission power (capacity) and a multimode fiber [7] in which signals are carried in individual spatial modes in a large-diameter core to expand the capacity.

2.2 New multiplexing technologies

NTT has begun to investigate the use of new multiplexing technologies such as space division multiplexing (SDM) and mode division multiplexing (MDM) in these new optical fibers. SDM and MDM are schematically illustrated in **Fig. 3**. MDM technology itself was proposed in the 1980s in short-distance transmission; in recent years, validation experiments using multiple-input multiple-output (MIMO) processing (from 2 × 2 to 3 × 3) have been reported. Along with the new transmission fibers to increase the power tolerance and suppress nonlinearity and with optical amplification bandwidth expansion through SDM and MDM, we are investigating ways to increase the transmission capacity by more than three orders of magnitude in the future.

3. Optical network technology initiative

3.1 Elastic optical path network

The essence of the elastic optical path network concept is adaptive spectrum allocation to an optical path. One benefit that the elastic optical path network yields is spectral savings achieved by exploiting spectral resources that had not been fully utilized. This results in an increase in network capacity. Opportunities for exploiting underutilized spectral resources are shown in **Fig. 4**. Let us consider an example in which we transport mixed-rate traffic. First, for client traffic that does not fill the entire capacity of a wavelength, the elastic optical path network provides intermediate bandwidth of an appropriate size, such as 200 Gbit/s. This makes the unused client bandwidth available for use. Second, for shorter optical paths, which suffer

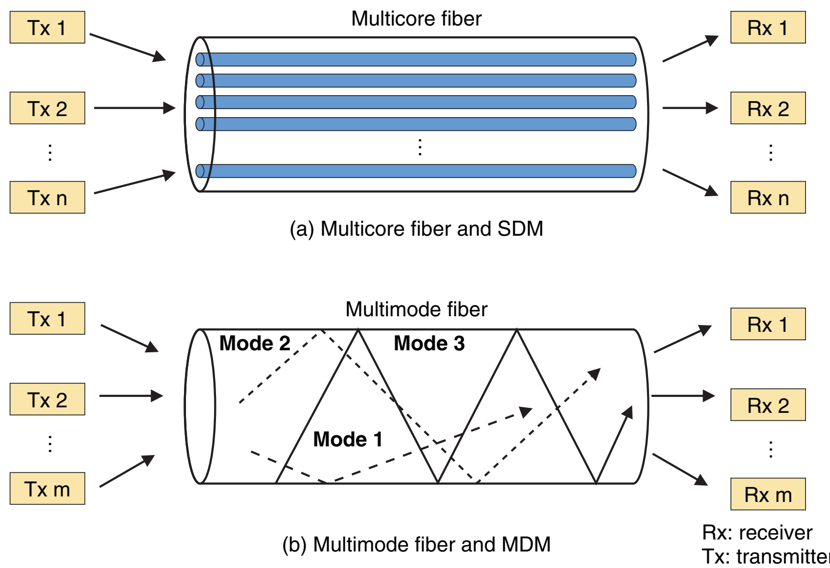

Fig. 3. New transmission fibers and multiplexing technologies.

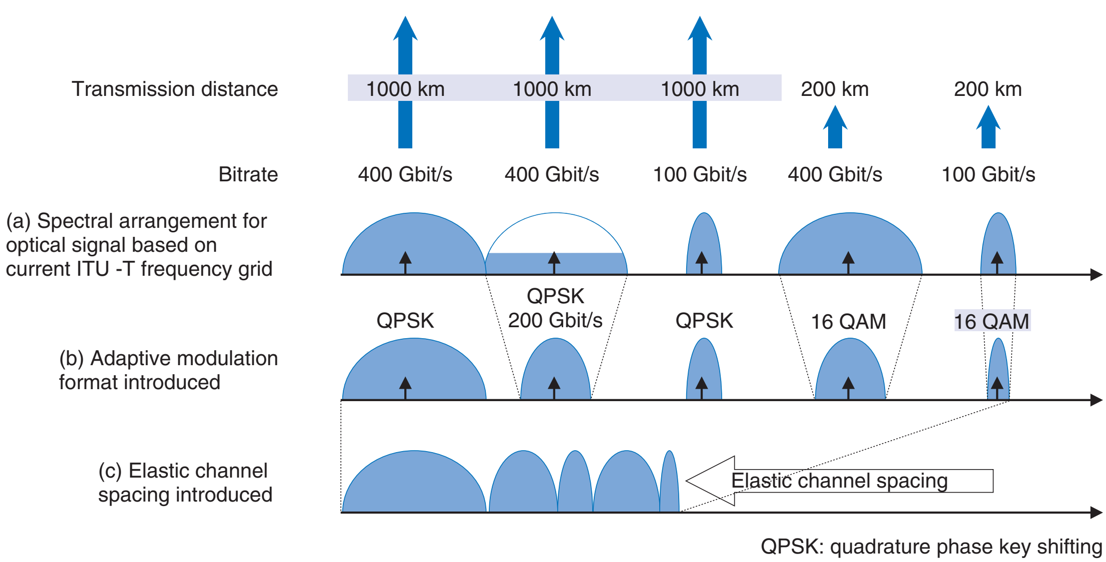

Fig. 4. Adaptive optical frequency resource assignment for elastic optical network based on user traffic volume and transmission distance.

from less SNR degradation, we use a more spectrally efficient modulation format, such as 16QAM (16-state quadrature amplitude modulation). We utilize the excess transmission margin for shorter optical paths. Finally, combined with elastic channel spacing, where the required minimum guard band is assigned between channels, we can utilize the excess channel spacing. In this way, elastic optical path networks accommodate a wide range of traffic in a highly spectrally efficient manner.

Enhanced network availability is another important benefit of the elastic optical path network. When considering the multiple failures that may occur during a severe widespread disaster, there could be surviving detour routes, thanks to the mesh network topology. However, such detour routes may be unable to support

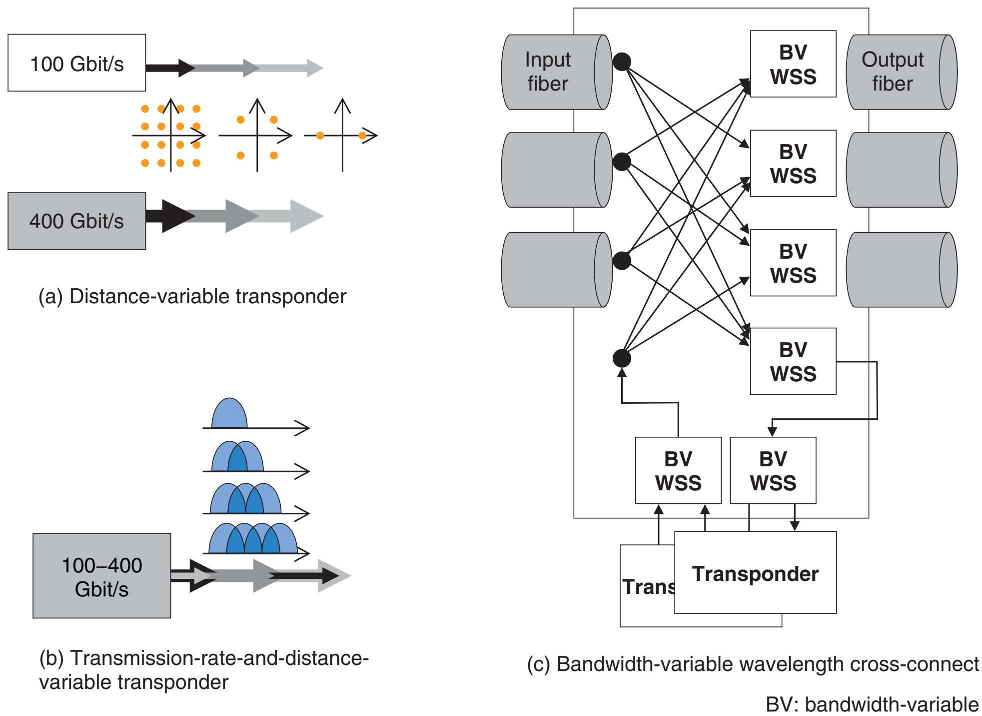

Fig. 5. Hardware technologies for elastic optical network.

sufficient spectral resources to transport the original data rate, and/or the length of the detour route could exceed the optical reach of the original optical signal. The unique features of adaptive spectral allocation and bandwidth/modulation-format optimization of the elastic optical network guarantee the minimum connection for high-priority traffic at the expense of bandwidth.

3.2 Enabling hardware technology

Emerging advanced modulation technology and the bandwidth-variable wavelength selective switch (WSS)*2 are two key enablers for the elastic optical path networks [8] [9]. By taking advantage of multi-level modulation and tightly spaced multi-carrier modulation based on optical orthogonal frequency division multiplexing (OFDM)*3, or Nyquist-WDM*4, we can select the optimum combination of three parameters for an optical signal, i.e., the symbol rate, number of bits per symbol, and number of sub-carriers, in order to achieve the required optical reach*5 (**Fig. 5(a)**) and/or transmission capacity (**Fig. 5(b)**) while minimizing allocated spectrum resources. The bandwidth-variable WSS is a 1 × N switch or filter providing a continuously tunable and variable seamless transmission spectrum. The flexible bandwidth reconfigurable optical add drop multiplexers (ROADMs) and wavelength cross-connects (WXCs) that use bandwidth-variable WSSs based on liquid crystal on silicon (LCoS) or digital light processing (DLP) technologies enable the forwarding of channels having arbitrary spectral widths to arbitrary output ports (**Fig. 5(c)**).

3.3 Management and control technology

To achieve the elastic optical path network, in which the required optical spectral resources are

*2 WSS: An optical switch that has one input and N outputs. It provides both wavelength multiplexing/demultiplexing functions and switching functions. The arbitrarily combined wavelengths in the input wavelength multiplexed signal can be divided into arbitrary outputs.

*3 OFDM: A digital modulation scheme that consists of multiple orthogonal subcarrier signals with the frequency spacing equal to the baud rate.

*4 Nyquist WDM: Wavelength division multiplexing of optical pulses having an almost rectangular spectrum with bandwidth ideally equal to the baud rate.

*5 Optical reach: Transmittable distance without optical-electrical-optical regeneration.

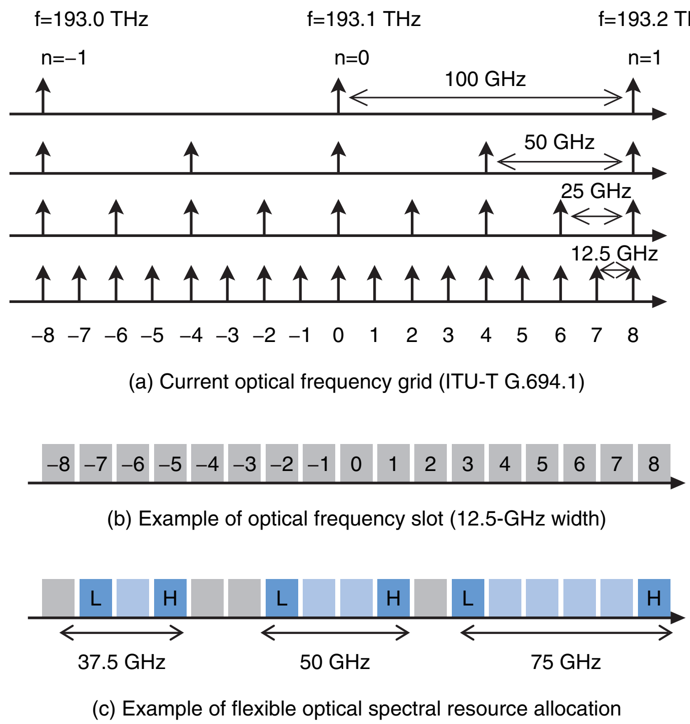

Fig. 6. Introduction of optical frequency slot based on flexible optical spectral resource allocation.

adaptively allocated to optical paths, we need a novel spectral resource notation scheme that expands the current ITU-T-standardized frequency grid (**Fig. 6(a)**). One promising approach is to introduce the concept of a frequency slot, as shown in **Fig. 6(b)**. For example, in correlating the current frequency grid with the minimum channel spacing, a 12.5-GHz-wide frequency slot is considered as a candidate. By allocating consecutive multiple slots to an optical path, we can specify the required spectral resources [10] (**Fig. 6(c)**).

The problem of calculating routes for optical paths in conventional transparent optical networks is called the routing and wavelength-assignment (RWA) problem with the wavelength-continuity constraint in the longitudinal direction along the route. Adaptive spectral allocation in elastic optical path networks introduces more severe constraints for spectrum-continuity in the longitudinal direction as well as on the frequency axis. We call this the routing and spectrum-assignment (RSA) problem. If the frequency slot concept is introduced, then the RSA problem results in a problem that can be solved by calculating a suitable route while guaranteeing the required number of consecutive slots along the route [8].

4. Conclusion

In this article, we introduced two technologies to support the future optical network: innovative optical transmission technology and elastic optical network technology. NTT is investigating, as a long-term initiative, transmission capacity expansion by more than three orders of magnitude by accelerating research on innovative optical transmission technology, namely new multiplexing technologies such as SDM and MDM used in a new power-tolerant and nonlinearity-tolerant enhanced transmission medium.

Furthermore, as a mid-term initiative, the introduction of the elastic and adaptive control concept to the optical layer lets us effectively utilize the SE and we are advancing elastic optical network technology research. While promising various benefits, the elastic optical path network concept brings new challenges in achieving cost-effective solutions at both the operational and equipment levels. We anticipate that such challenges will be overcome and that the elastic optical path networking technology will provide a more efficient and highly available optical network infrastructure for the future Internet and services.

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Service and Technology Overview of Multimedia Broadcasting for Mobile Terminals

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Abstract

This article briefly explains the multimedia broadcasting service for mobile terminals planned to start in Japan in spring 2012, after the frequency band currently used for terrestrial analog broadcasting became available in July 2011, and the technology that will support it. This service is based on the ISDB-Tmm (integrated services digital broadcasting, terrestrial mobile multimedia) system. Part of the system will use technology from NTT's research and development.

1. Introduction

Multimedia broadcasting for mobile terminals is scheduled to begin in Japan in spring 2012 using the ISDB-Tmm (integrated services digital broadcasting, terrestrial mobile multimedia) system*1 in the frequency band from 207.5 MHz to 222 MHz that became available after terrestrial analog television (TV) broadcasting ended in July 2011 [1].

The ISDB-Tmm broadcasting system is an expansion of the ISDB-T (T: terrestrial) system [2], [3] being used for terrestrial digital TV broadcasting and provides a service that combines two media, communications and broadcasting, which have different characteristics. As major features, the system makes use of the excellent mobile reception of terrestrial digital TV and offers extended capabilities such as improved video quality, the transfer of various kinds of large files such as video and voice, and interworking with communication functions. The main divisions in the system configuration are the broadcasting system and the information system. This article describes the planned application of technology that arose from NTT's research and development (**Fig. 1**).

In September 2010, the Ministry of Internal Affairs and Communications authorized Multimedia Broadcasting (mmbi) [4] as a consignment broadcaster (explained below) using a framework that separates hardware and software in the implementation of multimedia broadcasting in the form of consignment broadcasting and consigned content broadcasting [5]. mmbi then established Japan Mobilecasting, Inc. [6] in January 2011 and transferred the license to operate as a consignment broadcaster in February of that year (**Fig. 2**).

A broadcasting content consigner creates and organizes the programming, performs authentication, and handles charges and settlement as well as the broadcasting work for delivering the program; a consignment broadcaster broadcasts the data received from the consigner nationwide.

Of the frequency band opened up by the ending of analog broadcasting (90–222 MHz), 33 segments for nationwide broadcasting (207.5–222 MHz) are planned for use by Japan Mobilecasting, and mmbi is

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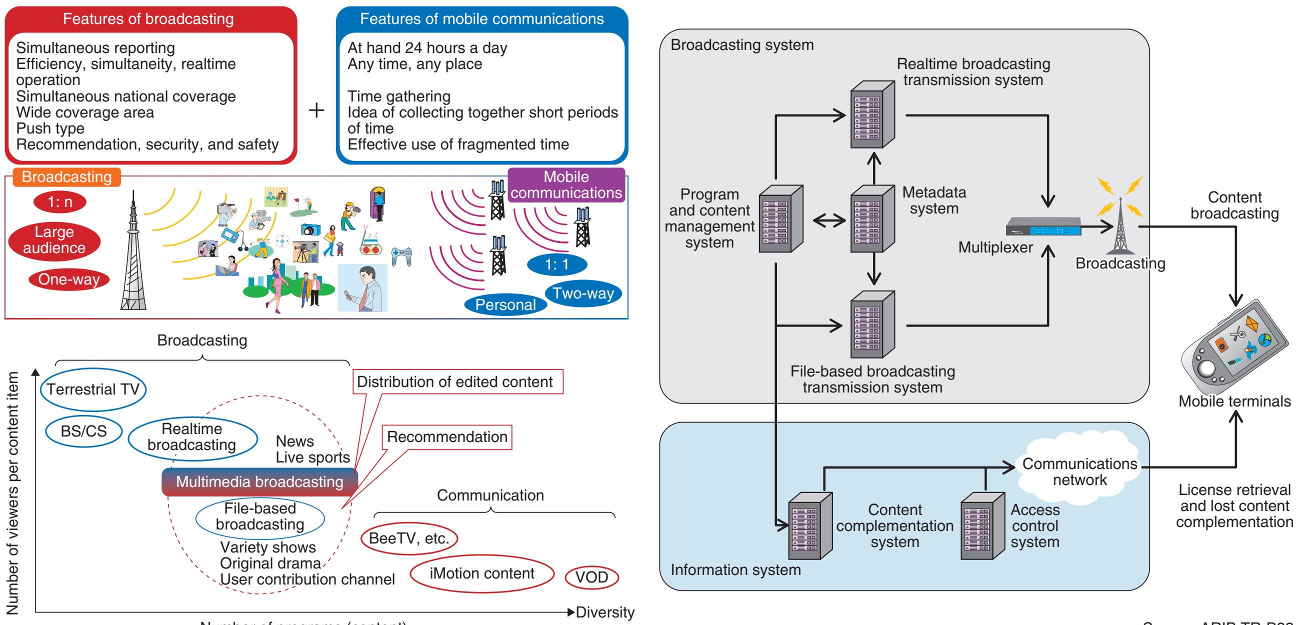
*1 ISDB-Tmm system: A multimedia broadcasting system for mobile terminals and specifications for multimedia broadcasting for mobile devices. It supports stored content in addition to the viewing of realtime video.



Source: ARIB TR-B33

ARIB: Association of Radio Industries and Businesses
BS: broadcasting satellite
CS: communications satellite
TR: technical recommendation
VOD: video on demand

Fig. 1. Multimedia broadcasting concept and system configuration.

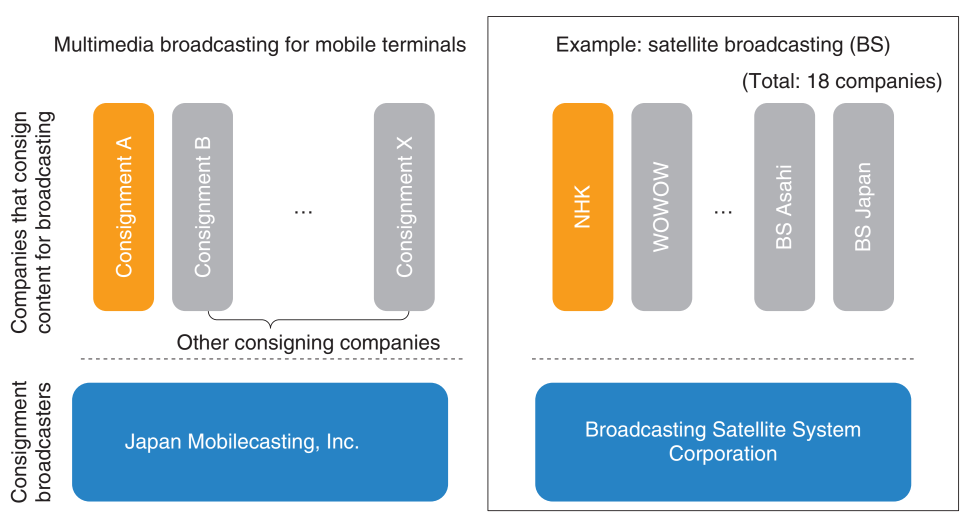


Fig. 2. Consignment broadcasters and content consigning companies.

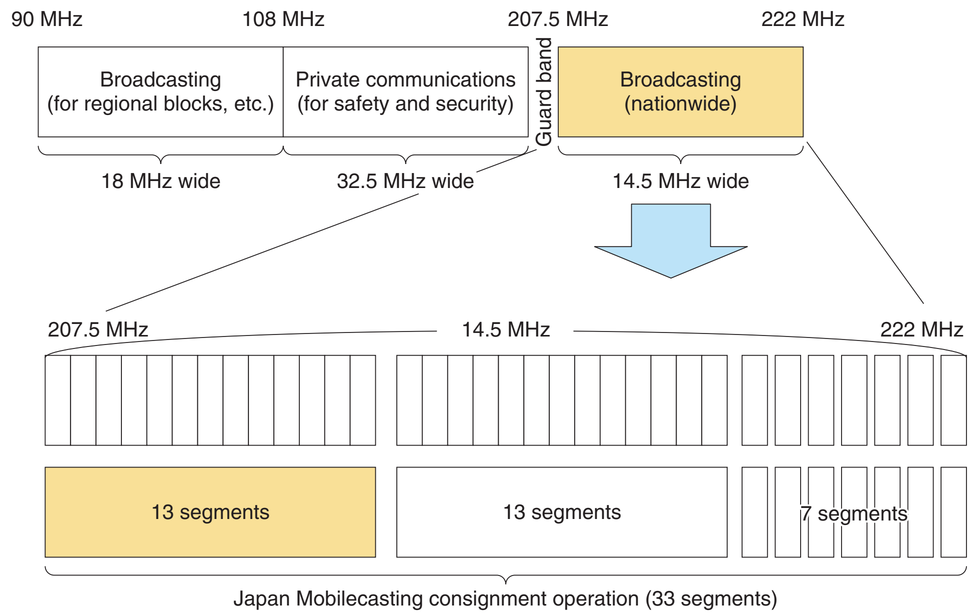


Fig. 3. Segment use.

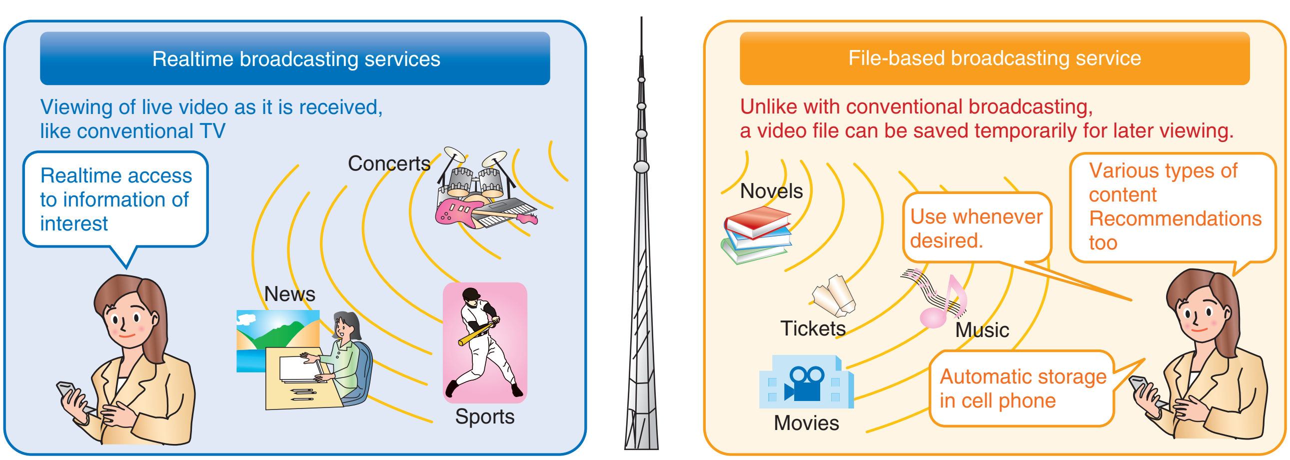


Fig. 4. Services provided by multimedia broadcasting.

planning to enter the consignment broadcasting business (**Fig. 3**).

2. Services provided by multimedia broadcasting

Services that are provided by multimedia broadcasting are broadly classified as those provided by realtime systems and those provided by stored content systems (**Fig. 4**).

2.1 Realtime broadcasting

Realtime broadcasting services involve program viewing at the time of the broadcast. That is to say, realtime broadcasting can be regarded as corresponding to the one-segment broadcasting (One-Seg) offered for cell phones and mobile terminals, but multimedia broadcasting extends that service in the ways described below.

Table 1. Image quality comparison.

	Format	Screen size	Frame rate (fps)
One-Seg	QVGA	320 x 180	Approx. 15
Multimedia broadcasting	QVGA	320 x 180	Approx. 15
	QVGA (added)	320 x 180	Approx. 30
	525HHR (added)	352 x 480	Approx. 30
	525SD (added)	720 x 480	Approx. 30

QVGA: quarter video graphics array
525HHR: 525 lines, half horizontal resolution
525SD: 525 lines, standard definition

(1) Improved quality

The quality of video in multimedia broadcasting supplements the One-Seg specification with three additional schemes (**Table 1**). ISDB-TMM uses 13 segments in contrast with One-Seg. Thus, even video that contains fast motion can be viewed clearly, and viewing with sufficient image quality is possible on large-screen tablets and smart phones and even on larger external displays that have HDMI (high-definition multimedia interface) as well as on conventional cell phones. For good audio quality, HE-AAC (high-efficiency advanced audio coding) and HE-AACv2 are provided in addition to the MPEG-2 AAC used for One-Seg. In the future, MPEG Surround will also be available as soon as the environment for it is prepared.

(2) Improved interworking with other media

One-Seg broadcasting also provided functions for interworking with various media, initiated by a TV program. Nevertheless, that system was focused on TV, and the interworking with other media was not necessarily active. In multimedia broadcasting, on the other hand, communication-derived content offered via a communication function is handled with relative freedom by the receiver. Multimedia broadcasting also inherently involves two different types of broadcasting system (realtime and stored). Because of those and other such factors, the system is being extended in the direction of improved interworking with One-Seg, multimedia broadcasting (both realtime and stored), and communication-derived content, etc., assuming that the receiving cell phones, which were originally planned to be the multimedia broadcasting receivers, will be equipped with those functions. In other words, the communication function can be considered to be a standard function of multimedia broadcasting receivers. To take fullest advantage of that feature, the system is being configured to deliver broadcast content and communication-derived content through seamless interworking.

