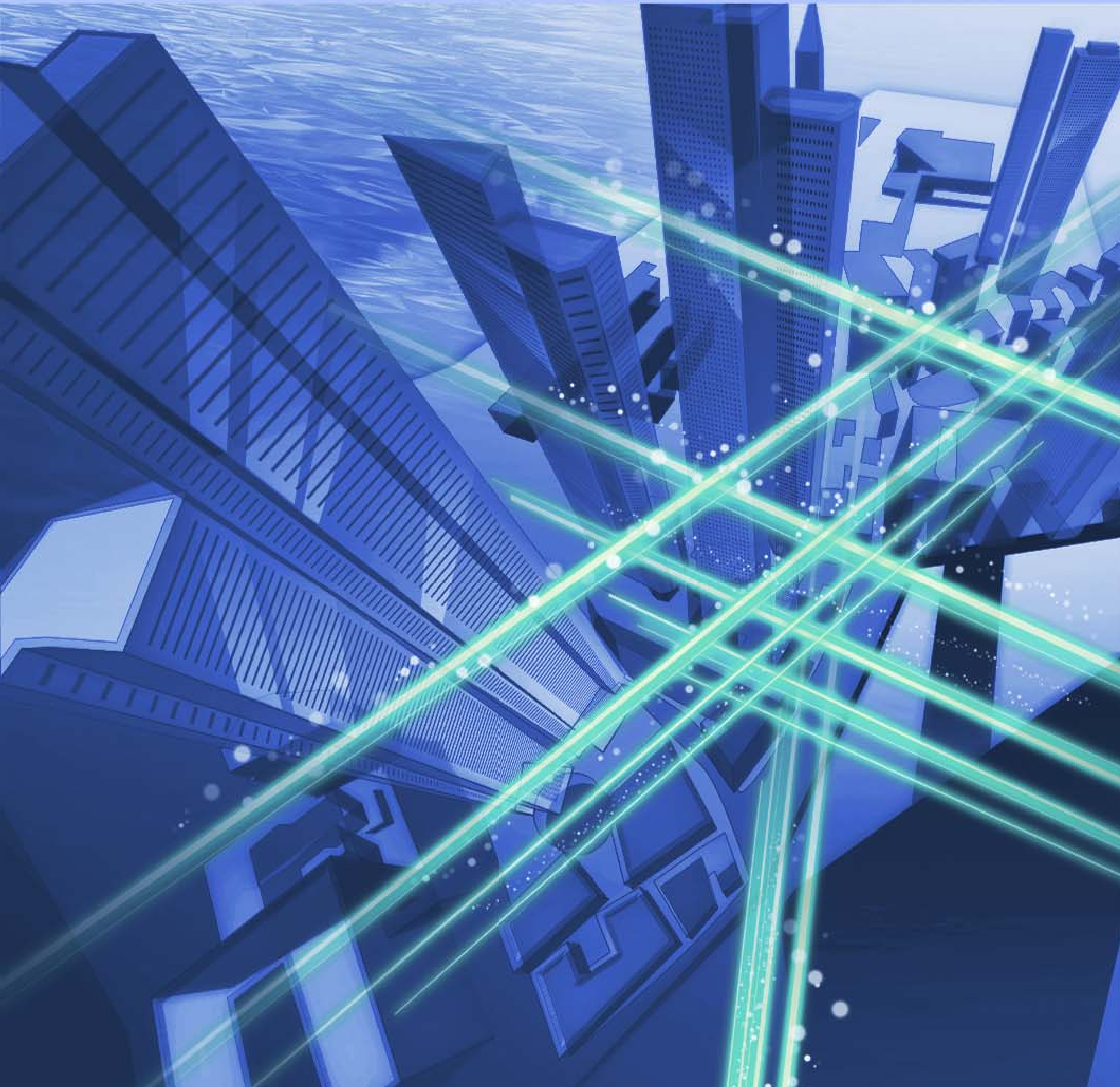
NTT Technical Review

6

2017



June 2017 Vol. 15 No. 6

NTT Technical Review

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Space Division Multiplexing Optical Transmission Technology to Support the Evolution of High-capacity Optical Transport Networks

Yutaka Miyamoto and Ryutaro Kawamura

Abstract

This article describes high-capacity space division multiplexing (SDM) optical transmission technology to support the evolution of broadband networks. A new spatial degree of freedom is introduced in optical transmission systems, optical node equipment, and optical fibers to overcome the physical limits of today's single-mode fiber based systems. Future SDM-based optical networks will achieve high capacities of over 1 Pbit/s in a single strand of fiber, a 100-fold increase in capacity, and node throughputs of more than 10 Pbit/s.

Keywords: spatially multiplexed optical communication, petabit-per-second optical communication, multi-core multi-mode fiber

1. Introduction

In recent years, the Internet has become an indispensable infrastructure offering broadband services such as video streaming and electronic commerce in support of daily life. Much effort is being devoted in mobile communications to develop 5G (fifth-generation) services, which will achieve low latency with large bandwidths in excess of 10 Gbit/s. The emerging IoT (Internet of Things) technologies based on the future network infrastructure are expected to enable new services that will be as ubiquitous and essential as the air around us.

The evolution of core and metro optical transport networks in NTT Group companies is shown in **Fig. 1**. The basic transmission medium of these networks has so far been single-mode fiber (SMF), which has only one waveguide (core) with a single waveguide mode per strand of optical fiber. In the NTT laboratories, we have been conducting timely research and development (R&D) on a state-of-the-art optical transport system that economically realizes the required transmission capacity. Our contributions have attained an increase in capacity of almost 5 orders of magnitude over the last 30 years (doubling every 2 years).

The digital coherent system [1] has been implemented in NTT's commercial network. Not only does it improve receiver sensitivity and spectral efficiency, but it can also greatly improve the compensation capability of distortion characteristics such as chromatic dispersion and polarization mode dispersion of optical fibers. Transport systems with 10-Tbit/s-class-capacity transport systems have been installed in commercial networks by using a polarization-division-multiplexed quadrature phase-shift keying (PDM QPSK) modulation format and the typical 50-GHz wavelength division multiplexing (WDM) spacing.