2.2 File-based broadcasting

Service provision by file-based broadcasting differs from realtime broadcasting in that the time scheduling and duration of viewing or use of the content is not the same as the scheduling and duration of the broadcast. That is to say, as the term *file-based* indicates, the service assumes that the receivers receive and temporarily store the broadcast content before it is actually viewed or used.

Thus, good content viewing or use can be expected even in locations that have poor reception of broadcast waves, such as underground areas or inside buildings. The content that is received and stored is in the form of ordinary files that are widely used by personal computers, so e-books, games, and various other types of content that cannot be handled by conventional broadcasting can be provided as well as video and audio. Because services can be premised on the receiver having a communication function, as mentioned above, services that are highly aware of interworking with the communication function are being planned.

2.2.1 Transmission technology

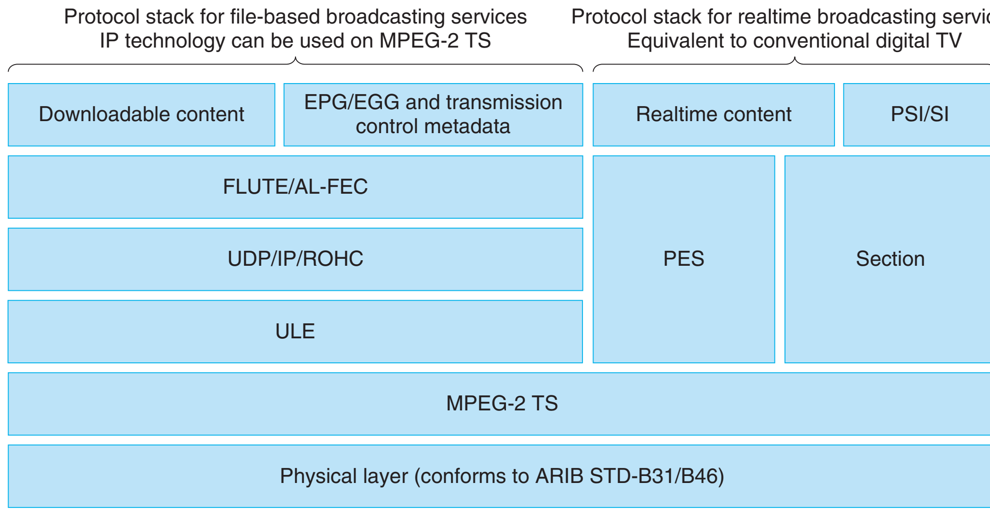
A major feature of file-based broadcasting is that any file can be delivered in a broadcast. To implement that feature, the protocol stack shown in **Fig. 5** and IP (Internet protocol) transmission technology are used. This transmission system has an application-layer forward error correction (AL-FEC) function that provides powerful error correction that can handle data loss over an extended time period—something that is difficult for the FEC function of the radio physical layer.

2.2.2 Stored content complementation technology

Although multimedia broadcasting uses powerful error correction to overcome errors in the received data caused by deterioration of broadcast reception conditions, if the limits of that function are exceeded (e.g., the receiver remains outside the broadcasting area), then the error correction function cannot produce the correct content. Nevertheless, content reception can be completed even though the broadcast has ended because the missing content can be received via the receiver's communication function (**Fig. 6**).

2.2.3 EPG/ECG metadata technology

File-based broadcasting differs from the conventional TV broadcasting service in that there is no concept of channels or scheduled times. On the other hand, file-based broadcasting requires content status



FLUTE: file delivery over unidirectional transport (see IETF RFC3926)
PES: packetized elementary stream
PSI/SI: program specific information, service information
ROHC: robust header compression
STD: standard
TS: transport stream
UDP: user datagram protocol
ULE: unidirectional lightweight encapsulation

Source: ARIB STD-B45

Fig. 5. Multimedia broadcasting protocol stack.

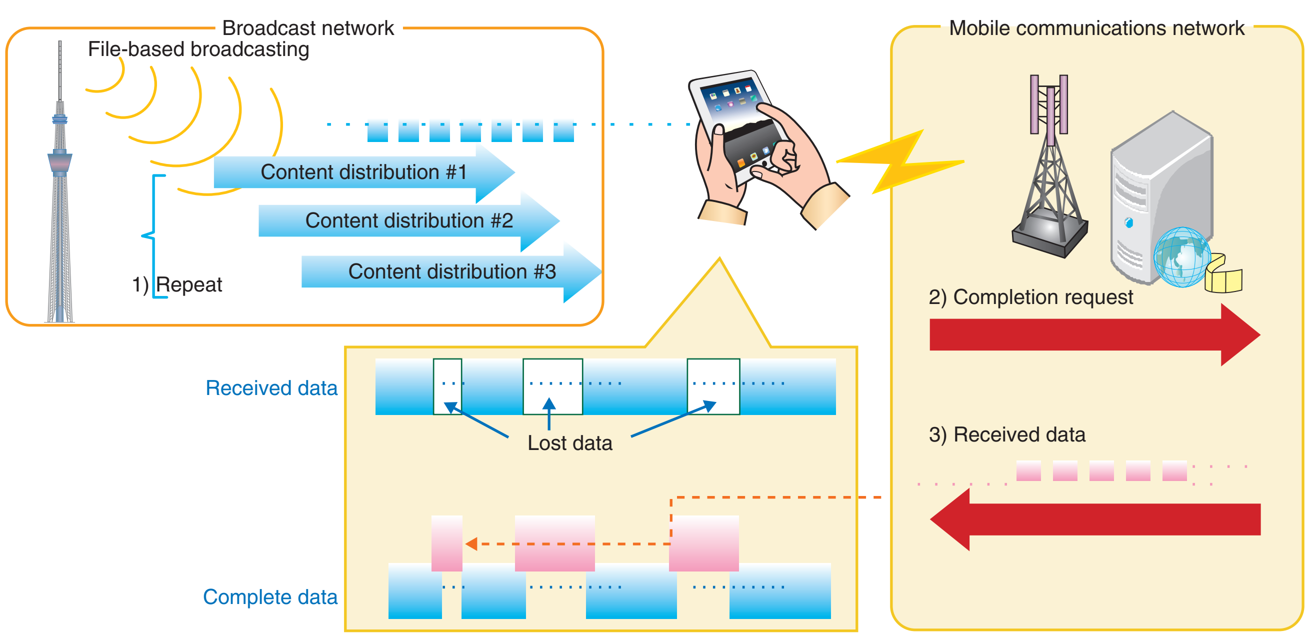


Fig. 6. Stored content complementation technology.

management, for example, prior to broadcasting, during storage, and of viewable (usable) content, which is not required by the previous form of TV broadcasting. Another requirement is a function for managing

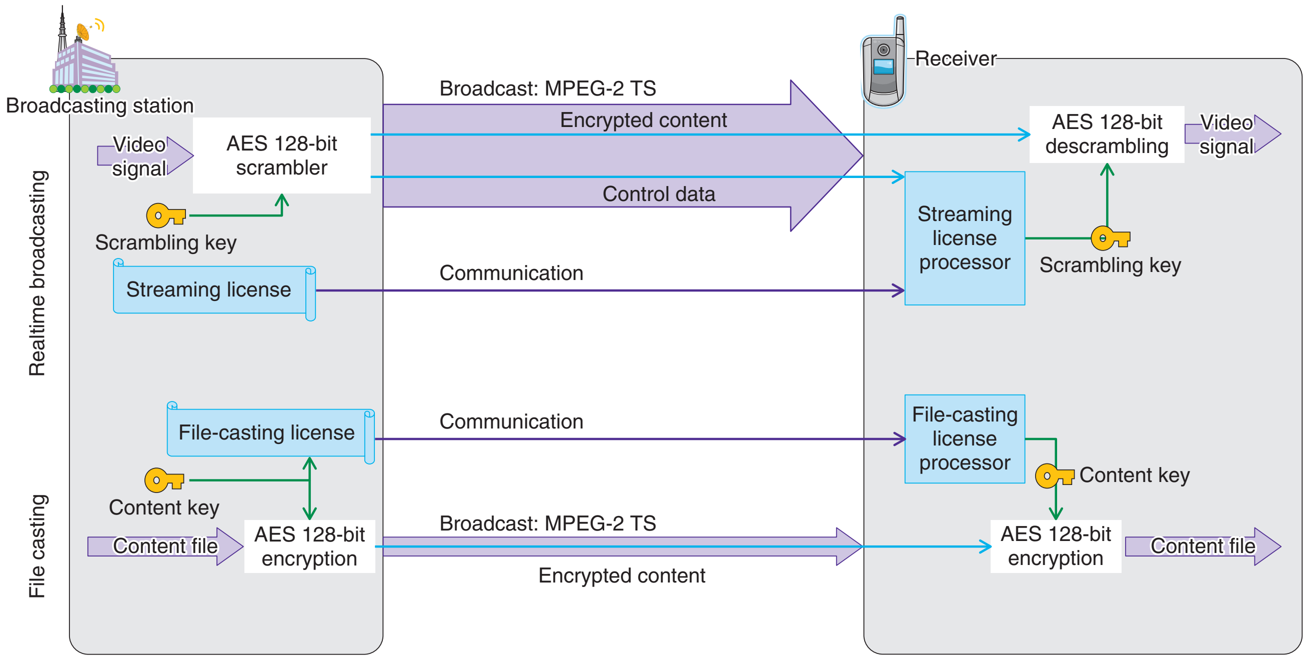


Fig. 7. Content protection and access control.

content with respect to the receiver's storage capacity and allowing the user to easily understand the storage status. The solution is electronic program guide & electronic content guide (EPG/ECG) metadata. This includes various types of information about individual programs and other items of content in the XML (extensible markup language) format that can be used by the receiver to present the user with information about content in a way that is easy to understand. It also provides a basis for recommending new content according to the user's prior content viewing (usage history).

2.2.4 Content protection and access control technology

Multimedia broadcasting differs from the One-Seg service in that it assumes a charged broadcasting model. In other words, it must be possible to permit content viewing (use) by users who pay a charge, but restrict viewing by users who do not pay the charge. Content protection and access control technology fulfills that requirement.

The main feature of the content protection and access control technology for multimedia broadcasting, as shown in **Fig. 7**, is delivery of the content by broadcasting and delivery of the license for viewing (using) the content via the communication channel. Another feature is the use of a stronger encryption algorithm than is used for previous digital broadcasting.

3. Conclusion

Multimedia broadcasting takes advantage of the many excellent features of the current terrestrial digital TV and further improves content quality, offers a file-based broadcasting service, and achieves content diversification through interworking with the communications function. An even greater variety of functional extensions is planned for the future. The other Feature Articles in this set introduce metadata technologies in multimedia broadcasting for mobile terminals [7], access control in multimedia broadcasting for mobile terminals [8], and storage-based broadcasting in multimedia broadcasting for mobile terminals [9].

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Metadata Technologies in Multimedia Broadcasting for Mobile Terminals

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Abstract

In this article, we explain metadata technologies with a focus on the use of metadata in multimedia broadcasting, which is a new type of broadcasting media service for mobile terminals that uses the new technical standard for broadcasting, ISDB-Tmm (integrated services digital broadcasting, terrestrial mobile multimedia), and offers both realtime and storage-based broadcasting services.

1. Introduction

Multimedia broadcasting is a broadcasting media service that provides live broadcast contents with high image and sound quality and storage-based broadcasting service in which contents are stored automatically and can be viewed anytime, anywhere. In particular, the storage-based service offers a wide variety of contents (images, documents, games, applications, files, and coupons in addition to video and audio programs). It enables that the integrated use of those two types of services and seamless browsing of their contents.

Our project has been researching and developing metadata technologies for content navigation, i.e., browsing, searching, retrieving, purchasing, and viewing content. In this article, we outline metadata, metadata delivery, and metadata operation in multimedia broadcasting and describe a metadata system that we have developed.

2. Metadata in multimedia broadcasting

Metadata in multimedia broadcasting consists of (1) EPG/ECG metadata, which contains information related to an electronic program guide (EPG) and electronic content guide (ECG) used for navigating content and (2) transmission control metadata, which contains information related to the reception, storage, and content complementation*1 of storage-based broadcast content. Metadata information elements and metadata usage are outlined in **Fig. 1** and explained below.

2.1 EPG/ECG metadata

The metadata schemas in multimedia broadcasting extend those in ARIB STD-B38 [1] and in TV-Anytime Phase 1 [2] and Phase 2 [3] to make them applicable to multimedia broadcasting service (ARIB: Association of Radio Industries and Businesses; STD: Standard). They consist of the nine metadata information elements described below. Among them, the coupon information element is newly introduced.

(1) Program information element

It describes general information about content such as Title, Synopsis, Genre, CreditList, and TitleImage. It is uniquely identified by a Content Reference Identifier (CRID).

(2) Group information element

It describes information about a group (series, package, etc.) of multiple program-information elements or multiple group-information elements. It is also uniquely identified by a CRID.

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*1 Content complementation: missing data is sent by the communication function and stored in order to complement the transmission by broadcasting and ensure that all of the content is received.

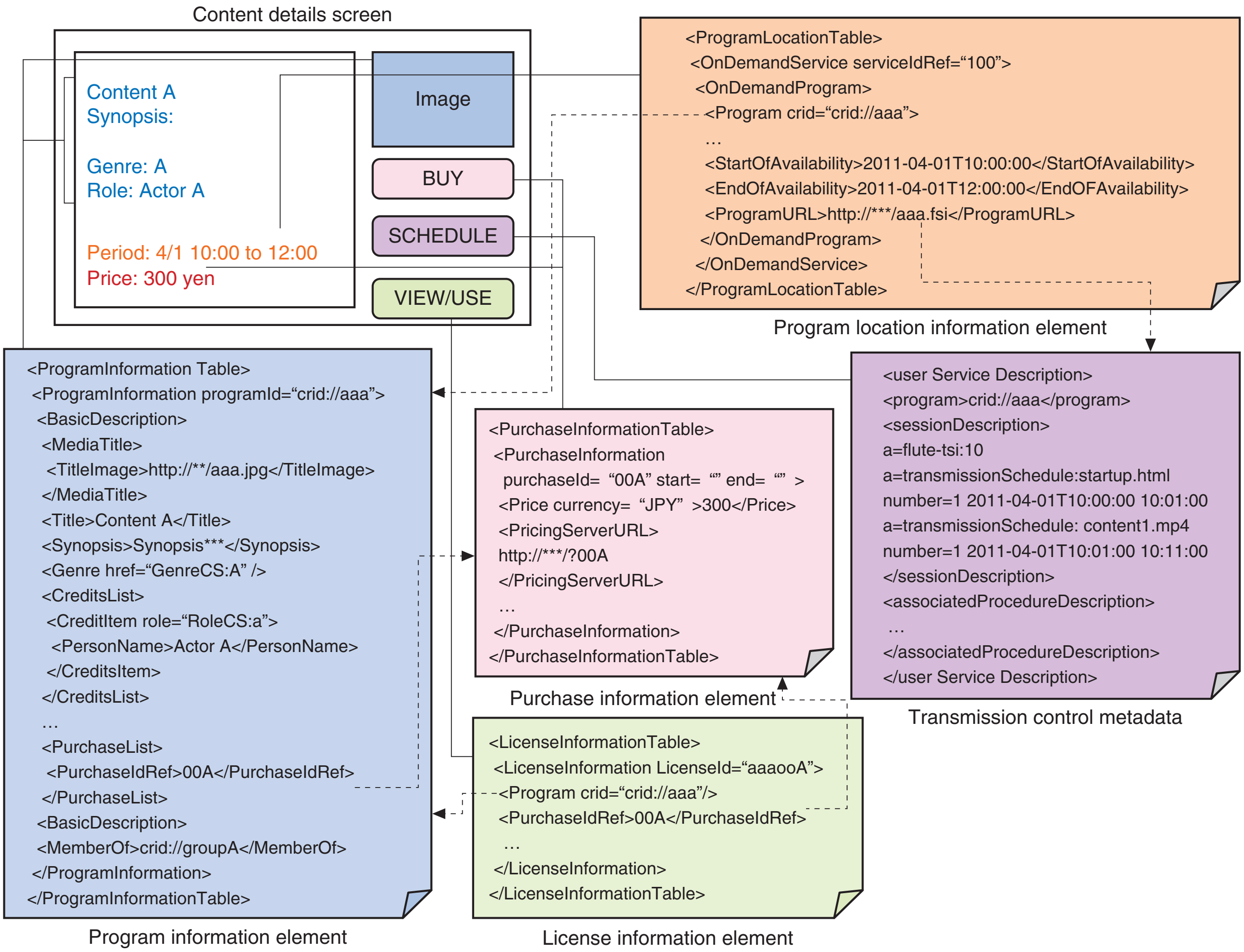

Fig. 1. Metadata in multimedia broadcasting.

(3) Program location information element

This element has been extended to describe real-time and storage-based broadcasting services. The OnDemandService element describes information about storage-based broadcasting content, such as the channel (serviceIdRef) in the OnDemandService element and the broadcast period (StartOfAvailability, EndOfAvailability) and the uniform resource identifier (URI) of transmission control metadata (ProgramURL) in the OnDemandProgram element. The BroadcastEvent element describes information about realtime broadcasting content, such as the channel, broadcast period, and output restrictions.

(4) Service information element

It describes information about the service (channel) such as service name, service synopsis, and logo.

(5) Purchase information element

It indicates a purchase item, which is the charging unit for an individual content item or group, and describes information about the purchase item such as sales period, price, sales pattern (PayPerView, PayPerMonth, etc.), and URI for purchasing (PricingServerURL).

(6) License information element

The License is uniquely determined by a content (Program) and product (PurchaseIdRef) set and supports a variety of charging formats. It describes the number of times the content can be viewed or used and the period during which the content can be viewed or used, etc. It also describes license-issuing conditions and preview information (number of times, ending time, etc.) of realtime broadcasting content.

(7) Segment information element

It describes information related to a scene in video and audio content such as the scene's start and end points, name, and thumbnail URI. It can also be applied to a chapter playback function.

(8) Segment group information element

It describes information related to a group (chapter list etc.) that combines multiple segment information elements.

(9) Coupon information element

A coupon service will be provided in multimedia broadcasting in accordance with market trends. The coupon information is newly introduced. It describes information about a coupon such as coupon name, amount of discount, and period of validity. It also describes the reference relationship with the product targeted by the coupon as well as the reference relationship with the content or purchase item from which the coupon is being provided.

2.2 Transmission control metadata

Transmission control metadata extends the metadata in the Third Generation Partnership Project (3GPP) [4] to make it applicable to multimedia broadcasting service. It consists of three information elements.

(1) User service description

It contains the two information elements described below and describes the CRID as a key for establishing the correspondence between EPG/ECG metadata and transmission control metadata. Furthermore, the CRID indicates the logical storage location of received content within the device. For example, if a device uses an SD (Secure Digital) memory card, the content is stored at /private/tmm/aaa/ (in the case of crid://aaa). In this way, the user can use the stored content even if he or she moves the SD memory card to another device.

(2) Session description

It describes information related to the reception of content such as a FLUTE (file delivery over unidirectional transport) session ID (a=flute-tsi), the destination address for broadcasting the content, and the content size. It also describes the file names of all transmitted objects, the transmission order of those objects, and the transmission period (a=transmission schedule), etc.

(3) Associated delivery procedure description

It describes information for content complementation such as the server URI and period for content complementation, which is a threshold for performing content complementation. It also describes the server URI and schedule for submitting a reception report, etc.

3. Metadata transmission and delivery

In multimedia broadcasting, metadata is provided by both broadcasting and communication. When it is transmitted by broadcasting, the bandwidth required for transmitting it and the frequency of its reception must be considered. Two methods have been proposed: one method transmits small amounts of metadata often (method A), while the other transmits large amounts of metadata periodically (method B).

3.1 Metadata transmission by broadcasting

(1) Metadata transmission method A

This method transmits the metadata for content that will be delivered within a few hours (e.g., 48 hours) from now. The metadata transmitted by this method is updated over time (e.g., at one-hour intervals) and the same metadata is periodically retransmitted within the time frame, as shown in **Fig. 2(a)**. This approach provides metadata for generating an EPG/ECG for the next few hours within a short time and for updating the EPG/ECG immediately when a program is changed.

(2) Metadata transmission method B

This method groups together the metadata for content that will be delivered within a fixed period (e.g., 2–7 days from the present) and transmits it as storage-based broadcast content. The metadata transmitted by this method is updated on a regular schedule (e.g., every day from 01:00 to 01:10), as shown in **Fig. 2(b)**. This approach provides the large amount of metadata for generating an EPG/ECG for a certain fixed period at one time and minimizes the bandwidth required for transmitting it.

3.2 Metadata delivery by communications

In this approach, the device sends a search request by either HTTP GET*2 or POST*3 to the metadata system operated by the service provider and receives metadata or a list of metadata (a list of CRIDs)

*2 GET: A method for requesting a page from a server.

*3 POST: A method used when transferring form data to a server.

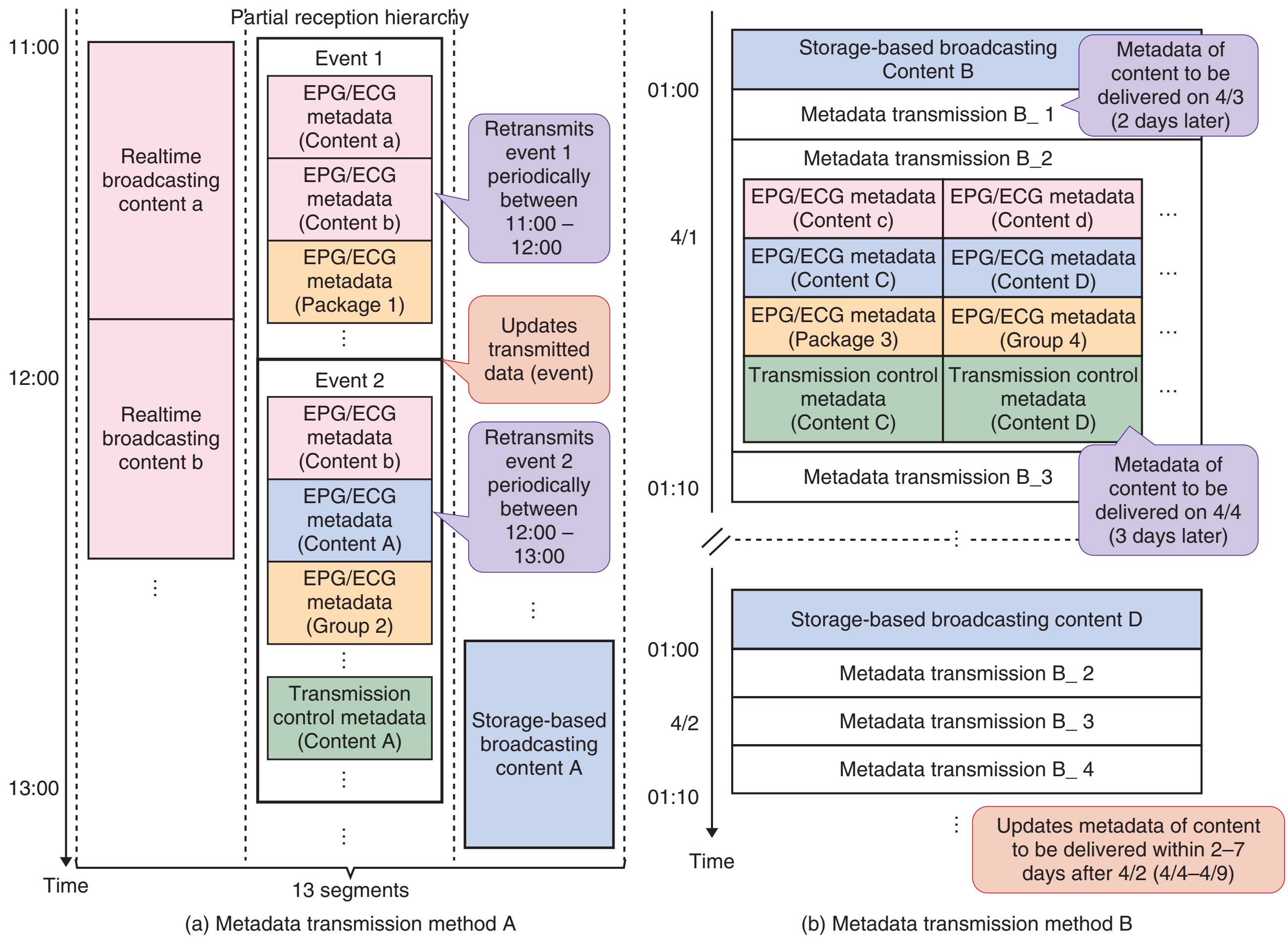

Fig. 2. Metadata transmission by broadcasting.

corresponding to the search request. There are several query patterns such as searching by content title, keywords, period, and cast and some sorting functions such as sorting search result by content title, release date, duration, etc.

4. Metadata usage

This section introduces the use of metadata for multimedia broadcasting with a focus on elements and attributes that have been added or extended for this purpose.

4.1 Content attributes

Multimedia broadcasting can handle a wide variety of content such as documents and applications in addition to video and audio programs. For this reason, a Content Properties element for describing the content attributes of the wide variety of content has been added. This element describes, for example, the type of content (audio, video, image, document, metadata set, etc.), file format (html, mp4, jpg, pdf, zip, container), and file size. Here, file size can be used to calculate the amount of memory needed to a store the content when it is ordered.

4.2 Device attributes

Many types of devices will be used in multimedia broadcasting and the specifications of mobile phones from different mobile carriers differ widely. This means that the type of content that can be handled will depend on the device. For this reason, a list describing the types of devices that can handle content (usable by all devices, usable by only devices of mobile carrier A, etc.) has been defined. Device attributes are described in the Genre element of metadata.

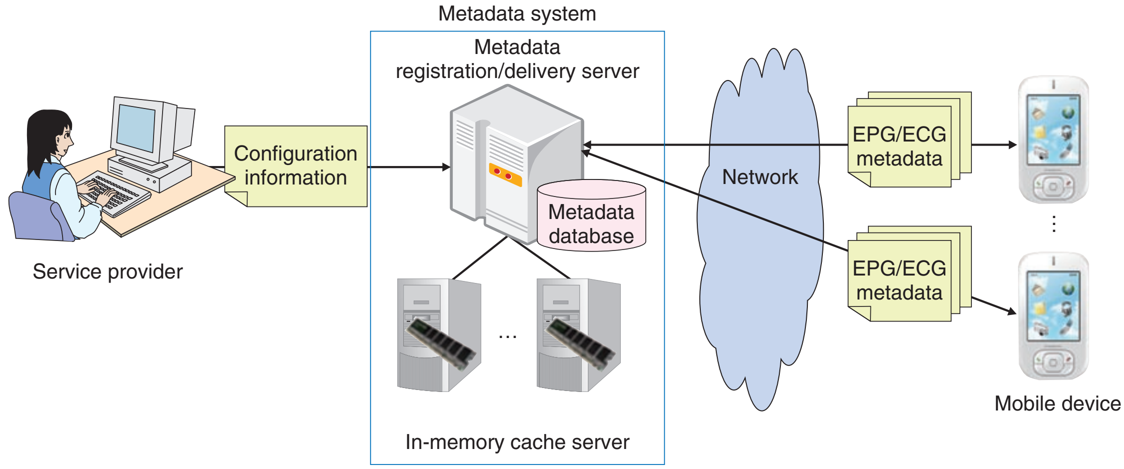

Fig. 3. Metadata system.

4.3 Version

The functions and features of devices (screen size, number of colors, supported audio/video codecs, etc.) are diverse and content specifications (profile and level of video, version of markup language, etc.) are also diverse. Moreover, new functions and specifications will be added.

To cope with this situation, version information is broken down by the functions that devices have and described in the keyword element of metadata. Here, the device compares the version information described in the metadata with its own version information and judges whether it can use the content corresponding to the metadata (it is judged to be usable if the device version is greater than or equal to the content version).

4.4 Event Information Table and metadata linkage

In multimedia broadcasting, both the EPG and ECG are generated using metadata. Moreover, to enable immediate EPG/ECG updating in response to program changes (extensions, interruptions, etc.), an Event Information Table (EIT) of the present, preceding, and subsequent programs is operated. The EIT is linked to EPG/ECG metadata by including the EIT's service ID and event ID in the EPG/ECG metadata's CRID.

4.5 Advanced expression

It is now common for mobile email and web pages to embed links, images, and pictograms. For this reason, EPG and ECG are being given the same advanced expression by encapsulating <A> or <img> tags in a CDATA section and they describe the CDATA section in the title or synopsis element of metadata.

5. Metadata system

The configuration of a metadata system for registering, managing, and delivering metadata by communications for use in multimedia broadcasting is shown in **Fig. 3**.

The metadata registration and delivery server receives configuration information from the service provider and generates EPG/ECG metadata, which conforms to the multimedia broadcasting schemas and registers that metadata in the metadata database. In the registration process, the EPG/ECG metadata is broken down into elements and attributes and registered in attribute tables in order to deal with a wide variety of searches. The metadata is also converted to binary format MPEG-7 (BiM) to minimize the data size and registered in a document table. The server is equipped with a function for receiving search requests from devices and returning search results.

The in-memory cache server manages a memory cache of search results and a memory cache for search requests set up beforehand on the operator side. In this process, reconstructed search requests are used as keys and the body of the search results are used as values.

If identical requests are received, the use of these caches can speed up the search response time (8.4 times faster on average than using the database) and reduce the processing load during simultaneous searches from many devices.

6. Future activities

The launching of commercial services for multimedia broadcasting requires the establishment of standards and technical reports, the development of a variety of systems, and trial operations. NTT Cyber Solutions Laboratories aims to contribute to the realization of multimedia broadcasting services and the linking of these services with other types of services and technologies.

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Access Control in Multimedia Broadcasting for Mobile Terminals

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Abstract

This article explains access control technology and content protection technology that will serve as content security measures when multimedia broadcasting is provided as a pay service. High-quality audio-visual streaming services based on ISDB-Tmm (integrated services digital broadcasting, terrestrial mobile multimedia) are planned for 2012. They are expected to include realtime services and storage-based services.

1. Introduction

ISDB-Tmm (integrated services digital broadcasting, terrestrial mobile multimedia), which will be used for multimedia broadcasting services that are scheduled to begin in Japan in 2012, can be considered to be one of the most advanced commercial schemes in terms of security technology supporting the content business and in terms of using the combination of broadcasting and communication. This article mainly explains the functional requirements for the content security technology, including what conventional technology is inherited and the potential for developing the conventional technology. Notices from the Japanese Ministry of Internal Affairs and Communications (MIC) and relevant standard specifications are also mentioned.

2. Content security technology

In the content business, the distribution of valuable content requires guarantees that the content will be used only as permitted. Content security technology serves to satisfy this requirement.

The multimedia broadcasting services are scheduled to include subscription-based services. Since the beginning of subscription-based digital broadcasting services, it has been possible to use the conditional access system (CAS) to restrict content viewing to the receivers used by contract-holders.

Businesses that handle products and digital content and apply security technology for digital transactions used in electronic payments are now common. Digital content differs from food products and other such goods in that its value as a commercial product remains the same even after use. Therefore, digital content must include a function for limiting its use to within the usage rights. Digital rights management (DRM) is one system that includes functions for both electronic payment management and content usage rights management.

For multimedia broadcasting, the realtime broadcasting service and the storage-based broadcasting service described in an MIC report [1] are assumed. Those services take advantage of the features of CAS and DRM. The service and access control technology requirements for the two services are described in **Table 1**.

3. Notices and standards related to ISDB-Tmm

ISDB-Tmm has been systematized and expanded, beginning with BS (broadcast satellite) in 2000 and then CS (communication satellite, ISDB-S) and terrestrial digital broadcasting (ISDB-T). It is important that these broadcast media were effectively configured so that they could be received by the same receivers.

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Table 1. Access control technology for multimedia broadcasting.

	Service requirements		Applicability of CAS/DRM	
	Realtime service	Storage-based service	CAS	DRM
Multicasting	Video distribution system with unlimited number of distributions	Access control does not work during storage.	◎	Unicast distribution; facility requirements correspond to transaction volume.
Realtime viewing	Video output can begin right after stream selection.	Viewing can begin only after the content has been stored and decrypted.	◎ Realtime (except for contract update)	A few seconds are required for license issuing.
Content storage	Not needed (personal-use recording permitted)	Anytime, anywhere within the usage rights	—	◎
Diversity of sales	Channel and program unit	Content unit	○	○
Setting of usage rights	Channel and program unit	Content unit	○	◎

Table 2. Comparison of content security schemes (access control).

		Multimedia broadcasting	Current broadcasting (ISDB-T)	IPTV (for reference)[*1]
Realtime	Scrambling	Scrambling key change (several seconds to several tens of seconds) MPEG2-TS packet unit[*2] (IPTV is MPEG2-TTS)		
		MIC Notice No. 40 Standardization: Association of Radio Industries and Businesses (ARIB)		Not specified by MIC Private sector standardization: IPTV Forum
	Encryption algorithms	MULTI2 64-bit block encryption AES, Camellia 128-bit block encryption	MULTI2 64-bit block encryption	Set independently by operator (realtime retransmission with consent of broadcasters) Usually AES, etc.
Storage-based	Encryption scheme	Mainly in units of content, usually files		
		Not specified by MIC	Not used	Not specified by MIC
	Encryption algorithm	Standardized by ARIB		Private sector standardization: IPTV Forum
		Not specified. ARIB STD-B25, Part 4 Encryption algorithm or equivalent recommended	Not specified. ARIB STD-B25 at least DES or equivalent recommended	AES
ITU international standardization status		Nothing directly, but it is possible to refer to ARIB STD-B25 from BT.1306 System C.		X.1191 describes an overview and requirements

Likewise, it is important to utilize new cryptanalysis technology as the processing power of computers increases.

Placing importance on the balance between consideration of implementing the ISDB-T system for cell phones and mobile terminals and effective use of secure-client modules already in wide use for cell phones etc. in multimedia broadcasting as well, the relevant MIC Notices have been compiled as Technical Conditions for Multimedia Broadcasting Systems for Mobile Terminals. That served as the basis for Ministerial Ordinance and Notice revisions. The results relevant to content security are listed and compared with current broadcasting and Internet protocol television (IPTV) in **Table 2**.

ISDB-Tmm was revised in an April 2010 Notice [2] related to the conventional digital broadcasting (ISDB-T) base. For the encryption algorithm used in

Table 3. Content protection methods.

Broadcast system	Entry control, etc.
Broadcasting channel	Content encryption
Communications channel	Content encryption
Receiver function	Content encryption
Storage memory	Content encryption
Renderer	Compliance by receiver manufacturers
External display	Use of HDCP (high-bandwidth digital content)* or other display device specifications that allow content encryption (* example of a de facto standard)

the scrambling method for realtime broadcast content, AES (advanced encryption standard) and Camellia, which differ in basic structure from 128-bit block encryption and have been thoroughly analyzed for encryption strength, were added to the MULTI2 64-bit block encryption to mitigate particular encryption risks. Broadcasters can select from among those three algorithms for their implementations. Moreover, "Conditional Access System Specifications for Digital Broadcasting" in Part 4 of ARIB STD-B25 was newly established as a standard specification (ARIB: Association of Radio Industries and Businesses; STD: Standard). Furthermore, "Multimedia Broadcasting Conditional Access System (CAS) Operation and Receiver Specifications" in section 5 of ARIB TR-B33 and "Content Protection for Multimedia Broadcast" in section 8 are set as technical reports (TRs).

4. Access control

Most content must be protected by a certain minimum strength of security throughout the process from the moment the broadcaster obtains the content until the broadcast (including content complementation) and during the viewing or use at the receiver until the content is deleted. Content security technology requires content protection technology.

4.1 Content protection technology

The methods for protecting content from the time of broadcast up to storage in the receiver's memory device are described in **Table 3**. Even if the receiver is owned by a legitimate contract holder, any weakness in its security might be exploited in an attempt to use the content in ways outside the content rights. The strength of content protection depends largely on the implementation of the rendering function (video decoding etc.), which is the main target of such threats.

Broadcasters and receiver manufacturers agreed specific compliance rules that are based on the content rights holder's consent for using and implementing content protection functions in the receiver on the basis of those rules.

One approach that is being considered allows combinations of validity period for viewing, number of replays, and other such use content usage rights restrictions to be set as Rights Management and Protection Information (RMPI) so that the conditions for content use can be selected for each item of content.

4.2 Access control requirements

Since the broadcast content is transmitted via a broadcasting channel, the signal might be received by anyone within the broadcasting service area. Conditional access is technology for restricting use of content to only the receivers for which there is a subscription contract for pay services etc.

In the conditional access method (**Fig. 1**) for the content, the scrambling key for decrypting the content, *Ks*, is encrypted and broadcast as the ECM (Entitlement Control Message) in sync with the content packets (by multiplexing). The ECM includes the subscription contract information and the corresponding scrambling key (*Ks*). Because the scrambling key is broadcast in sync with the video and audio, the receiver can use that key to play the video and audio immediately after a channel for which a contract exists has been selected. The subscription contract information for each receiver is sent to the receiver as the EMM (Entitlement Management Message) via the broadcasting channel or communications channel. In this way, the most recent contract information is updated in the EMM and viewing control for a very large number of users can be achieved by reference to the ECM that is broadcast in sync with the content.

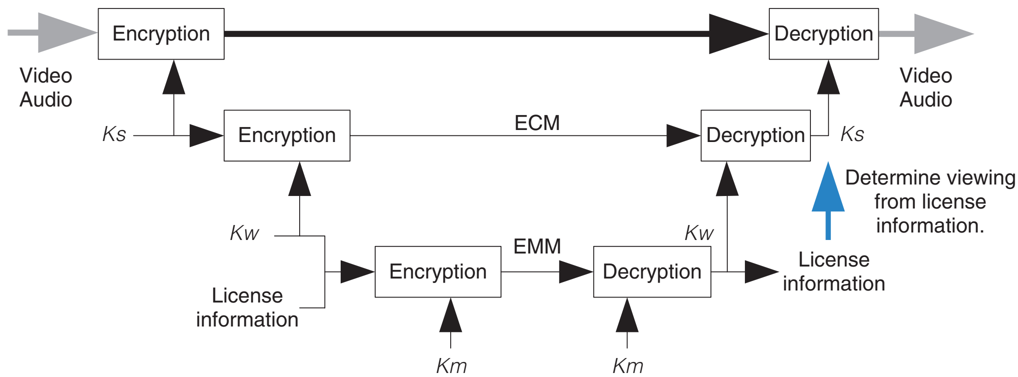

Fig. 1. Overview of CAS.

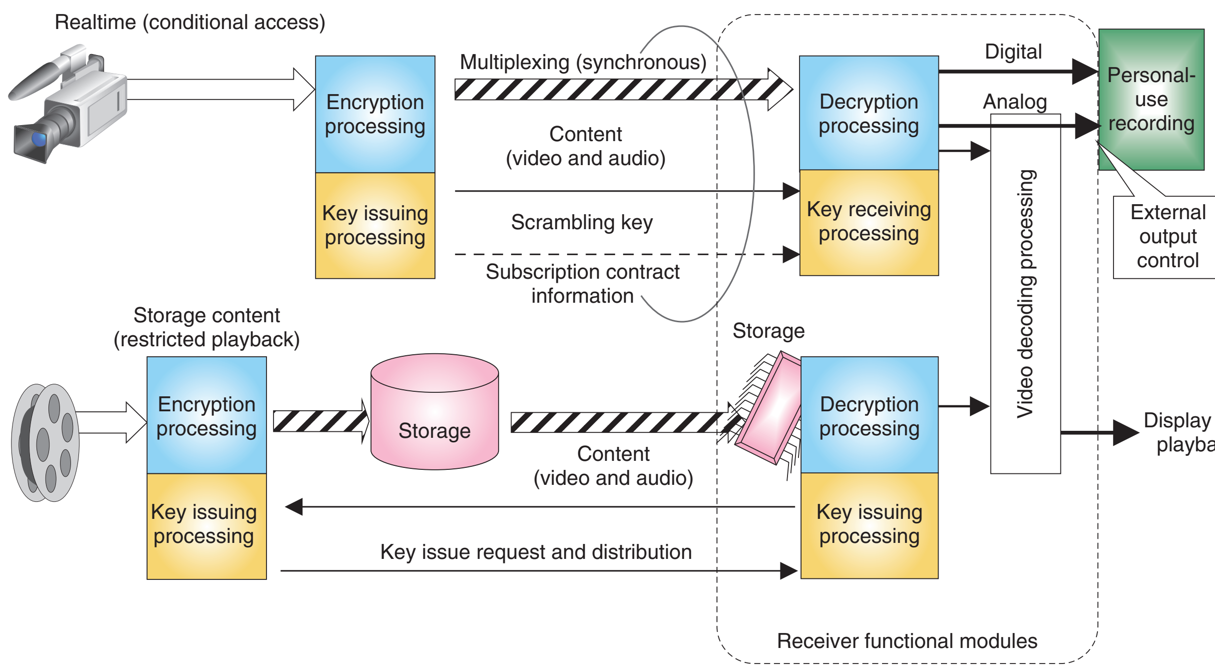

Fig. 2. Content security system.

4.3 Implementation requirements related to development and operating costs

The most important factor that is common to all security measures for application to commercial services for ordinary consumers is the cost-to-performance ratio. With respect to content protection, a much higher level of security is desirable to prevent loss of profit by the content provider. On the other hand, systems that have stronger content security are more expensive. Consequently, use of an excessively strong security function leads to a decrease in the user experience by lowering system performance, effectively increasing the cost of service provision. Furthermore, not all of the requirements are satisfied by security technology: legitimate use by the subscriber according to the terms of the legal contract with the service provider is related to effectively inexpensive provision of service at good quality. The actual implementation of the receiver functions takes this kind of security balance into account.

5. Security implementation technology

Because pay services are assumed for multimedia broadcasting services, the services can be implemented with security on the basis of ARIB STD-B25, the standard specifications for the technology currently being used for BS, CS, and terrestrial digital while addressing the following concerns.

- The receiver implementation shall not specify physical shapes.
- Because the broadcasting is done in a narrow bandwidth, the EMM, which is specific information for individual subscribers, shall be delivered mainly via a communications channel.
- Receiver cost should be reduced by sharing the security functions implemented in cell phones etc.

The content security system planned for multimedia broadcasting is illustrated in **Fig. 2**. The upper part of the figure shows a system for realtime broadcasting service and the lower part shows one for storage-based service.

Current commercial broadcasting does not include storage-based services, but ARIB TR-B27 [3] summarizes the results of studies on services for the digital broadcasting system based on a home server as a technical report. We consider that storage-based services can be implemented by specializing some of the service functions of the digital broadcasting system based on a home server. For storage-based services, it will be necessary to receive an encryption key. The issuing of the key is referred to as the issuing of a license. The main information contained in that license is 1) link information to the content, 2) a key for decrypting the content, and 3) RMPI that specifies the content usage rights.

6. Conclusion

Multimedia broadcasting is the newest service in digital broadcasting. Its technical architecture can be expected to engender services make the most of the advantages of telecommunication and broadcasting technologies through the fusion of cell phone and receiver functions. In addition to inheriting technology from the ISDB architecture, there is high cross-compatibility with the IPTV technical architecture, so services that implement horizontal integration of media can also be expected.

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Storage-based Broadcasting in Multimedia Broadcasting for Mobile Terminals

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Abstract

This article outlines the technology behind storage-based broadcasting, which is provided in addition to realtime broadcasting in multimedia broadcasting for mobile terminals. It can deliver large files of multimedia content to users in an efficient manner via broadcast systems.

1. Introduction

Storage-based broadcasting services will be provided as well as realtime ones in multimedia broadcasting for mobile terminals using the ISDB-Tmm (integrated services digital broadcasting, terrestrial mobile multimedia) standard. Storage-based broadcasting is a new broadcast service that enables large files of multimedia content to be delivered to receivers over broadcast systems. In such services, users will be able to watch and enjoy content during the allowed period for viewing or using it.

2. Technologies for storage-based broadcasting

The ISDB-Tmm protocol stack is shown in **Fig. 1** and the process flow from the content file to the transmission of TS (transport stream) packets[*1] is shown in **Fig. 2**. Realtime broadcasting in ISDB-Tmm is provided by a packetized elementary stream (PES) on an MPEG-2 TS (Motion Pictures Expert Group-2 Transport Stream), the same as in ISDB-Terrestrial (ISDB-T). Storage-based broadcasting, on the other hand, uses a number of protocols for the transmission of various content files over the broadcast system. These protocols include AL-FEC (application layer, forward error correction) coding, FLUTE (file de1ivery over unidirectional transport), UDP/IP (user datagram protocol, Internet protocol), ROHC (robust header compression), and ULE (unidirectional lightweight encapsulation). Storage-based broadcasting also specifies a new file repair mechanism that uses the cellular network to recover lost data over the broadcast system.

3. AL-FEC coding

In storage-based broadcasting, AL-FEC coding is applied to content files to enhance their packet loss tolerance even in severe wireless channel conditions for mobile reception. AL-FEC coding generates source symbols and parity symbols from the content file (object) and applies time interleaving before transmission to them. The AL-FEC coding mechanism is outlined in **Fig. 3**. The AL-FEC coding partitions the object to be transmitted into source symbols, from which parity symbols are generated. Symbols that are lost in the wireless channel can be recovered from the source and parity symbols.

3.1 LDPC-Staircase

In ISDB-Tmm, LDPC-Staircase (low-density

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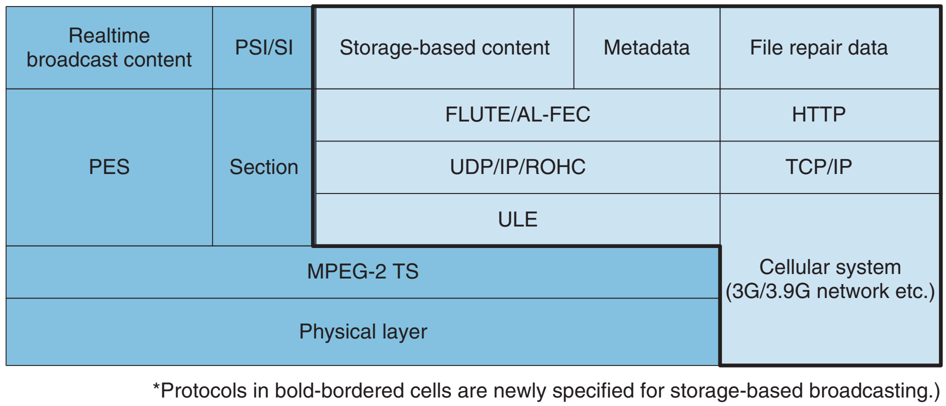
*1 TS packets: Packets used in transmission-multiplexing systems mainly in broadcast networks as specified in MPEG-2 Systems.



G: generation
HTTP: hypertext transfer protocol
PSI/SI: program specific information, service information
TCP/IP: transmission control protocol, Internet protocol

Fig. 1. ISDB-Tmm protocol stack.

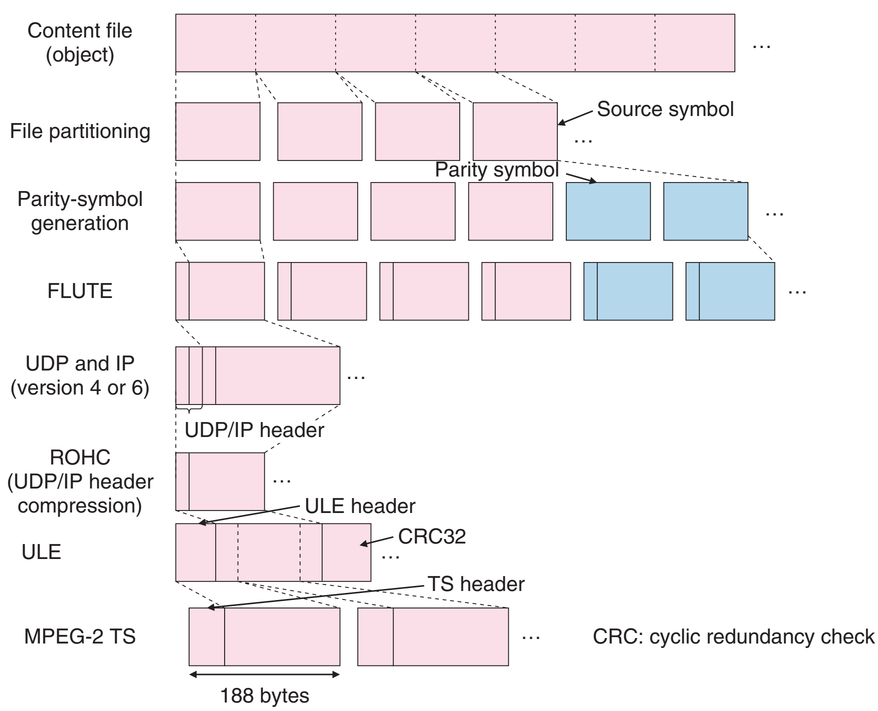


Fig. 2. Process flow from content file to TS packet generation.

parity check staircase) [1] codes are used as an AL-FEC coding scheme. LDPC-Staircase uses a parity check matrix for encoding and decoding. This check matrix consists of two matrices: a left-side matrix and right-side one. The left matrix indicates the source symbols, and the right one indicates the parity symbols. The left matrix is created by inserting 1s in elements selected by a random sequence and degrees. The right matrix is created by simply inserting 1 into matrix elements (i, i-1). An example of a parity check

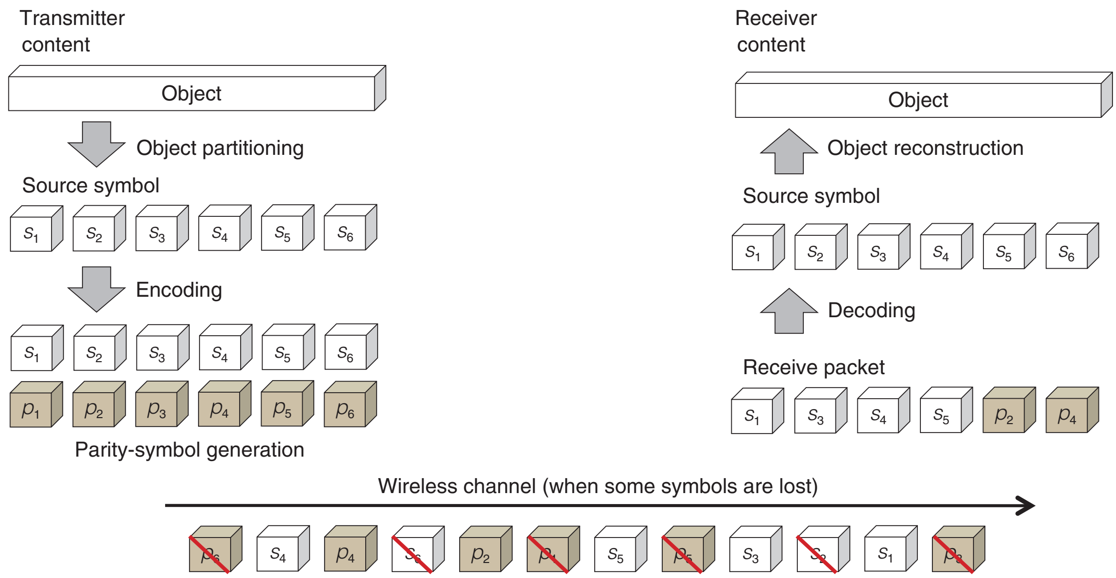


Fig. 3. Outline of AL-FEC coding.

Staircase check matrix in LDPC coding

$$\left(\begin{array}{cccccc|cccccc} 1&0&0&1&0&1&1&0&0&0&0&0\\ 0&0&1&0&1&1&1&1&0&0&0&0\\ 0&1&0&1&1&0&0&1&1&0&0&0\\ 1&1&0&0&0&1&0&0&1&1&0&0\\ 0&1&1&0&1&0&0&0&0&1&1&0\\ 1&0&1&1&0&0&0&0&0&0&1&1 \end{array}\right)\begin{pmatrix} s_1\\ s_2\\ s_3\\ s_4\\ s_5\\ s_6\\ p_1\\ p_2\\ p_3\\ p_4\\ p_5\\ p_6 \end{pmatrix} = 0$$

Left-side check matrix   Right-side check matrix

Fig. 4. Example of a parity check matrix in LDPC-Staircase.

matrix is shown in **Fig. 4**. Here, the symbols S_1-S_5 and P_1-P_6 indicate source symbols and parity symbols, respectively.