We have also confirmed the feasibility to upgrade to optical networks with a capacity of 20 Tbit/s per fiber and a channel capacity of 400 Gbit/s in the field. To achieve this, we employed twin-subcarrier multiplexing and high-speed digital signal processing

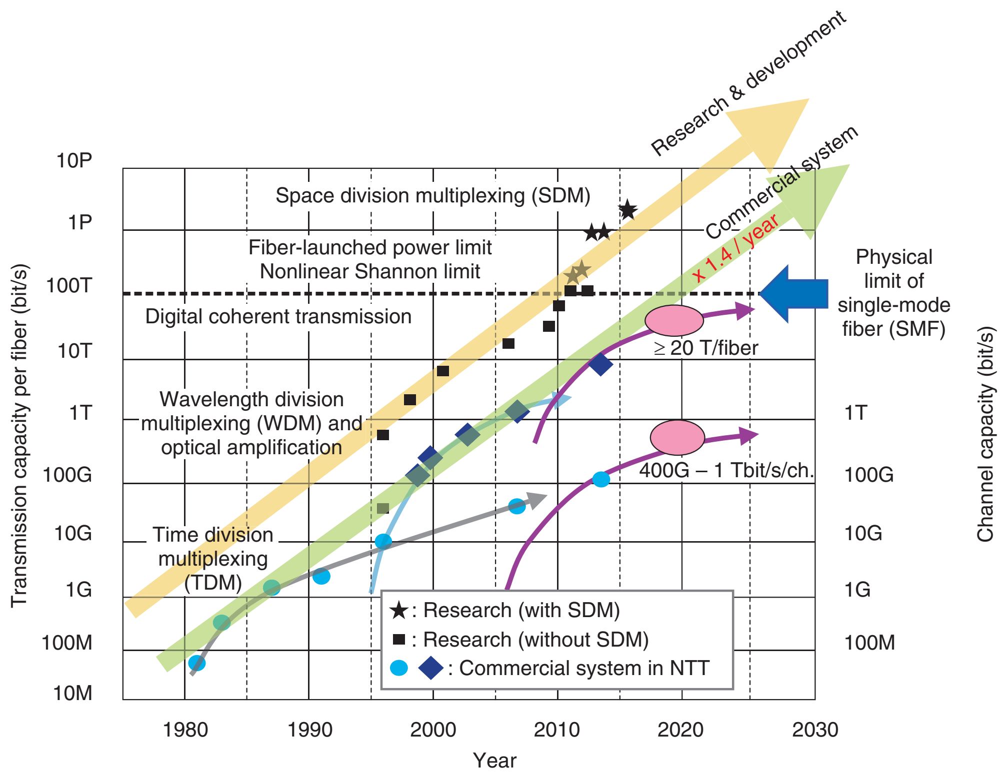

Fig. 1. Evolution of high-capacity optical transport network.

techniques based on 16-quadrature amplitude modulation (QAM)*1 [2].

In laboratory experiments, we demonstrated the record transmission capacity of 102 Tbit/s across a single SMF by using the subcarrier multiplexed PDM 64-QAM format [1]. Furthermore, we can significantly improve the scalability of optical networks without electrical signal regeneration by introducing reconfigurable optical add/drop multiplexer (ROADM) nodes. The above-mentioned 100-Gbit/s digital coherent channels are implemented in the existing high-capacity optical networks with multi-degree ROADMs, where the 100-Gbit/s channels can be set at arbitrary wavelengths and arbitrary directions (**Fig. 2**).

Efforts to increase the capacity of conventional SMF-based optical communication systems beyond 100 Tbit/s while keeping the same repeater spacing as the conventional network have reached or exceeded the ultimate physical limit of SMF (the so-called *capacity crunch*) due to the fiber nonlinear effect*2 and the fiber fuse phenomenon [3, 4]. Furthermore, in future optical node systems, several fundamental technologies such as highly integrated optical switching and high-density wiring and connectors will be required in order to substantially improve node throughput in step with the increases in transmission capacity.

We have conducted extensive R&D on space division multiplexing (SDM) optical communications that can offset these limiting factors and thus achieve further increases in both transmission capacity and optical node throughput [3–5]. In this article, we review the current status and the future prospects in this field. We present recent activities in the NTT laboratories involving SDM optical communications technologies that demonstrate over 1-Pbit/s long-haul transmission performance, and a potential optical switching node system with node throughput of more than 10 Pbit/s.

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*1 QAM: A highly efficient digital modulation scheme whereby the amplitude and phase of the signal's electric field are modulated to multiple levels in order to transmit multi-level symbols.

*2 Nonlinear effects: Phenomena that cause signal distortion such as the modulation of an optical signal's phase and frequency.

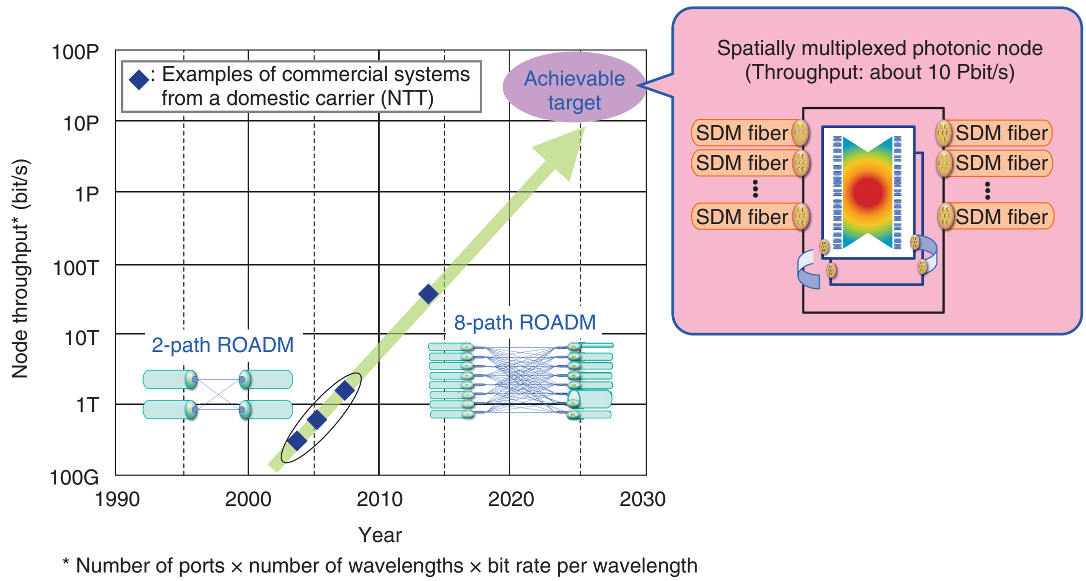

Fig. 2. Enhancing node throughput by means of SDM photonic node technology.