3.2 Comparison of AL-FEC coding systems

To select an AL-FEC coding algorithm for ISDB-Tmm, we evaluated three algorithms at the same computational complexity. These three algorithms were (1) DSM-CC (digital storage media command and control) (2) Reed-Solomon codes*2, and (3) LDPC-Staircase. The simulation conditions are listed in **Table 1** and simulation results in terms of receive success rate (ratio of users who eventually received the full content to all users) versus TS packet error rate are shown in **Fig. 5**. The simulation results reveal that to achieve a receive success rate of 95%, the TS packet error rate must be less than 1% for DSM-CC but can be as high as 8% for Reed-Solomon codes and 13% for LDPC-Staircase. Thus, according to these results, LDPC-Staircase is the most tolerant algorithm to packet loss in the broadcasting system.

4. FLUTE

The FLUTE protocol manages content-transmission sessions in a broadcast network. An example of mapping from a FLUTE session to MPEG-2 Systems in ISDB-Tmm is shown in **Fig. 6**. In ISDB-Tmm, a set of information to be delivered to the users such as video or data is treated as a single object and managed by a Transport Object Identifier (TOI). One item of content managed by the Transport Session Identifier (TSI) is composed of multiple objects. This content is transmitted on MPEG-2 Systems by mapping the TSI to a Packet Identifier (PID)*3. FLUTE transmits a File Delivery Table (FDT) instance periodically to provide various types of attribute information about the content being transferred.

*2 Reed-Solomon codes: Error-correcting scheme used in digital devices.

*3 PID: Value used for identifying a TS packet in MPEG-2 Systems.

Table 1. Simulation conditions.

	Retransmission	Reed-Solomon Codes	LDPC-Staircase
Size of sent file	100 Mbytes		
Packet size	940 bytes (five MPEG-2 TS packets)		
Loss rate	0.1–25% (MPEG-2 TS)		
Notes	Same data was transmitted three times periodically.	One block was generated from 12 packets. 24 FEC packets were generated per block.	Calculations assumed an average order* of 10

* Order: Value indicating how many source symbols were used on average to generate a parity symbol compared with nearly fixed computational complexity.

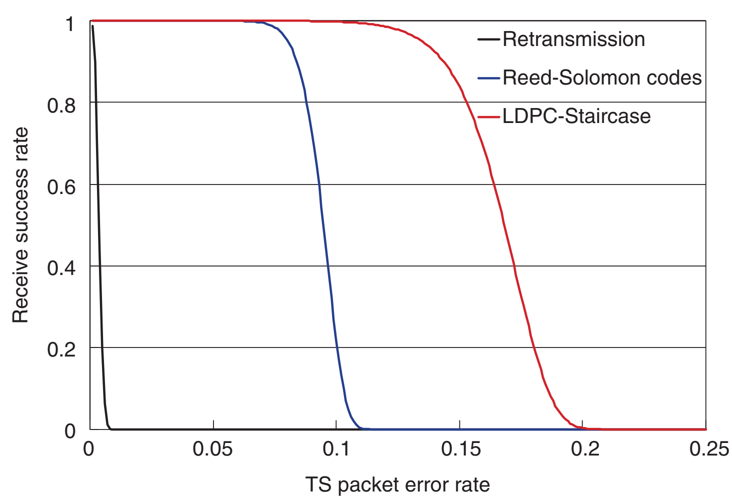


Fig. 5. Simulation results.

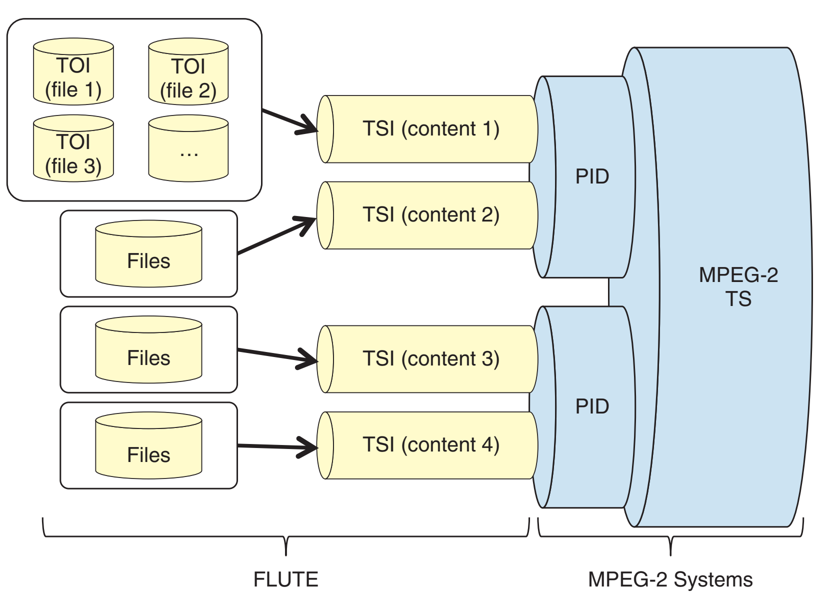


Fig. 6. Mapping from FLUTE to MPEG-2 Systems.

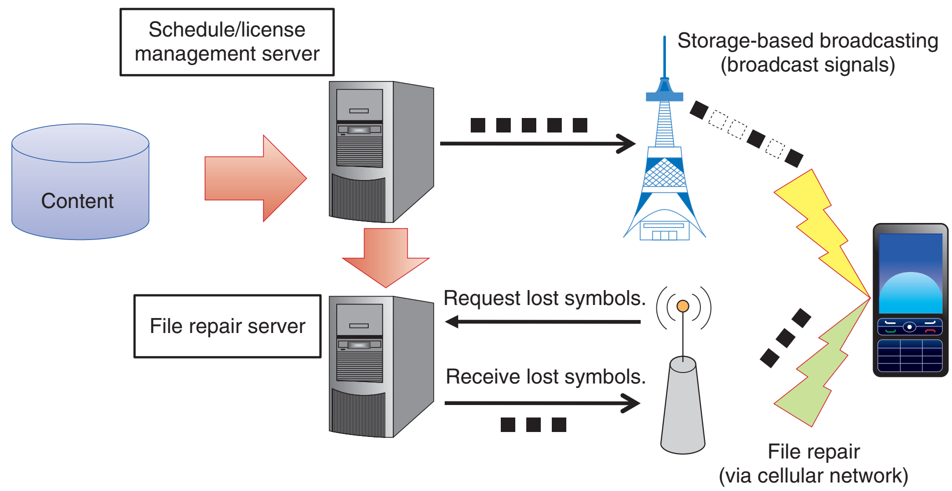


Fig. 7. File repair.

5. UDP/IP/ROHC

After FLUTE, UDP, and IP headers have been added, ROHC is applied to packets as a header-compression protocol considering that the frequency of information changes in the UDP and IP headers is very low. ROHC treats a flow of IP packets having the same header information (next header, source/destination IP addresses, source/destination port numbers) as a single set (context) and transmits only updated information in a UDP/IP header. For example, the 28 bytes normally required for the UDP/IP headers in IPv4 can be compressed to as little as 1 byte.

6. ULE

ISDB-Tmm uses encapsulation by ULE to transmit content files converted to IP packets on MPEG-2 Systems. When this standard was established, a value of Ox22F1 was registered for the ROHC Ethertype in the ULE header by IEEE (Institute of Electrical and Electronics Engineers).

7. File repair

7.1 File content repair mechanism

For storage-based service, it is important to provide reliable reception even when content is transmitted over a severe broadcasting channel. After AL-FEC decoding, portions of received content file that have been lost can be obtained via the cellular network, as shown in **Fig. 7**. In this file repair method, the receiver first identifies lost symbols in objects. It downloads source symbols needed for file repair from the file repair server over the cellular network and repairs the content. The file repair server transmits the lost content portions requested by the receiver using the content-range header in HTTP. The use of HTTP enables a generic HTTP server to be used as a file repair server.

There are two types of timing for file repair mechanisms, manual repair and automatic repair, which are defined with the aim of making content viewing more convenient for users. Manual repair is performed when the user begins to view the content, and automatic repair is performed automatically in advance of viewing. Congestion in the cellular network is avoided by distributing the file repair timing among users.

7.2 Unequal error protection

The early part of the content is likely to be viewed during file repair since manual file repair is being performed when the user starts viewing the content. If the packet loss tolerance of this early part could be increased by setting a high degree of redundancy by AL-FEC coding, it would be possible to achieve a smoother user experience. To do this, ISDB-Tmm uses unequal error protection (UEP), which enhances LDPC-Staircase coding. While the left-side matrix in LDPC-Staircase coding is normally arranged with 1s in a random manner, the UEP method notifies the receiver of the columns to give a high-density distribution of 1s. Applying UEP to LDPC-Staircase coding can increase packet-error resistance in early content by about 15% [2].

7.3 Optimal packet selection for file repair

For file repair, requesting all source symbols would increase the traffic load in the cellular network. It is therefore important to use received symbols effectively and to efficiently reduce the number of repair-request symbols. ISDB-Tmm has a scheme for optimally selecting packets for file repair. This scheme reduces the number of repair packets by about 50% compared with all lost packets being requested. When converted to TS packet error rate, this equates to an improvement in packet loss resistance of 7–8%.

8. Concluding remarks

Storage-based broadcasting is a new service that can deliver large files of multimedia content to users efficiently by using extensions to the ISDB-T standard. A storage-based service based on multimedia broadcasting is scheduled to be launched in Japan in spring 2012.

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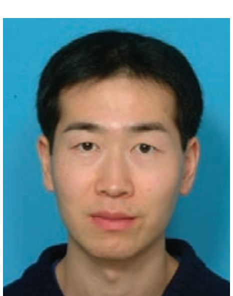

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Ultralow-energy All-optical Switches Based on Photonic Crystal Nanocavities

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Abstract

Photonic crystal cavities having a wavelength-sized volume exhibit a strong light-matter interaction, which makes possible all-optical switches operating with ultralow energy consumption. Using the combination of an extremely small photonic crystal nanocavity and strong carrier-induced nonlinearity in InGaAsP, we have successfully demonstrated low-energy switching in the attojoule range for the first time. This switching energy is more than two orders of magnitude lower than that of previously reported optical switches. The ultrasmall cavity also contributes to fast carrier diffusion and hence a fast switching response of 20 ps at minimum. These all-optical switches with their small size and low-energy, fast-response operation may open up the possibility of a dense photonic network on a chip.

1. Introduction

Photonics has played a key role in the progress of long-haul network links. On the other hand, although data processing at nodes or routers is still performed with integrated electronic circuits, their increasing power consumption and heat generation during high-bitrate operation is now becoming an obstacle to further improvements in network speed and traffic capacity. All-optical data processing with integrated photonic circuits is therefore expected to reduce the amount of power consumed by their electronic counterparts while keeping the high-speed properties of optical signals [1]. However, current photonic processing devices generally require a very high driving energy and are too big for integration, though future interconnect technology will demand micrometer-scale optical components in a chip consuming less than a femtojoule per bit [2]. These problems arise from the difficulty of confining light in a small volume and the weakness of light-matter interactions.

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Photonic crystal (PhC) cavities, which exhibit a high cavity quality factor (Q) and an ultrasmall modal volume (V), are promising candidates as platforms on which to construct devices with dimensions on the order of a few wavelengths of light in matter. Since optical nonlinearities can be greatly enhanced in high-Q, small-V cavities (the optical-field intensity is enhanced in proportion to Q/V), very low operating energy/power can be expected if we apply them to various functional devices. The all-optical switch, which enables gating of an optical signal, should be one of the fundamental elements for constructing photonic circuits [3]–[6], and it is a straightforward example of light-matter interaction enhancement by nanocavities [7]–[9].

A PhC nanocavity is schematically illustrated in **Fig. 1(a)**. A two-dimensional array of airholes is patterned into a semiconductor thin plate having a thickness of ~200 nm. A line defect and a point defect in the array can act as an input/output waveguide and a nanocavity, respectively. The PhC nanocavity can strongly confine light, thereby achieving a strong light-matter interaction and optical nonlinear functionalities [10], [11]. The operating principle of

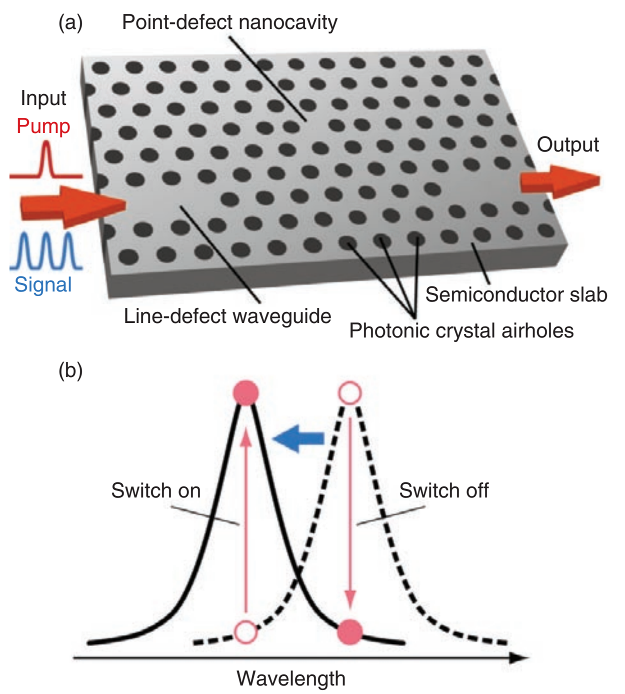

Fig. 1. All-optical switch based on photonic crystal nanocavity. (a) Structural schematic of PhC-nanocavity switch formed in semiconductor (InGaAsP) slab. (b) Operating principle of all-optical switching. Switch-on or switch-off operation is selected by the initial setting of the signal wavelength.

all-optical switching is shown in **Fig. 1(b)**. The pump and signal light pulses are injected into the waveguide simultaneously. The pump light generates carriers in the nanocavity and induces a wavelength shift in the resonant transmission spectrum, which makes it possible to control the signal light output.

This article clarifies the design principle for a PhC-nanocavity-based switch, namely, what type of cavity, nonlinearity, and material we should use. Devices based on our designs exhibit all-optical switching with operating energy in the attojoule range and a time window of a few tens of picoseconds. Our results clearly show that PhC nanocavities enable unprecedented all-optical switches that may lead to high-speed, low-power information processing on a chip.

2. Design

2.1 Smallest PhC cavity

Although we said that a high Q/V ratio is preferable for a lower switching energy, that is a bit too simple. In practice, we need to choose an appropriate Q according to the target operating speed because the photon lifetime in a cavity is proportional to Q. In contrast, cavity volume V should always be as small as possible. In this study, we used a lattice-shifted cavity (hereinafter referred to as an H0 cavity) [12]. The cavity mode consists of only two primary antinodes (**Fig. 2(a)**). Importantly, the H0 cavity has the smallest V among dielectric-core PhC cavities. In our simulation, V was calculated to be only 0.025 μm^3.

Another limiting factor for operating speed is the carrier relaxation time (τ_c). Generally, τ_c is as long as the nanosecond order, but PhC nanocavities offer an efficient way to reduce it. When the cavity becomes ultrasmall, the photogenerated carriers rapidly diffuse out from the cavity, and τ_c becomes small [13]. We numerically solved the carrier diffusion dynamics in a PhC nanocavity. First, we investigated the carrier dynamics without a cavity but assuming an initial Gaussian carrier distribution centered at a certain point in a defect-free PhC lattice. In Fig. 2(a), four black lines show the decay for different initial distribution sizes. They clearly show that a small excitation leads to surprisingly fast diffusion. We investigated more realistic cases with an H0 cavity, as shown by the red line. The fitted τ_c values are as short as 3.5 ps. The time evolution of the carrier distribution for the H0 cavity is shown in **Fig. 2(b)**. The carriers are initially localized in the cavity mode and then start to spread out. This result implies that we can expect a switching bandwidth of nearly 100 GHz. Consequently, it shows that an H0 cavity switch is promising in terms of high-speed response.

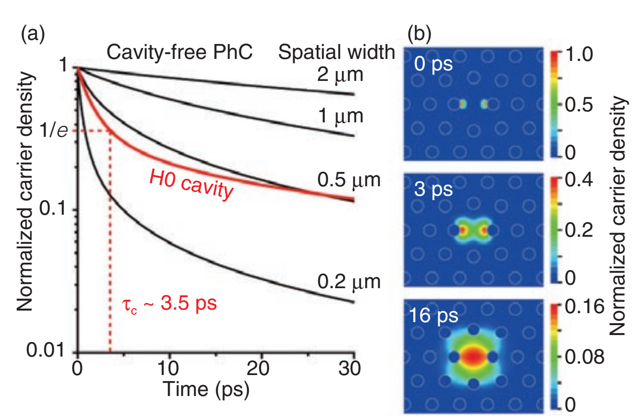

Fig. 2. Simulation results for carrier decay (a) Simulated carrier decay for an H0 cavity (red) and cavity-free PhCs (black). The Gaussian carrier distribution with different spatial widths is set for the cavity-free PhCs. (b) Time evolution of the carrier density distribution for H0 cavity.

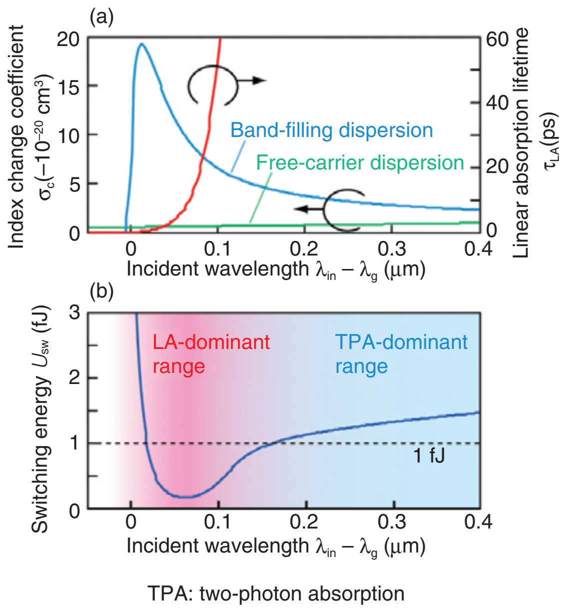

Fig. 3. Material optimization for minimizing switching energy. (a), Index change with carrier density (left axis) and linear absorption lifetime (right axis) as a function of incident wavelength detuning from a bandgap wavelength. (b) Calculated switching energy for parameters of InGaAsP-based H0 cavity.

2.2 Material optimization

To obtain lower switching energy, we want the pump light to be efficiently absorbed in the cavity and the subsequent refractive-index change to be large. InGaAsP is one compound semiconductor that exhibits these features effectively compared with other materials such as Si and GaAs at a wavelength of 1.55 µm.

Figure 3(a) shows the calculated index change and the linear absorption lifetime as a function of the incident wavelength detuning from the bandgap wavelength $\lambda_{in} - \lambda_g$. In our switch, all-optical switching relies on band-filling dispersion (BFD) and free-carrier dispersion in InGaAsP to obtain a refractive index change [14]. Since BFD depends strongly on the position of the electronic band-edge wavelength, we need to find an appropriate InGaAsP composition to suit the cavity's resonant wavelength. On the other hand, optical absorption relies on linear absorption (LA) and nonlinear two-photon absorption (TPA). LA also becomes stronger in the vicinity of the band-edge wavelength and allows efficient absorption. The important point is that excess absorption induces a degradation of cavity Q and increase in switching power, so appropriate adjustment of the composition is needed in order to minimize the switching energy.

The calculated switching energy U_{sw} for the H0 nanocavity is shown in **Fig. 3(b)**. In the vicinity of the band edge, LA boosts the absorption efficiency and BFD enhances the nonlinear resonance shift, thereby effectively reducing U_{sw}. This results in a minimum value of less than 1 fJ at around $\lambda_{in} - \lambda_g = 0.05$ to 0.1 µm. We adjusted the InGaAsP composition to set the photoluminescence peak to 1.47 µm for an operating wavelength of around 1.55 µm.

3. Switching demonstration

3.1 Fabricated H0 nanocavity

We fabricated H0-PhC cavities in an InGaAsP slab using standard top-down processes, including electron-beam lithography and Cl_2-based dry etching. A top-view image of the device is shown in **Fig. 4(a)**. The air-hole diameter, lattice period, and slab thickness are 230, 460, and 200 nm, respectively. The H0 cavity, which was formed by shifting two neighboring air holes by 85 nm in opposite directions, is coupled with input and output PhC waveguides. The transmission spectrum acquired by scanning a wavelength of continuous-wave light is shown in **Fig. 4(b)**. The periodic peaks in the spectrum are not a nanocavity mode, but appear as a result of interference with the Fabry-Pérot resonance caused by the facet end of the waveguide. The fitting curve (black) clarifies the nanocavity mode, indicating that the resonant wavelength λ_{cav} and linewidth are 1567.8 nm and 0.24 nm, respectively. The cavity Q factor is 6500 and the corresponding photon lifetime is τ_{ph} = 5.4 ps, which is slightly longer than the calculated carrier relaxation time of 3.5 ps and is thus unlikely to restrict the switching recovery time.

3.2 Pump-probe measurement

To measure the switching dynamics, we used a degenerate pump-probe technique with an optical pulse width of 14 ps [7], [15]. The center wavelength of the pump pulse was always set to the resonance wavelength, while the wavelength of the probe pulse λ_{probe} was set with detuning $\Delta\lambda_{det} = \lambda_{probe} - \lambda_{cav}$. Switching dynamics for different values of $\Delta\lambda_{det}$ are shown in **Fig. 4(c)**. For $\Delta\lambda_{det}$ = 0.0 nm, the transmission of the probe pulse was abruptly switched *off* when the pump pulse temporally overlapped the probe pulse. On the other hand, the probe transmission was switched *on* for $\Delta\lambda_{det}$ = –0.3 nm and –0.6 nm

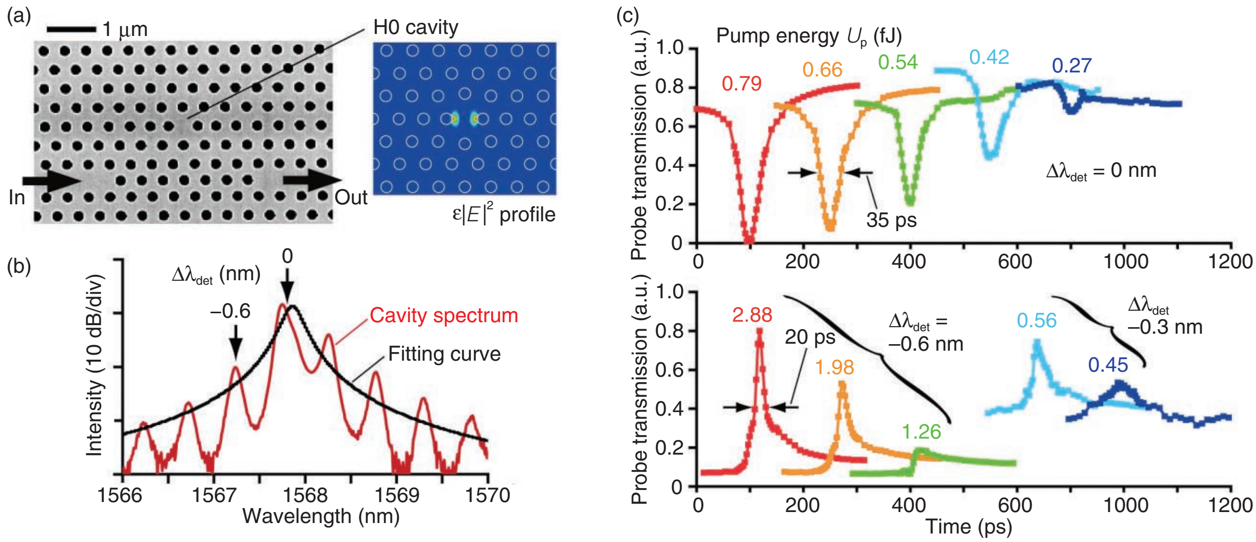

Fig. 4. Switching dynamics of PhC nanocavity acquired by pump-probe measurement. (a) Top-view image and simulated modal distribution of H0 PhC nanocavity. (b) Transmission spectrum scanned with a wavelength-tunable continuous-wave laser. (c) Switching dynamics measured by pump-probe method. Upper and lower plots correspond to results for switch-off and switch-on operations, respectively. Different colors denote results for different pump energies.

because pump-induced carrier nonlinearity induced a resonant blueshift. Switching energies of 420 and 660 aJ were achieved for contrasts of 3 and 10 dB, respectively. These energies are over two magnitudes lower than those reported for Si- and GaAs-based PhC cavities. It should be noted that the switching time window is only 20–35 ps. This value is much shorter than the carrier recombination lifetime (several hundred picoseconds), which is attributable to the rapid carrier diffusion. The improvement in energy and speed is attributed to the ultrasmall size of the cavity and the strong nonlinearity of InGaAsP.

3.3 Gate switching for 40-Gbit/s signal

We performed an experiment in which we extracted a pulse from a repetitive signal train to demonstrate the practicality of our all-optical switches. As shown in **Fig. 5**, we generated a signal train with four pulses with a 25-ps period (40-Gbit/s repetition). We also injected a pump pulse so that it temporally overlapped the second signal pulse to switch it selectively. Output signal pulses show the result of the pulse extraction experiment; they indicate that the second pulse (indicated by an arrow) was selectively switched off or on. These results are promising in terms of the suitability of PhC nanocavity switches for 40-Gbit/s operation.

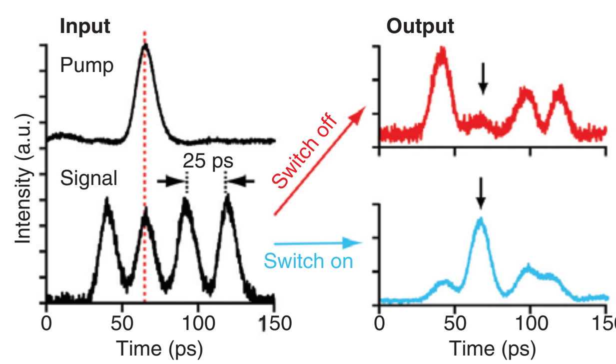

Fig. 5. Gate switching for a signal pulse train at 40 Gbit/s. The pump pulse temporally matches the second signal pulse, and output signals indicate the operations for the switch-off and switch-on regimes.

4. Comparison of all-optical switches

Various all-optical switches are compared in **Fig. 6(a)** in terms of their switching energy per bit and switching time. It is clear that our switch can operate with energy approximately two or more orders of magnitude less than for previously reported ones and has entered the attojoule energy range for the first time. In addition, the previous all-optical switches suffer from a trade-off between switching

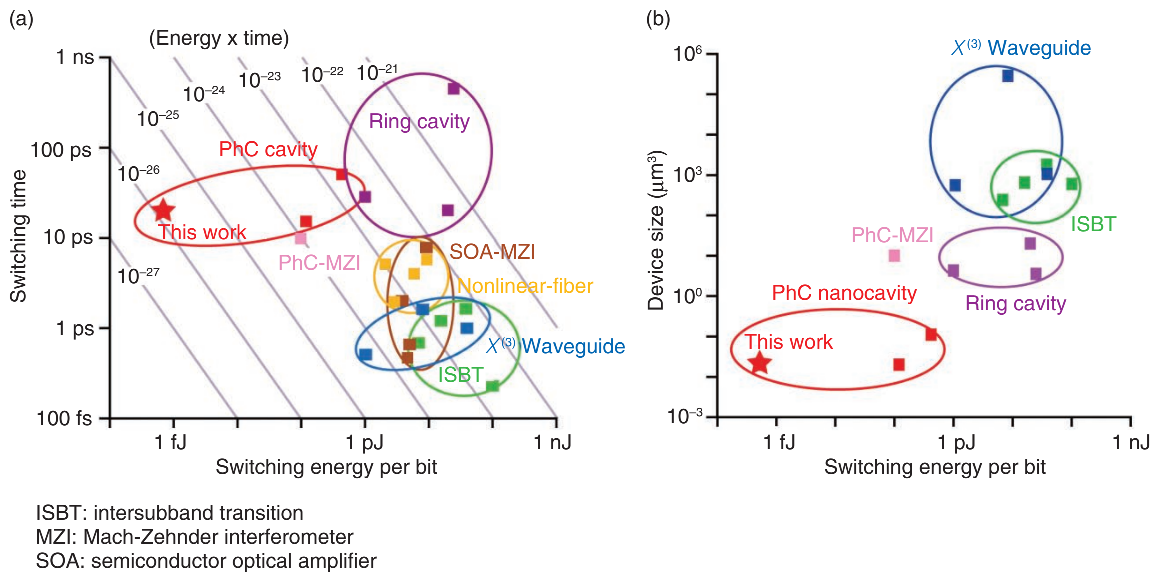

Fig. 6. Comparison of all-optical switches. (a) Switching time vs. switching energy. (b) Device size vs. switching energy.

time and energy; that is, the energy-time product is limited to around 10^{-24}–10^{-22}. On the other hand, our device clearly overcomes this limitation, exhibiting an energy-time product of 10^{-26}. This is attributed to the ultrasmall size of our cavity. On-chip all-optical switches are compared in **Fig. 6(b)** in terms of switching energy and device size. Our device exhibits both the smallest size and lowest energy. Although all-optical switches involving third-order nonlinearity [16] and inter-subband transition [5], [6] can operate at a much higher bitrate, their high energy consumption and large size might be unacceptable for an on-chip integrated circuit. With our device, assuming 1000 devices on a single chip all operating at a bitrate of 10 Gbit/s, the power consumption is only a few milliwatts. In addition, the ultrasmall size of our device lets us integrate 1000 devices with a small footprint of less than 0.01 mm^2 (assuming a footprint for a single device of less than 10 μm^2). Consequently, the low-power, ultrasmall, and fast PhC-nanocavity switch studied here is unique.

5. Conclusion

We demonstrated all-optical switching with extremely low power consumption using a PhC nanocavity. The achievement of such a densely integrable PhC-nanocavity switch is very important because it will enable low power consumption in the milliwatt range, even in an integrated chip including thousands of devices with a sub-mm^2-order footprint, and it operates at 40 Gbit/s. A wide variety of low-power optical devices, such as optical bistable memory and logic elements [17], [18], should be achievable in a similar way. These PhC-nanocavity-based functionalities are promising for use in optical processing in chip-scale photonic integration.

Acknowledgments

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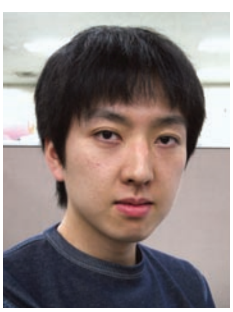

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Hyper Multi-point Satellite Communications System and Field Trial Results

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Abstract

This article presents our newly developed hyper multi-point data-gathering satellite communications system for enhancing the frequency utilization of satellite transponders and the results of field trials for evaluating its feasibility using the Japanese Engineering Test Satellite VIII. We have developed a prototype system that can collect various types of sensor data with high frequency utilization efficiency from a large number of data-sensing stations scattered over a wide area in a unified manner. The experimental results show that this system successfully collected sensor data having different characteristics such as frequency and data size simultaneously and efficiently.

1. Introduction

Several natural disasters such as large earthquakes, giant tsunamis, and large hurricanes have recently occurred in the world and there is strong demand for a system that can predict the occurrence of natural disasters and reduce the damage inflicted by them. In meeting this demand, nationwide or region-wide sensor networks that gather environmental sensor data are expected to play key roles.

Satellite communications has the inherent capability to offer a good solution for this type of application. However, conventional satellite communications systems cannot cope efficiently with small amounts of data transmitted from large numbers of data-sensing stations (DSSs). They waste satellite transponder bandwidth on small-size data because (1) conventional access control schemes, including both random access and demand assignment schemes, are inefficient at handling large amounts of small-size data and (2) guard bands that are wider than the data bandwidths are required because of the inadequate frequency stability of local oscillators in DSSs. To address these problems, we have proposed a hyper multi-point data gathering satellite communications system that offers highly reliable, extremely wide coverage and a cost-efficient sensor network infrastructure.

To better utilize the satellite transponder bandwidth, our system uses dynamically assigned frequency division multiple access (FDMA) combined with a highly efficient and flexible channel allocation scheme. In this scheme, DSSs transmit signals using various frequency slots and time slots simultaneously. To receive/send such signals, a novel modem for a data-gathering station (DGS) that can demodulate hundreds of arbitrarily assigned multicarrier signals and a precise frequency control scheme for DSSs have been developed. This article describes our developed technologies and the results of field trials for evaluating system feasibility.

2. Hyper multi-point satellite communications system

The concept is shown in **Fig. 1**, and major system features are listed in **Table 1**. The basic procedure of

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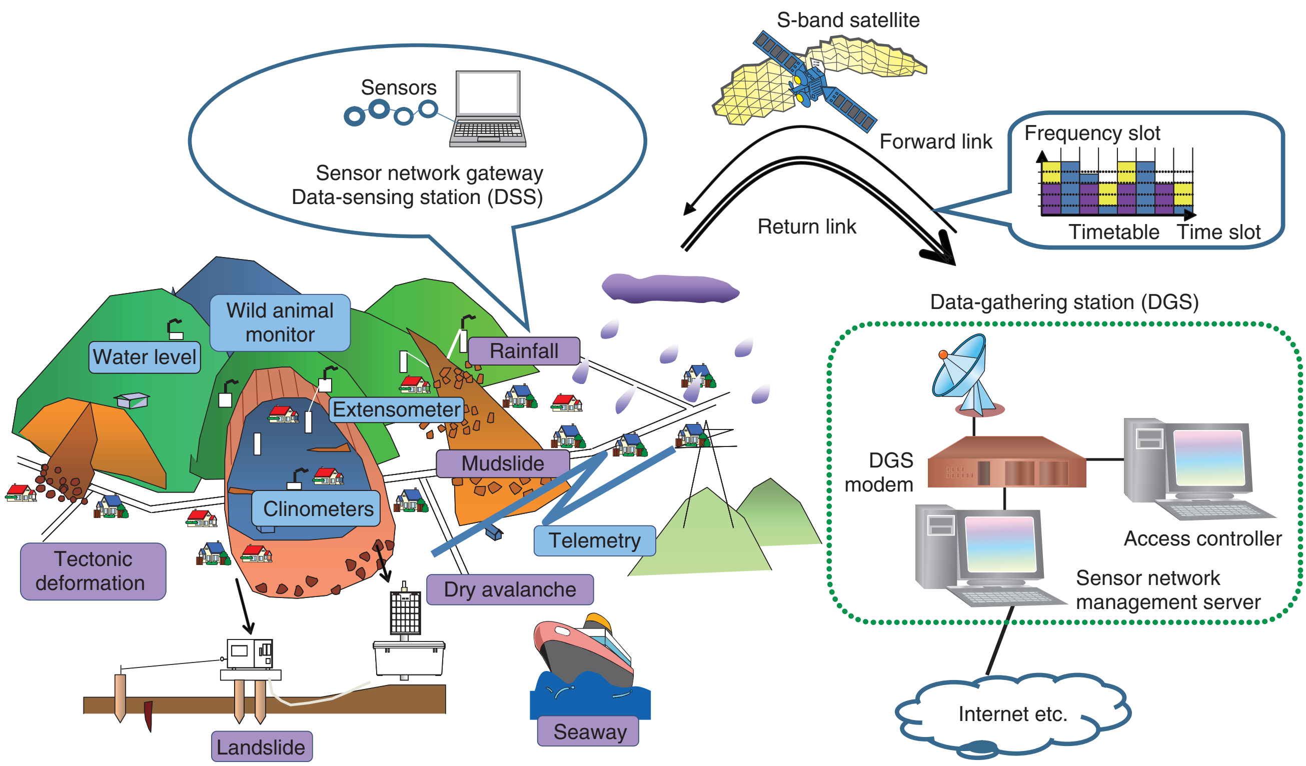


Fig. 1. Hyper multi-point data-gathering satellite communication system.

Table 1. System features.

No. of sensor stations	Tens of thousands	
System bandwidth	1–10 MHz	
Frequency band	2-GHz band	
Multiple access	FDMA (RTL), TDM (FWL)	
No. of carriers	FWL	1 (per system)
	RTL	1 (per DSS) Several hundreds per system
Carrier spacing (RTL)	1 kHz (min.)	
Carrier bandwidth	From 1 kHz to several-hundred kilohertz	
Time slot length (RTL)	1 s	
Modulation	BPSK, QPSK	
Channel filter	Root roll-off, α=0.2	
Forward error correction	Turbo product code (R=0.66)	
Layer 2 protocol	Dedicated	
Layer 3 and higher layer protocols	UDP/IP	

BPSK: binary phase key shifting
QPSK: quadrature phase key shifting
TDM: time division multiplexing
UDP/IP: user datagram protocol, Internet protocol

Table 2. Example of sensing data acquisition conditions.

System bandwidth	Uplink	2.501988–2.503 GHz
	Downlink	2.656988–2.658 GHz
Modulation, forward error correction		QPSK/turbo product, R=0.66
FWL bandwidth		64 kHz
RTL bandwidth		1–512 kHz (9 steps)
Channel spacing		1 kHz min.
Earth station EIRP		33.4 dBW max.
DGS frequency stability		$< 5\times10^{-11}$
DSS frequency stability		10^{-6}

EIRP: effective isotropic radiated power

our system is as follows: (1) A sensor network management server administers the sensor network and knows DSS characteristics such as data amount and observation period. On the basis of these characteristics, the sensor network management server requests an access controller to assign a set of channels for the DSSs. (2) The access controller pre-assigns channel resources, i.e., time and frequency slots, to each DSS as a timetable, which is optimized by the optimal resource assignment algorithm. The DGS then sends the timetable to each DSS through the forward link (FWL) channel. The FWL channel is also used as a frequency and timing reference of the system. (3) The DSSs transmit their sensor data through the return link (RTL) traffic channel by referring to the above-mentioned information provided by the FWL channel. (4) The transmitted data is finally aggregated by the sensor network management server, which delivers information to customers via terrestrial networks such as the Internet. To minimize the antenna size, equipment size, and DSS power consumption, a mobile satellite service band such as the S-band is preferable. Unfortunately, this band has a very limited bandwidth of 35 MHz. Therefore, the main feature of our system is that all DSSs, which synchronize their frequencies with a high degree of accuracy, can utilize a narrow bandwidth to gather a large amount of data efficiently. To achieve this, we have developed three novel technologies [1], [2], which are explained below:

- highly efficient channel allocation algorithm,
- dynamic and collective demodulation for DGS, and
- highly accurate frequency synchronization for DSS.

3. New technologies

3.1 Channel allocation algorithm

Considering the number and variety of sensors involved, our channel allocation scheme must handle a wide variety of sensing data transmission characteristics while securing reliable transmission by avoiding data collisions on the satellite link. Major sensing data acquisition conditions were surveyed and are summarized in **Table 2**. There is a wide variety of data sizes and data acquisition intervals for each of the measurements taken.

Data generation timing is roughly designated before data sensing begins. Consequently, it is hoped that channel pre-assignment will increase the frequency utilization efficiency and make it possible to accommodate more DSSs. As shown in **Fig. 2(a)**, the simplest way of making the timetable is to pre-assign a channel exclusively to each DSS regardless of its data acquisition interval. This method, however, wastes the frequency and time slots.

To effectively use the timetable's vacant slots, we rearrange the timetable by using an optimization algorithm. It uses a heuristic approach based on a multi-start local search [3] combined with the greedy method [4]. The procedure is as follows:

Step 1. The transmission data is first classified into several groups depending on data acquisition conditions, and each group is assigned to a different number of time slots.

Step 2. The transmission timing of each data item is moved within its permissible delay time to an appropriate frequency and time slot to minimize total transmission bandwidth by using the greedy method. This step is carried out group by group.

Step 3. Steps 1 and 2 are repeated N times. At the same time, the multi-start local search is changing the data classification to reduce the total transmission bandwidth (see **Fig. 2(b)**).

As a result, we can obtain the timetable shown in **Fig. 2(c)**, in which the frequency and bandwidth of the transmitted signals are arbitrarily changed time slot by time slot. For example, with our algorithm, the number of unused frequencies and time slots in the timetable is less than 5% when the number of DSSs is more than ten thousand.

3.2 Dynamic and collective demodulation

To enable the demodulation of hundreds of arbitrarily assigned multi-carrier signals, a novel modem for the DGS was developed, as shown in **Fig. 3**. This modem's module uses a fast Fourier transform (FFT)

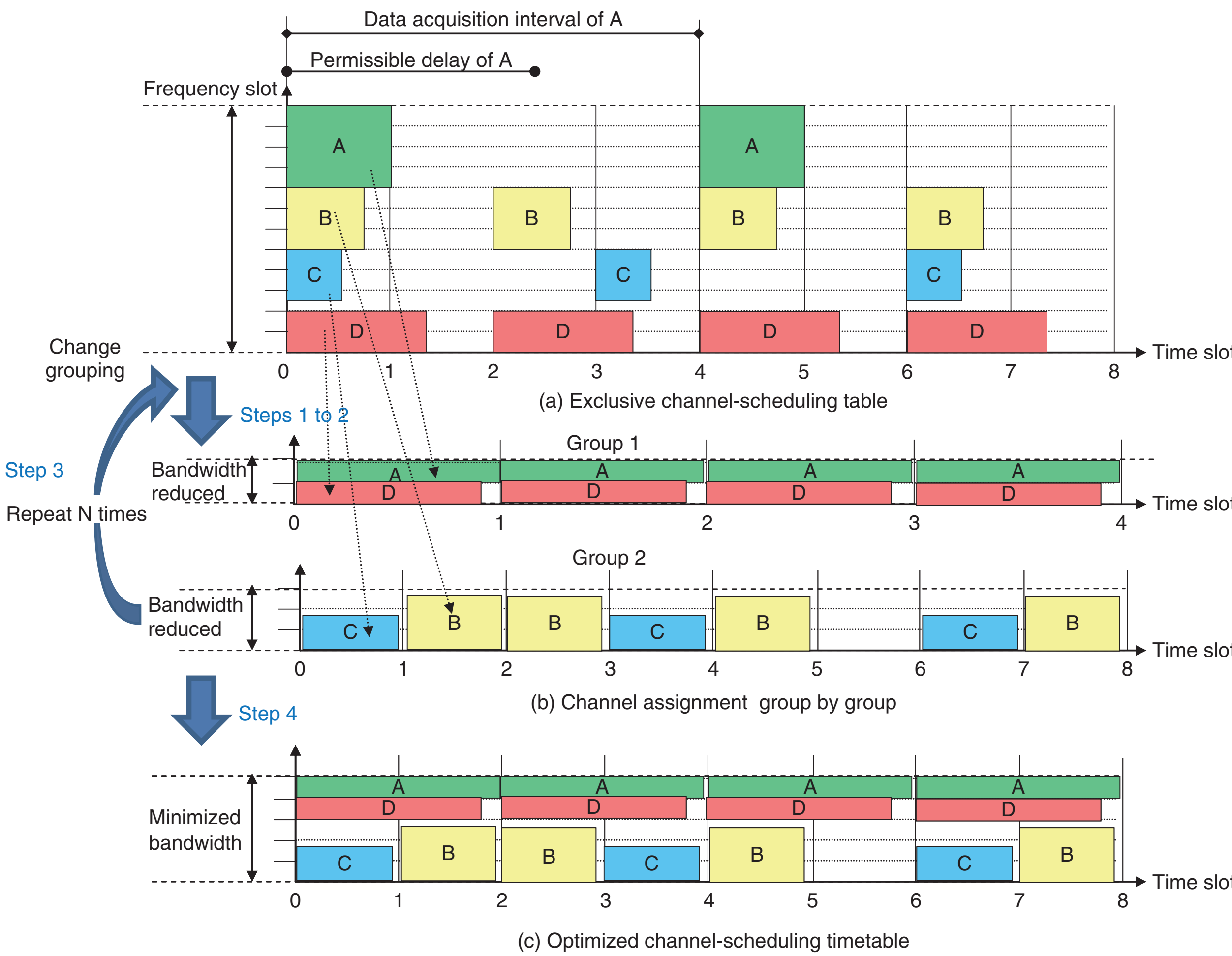


Fig. 2. Timetable rearrangement.

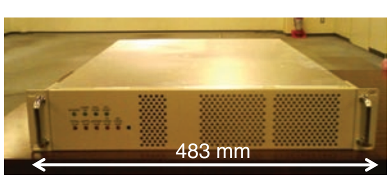


Fig. 3. Front view of DGS modem.

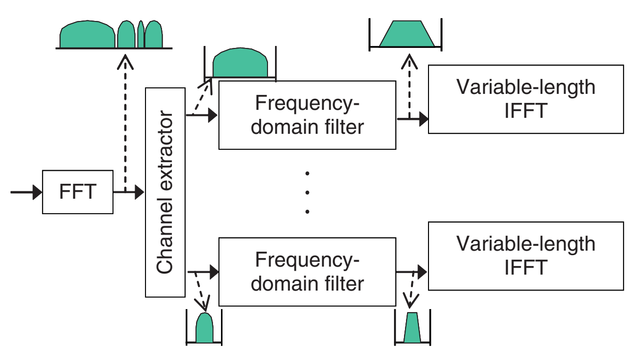


Fig. 4. Principle of FFT-type block frequency demultiplexer.

type of block frequency demultiplexer as well as a multi-carrier burst modem with time-sharing operation.

The principle configuration of the FFT-type block frequency demultiplexer is shown in **Fig. 4**. The received signal is converted into the frequency domain by FFT. Next, it is separated directly in the frequency domain and filtered. Finally, the separated components are individually reconverted to the time domain by using variable-length inverse FFT (IFFT). Arbitrarily and dynamically allocated signals are

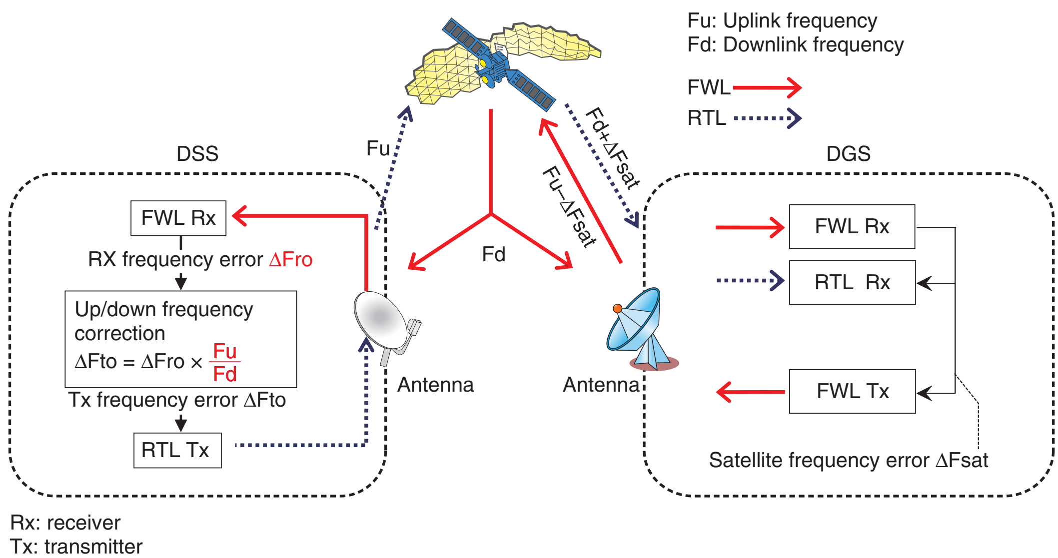


Fig. 5. Principle of high-accuracy frequency synchronization.

freely multiplexed in the frequency domain, and the variable-length IFFT circuits can handle hundreds of signals simultaneously with small-scale circuits.

3.3 Frequency synchronization

To control the transmission frequency of the DSS with high accuracy, and thus allow the guard band to be narrowed, we developed a frequency synchronization scheme, as shown in **Fig. 5**. First of all, the DGS receives its own FWL channel via a satellite. It then controls the FWL channel frequency by applying closed-loop transmission automatic frequency control to compensate for frequency error (ΔFsat) caused by the satellite transponder. As a result, the frequency error of FWL from the satellite becomes nearly equal to zero.

Therefore, each DSS can detect the reception frequency error (ΔFro) of its own equipment by referring to the FWL frequency. The transmission frequency error ΔFto is deduced from ΔFro by multiplying ΔFro by the uplink/downlink ratio Fu/Fd, as shown in Fig. 5. Consequently, the transmission frequencies of all DSSs are synchronized with high accuracy. Moreover, the guard band can be narrowed without using special oscillators such as rubidium-based devices for each DSS.

4. Field trial

4.1 Configuration

To evaluate the system's feasibility, we have carried out field trials using the ETS-VIII (Japanese Engineering Test Satellite VIII) [5]. As shown in **Fig. 6**, two DSSs located 350 km apart were used to verify the technical feasibility. The DGS, DSS, and earth station antenna used in the test are overviewed in **Fig. 7**. To suppress the system cost, a temperature compensated crystal oscillator, which is generally used in cellular phones and has frequency accuracy on the order of 10^{-6}, was used in each DSS. In the DGS, a rubidium oscillator was used to ensure highly accurate FWL signals. The access controller and the sensor network management server were connected to the DGS modem through the router.

4.2 Frequency accuracy

The FWL frequency error at the DGS receiver input side is shown in **Fig. 8**. It is clear that the frequency error is less than 0.2 Hz. In the S-band, this frequency accuracy is on the order of 10^{-11}. This result, therefore, shows that our technique achieves high FWL frequency precision by removing frequency error factors such as a satellite's Doppler shift.

Next, ΔFro on DSSs detected from the FWL signal and the frequency error of the RTL signal of DGS input are shown in **Figs. 9** and **10**, respectively. In Fig. 10, L, M, and H on the horizontal axis show the

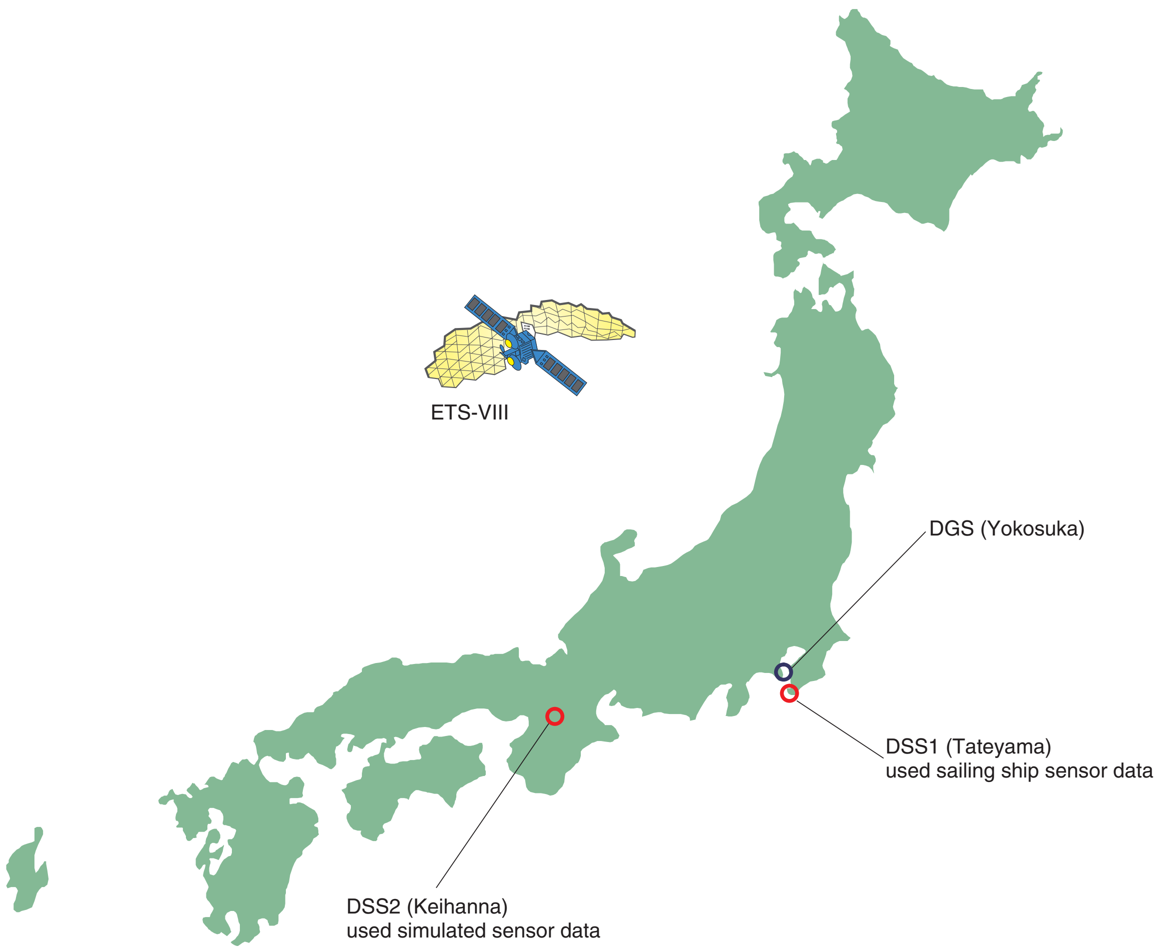


Fig. 6. Field test configuration.