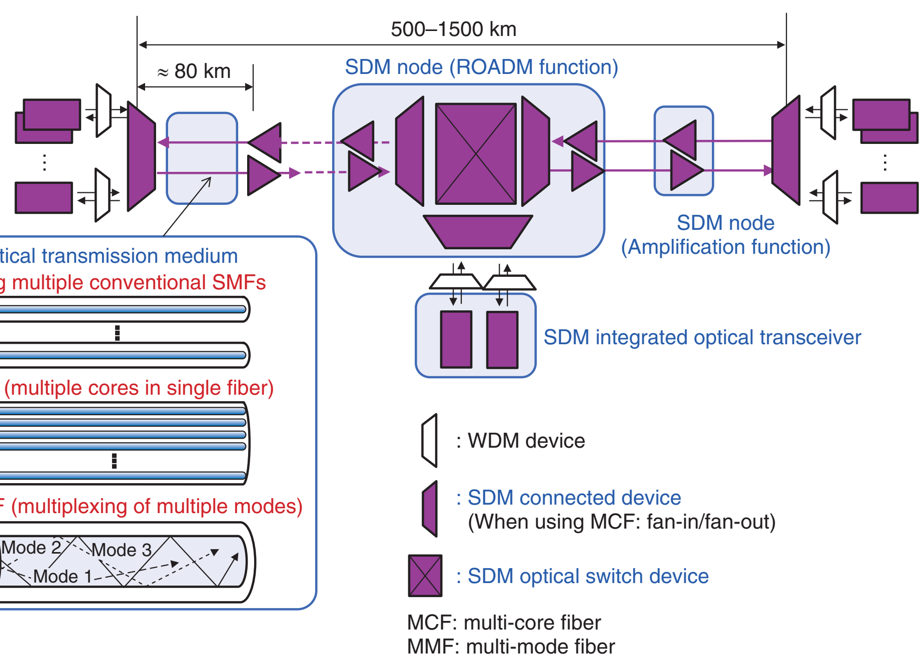

Fig. 3. Configuration of high-capacity optical transport network using SDM optical communications technology.

2. Overview and benefits of SDM optical communications system technology

An overview of an SDM optical communications system is shown in **Fig. 3**. The principal components of this system are the SDM optical transmission medium, SDM nodes with optical amplification and ROADM functions, and an SDM integrated optical transceiver. Typical candidates for the optical transmission medium of an SDM optical transmission

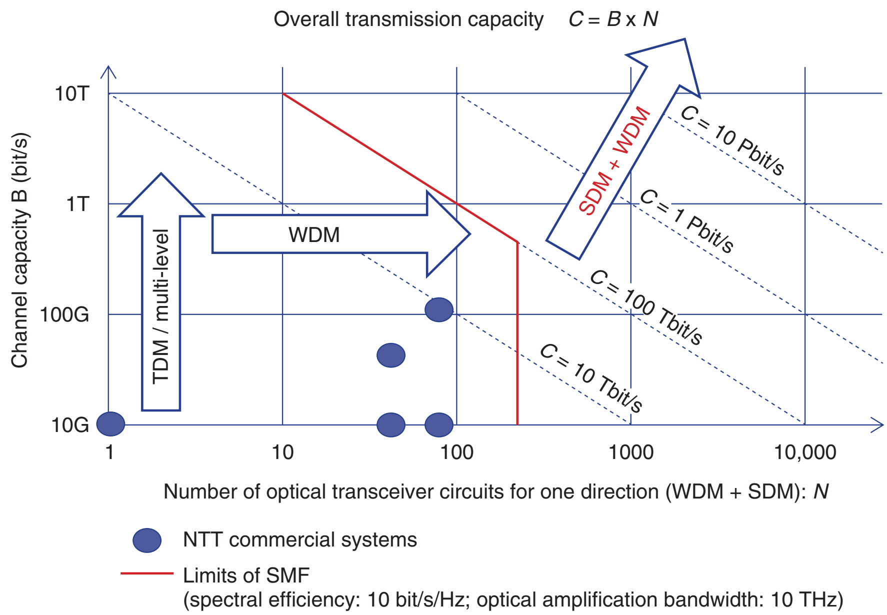

Fig. 4. Possible combination of SDM and WDM in future high-capacity SDM optical transport network.

system are shown on the left side of the figure. A set of conventional SMFs used as the SDM optical transmission medium is shown in Fig. 3(a), and a multicore fiber (MCF) consisting of multiple cores in a single optical fiber is shown in Fig. 3(b). A multimode fiber (MMF) that uses different modes to transmit different signals across the single core is depicted in Fig. 3(c).

In high-capacity SDM node systems, spatially multiplexed WDM signals (SDM/WDM signals) are simultaneously amplified and transmitted to achieve an economical long-haul transmission system. Any channel can be sent to an arbitrary wavelength in an arbitrary direction (the typical number of directions is eight) without the need for optical-electrical conversion. The optical node system exemplified by Fig. 3(a) can effectively utilize the existing SMF infrastructure and achieve flexible accommodation of traffic demands in the short term.

The multiplexing structures of existing optical communications systems and future SDM optical communications systems are compared in **Fig. 4**. In existing SMF-based commercial systems, the channel capacity has been increased up to 100 Gbit/s by means of time division multiplexing (32 Gbaud) and multi-level coding (QPSK). The typical WDM channel count N is around 100 in today's SMF-based systems (i.e., N is the number of multiplexed optical transceiver circuits). The WDM signals are simultaneously amplified and transmitted through several optical inline amplifiers and optical nodes. Such configurations achieve economical high-capacity long-haul transmission systems with an overall transmission capacity ($C = B \times N$) of 10 Tbit/s.

The available number of channels in a conventional WDM system is determined by the signal bandwidth of optical amplifiers, roughly 4–5 THz in the C band or L band, or up to about 10 THz if the two bands are used in parallel (C and L bands). Practical high-capacity systems have been implemented by installing hundreds of high-speed optical transceiver circuits in a limited equipment space without excessive power consumption, making full use of the available optoelectronic device performance.

Multi-level modulation can improve the spectral efficiency (SE) and thus increase the channel capacity. However, we have to consider the trade-off between SE and transmission distance if we are to maintain backward compatibility with the existing system. It is possible to increase the channel capacity up to 200 Gbit/s by enhancing the SE up to 4 bit/s/Hz with medium transmission reach through the use of PDM 16-QAM signals. However, the transmission distance is severely limited if the SE is increased up to 10 bit/s/Hz by using a higher-order QAM format [1].