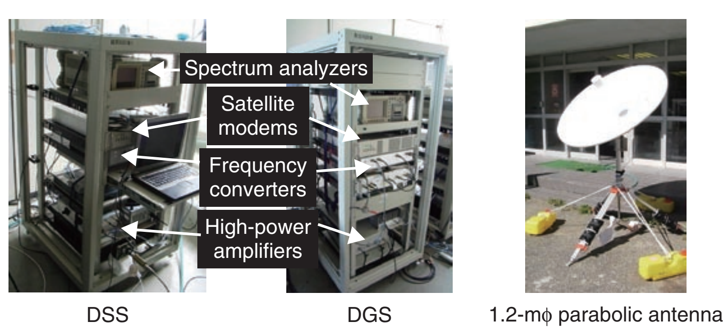


Fig. 7. Equipment used in the field trial.

center frequencies of the RTL, i.e., the bottom, middle, and top of the system bandwidth, respectively. In Fig. 9, we can see that ΔFro values were several hundred hertz and fluctuated over time. These errors are reasonable because the DSS's local oscillator stability was on the order of 10^{-6}. Despite the large frequency errors in DSS, the RTL frequency errors at the DGS receiver input were within ±2 Hz. This frequency accuracy is on the order of 10^{-10}. Therefore, the effectiveness of our technique was confirmed.

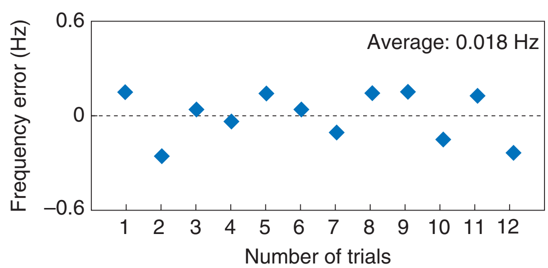
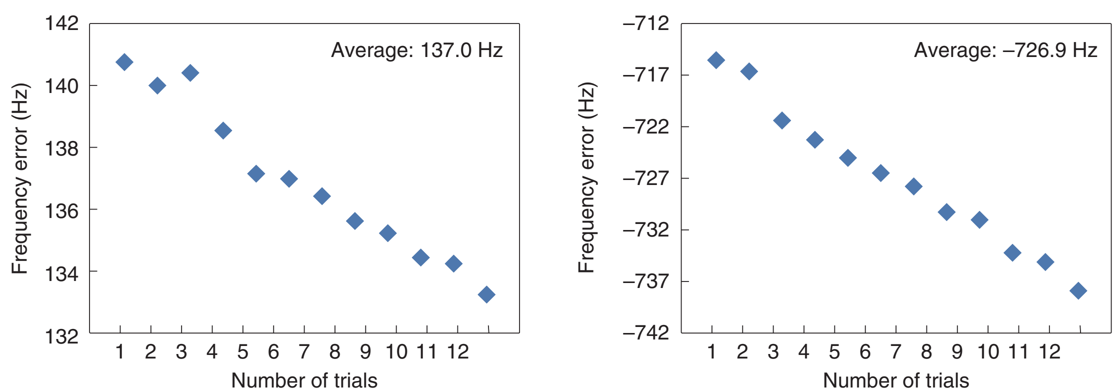


Fig. 8. FWL frequency error at DGS input.

4.3 Transmission performance

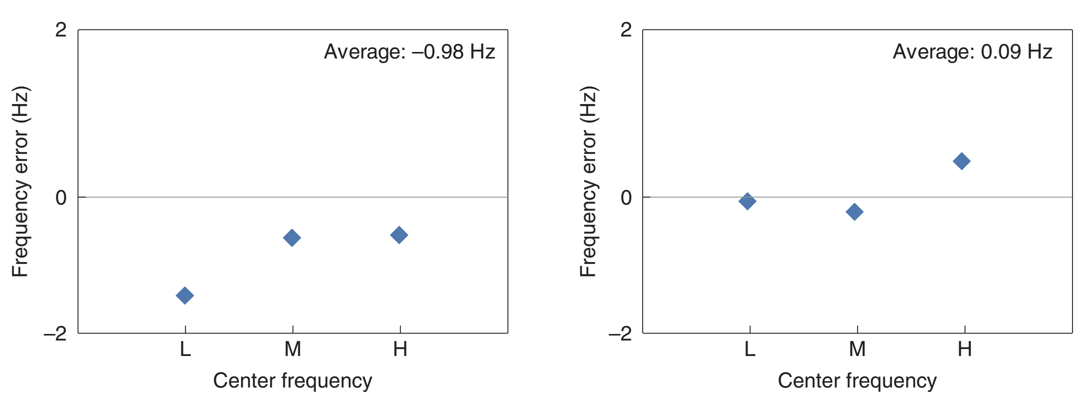
Since the timetable (**Fig. 11(a)**), made out of seven time slots, was applied repeatedly, the spectrogram of the RTL signals shown in **Fig. 11(b)** indicates that each DSS successfully transmitted the RTL signal in sync with the timetable. The bit error rate (BER) characteristics of the RTL signal were measured under the condition that the bandwidth and frequency were dynamically controlled. As shown in **Fig. 12**, the degradation in BER characteristics, in terms of the ratio of the energy per bit to noise power spectral density (E_b/N_0), was less than 1 dB compared with the simulation result. Packet transmission test results using four timetable patterns are shown in **Table 3**. Four timetables (A, B, C, and D) allocated different amounts of resources to DSS1 and DSS2, so that they



(a) DSS1 (Tateyama)

(b) DSS2 (Keihanna)

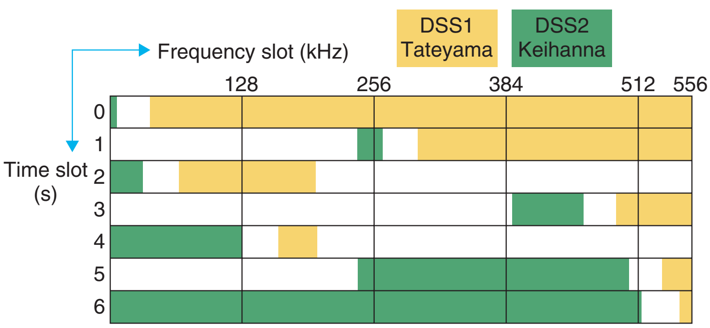
Fig. 9. ∆ Fro detected by the DSS.



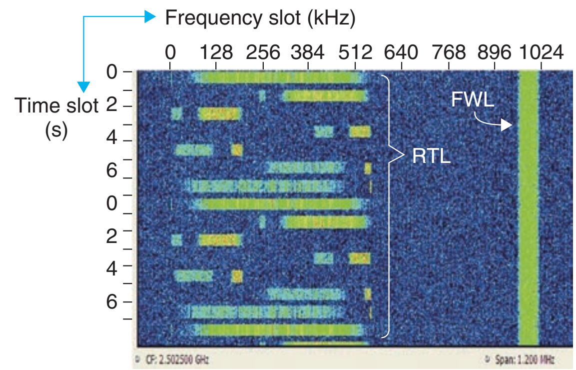
(a) DSS1 (Tateyama)

(b) DSS2 (Keihanna)

Fig. 10. Frequency errors on RTL at the DGS input.



(a) Transmitted timetable



(b) Spectrogram at DGS input

Fig. 11. Timetable performance.

Table 3. Throughput of packet transmission.

Test condition					Results		
Timetable	DSS	Assigned capacity (kbit/s)	Packet length (byte)	Packet interval (s)	No. of packets Tx	No. of packets Rx	Measured throughput (kbit/s)
A	1	12.8	320	0.2	3012	3012	12.8
	2	163.8	1514	0.077	7888	7888	156.5
B	1	163.8	1514	0.077	7832	7832	156.5
	2	12.8	320	0.2	3044	3044	12.8
C	1	2.6	320	1	561	561	2.5
	2	20.5	720	0.333	1083	1083	17.2
D	1	20.5	720	0.333	1085	1085	17.2
	2	2.6	320	1	600	600	2.6

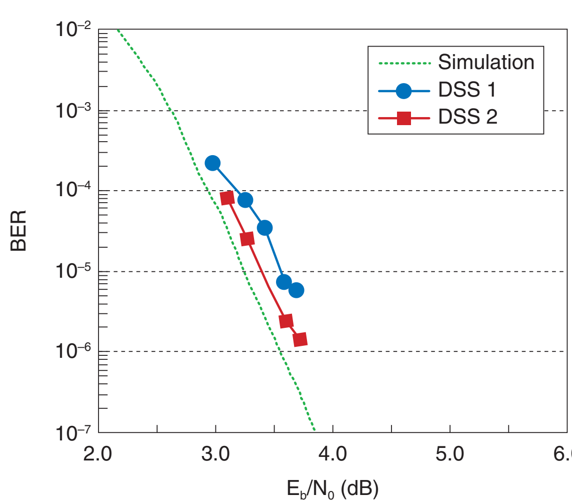


Fig. 12. BER characteristics.

achieved various throughput values. As we can see, all packets were received without any packet loss, and throughput was nearly equal to the allocated capacity. These results show that our system worked as expected and confirmed the system's effectiveness.

5. Conclusion

We carried out a field test of our hyper multi-point data gathering satellite communications system. The system features an optimal resource assignment algorithm for various types of sensor data, a highly accurate frequency synchronization scheme, and a dynamically assigned frequency division multiple access scheme. These enhance the frequency utilization efficiency of a satellite-aided sensor network.

Acknowledgment

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Polarization-tracking-free Satellite Communications System Using Adaptive Polarization Division Multiplexing

Yoshinori Suzuki† *, Fumihiro Yamashita, Katsuya Nakahira, Hiroki Uchiyama, and Kiyoshi Kobayashi*

Abstract

We have developed a novel Ku-band broadband mobile satellite communications system called the adaptive polarization division multiplexing (APDM) system. It eliminates the need for a polarization-tracking device in earth stations and improves the spectrum utilization efficiency. This article overviews the concept of the APDM system and describes the technologies that make the system possible. Experiments have shown that the system can provide practical polarization-tracking-free Ku-band broadband mobile satellite communications.

1. Introduction

Broadband mobile satellite communications services are already being offered to passengers on trains, airplanes, and vessels via the Ku band [1], [2]. However, the earth stations (ESs) are still expensive because they need a highly accurate auto-tracking directional antenna. This antenna must track not only satellite direction but also polarization precisely to avoid interference from other satellite users and/or other polarization users. This requirement means that ESs for mobile satellite communications are expensive.

Insufficient polarization tracking leads to harmful cross-polarization interference and degrades frequency utilization efficiency. To solve these problems, we introduced a novel Ku-band broadband mobile satellite communications system with a simple satellite-tracking antenna called the adaptive polarization division multiplexing (APDM) system. It allows each user ES to freely utilize both polarization and frequency resources. This article overviews the concept of the APDM system, introduces the technologies that make the system possible, and presents the results of satellite experiments.

2. System overview

To achieve an attractive Ku-band broadband mobile satellite communications system, we aim to use a polarization-tracking-free antenna at the ES and improve the spectrum efficiency by using dual-polarization satellite transponders.

To eliminate the polarization tracking mechanism from the ES without creating harmful interference at other ESs, our approach is to utilize vertical-polarization (V-pol.) and horizontal-polarization (H-pol.) resources simultaneously. The signal transmission model of the APDM system is shown in **Fig. 1**. The ES creates and transmits two polarized signals. Since the ES of the APDM system does not track the

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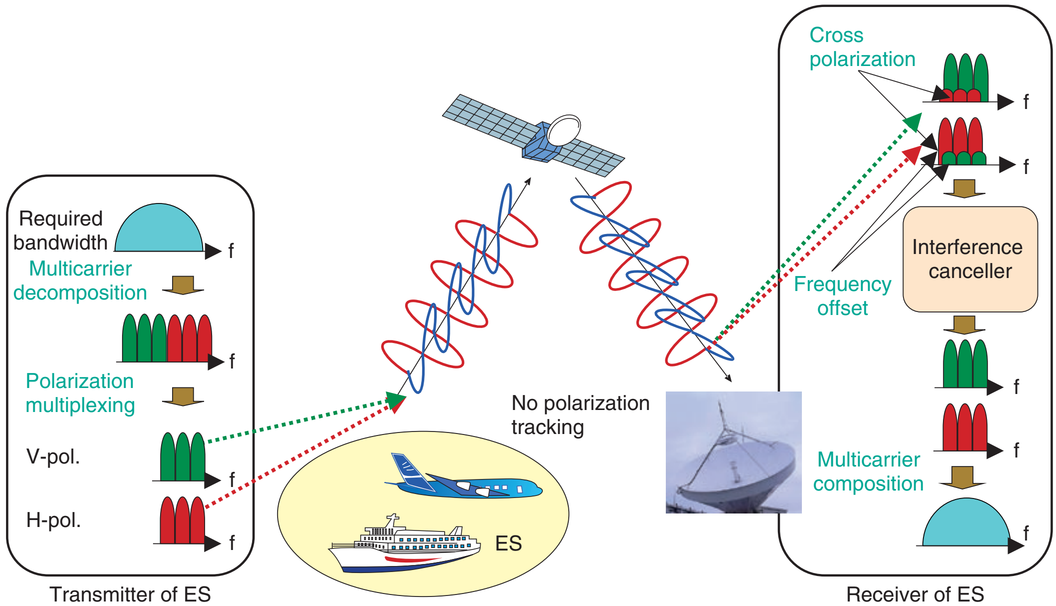

Fig. 1. Signal transmission model of the APDM system.

polarization status, the quality of received signals is degraded because of the existence of cross-polarization interference. However, since both signals have the same frequency, which is unique to each ES, the cross-polarization interference never harms other ESs. Moreover, since the cross-polarization signal is originally the user's own signal, it can be simply detected and removed by the interference canceller in the receiver [3]. The APDM system prevents any significant quality degradation even though it has no polarization tracking device.

We also use multicarrier decomposition/composition, as shown in Fig. 1, to improve the frequency utilization efficiency [4]. A typical Ku-band satellite communications system uses demand assign multiple access as the access method. Since each ES releases assigned frequency slots after disconnection, the satellite's unused frequency slots, which may not be wide enough to reallocate to other ESs, are fragmented. An example of transponder frequency allocation is shown in **Fig. 2**. To fully utilize these slots, the transmitter splits the signal into multicarrier signals corresponding to the transponder's available frequency slots. These split signals are converted into the assigned frequency slots by the frequency multiplexer.

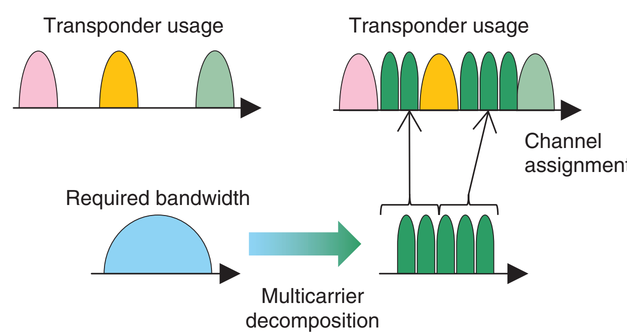

Fig. 2. Channel allocation by multicarrier distribution.

3. Developed technology

For the APDM system shown in Fig. 1, we have developed an APDM modem and a channel control unit (CCU); these are the key components of this system. The most important function of the APDM modem is to cancel cross-polarization. Since conventional satellite communications system users are assigned only a single polarization channel (either V-pol. or H-pol.), the satellite transponder frequencies for V-pol. and H-pol. may be asynchronous. Therefore, the interference canceller must work properly under the condition of asynchronous V/H frequency conversion. A block diagram of our interference canceller [3] is shown in **Fig. 3**. It eliminates asynchronous V/H frequency offsets as well as cross-polarization interference in a hybrid manner. In

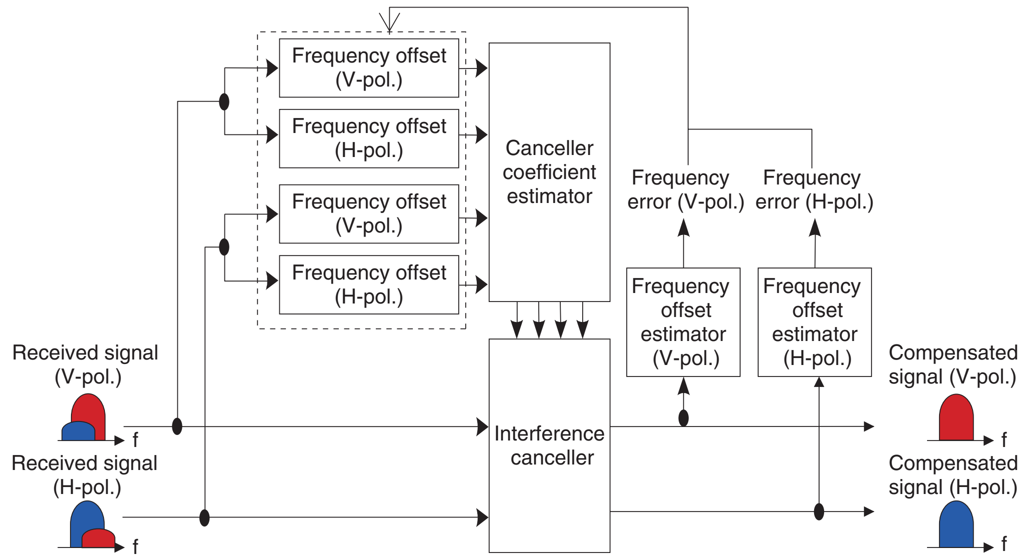

Fig. 3. Block diagram of cross-polarization interference canceller.

Fig. 4. APDM modem.

Table 1. Main specifications of APDM modem.

Modulation	BPSK, QPSK, and 16QAM
Number of carriers	0–128/polarization
Number of users	0–25
Carrier frequency separation	100 kHz (minimum)
Bitrate	80 kbit/s to 5.12 Mbit/s
Forward error correcting	Turbo product code (encoding rate: 0.66)

practice, cross-polarization is cancelled at the V/H interference canceller by using the received unique word.

To support multicarrier systems, the APDM modem has a flexible frequency multiplexer/demultiplexer that exploits frequency domain signal processing [5]. A photograph of the APDM modem is shown in **Fig. 4** and its main specifications are listed in **Table 1**.

Because the APDM system must use V/H polarization resources simultaneously, it obviously cannot use the conventional channel access method that uses only a single polarization. Our solution was to develop a novel channel assignment algorithm and a CCU for the APDM system [6]. The channel assignment algorithm optimizes the bandwidth and number of carriers as well as the modulation schemes for the required connection mode (APDM mode or conventional mode) and transmission rate under V/H polarization usage.

4. Satellite experiments and results

To confirm the feasibility of the APDM system, satellite experiments were carried out. The experimental setup is shown in **Fig. 5**. Three ESs—a base station (BS), fixed station (FS), and simulated mobile station (MS)—were set at different locations. The simulated mobile station utilized a ship motion simulator that mechanically imposed three kinds of dynamic ship motion (forward ship movement in low waves and high waves and circular ship movement) on the auto-tracking satellite directional antenna. Each motion was based on field measurement. Circling motion has the biggest impact on the change in polarization angle.

Examples of the constellation before and after interference cancellation are shown in **Figs. 6(a)** and **(b)**, respectively. As shown in Fig. 6(a), the transmitted V/H signals were mixed and rotated owing to cross-polarization interference and V/H asynchronous

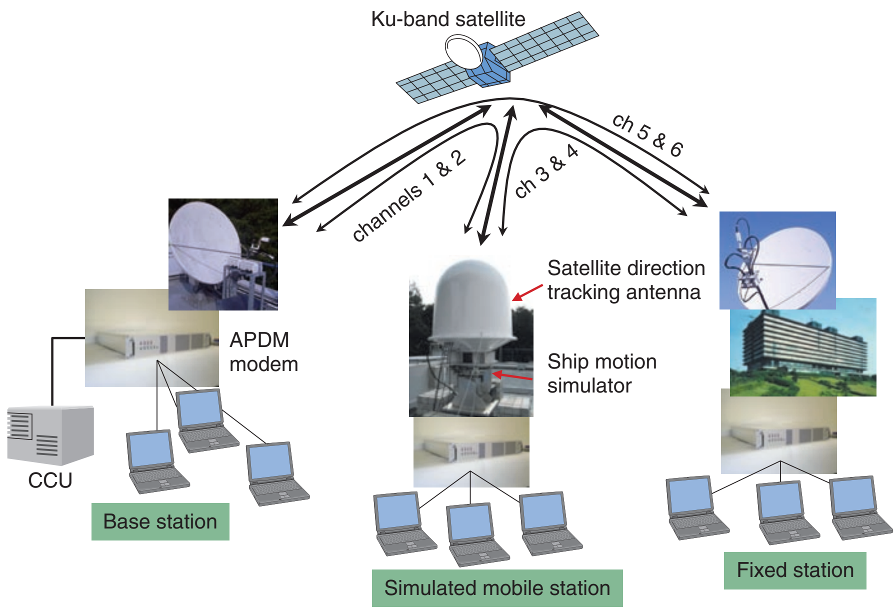

Fig. 5. Overall configuration for satellite experiment.

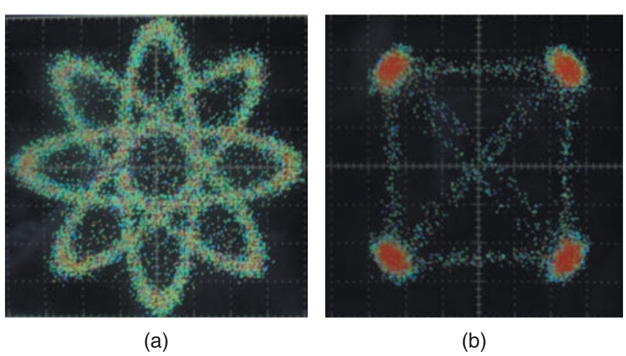

Fig. 6. Signal constellation: (a) before interference canceller and (b) after demodulation.

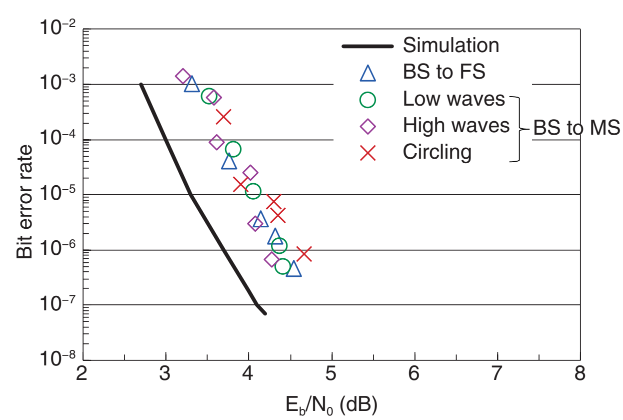

Fig. 7. Bit error rate performance.

frequency offsets. After interference cancellation, however, the transmitted V/H signals were demodulated individually without any cross-polarization interference; the frequency offsets are shown in Fig. 6(b).

Examples of the bit error rate performance measured in the BS-to-FS and BS-to-MS links are shown in **Fig. 7**. The polarization angle in the BS-to-FS link was adjusted to act as a reference. The degradation in the required ratio of the energy per bit to noise power spectral density (E_b/N_0) was about 0.8 dB compared with computer simulation regardless of the ship motion.

Finally, we verified the CCU-based channel management. The spectrum of the satellite transponder after the assignment of the channels listed in **Table 2** is shown in **Fig. 8** as an example. As each carrier's transmission rate was about 80 kbit/s, it was also confirmed that channel assignment was carried out as intended. Note that the carrier on the left (V-pol.) is a CCU control channel.

Table 2. Channel parameters and assigned carrier number by CCU.

Channel number	Link	Required bitrate (kbit/s)	Assigned carrier number
ch 1	BS to MS	1280	16
ch 2	MS to BS	640	8
ch 3	MS to FS	960	12
ch 4	FS to MS	480	6
ch 5	FS to BS	480	6
ch 6	BS to FS	320	4

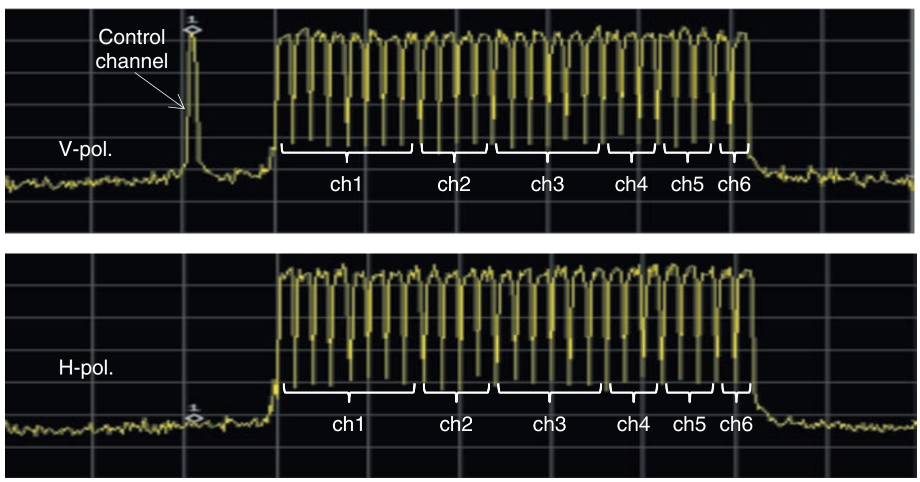

Fig. 8. Channel assignment by CCU.

5. Conclusion

This article described the APDM satellite communications system and feasibility evaluation experiments conducted on a polarization-tracking-free Ku-band broadband mobile satellite communications system. Satellite experiments confirmed that a polarization-tracking-free Ku-band system can be achieved by raising the link margin by 0.8 dB.

Acknowledgment

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UMS: Software to Automate Operators' Actions

Fumihiro Yokose† *and Akira Inoue*

Abstract

We have developed a unified management support system (UMS), which is software that reduces the workload on operators and operating costs by automating operations. UMS makes it extremely easy for an operator who is not a computer expert to record and replay actions taken on systems. Since most modern systems are extremely complex, UMS can improve system operation efficiency. This article describes the features and technologies of UMS and gives usage examples.

1. Introduction

Effective operations support systems (OpSs) are essential to achieve efficient advanced operations. For example, the management of one access network requires the information management functions provided by several OpSs. Without these OpSs, we could not build and operate commercial access networks and provide high-quality network services to customers.

The key to OpS efficiency is providing support to operators because they cannot be replaced by systems because they make sophisticated judgments and perform field work. Thus, OpSs must be easy for operators to use. However, this is not always true: modern OpSs provide many sophisticated operations. The key problem is that the OpS interface is not user-friendly, and trying to work with its characteristics can be very time-consuming and expensive. An OpS interface that is unsuitable for operator interaction leads to excessively high error rates and failures.

Our solution is a unified management support system (UMS). UMS is software that automatically manipulates, or automates, the OpS interface on behalf of the operator. It improves the ease-of-use of the OpS and reduces the operator's workload. Consequently, UMS reduces operating costs.

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2. Approach

2.1 Problems with OpS interface

Operations vary over time, but it is often difficult to continue using the same OpS interface. Moreover, modifying an OpS interface is not easy because it takes time and money. While it is possible to implement a new operation by using the original OpSs, the operator's workload will be much greater because the original interface was not designed to support the new operation. This leads to high operating costs.

Another problem is that databases slowly become corrupted owing to changes in the managed entities over time. The solution is to occasionally indentify the actual situation and alter the corresponding database entries. However, we cannot directly alter the databases because the data must be checked by the logic written into the OpSs, and usually only the OpSs can access and modify databases. Thus, we need a tool that eliminates the manual work needed to feed data items through the appropriate OpSs to check for consistency and perform any necessary updates.

Consider, for example, the case in which a new high-speed plan on the access network is started. The OpS that handles customer records does not to be modified, but the new plan uses new equipment, so an operator in the field should confirm the equipment with the equipment-management OpS. Thus, the operators' workload will be high.

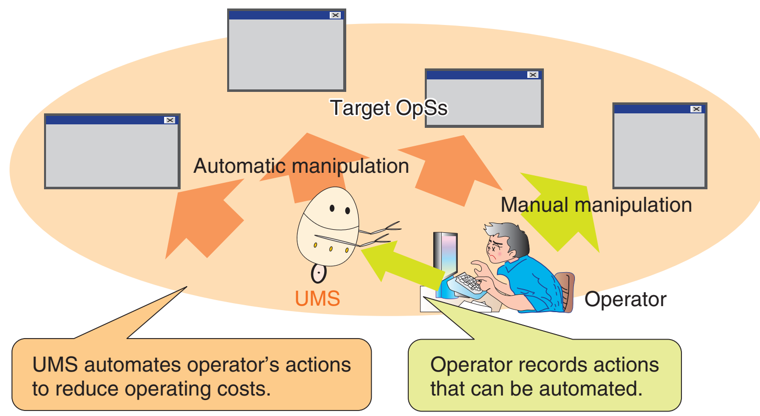


Fig. 1. Approach of UMS.

2.2 Solutions

A prime objective of UMS is to reduce operating costs. To achieve this, UMS eliminates operator actions that can be automated (**Fig. 1**). Thus, UMS can reduce the operator's workload and improve the efficiency of operations.

3. System overview

UMS has two particular features.

3.1 No modification of target OpS

The target OpS does not need to be modified because UMS manipulates the target OpS in the same way as the operator. Actually, OpS manipulation means manipulating the client-side application of the OpS by actions such as clicking a button and inputting a string into a textbox on a personal computer or other terminal. UMS can record and replay these actions without any OpS modification. Thus, UMS can automate most operations at low cost and in a short time.

This approach is similar to the macro function well known to software programmers. However, creating a macro function would require alterations to the OpS. Moreover, a macro function would not be able to access or control other OpSs. UMS automates operations that involve multiple OpSs without any of them being modified.

3.2 Automation by field operators

UMS is designed to support field operators since they are the intended users of OpSs. While field operators are specialists in operations, they are not necessarily computer specialists, and most operators have difficulty in creating advanced programs. To overcome this problem, UMS provides a visual editor and automatic recording via operator example. As a result, it can be used by any operator, even computer novices.

4. Usage examples

Two usage examples are shown in **Fig. 2** and described below.

4.1 Automation of repeated and stylized operations

UMS can automate repetitive and stylized operations. An example of a repeated and stylized operation is database correction. In this operation, operators input a lot of correct equipment data into an OpS at a time. The operation proceeds as a specific action flow consisting of, in this example, initiating a search, entering the search target, selecting a search result (target equipment), opening an window containing information about the target equipment, updating the target equipment's data items in the window, and closing the windows.

UMS lets the operator easily record the actions needed for one cycle, and it then executes the actions iteratively. Therefore, UMS can easily automate repeated and stylized operations.

4.2 Prevention of data mismatch

UMS is effective at preventing data mismatches arising from human error. When the operator must enter data items into several OpSs, he or she must accurately complete all the entries by hand. The operations involved are troublesome and errors such

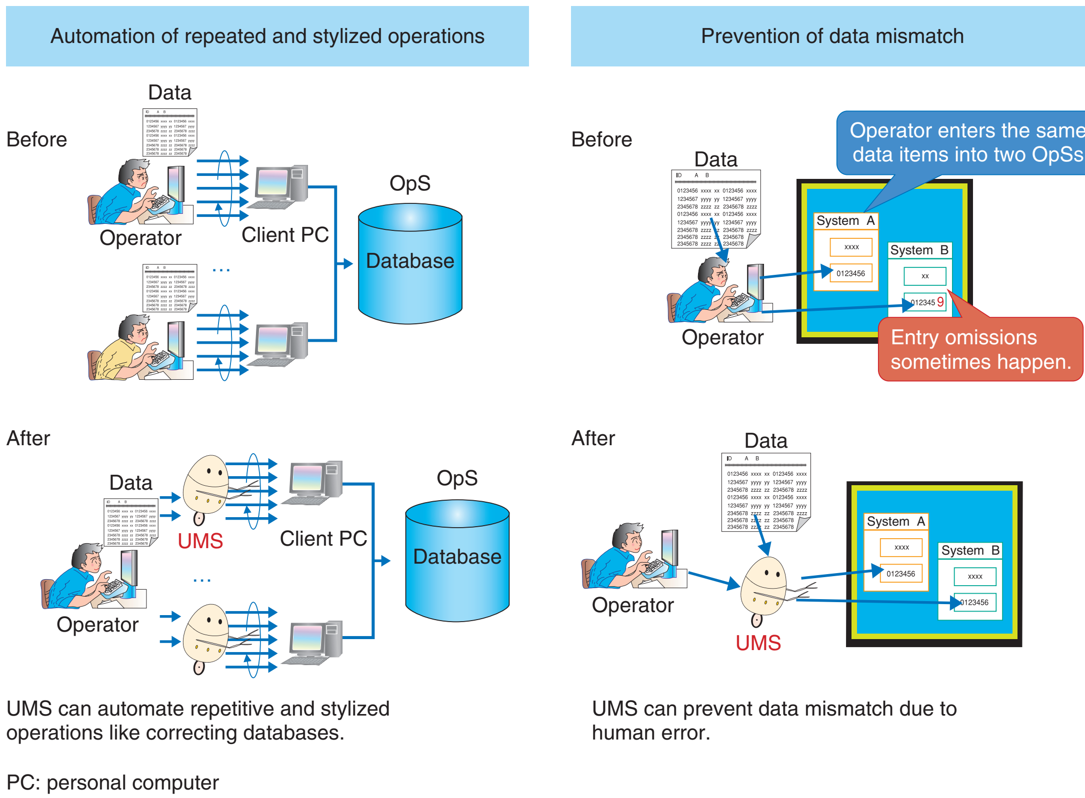


Fig. 2. Usage examples of UMS.

as entry omission and erroneous data entry may occur. As a result, the operations are likely to produce data mismatches.

With UMS, the operator can automate the operations needed for populating multiple OpSs with the appropriate data items, while, at the same time, automatically checking the correctness of data items against the logic of each OpS. Therefore, UMS can prevent data mismatches caused by human error.

5. Technologies

UMS has four key modules: a scenario auto-generation module, a visual editor module, a module for handling data at runtime, and a plug-ins module (**Fig. 3**). This section describes the technologies used in these modules.

5.1 Scenario auto-generation

A scenario is information that specifies actions and the interface manipulation flow for automation. The operator can automatically generate a scenario by performing desired actions manually. UMS detects the operator's OpS manipulation events and infers his/her actions. It adds the actions to a scenario according to the manipulation flow.

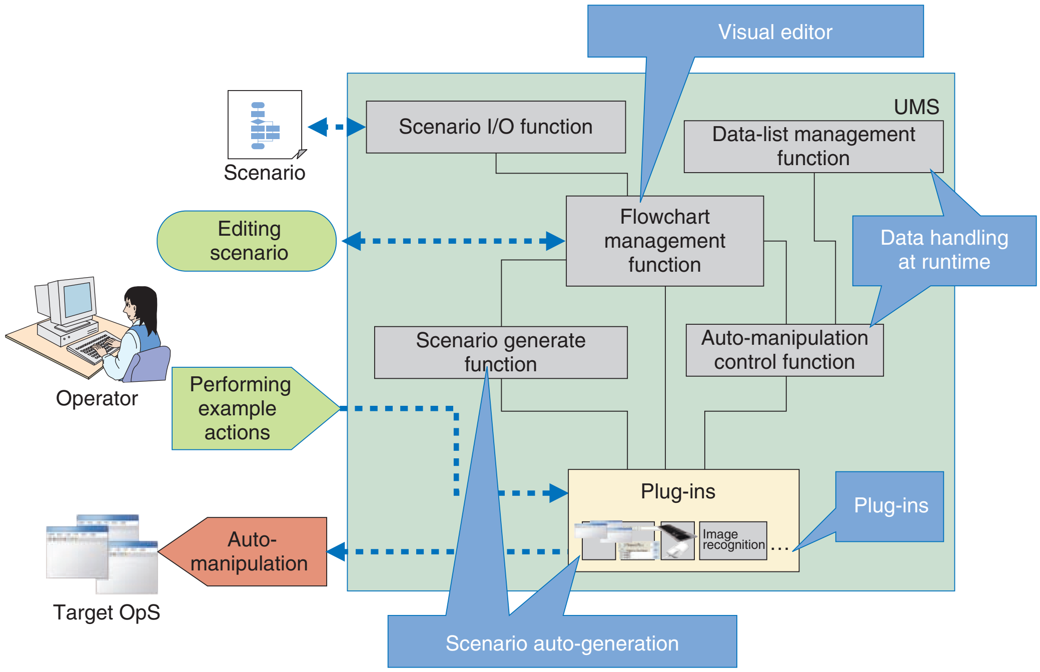
5.2 Visual editor

UMS uses flowcharts for intuitive viewing and editing of scenarios (**Fig. 4**). An operator can understand a scenario as a visual presentation (flowchart) and can edit the scenario in an intuitive manner without coding.

5.3 Data handling at runtime

The same operation will use different data in each cycle, so UMS provides a data management function in addition to the scenario management function. When UMS reruns a scenario, it identifies the variables in the scenario and accesses the appropriate data list to discover the values of the variables to be entered, record by record (**Fig. 5**).

After recording the scenario, UMS creates an empty Excel or CSV (comma-separated values) file (the data list) whose column headers reflect the variables entered by the operator and those returned from



I/O: input/output

Fig. 3.   UMS technologies.

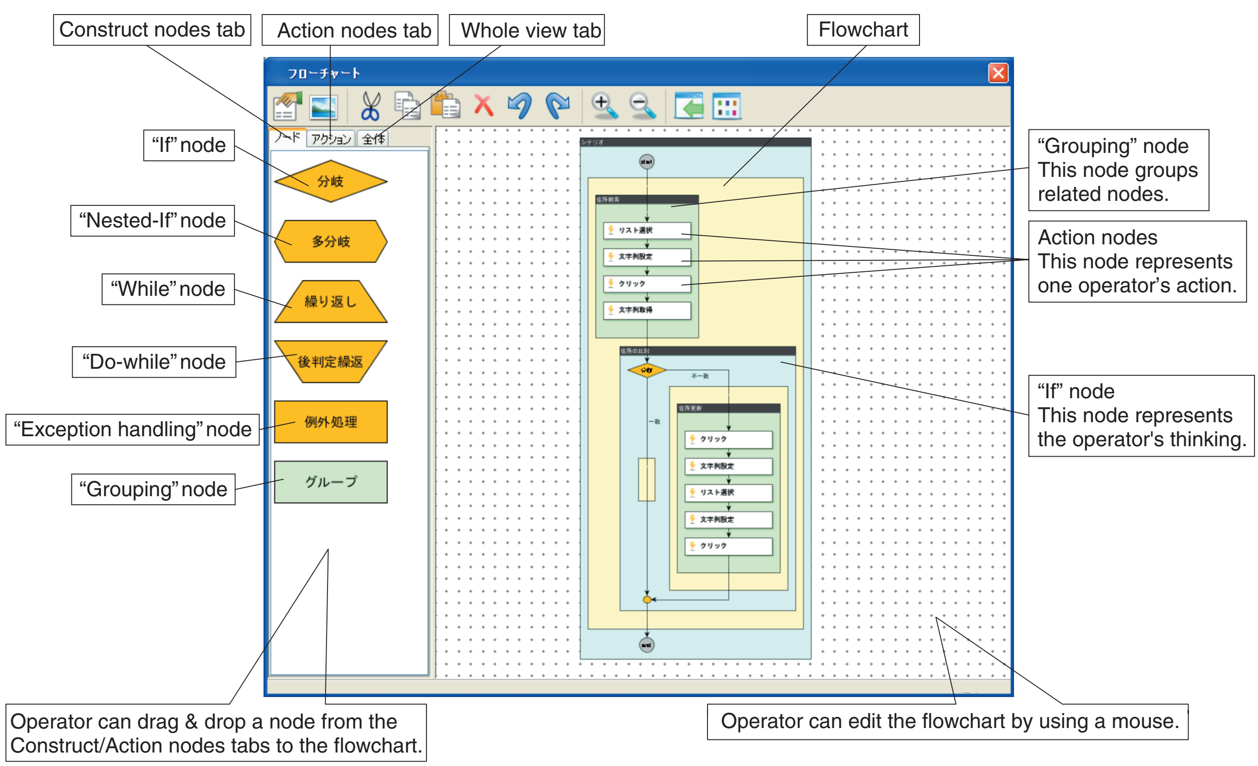


Fig. 4.   Visual editor of UMS.

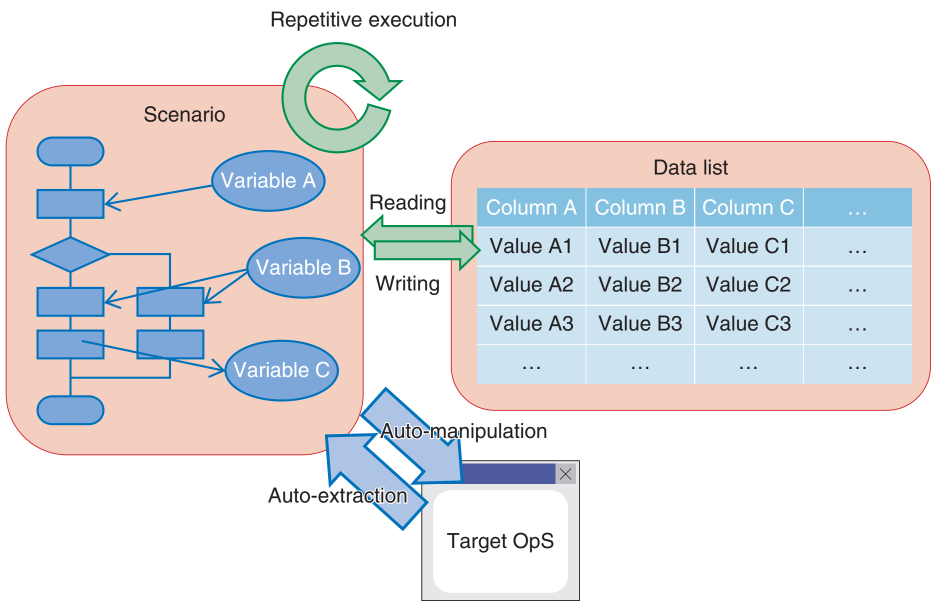


Fig. 5. Data handling at runtime.

Table. 1. Comparison with similar software.

	UMS	UWSC *1	Test automation software *2
Features	UMS is mainly for field operators and enables the operator to automate an operation intuitively.	UWSC has general versatility because it is based on replaying mouse and keyboard actions. It has good flexibility due to its high-level script functionality.	Software specialized for developing software. It has many test automation functions.
Required skill	Operator can make a scenario intuitively without coding by using scenario auto-generation, the visual editor, and other features.	Operator should create/edit text-based scripts. This requires considerable coding skill.	A visual editor is available, but it is aimed at software developers.
Data handling	Operator can input/output data to/from operations easily by using a CSV or Excel file (data format is fixed).	Operator should write scripts to input and output data.	Operator should write scripts to input and output data.

*1: http://www.uwsc.info/
*2: Micro Focus TestPartner, HP WinRunner/QuickTest Professional, IBM Rational Functional Tester Plus, etc.

the front OpS. The operator can also create data lists manually. Moreover, the operator can also use data lists that were extracted from an OpS. While executing a scenario, UMS can copy data output by an OpS and enter it into the appropriate data list record for later reuse.

5.4 Plug-ins

Considering future scalability, we designed UMS's architecture so that its functions can be easily extended. UMS contains program code that depends on the operating system, browser, and so on because it must detect the operator actions and replay them. Accordingly, we separated this code from the main UMS program as plug-ins. In the future, when we adapt UMS to other environments, such as a new operating system or new browser, we will only have replace the plug-ins. Moreover, we can add new functions to UMS by means of new plug-ins.

5.5 System requirements

The current version of UMS runs on Microsoft

Windows and can automate actions related to typical graphical-user-interface-based applications and Microsoft Internet Explorer. In addition, low-level UMS functions include mouse and keyboard control. These functions can automate applications on other platforms (e.g., Java and Flash) and applications running in a server-based computing environment (e.g., Citrix XenApp).

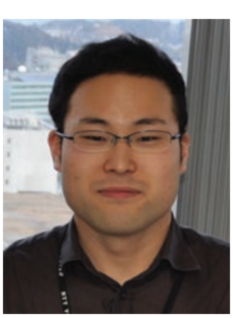
6. Comparison with other similar software

A lot of software has been created to automate users' (operators') manipulation actions. UMS is compared with alternatives in **Table 1**. UWSC and test automation software offer high functionality, but require the user to have advanced computer skills. On the other hand, UMS provides a visual editor and other functions that eliminate the need for advanced computer skills. Since its main purpose is to automate operations, UMS makes it easier to input/output data than the alternatives. Some other software has more flexibility in terms of data input/output, but requires the operator to write scripts.

7. Conclusion

Our unified management support system, UMS, can automate and link many OpSs without modification; an operator can automate operations by himself or herself. UMS is especially effective at automating repetitive and stylized operations. As a result, it reduces the operators' workloads and operating costs.

We are now utilizing UMS in the field and gathering results. We intend to discover and eliminate its weaknesses. In the future, we will try to further reduce operating costs.



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ITU-T Kaleidoscope Academic Conference 2010—Participation Report

Masahiko Jinno†

Abstract

Kaleidoscope 2010, the third academic conference hosted by ITU-T (International Telecommunication Union, Telecommunication Standardization Sector), took place in Pune, India, on December 13–15, 2010. Its theme was "Beyond the Internet?—Innovations for future networks and services". Selected papers contributed from the world's universities, industries, and academic institutions, including NTT, were presented and discussed.

1. Introduction

ITU-T (International Telecommunication Union, Telecommunication Standardization Sector) Kaleidoscopes are peer-reviewed academic conferences that highlight multidisciplinary aspects of future information and communications technologies (ICTs) through contributions from the world's universities, industries, and academic institutions. Their aim is to increase the dialogue between experts working on ICT standardization and academia. ITU-T hopes that by viewing technologies through a *kaleidoscope*, the conferences will also seek to identify new topics for standardization. The first Kaleidoscope conference was held in Geneva, Switzerland, in 2008 focusing on "Innovation in NGN" (NGN: Next Generation Network) [1]. Following the second conference held in Mar del Plata, Argentina, on "Innovations for Digital Inclusion" [2], ITU-T Kaleidoscope 2010 (K-2010) took place in Pune, India, on December 13–15, 2010 [3]. It addressed the theme "Beyond the Internet?—Innovations for future networks and services" and focused on innovative technologies that could challenge the fundamental networking design principles of the Internet. NTT has contributed to the Kaleidoscopes from the beginning, and this time we gave a presentation on elastic and adaptive optical networks from the perspectives of possible adoption scenarios and future standardization. In this article, I present a brief report of NTT's participation in K-2010.

2. Conference overview

K-2010 was held at Sinhgad Technical Education Society (STES) in Pune, India, and had 329 registered participants from 24 countries. The conference program consisted of three keynote speeches, four invited talks, and 37 regular presentations that were carefully selected from 115 submitted papers.

The opening ceremony included the inaugural speech from the local authority, welcome speeches from the host and from K-2010 partners, and the opening address from the Director of ITU TSB (Telecommunication Standardization Bureau). The conference program followed the Indian protocol of presenting the keynote speakers and session chairs with flowers, coconuts, and Indian traditional scarves. Session 1, the keynote session, was presided over by Yoichi Maeda (TTC (Telecommunication Technology Committee), Japan), K-2010 General Chairman. This year's keynote speeches were delivered by Uday B. Desai (Director, Indian Institute of Technology, Hyderabad, India, "Modern academia: teaching, research, development, patents and standards"), Tadao Saito (Professor Emeritus, University of Tokyo, Japan, "Vehicle communication: a future telecommunication market"), and Detlev Otto (CTO, Nokia Siemens Networks, Germany, "Future of

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communications? The individual user experience"). The following seven regular sessions dealt with "Rethinking the network", "The future internet is for all", "Protocol evolution and the future internet", "Service innovations in the future internet", "Regulation, standardization and stakeholder participation", "Radio technologies and the future internet", and "Future internet and the environment".

K-2010 included two special sessions as new events: the "Standards corner" and "Jules Verne's corner". The Standards corner provided highlights on standardization activities in ITU-T relevant to the conference theme, including IPTV-GSI, FGFN, MyFIRE project, and Future Access Networks. It also introduced the participants to the ITU-T standardization activities and to a related industry perspective. The first Jules Verne's corner (JVc) was intended to include in the Kaleidoscope program a session dedicated to the views of extremely advanced minds, able to think of 50 years and beyond as Jules Verne himself did in his literature. The objective was to share thoughts that might help develop communication concepts to generate the spark that could *make possible the impossible* during the second half of the 21st century.

Alongside K-2010, the following events took place at the same venue, from 13 to 17 December 2010: Standardization Tutorial, ITU IPTV-GSI event, ITU IPTV Interoperability event, IPTV Workshop, Global ICT Standardization Forum for India (GISFI) Standards meeting, and MyFIRE project event.

An official report on K-2010 is available on the ITU-T webpage [4].

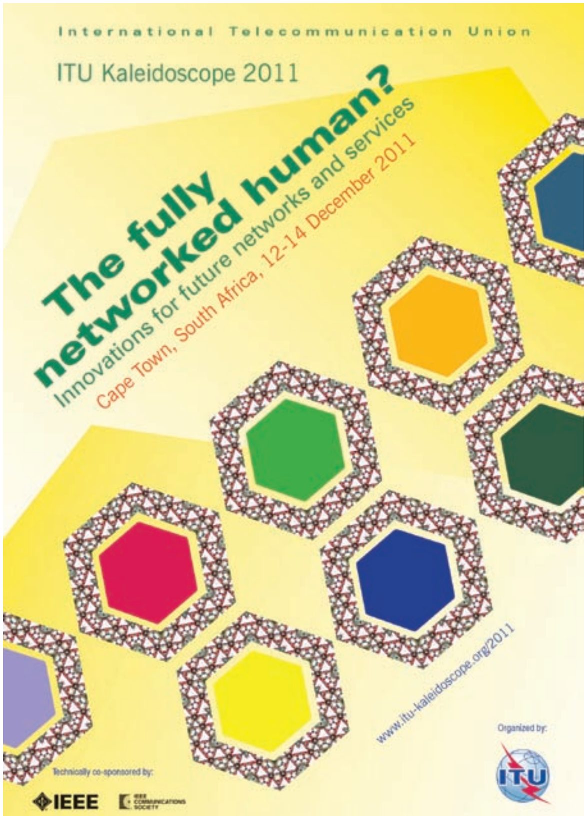
3. NTT's contributed paper

As a promising approach to cost-effectively accommodating the continuing growth in Internet protocol (IP) traffic, NTT recently proposed introducing elasticity and adaptation into optical transport networks through more flexible spectrum allocation, where the required minimum spectral resources are allocated adaptively according to traffic demand and network conditions [5], [6]. With future optical networks facing an impending capacity crunch, the spectral-efficiency-conscious networking approach has attracted growing interest and a number of bandwidth-variable optical network models have been investigated [7]–[10]. Since the introduction of elasticity and adaptation will be a big leap forward from conventional rigid and fixed optical networks, we believe that early initiatives by the standardization bodies to study possible extension of the standards for the Optical Transport Network (OTN), automatically switched optical network (ASON), and generalized multiprotocol label switching (GMPLS) in terms of optical network resource utilization efficiency will greatly support the rapid advance and adoption of more efficient and scalable optical networks.