Therefore, when considering channel capacities beyond 400 Gbit/s, the combination of subcarrier

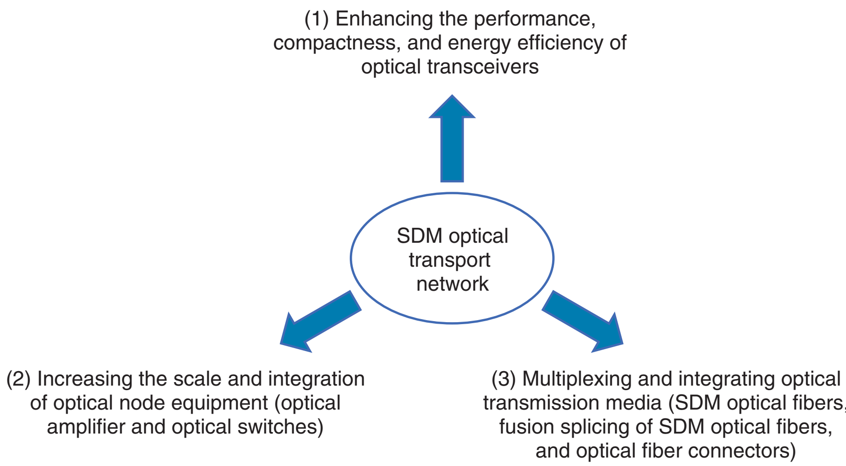

Fig. 5. Key technologies of SDM optical transport network.

multiplexing and/or a high symbol rate is a potential solution, while keeping the existing order of the QAM format low so as to ensure long transmission reach. Since the SE does not increase with this strategy, this naturally requires that the channel bandwidth increase in proportion to the channel rate. As a result, the number of WDM channels accommodated in the typical optical amplifier bandwidth naturally decreases, as shown in Fig. 4. Because the channel capacity growth rate (increasing roughly tenfold over 20 years) is more gradual than the total capacity growth rate as shown in Fig. 1, we have to effectively combine SDM and WDM technologies to ensure the same number of optical channels as before.

Therefore, if future ultra-high-capacity SDM transmission systems are to have a total capacity C of more than 1 Pbit/s, the required number of optical transceiver circuits implemented will increase to 10 and even 100 times that of a conventional SMF system. Thus, SDM technologies such as scalable integrated optical switching nodes as well as compact integration of optical transceiver circuits are the key to realizing economical high-capacity SDM optical transport networks.

3. Core technologies of SDM optical communication infrastructure

In the Feature Articles in this issue, we describe the current state of R&D and the future prospects of SDM optical communications technologies from the following three key aspects (**Fig. 5**).

(1) Enhancing the transmission performance, compactness, and energy efficiency of optical transceivers (transmission equipment)
(2) Increasing the scale and integration of optical node equipment (optical amplifier and optical switches)
(3) Multiplexing and integrating optical transmission media (SDM optical fibers, fusion splicing of SDM optical fibers, and SDM optical fiber connectors)

Transmission equipment (1) involves general technologies for both conventional SMF-based optical communications systems and future SDM optical communications systems. In one Feature Article, we describe the impact of inter-core crosstalk characteristics and efficient digital signal processing in terms of realizing spatially multiplexed long-haul optical communications systems [6]. We also explain the feasibility of petabit-per-second-class long-haul transmission. In a high-capacity SDM optical transport network, the number of multiplexed optical transceiver circuits will be one or two orders of magnitude higher than that of the conventional SMF-based system. Therefore, to realize an economical high-capacity energy-efficient optical network, it is very important to increase the transmission reach without optical-electrical conversion in the optical node, since reducing the number of optical transceiver circuits is critical for reducing the total system power consumption.

With regard to SDM node technology (2), the final target is to increase the throughput of optical nodes by over 100 times and to improve the transmission capacity to more than 1 Pbit/s. For this purpose, we

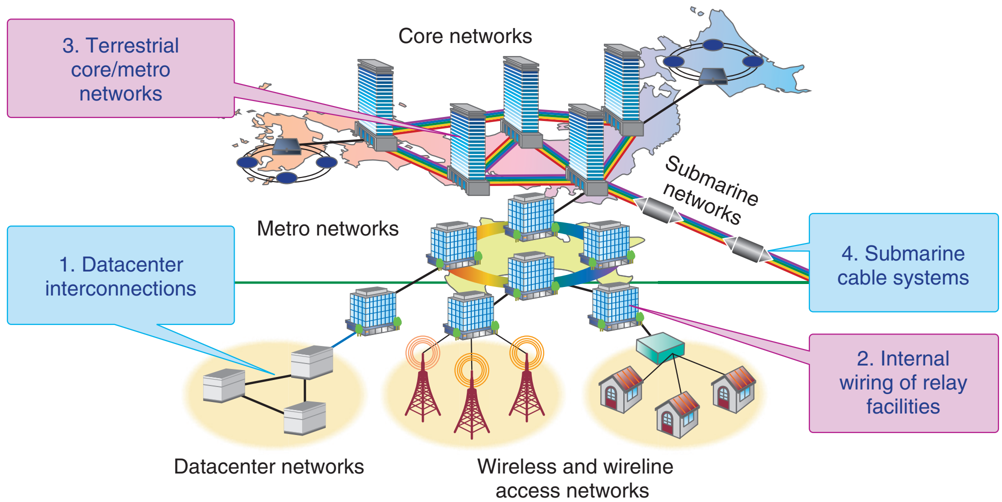

Fig. 6. Application areas of SDM optical communications.

have introduced novel optical node architectures and novel device integration technologies in SDM optical amplifiers and SDM integrated optical switches. We describe the recent R&D activities in this field [7, 8].

Finally, with regard to multiplexing and integration of optical transmission media (3), we describe the issues and feasibility of optical fiber transmission media for dense SDM (DSDM) with the SDM levels of 30 and beyond. We describe the current state of MCF, MMF, and multi-core multi-mode fiber (a combination of both) [9], as well as the connection devices between new SDM fibers and existing SMF and splicing techniques and connector technology for new SDM fibers [10]. The NTT laboratories have been commissioned by organizations including the Ministry of Internal Affairs and Communications of Japan and EC Horizon 2020, and the National Institute of Information and Communications Technology to accelerate our R&D in this field [4, 5].

4. Future prospects

The application areas where the future SDM optical communications system is expected to be applied are shown in **Fig. 6**. There is strong demand for short-distance applications such as datacenter interconnections and the internal wiring of SDM network elements in terms of compactness and low-power operation. Such applications have great potential in this field.

For medium-term SDM system application in terrestrial core/metro networks, it is promising to consider an SDM system that effectively uses existing installed SMF fiber cables as shown in Fig. 3(a). Furthermore, the use of high-capacity SDM optical fiber cables is expected to support the implementation of economical core/metro high-capacity optical networks with a capacity of more than 1 Pbit/s, as it will promote standardization and practical applications. In ultra-long-haul submarine cable systems that must accommodate the traffic growth of international communications, SDM optical communication technology is expected to offset the capacity crunch of conventional SMF-based systems and power supply constraints (i.e., power crunch), both of which are critical constraints in ultra-long-haul submarine cable systems.

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

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Dense Space Division Multiplexing (DSDM) Long Distance Optical Fiber Transmission Technology

Takayuki Mizuno, Kohki Shibahara, Doohwan Lee, Takayuki Kobayashi, and Yutaka Miyamoto

Abstract

Multi-core and multi-mode space division multiplexing (SDM) technology is being studied as an optical transmission technology targeted for the next generation high-capacity optical communication network. In this article, we describe the latest trends in optical transmission using SDM technology. We introduce the world's most advanced ultra-high-capacity long distance optical transmission realized by dense space division multiplexing (DSDM) with a spatial multiplicity above 30, which was achieved in joint global academic and industrial research collaborations.

Keywords: dense space division multiplexing (DSDM), multi-core multi-mode, long distance high-capacity optical fiber transmission

1. Introduction

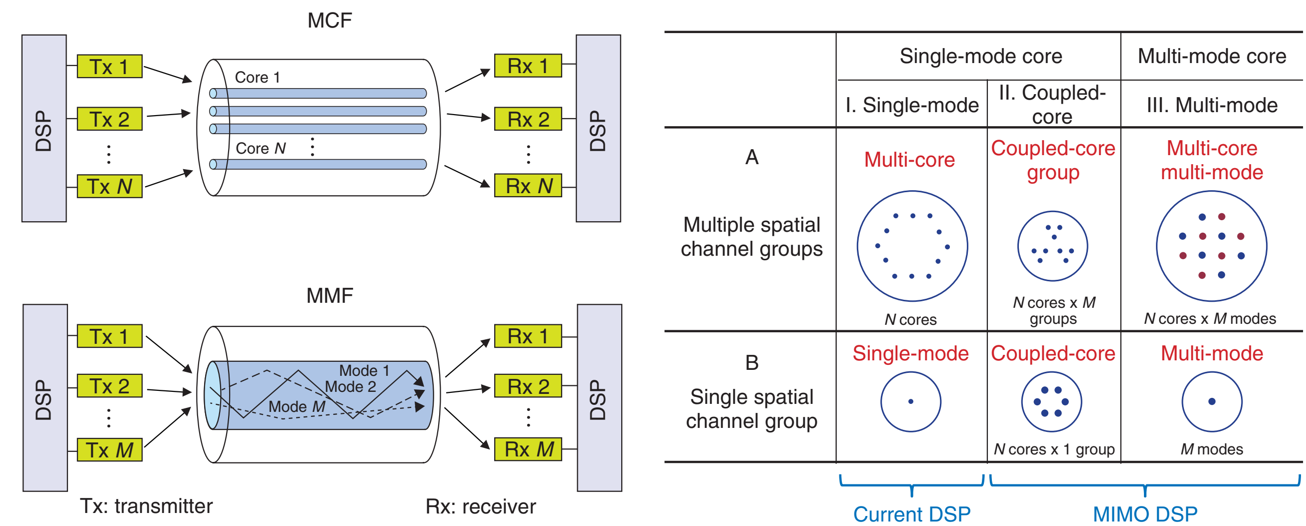
With the rapid spread of new information and communication services such as cloud computing, wireless communication, and high-definition video communication services, the data traffic flowing through the optical network is expected to continue to increase. Along with this traffic growth, a further increase in transmission capacity over optical fiber is required. The NTT laboratories have been developing optical transmission technologies over the past 30 years involving time division multiplexing, wavelength division multiplexing, and digital coherent technology, and have succeeded in realizing a 100-Tbit/s-class high transmission capacity per optical fiber in research, and a 10-Tbit/s-class transmission capacity in commercial large-capacity backbone optical transmission systems.

To further increase the transmission capacity, it is necessary to increase the power input to an optical fiber. However, increasing the power too much will give rise to nonlinear optical effects and a fiber fuse phenomenon. Thus, there is an upper limit to the allowable optical power transmitted through a fiber. The capacity limit due to these physical limits is known to be around 100 Tbit/s, and we may reach this upper limit within the next decade in commercial communication systems.

At NTT Network Innovation Laboratories, we have been promoting research on spatial multiplexing technology since 2009 in cooperation with related research groups within NTT, and in collaboration with other companies and universities, in order to realize the next generation ultra-high-capacity optical transmission technology.

Space division multiplexing (SDM)*1 is attracting attention as a state-of-the-art optical transmission technology that can increase the transmission capacity by several orders of magnitude relative to a conventional single-mode fiber (SMF) by spatially multiplexing optical signals in a transmission line. Advanced research is being conducted in various

*1 SDM: An optical transmission technology that multiplexes and transmits optical signals using a spatial dimension. Global research and development is progressing towards next generation high-capacity optical transmission technology.



(a) Schematic of SDM optical transmission system using multi-core fiber (MCF) and multi-mode fiber (MMF) as a transmission medium

(b) SDM optical transmission methods

DSP: digital signal processing
MIMO: multiple-input multiple-output

Fig. 1. SDM optical transmission technology.

research institutions around the world. A schematic of an SDM optical transmission system using a multi-core fiber (MCF) and a multi-mode fiber (MMF) as a transmission medium is shown as a representative example in **Fig. 1(a)**. With SDM, we can increase the transmission capacity by *N* or *M* times that of SMFs currently being used in backbone optical networks, where *N* and *M* are the number of cores and modes, respectively. Various SDM optical transmission methods have been reported so far and are depicted in a matrix in **Fig. 1(b)**.