The paper presented by NTT at the K-2010 was written by my colleagues and I from the perspective of future standardization to clarify what standards should be inherited, what standards should be extended, and what standards should be created as the starting point regarding study of the possible extension of OTN and ASON/GMPLS standards toward spectrally efficient elastic optical path networks [11]. In the presentation, I first overviewed the architecture, enabling technologies, and benefits of the elastic optical path network where the required minimum spectral resources are adaptively allocated to an optical path according to various network conditions including actual client traffic demand, physical network conditions, and the available bandwidth on the route. I then introduced a novel concept that network operators need to be aware of in order to allocate appropriate spectral resources to an end-to-end optical path. This concept is an optical corridor concept, which is an end-to-end spectrum window that is to be open at every wavelength cross-connect on the route. Possible adoption scenarios from current rigid optical networks to elastic optical path networks were also presented. One possible scenario is to introduce elasticity and adaptation on a step-by-step basis from the link level to the network level and from the static level to the dynamic level, probably led by the development of future higher-bitrate OTN interfaces. An earlier adoption possibility might be the introduction of distance-adaptive spectrum allocation to achieve cost-effective 100-Gbit/s-class reconfigurable optical add/drop multiplexer (ROADM) systems. As the starting point for studying the possible extension of OTN and ASON/GMPLS standards in terms of optical network efficiency, I clarified what should be inherited, what should be extended, and what should be created. Finally, I introduced some candidates for the structure and mapping of the OTN frame and some physical aspects with possible extension of the current frequency grid.

4. Concluding remarks

ITU-T Kaleidoscope 2010 focused on innovative technologies that could challenge the fundamental



networking design principles of the Internet. NTT presented a paper about possible adoption scenarios and potential standardization study items for elastic optical path networks to facilitate early initiatives for future standardization by the relevant standardization bodies. A detailed and updated version of our presentation will be published in the October Issue of the Standards Series of IEEE Communications Magazine.

The fourth ITU-T Kaleidoscope academic conference will take place in Cape Town, South Africa, on December 12–14, 2011 on the theme of "The fully networked human?—Innovations for future networks and services". Additional information is available on the conference webpage [12].

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He received the M.E. degree in electronics engineering from Kanazawa University, Ishikawa, in 1986. He joined NTT to study ultrafast optical signal processing for high-capacity optical time division multiplexed transmission systems. From 1993 to 1994, he investigated optical sampling and optical time-domain reflectometry as a guest scientist at the National Institute of Standards and Technology (NIST), Boulder, Colorado, USA. He received the Ph.D. degree in engineering from Osaka University in 1995 for his work on ultrafast optical signal processing based on nonlinear effects in optical fibers. From 1996, he conducted pioneering research on ultrawideband DWDM transmission systems in the L- and S-bands. In 2005, after two year's experience in developing wireless and wired access systems at NTT WEST, he started researching photonic networks with a focus on GMPLS and application-aware photonic networking in NTT Network Innovation Laboratories. His current interests include the architecture, design, management, and control of spectrally efficient elastic optical path networks, bandwidth-ROADMs/WXCs, and rate/format flexible optical transceivers. He has authored or co-authored over 150 peer-reviewed journal and conference papers during his 25-year career. He received the Young Engineer's Award in 1993 and the Best Tutorial Paper Award in 2011 from the Institute of Electronics, Information and Communication Engineers (IEICE), and Best Paper Awards from the 1997, 1998, and 2007 Optoelectronics and Communications Conferences (OECC) and the 2010 ITU-T Kaleidoscope Academic Conference.

Corrosion Fractures in Wire Grips

Abstract

This article describes corrosion fractures in wire grips and introduces countermeasures to this problem. It is the sixth in a bimonthly series on the theme of practical field information about telecommunication technologies. This month's contribution is from the Materials Engineering Group, Technical Assistance and Support Center, Maintenance and Service Operation Department, Network Business Headquarters.

1. Introduction

Utility poles, messenger wires, and other facilities that support telecommunication cables over an aerial span progressively deteriorate over time owing to exposure to the natural environment. However, their reliability can be improved by using designs that provide a large safety margin and by selecting products that are more suitable for the target environment. Nevertheless, there are situations in which damage can still occur because of various external factors, such as fatigue-induced fractures in areas that experience strong winds, saline damage in coastal areas, and damage caused by sulfur in hot-spring regions. Another factor in the electrolytic corrosion of metallic materials is stray current from railway lines. While it is known that electrolytic corrosion can occur in lead-covered cables or lead conduits, it can also cause problems in aerial facilities via ground lines. The wire grip that terminates a messenger wire is equipped with a ground clamp, and the flow of ground current in the ground line can cause electrolytic corrosion to occur in the wire grip and ground clamp. This article reports on corrosion-related fractures that occurred where ground clamps were attached to wire grips and messenger wires.

2. Wire grip

A wire grip is a fastener for attaching a messenger wire or guy wire to a utility pole. It can be applied quickly by simply twisting it around the messenger or guy wire manually and its gripping force remains constant over the long term. It is thus an important component that plays the role of terminating a messenger wire supporting a telecommunication cable or a guy wire maintaining a weight balance. The fracturing of a wire grip can consequently lead to a major accident. To prevent such accidents from occurring, wire grips must be appropriately maintained.

3. Case study: fracture in aluminium corrosion-resistant wire grip

3.1 Facility configuration

This case study concerns an accident in which an overhead telecommunication cable fell to the ground because of a fracture in the aluminium corrosion-resistant wire grip where the ground clamp was attached. The facilities involved in this accident consisted of an aluminium corrosion-resistant wire grip (cross-sectional area: 30 mm^2) used with a No. 1 thimble, a 30AW messenger wire (consisting of 30-mm^2 aluminium corrosion-resistant strands) terminated by the wire grip, and a 0.4-30CA telecommunication cable (deployed in 1985) supported by the messenger wire. The wire grip and messenger wire were assumed to have been installed in 1985, the same year as the telecommunication cable, while the ground clamp was known to have been installed in 1988. The cable pathway ran alongside a roadway and parallel to a railway in a coastal area having many factories. The section of cable where the corrosion-related accident occurred was located about 600 m from the coast.

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3.2 Observation of samples

When the fractured wire grip and ground clamp were examined, it was found that the portion of the ground clamp in contact with the wire grip was heavily corroded. Moreover, the wire grip was severely wasted away in a region 20–30 mm from the fracture point (**Fig. 1**) indicating that the corrosion had progressed locally. Since a maximum wastage of 1.03 mm occurred in a strand with a diameter of 2.60 mm over a 21-year period from 1988, the corrosion rate was 49 μm per year. The normal corrosion rate of aluminium is 0.4–0.6 μm/year even in coastal areas [1], and since the standard thickness of the aluminium covering in the aluminium corrosion-resistant wire grip is 180 μm, a corrosion rate of 49 μm/year is extremely high. When the ground clamp was examined, red rust could be observed in the bolt section and main body. Moreover, in the section of the ground clamp in contact with the wire grip, some of the strands of the wire grip were found to have fused with the ground clamp (**Fig. 2**). Corrosion had also occurred on the wire grip on the other side of the utility pole at the point where the ground clamp was attached.

The above facility configuration and the sample observation results made electrolytic corrosion at the ground clamp a prime suspect. To check whether current had been flowing through the messenger wire or wire grip, NTT EAST personnel conducted a survey in the field.

3.3 Survey details and results

The survey covered a range of about 4 km from the point of the fracture accident. A digital clamp meter was used to measure current (AC and DC) in messenger wires, wire grips, and ground lines, and a multitester was used to measure resistance between a ground clamp and messenger wire, between a ground

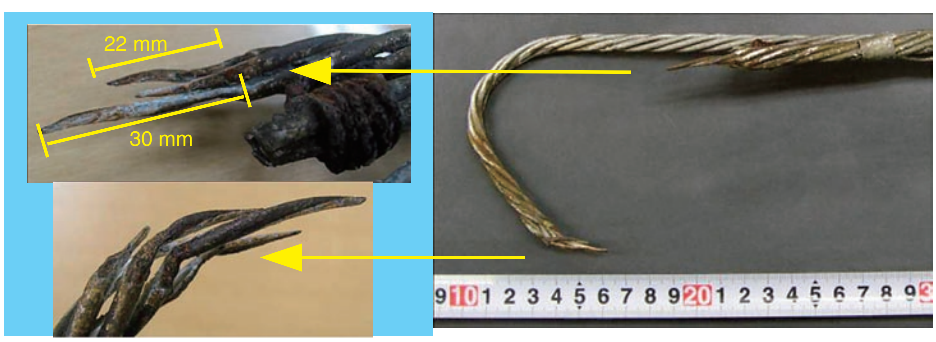

Fig. 1. Fractured aluminium corrosion-resistant wire grip.

Fig. 2. Ground clamp (on the side opposite the fractured wire grip).

clamp and wire grip, etc. For each utility pole, the complete set of measurements was performed twice—first in the morning and once again in the evening—to see whether the values depended on the time of day. At the time of the survey, the fractured wire grip and corroded wire grip had already been repaired.

Measurement results are shown in **Figs. 3** and **4**. No AC was observed at any location, but DC was observed in the section from utility pole A to utility pole C (about 2 km). At the fracture accident location, a DC value of 9 mA was measured at 10:00 AM and 10 mA was measured at 4:00 PM. The direction of current flow changed for the two measurement times at the same measurement location. Furthermore, in the surveyed range, no corrosion was observed in messenger wires, wire grips, or metallic components even in those segments in which DC was measured.

3.4 Inferred cause of fracture

The results of measuring current and resistance and making observations suggest that current was flowing through the point of contact between the wire grip and ground clamp under investigation here, which caused electrolytic corrosion to occur and progress and this caused the messenger wire to fracture.

The occurrence of a potential difference due to the effects of stray current can generate a current loop along the path: earth, ground rod, messenger wire, ground rod, and earth. If the ground clamp, messenger wire, and wire grip are insulated and if their surfaces get wet (from rain or other sources), current flows through this film of water, creating the possibility of electrolytic corrosion in the messenger wire and wire grip. Since the contact resistance between a ground clamp and wire grip is high, we inferred that current did indeed flow through a water film, which resulted in the generation of electrolytic corrosion.

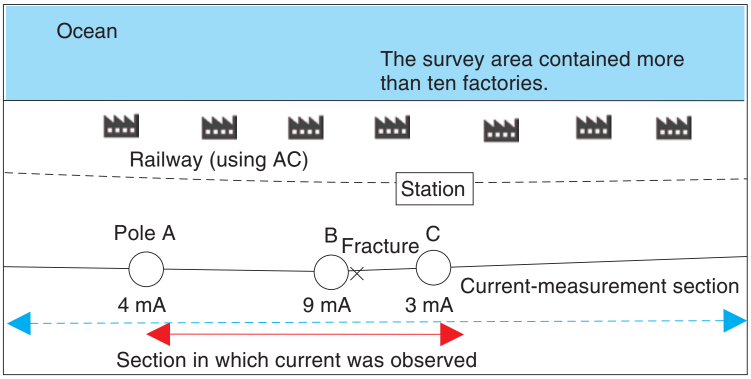

Fig. 3. Facility configuration and measurement results.

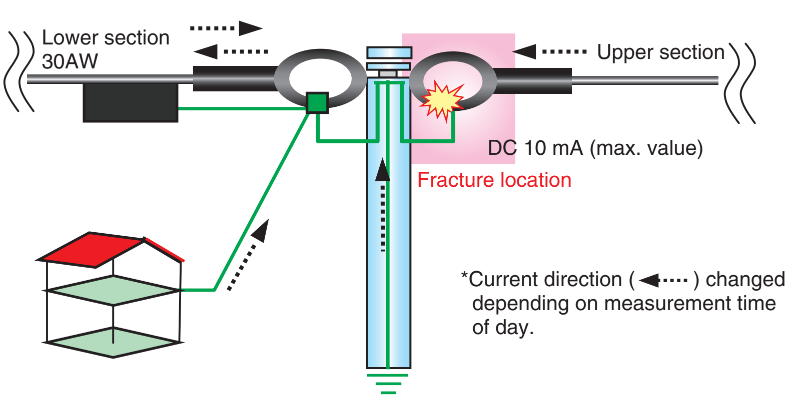

Fig. 4. Current-measurement results at utility pole B.

Rainwater can easily collect between a ground clamp and wire grip, and since the fracture point was located only about 600 m from the coastline, it is possible that rainwater containing particles of sea salt promoted the electrolytic reaction.

Although a railway is frequently the source of current in messenger wires and similar facilities, it was found that the nearby railway in this case used AC, and since no AC was be detected in this survey, it was concluded that the railway was not the source of current. There were also many factories in the area, but as the direction of observed DC changed according to time, it was difficult to estimate the gradient of the potential difference. In addition, the locations where current was observed extended across a wide range, which prevented the current source from being isolated. However, as the highest current value was observed at the fracture accident location, it was inferred that this location was situated in an environment in which electrolytic corrosion could easily occur.

3.5 Countermeasures

The most effective countermeasure here would have been to deal appropriately with the source generating the current, but since the source could not be isolated in this survey, countermeasures on the facility side had to be taken and countermeasures will continue to be needed in the future. If the contact resistance between a ground clamp and wire grip is sufficiently small, a potential difference does not arise and electrolytic corrosion generation can be prevented. In the survey, the resistance between ground clamp and wire grip was measured* in many locations and a measurement reading of 0 Ω was obtained in all cases. It was therefore concluded that electrolytic corrosion would not be a problem even in areas where DC was observed. However, older-type ground clamps are zinc coated to prevent corrosion of the iron materials, but if that zinc plating disappears, the aluminium portion of the aluminium corrosion-resistant wire grip can come into contact with iron, generating bimetallic corrosion. Furthermore, as the resistance at such a corrosion location is high, the corrosion will be further accelerated by electrolysis whenever DC flows. Thus, in the section between utility poles A and C where current was observed, special attention must be paid to locations with the older-type ground clamps in future facility inspections. By contrast, the latest ground clamps are manufactured by zinc alloy die-casting, which means that bimetallic corrosion will not be a problem as long as aluminium corrosion-resistant wire grips are used. In other words, replacing the older-type ground clamps with new ones could also be an effective countermeasure.

Furthermore, if a ground clamp is to be installed in existing facilities and the installation point is soiled or corroded, contact resistance will be high, which will make it easy for electrolytic corrosion to occur when current is flowing. Contact resistance will also be high if the ground clamp itself is soiled. Therefore, old parts should not be used and the contact area should be cleaned thoroughly before a new ground clamp is installed. Likewise, continuity checks between the wire grip and ground and between the messenger wire and ground should be performed.

* Measured using a Sanwa CP-7D analog multitester; working range: 0–0.4 Ω

4. Related case studies on corrosion

4.1 Fracture of aluminium corrosion-resistant messenger wire

Electrolytic corrosion can occur in messenger wires in the same way as in wire grips. This section presents a case study of a corrosion-related fracture at the location where a ground clamp was attached to an aluminium corrosion-resistant (AW) messenger wire. The accident occurred about 1500 m from the ocean in a river delta in a residential area dotted with small iron works and other small factories. The fractured wire was of the 30AW type deployed in 1980. The corrosion in this fractured wire is shown in **Fig. 5**. A sudden wasting away of messenger wire not seen in crevice-type corrosion was observed at the boundary between the corroded and normal parts of the messenger wire. It was therefore inferred that current was flowing in this boundary region causing electrolytic corrosion to occur.

Fig. 5. Fractured AW messenger wire.

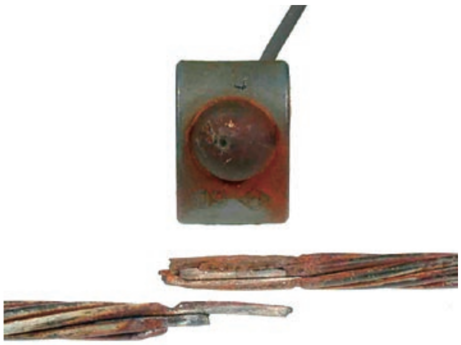

Fig. 6. Fractured SW messenger wire.

4.2 Fracture of steel-wire messenger wire

The same kind of attention must also be paid to zinc-coated steel-wire (SW) messenger wire. When the contact resistance between the messenger wire and ground clamp is high and a potential difference exists, the formation of a water film having ionic conductivity will result in the flow of current and the occurrence of an electrolytic reaction. Once the messenger wire begins to act as an anode, its wire strands can erode as a result of an electrochemical reaction. Furthermore, in coastal areas, sea-salt particles can penetrate the water film, which makes it easy for an ionic conductive water film to form. An example of electrolytic corrosion in an SW messenger wire is shown in **Fig. 6**.

The countermeasures described above can also be effective when attaching ground clamps to SW messenger wire. Moreover, since surface resistance is high in the phase preceding the appearance of red rust on the messenger wire; that is, when the zinc coating corrodes and white rust begins to appear, this white rust must be removed. The SW messenger wire is more susceptible to corrosion than AW messenger wire, so special attention must be paid when ground clamps are attached to existing SW messenger wires.

5. Conclusion

This article presented case studies of fractures in wire grips and messenger wires and described countermeasures to this problem. Although unexpected failures are bound to occur in facilities exposed to the natural environment, if appropriate measures are taken beforehand, the occurrence of fracture accidents can be minimized. The NTT EAST Technical Assistance & Support Center is working to clarify the causes of abnormal failures and to establish measures to combat them with the aim of improving the reliability of telecommunication facilities.

Reference

[1] C. Leygfaf and T. E. Graedel, “ Atmospheric Corrosion,” Wiley-Interscience; 1st edition, p. 251, 2000.

External Awards

LOIS Best Paper Award
Winners: Takeshi Kurashima[*1], Tomoharu Iwata[*2], Go Irie[*1], and Ko Fujimura[*1]
*1 NTT Cyber Solutions Laboratories
*2 NTT Communication Science Laboratories
Date: May 19, 2011
Organization: IEICE Life Intelligence and Office Information System (LOIS) Technical Group

For "Travel Route Recommendation Using Geotags on Photo Sharing Service".
Published as: T. Kurashima, T. Iwata, G. Irie, and K. Fujimura, "Travel Route Recommendation Using Geotags on Photo Sharing Service," IEICE Tech. Report, Vol. 109, No. 450, pp. 55–60, 2010.

Papers Published in Technical Journals and Conference Proceedings

Single-electron Stochastic Resonance Using Si Nano-wire Transistors

K. Nishiguchi and A. Fujiwara

Proc. of the International Symposium on Nanoscale Transport and Technology (ISNTT2011), p. 133, Atsugi, Kanagawa, Japan.

We demonstrate stochastic resonance (SR) with single electrons (SEs) using nanoscale metal-oxide-semiconductor field-effect transistors (MOSFETs). The input signal applied to a MOSFET modulates SE transport in an average manner based on non-linear characteristics. On the other hand, an individual SE goes through the MOSFET in a completely random manner, which corresponds to shot noise. SEs transferred to a storage node are counted precisely by the other MOSFET and used as an output signal. The correlation between the input and output signals is improved by taking advantage of extrinsic noise as well as the intrinsic shot noise composed of SEs. It is confirmed that the shot-noise-assisted SR allows fast operation with a simple system. Pattern perception utilizing SR is also demonstrated.

A Silicon Nanowire Ion-sensitive Field-effect Transistor with Elementary Charge Sensitivity

N. Clément, K. Nishiguchi, J. F. Dufreche, D. Guerin, A. Fujiwara, and D. Vuillaume

Appl. Phys. Lett., Vol. 98, No. 1, p. 014104, 2011.

We investigate the mechanisms responsible for the low-frequency noise in liquid-gated nanoscale silicon nanowire field-effect transistors (SiNW-FETs) and show that the charge-noise level is lower than the elementary charge. Our measurements also show that the ionic strength of the surrounding electrolyte has a minimal effect on the overall noise. Dielectric polarization noise seems to be at the origin of the $1/f$ noise in our devices. The estimated spectral density of charge noise $Sq = 1.6\times10^{-2}\ e/\mathrm{Hz}^{1/2}$ at 10 Hz opens the door to metrological studies with these SiNW-FETs for the electrical detection of a small number of molecules.

Evaluation of a Gate Capacitance in the Sub-aF Range for a Chemical Field-effect Transistor with a Silicon Nanowire Channel

N. Clément, K. Nishiguchi, A. Fujiwara, and D. Vuillaume

IEEE Trans. Nanotechnology, Vol. PP, No. 99, pp. 1–8, 2011.

An evaluation of the gate capacitance of a field-effect transistor (FET) whose channel length and width are several tens of nanometers is a key point for sensors applications. However, experimental and precise evaluation of capacitance in the attofarad range or less has been extremely difficult. Here, we report an extraction of the capacitance down to 0.55 aF for a silicon FET with a nanoscale wire channel whose width and length are 15 and 50 nm, respectively. The extraction can be achieved by using a combination of four kinds of measurements: current characteristics modulated by double gates, random-telegraph-signal noise induced by the trapping and detrapping of a single electron, dielectric polarization noise, and current characteristics showing Coulomb blockade at low temperature. The extraction of such a small gate-capacitance enables us to evaluate electron mobility in a nanoscale wire using a classical model of the current characteristics of a FET.

A Theater for Viewing and Editing Multi-sensory Content

K. Hirota, S. Ebisawa, T. Amemiya, and Y. Ikei

IEEE International Symposium on VR Innovation (ISVRI2011), pp. 239–244, Singapore.

This research has been carried out as part of a multi-sensory theater project that aims at establishing technology to integrate a range of sensations such as visual, audio, force, tactile, vestibular, and odor into passive and interactive media content and communications. This paper describes the approaches that are being examined and the current status of the project. As a platform for the experiments, a prototype version of a multi-sensory theater has been implemented. The theater is equipped with devices that present wind and olfactory sensations. The sensation of wind is generated by both computer-controlled fans and air nozzles connected to a source of compressed air, and the olfactory sensation is presented by emitting odorants into the air. To facilitate the creation of content, a framework for editing multi-sensory information was constructed, in which all of the devices were connected to and controlled by a sequencer based on a MIDI interface.

Standardization Trend of Recent Wireless LANs

Y. Kojima

ARIB Bulletin, the Association of Radio Industries and Businesses (ARIB), No. 73, 2011 (in Japanese).

This article explains the trend of recent wireless LAN standardization for IEEE802.11 and Wi-Fi.

Training Conditional Random Fields Based on Segment-wise Maximum Figure-of-merit Functions

J. Suzuki and H. Isozaki

Journal of IEICE, the Institute of Electronics, Information and Communication Engineers (IEICE), Vol. J94-D, No. 5, pp. 908–918, 2011 (in Japanese).

This paper proposes a framework for training conditional random fields (CRFs) to maximize a figure-of-merit function for task evaluation. Specifically focusing on sequence segmentation tasks such as chunking and named entity recognition tasks in the natural language processing field, this paper introduces an objective function that emulates the segment-wise F-score, which is generally used as an evaluation measure for these tasks. Our experiments show that the segment-wise F-score optimization performs better than standard ML (maximum likelihood) and MAP (maximum a posteriori) training of CRF since it reduces the mismatch between the objective function of CRF training and the task evaluation measure.

Single-electron Counting Statistics of Shot Noise in Nanowire Si Metal-oxide-semiconductor Field-effect transistors

K. Nishiguchi, Y. Ono, and A. Fujiwara

Appl. Phys. Lett., Vol. 98, No. 19, p. 193502, 2011.

Shot noise in the transport of single electrons in a Si metal-oxide-semiconductor field-effect transistor is monitored by real-time measurement with a high-charge-sensitivity electrometer. In the current range between zepto- and attoamperes, the current characteristics are found to be divided into two regimes: a temperature-independent regime in the lower current range and a temperature-dependent one in the higher current range. A time-domain analysis reveals that, for both regimes, the single-electron transport obeys a pure Poisson process with the Fano factor being nearly unity, while the shot noise is suppressed with reduced Fano factors around the boundary.

High Output Power (~400 μW) Oscillators at around 550 GHz Using Resonant Tunneling Diodes with Graded Emitter and Thin Barriers

M. Shiraishi, H. Shibayama, K. Ishigaki, S. Suzuki, M. Asada, H. Sugiyama, and H. Yokoyama.

Appl. Phys. Express, Vol. 4, No. 6, p. 064101, 2011.

We report resonant tunneling diode (RTD) oscillators with a high output power of around 400 μW at frequencies of 530–590 GHz. RTDs with a graded emitter and thin barriers were employed to obtain large negative differential conductance at high frequencies for high output power. An optimized structure of offset slot antennas was also used to maximize the radiation conductance. The highest output power obtained in this study was 420 μW at 548 GHz for an RTD with a peak current density of 24 mA/μm^2; the RTD was placed 58 μm away from the center of a 130-μm-long slot antenna.

Asymptotic Local Hypothesis Testing between a Pure Bipartite State and the Completely Mixed State

M. Owari and M. Hayashi

arXiv, Cornell University Library, Vol. 1105, No. 3789, pp. 1–14, 2011.

In this paper, we treat asymptotic hypothesis testing between an arbitrary known bipartite pure state and the completely mixed state under one-way local quantum operations assisted by classical communication (LOCC), two-way LOCC, and separable positive operator valued measures (POVMs). As a result, we derive analytical formulas for Stein's lemma type of optimal error exponents under all one-way LOCC, two-way LOCC, and separable POVMs; the Chernoff bounds under one-way LOCC POVMs and separable POVMs; and the Hoeffding bounds under one-way LOCC POVMs without any restrictions on a parameter and under separable POVMs in a restricted region of a parameter. We also numerically calculate the Chernoff and Hoeffding bounds for a class of three-step LOCC protocols in low-dimensional systems and show that these bounds not only outperform the bounds for one-way LOCC POVMs, but almost approximate the bounds for separable POVMs in the region of a parameter where the analytical bounds for separable POVMs are derived.

Non-stationary Noise Estimation Method Based on Bias-residual Component Decomposition for Robust Speech Recognition

M. Fujimoto, S. Watanabe, and T. Nakatani

Proc. of the 36th International Conference on Acoustics, Speech and Signal Processing (ICASSP2011), IEEE, pp. 4816–4819, Prague, Czech Republic.

This paper addresses a noise suppression problem, namely the estimation of non-stationary noise sequences. In this problem, we assume that non-stationary noise can be decomposed into stationary and non-stationary components. These components are described respectively as the bias factor and the residual signal between the bias component and noise in each frame. This decomposition clarifies the role of each component, thus enabling us to apply a suitable parameter estimation technique to each component. In this paper, the bias component is estimated by the EM (expectation maximization) algorithm with the entire observed signal sequence. On the other hand, the residual component is sequentially estimated by multiplying the extended Kalman filter with the EM algorithm. In the evaluation results, we confirmed that the proposed method improved speech recognition accuracy compared with noise estimation methods without component decomposition.