The transmission capacity per optical fiber is plotted as a function of transmission distance in **Fig. 2**. These examples have been demonstrated in recent transmission experiments using SDM technology. In 2012, a transmission experiment reported a 305-Tbit/s capacity over a 10.1-km 19-core MCF, proving for the first time that the capacity could exceed the capacity limit of an SMF by using SDM technology. In the same year, NTT Network Innovation Laboratories collaborated with optical device research groups in NTT, an optical fiber manufacturing company, and universities in Japan and Europe to demonstrate the world-first 1-Pbit/s transmission [1] using a one-ring structured 12-core MCF, which is an order of magnitude larger than the capacity limit of an SMF. The following year, in 2013, we demonstrated the first capacity distance product exceeding 1 Ebit/s x km by applying a bi-directional transmission scheme in a two-ring structured 12-core MCF to reduce inter-core crosstalk [2].

Although SDM optical transmission technologies have proven that they can exceed the capacity limit of a conventional SMF, it is necessary to further increase spatial multiplicity, that is, the number of cores or modes multiplexed in an optical fiber, to further increase capacity. Therefore, developing new technologies for massive spatial multiplexing is the next challenge.

2. Towards dense space division multiplexing (DSDM)

We have been working to further increase the capacity of optical fiber transmission systems using SDM technology by developing new fundamental technologies with the goal of realizing dense space division multiplexing (DSDM)[*2] with a spatial multiplicity of 30 or more. To establish DSDM long distance optical transmission using an MCF, we must

*2 DSDM: High density SDM technology with spatial multiplicity above 30, which we proposed and demonstrated in 2014 for the first time.

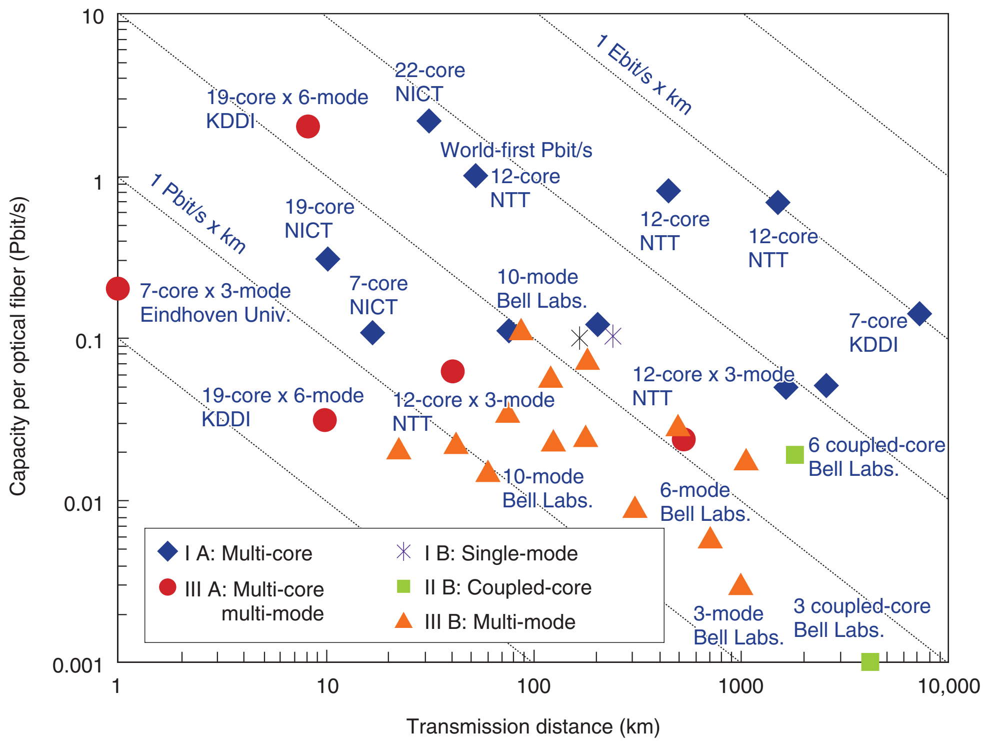


Fig. 2. Transmission capacity per optical fiber as a function of transmission distance.

arrange 30 or more cores in an optical fiber with a cladding diameter within 250 µm, taking fiber strength and reliability into consideration. At the same time, each core should have an effective area of 80 μm^2 or more, which is equivalent to that of a conventional SMF. Since the core arrangement in the optical fiber becomes dense, crosstalk between cores increases, which leads to the degradation of transmission quality.

As an example, the inter-core crosstalk after 1000-km transmission is shown in **Fig. 3** as a function of spatial multiplicity. The vertical axis indicates the worst inter-core crosstalk in an MCF after 1000-km transmission for terrestrial optical communication systems. The higher a position is on the graph, the lower the crosstalk value is, which means that the effect of crosstalk from signals in other cores is small on long distance transmission characteristics.

The dotted lines in the graph are the inter-core crosstalk values required for each modulation format, assuming a Q-factor penalty of 0.5 dB. The higher the multilevel degree, the larger the transmission capacity can be with the same resource, but the crosstalk requirement becomes stricter. For example, it is necessary to suppress the inter-core crosstalk to less than –25 dB to apply a polarization division multiplexed 16-quadrature amplitude modulation (16-QAM)*3 format. As shown in Fig. 3, as we increase the number of cores by 7, 12, and 19, the core arrangement becomes dense, so the inter-core crosstalk increases. Therefore, we have set the spatial multiplicity of 30 to 100 and the inter-core crosstalk of < –25 dB as the target area for achieving DSDM long distance optical transmission.

3. World's first DSDM optical transmission

As a first approach, we examined the combination of multi-core and multi-mode optical transmission. In mode-division multiplexed optical transmission, the application of multiple-input multiple-output (MIMO)*4 signal processing, a technique used in

*3 16-QAM: A modulation format that associates 16 values of digital signals with 16 types of intensity and phase combinations of the optical signals in a carrier wave, and transmits 4 bits per modulation.

*4 MIMO: A digital signal processing method used in practical wireless communication systems. Application to SDM transmission systems is being considered for the purpose of separating spatially coupled optical signals.

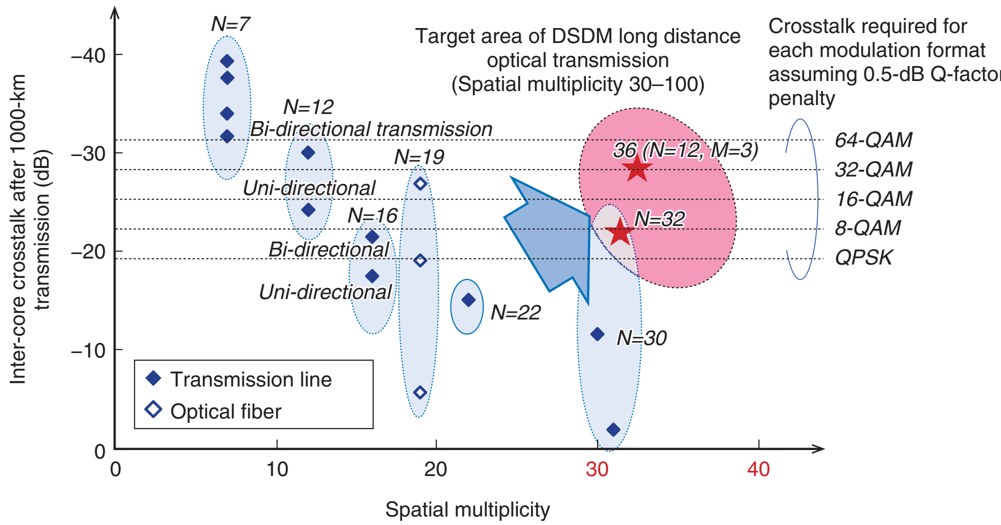


Fig. 3. Inter-core crosstalk after 1000-km transmission as a function of spatial multiplicity.

commercial wireless communication systems, is being considered in order to separate optical signals between different modes that are coupled during propagation. The amount of computation required for MIMO signal processing is proportional to the magnitude of the differential mode delay (DMD)*5. Since there is a limit to the load that can be tolerated by digital signal processing (DSP), it is necessary to suppress DMD. In addition, mode dependent loss (MDL)*6 has a tremendous effect on the transmission characteristics in mode-division multiplexed transmission.

While conducting research on multi-mode transmission, we found that it was difficult to fully compensate for the degradation caused by MDL with DSP, and MDL was one of the largest factors limiting the transmissible distance. As described above, advanced technology is essential even in mode-division multiplexing itself, and it was extremely difficult to realize multi-core and multi-mode optical transmission at the same time. Thus, there had been no reports on multi-core multi-mode transmission from any research institute at that time.

With a view to solving these issues, we proposed a novel parallel MIMO time domain equalization method to reduce the load of DSP. Also, in cooperation with an optical fiber manufacturer and universities, we developed a low-loss and low-crosstalk multi-core multi-mode optical fiber. Furthermore, in cooperation with research groups in NTT studying optical devices, we developed a multi-core multi-mode fan-in/fan-out (FI/FO) device for spatial multi/demultiplexing, a low-loss mode multi/demultiplexer based on a silica planar lightwave circuit (PLC), and an integrated optical receiver for SDM systems fabricated using commercially available silica PLC technology. We combined these fundamental technologies and in 2014 successfully achieved multi-core multi-mode DSDM optical transmission for the first time in the world, with a spatial multiplicity of 36 (12-core multiplexing × 3-mode multiplexing) [3]. The combination of the multi-core and multi-mode transmission greatly enhanced the spatial multiplicity because of the multiplication effect of the core and mode multiplexing.

In 2015, we proposed a novel parallel MIMO frequency domain equalization method to further reduce the complexity of DSP and moreover realized a graded-index type multi-core multi-mode optical fiber with an order of magnitude lower DMD. In addition, we realized a free-space optics type MDL

*5 DMD: Difference in group delay time between modes. It is known that the DMD can be reduced by using the graded-index type refractive index distribution. Reducing DMD will reduce the load of digital signal processing in multi-mode transmission.

*6 MDL: Loss difference between multiple modes. It is one of the largest factors limiting the transmission distance in mode-division multiplexed optical transmission.

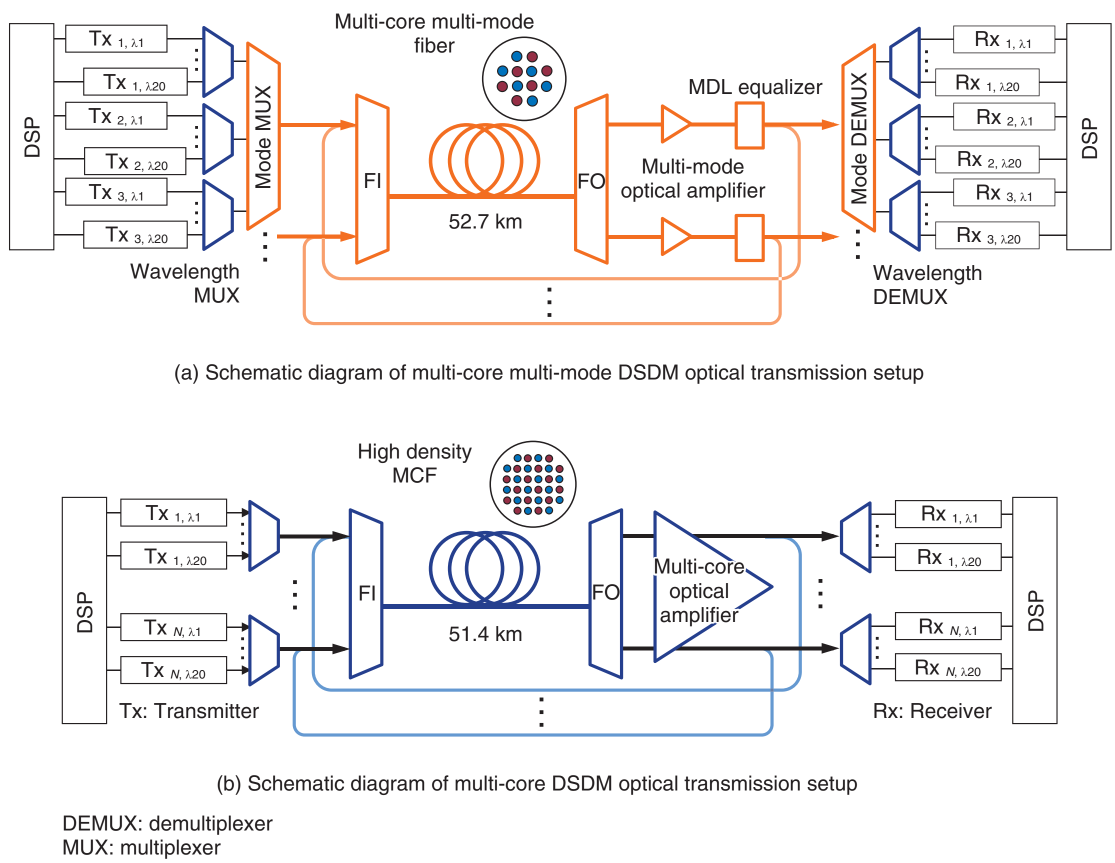


Fig. 4. DSDM optical transmission technology.

equalizer and a multi-mode optical amplifier with low mode dependency in gain, both of which greatly reduce the MDL in the optical transmission line. These DMD and MDL suppression technologies made it possible to achieve long distance multi-mode transmission, and this enabled us to successfully demonstrate the world-first long distance multi-core multi-mode DSDM optical transmission over 527 km [4]. A schematic diagram of the multi-core multi-mode DSDM optical transmission setup we used in the experiment is shown in **Fig. 4(a)**.

4. World's first multi-core DSDM long distance optical transmission

As another approach, we have also been conducting studies of high density MCF in a Japanese-European collaboration [5]. In our first study, we fabricated high density 30-core and 31-core MCFs about 10 km long and confirmed good transmission characteristics. However, the crosstalk between cores was large, and thus, these MCFs were not suitable for long distance optical transmission. We improved the MCF design and fabricated a 32-core high density MCF 51.4 km in length. With this MCF, we succeeded in suppressing the core-to-core crosstalk to less than –21.6 dB even after 1000-km transmission, and we reached the target area of DSDM transmission shown in Fig. 3 for the first time with a single-mode MCF.

In 2016, we demonstrated the first multi-core DSDM long distance optical transmission exceeding 1600 km [6] using this low-crosstalk high density MCF. A schematic diagram of the multi-core DSDM optical transmission setup we used in the demonstration experiment is shown in **Fig. 4(b)**. The long distance DSDM transmission with a spatial multiplicity higher than 30 and a transmission distance over 1000 km was a world-first achievement and has been the only successful such demonstration up until now.

To use this multi-core DSDM optical transmission in a real system, a high density multi-core optical amplifier is essential. In cooperation with the

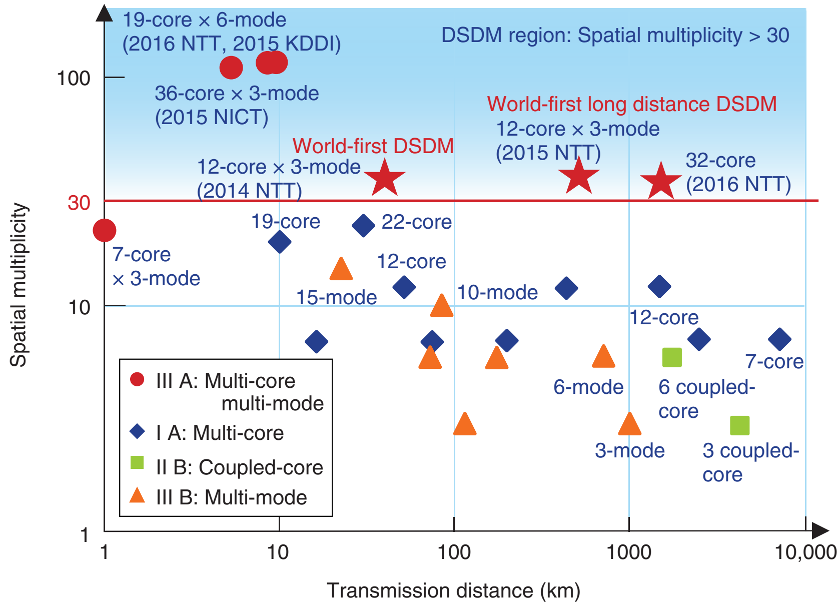


Fig. 5. Spatial multiplicity versus transmission distance.

members of the EU-Japan project, we also conducted studies on MCF amplifiers and developed a 32-core cladding-pumped multi-core erbium/ytterbium-doped fiber amplifier (MC-EYDFA) for the first time. Using the 32-core MCFs and the 32-core MC-EYDFA, we have constructed a 111.6-km 32-core inline amplified DSDM transmission setup and experimentally verified good transmission characteristics over all 32 cores [7].

The spatial multiplicity versus transmission distance in SDM optical transmission reported so far is shown in **Fig. 5**. At the beginning of our study on DSDM, the highest spatial multiplicity reported in multi-core optical transmission was 19. For 1000-km-class long distance optical transmission, the spatial multiplicity was even more limited, with 12 being the maximum. Under these circumstances, we succeeded in 2014 in carrying out the first DSDM optical transmission with a spatial multiplicity above 30. Moreover, we extended the transmission distance from 40 km to over 500 km, and then to over 1600 km with DSDM. More recently, other research institutes have subsequently studied DSDM, and DSDM with spatial multiplicity above 100 has been reported.

5. Future directions

In this article, we introduced the latest trends in SDM optical transmission technology and the DSDM optical transmission system with efforts to further increase the transmission capacity for the next generation high-capacity optical communication technology. We will continue to promote the research and development of SDM optical transmission technology as part of efforts to achieve an ultra-high-capacity long distance optical transmission system as the foundation for the future optical network.

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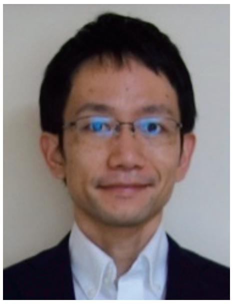

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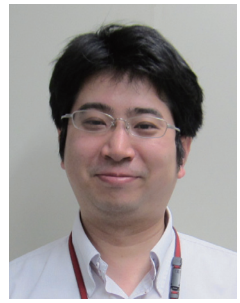

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Dense Space Division Multiplexing (DSDM) Photonic-node Platform Technology

Mitsunori Fukutoku, Kenya Suzuki, Akio Sahara, Fumikazu Inuzuka, and Yutaka Miyamoto

Abstract

Optical infrastructure networks transporting high-volume traffic have been built using photonic node technologies such as optical signal transmission, optical signal wavelength multiplexing and demultiplexing, and reconfigurable optical add/drop multiplexers. This article gives an overview of photonic nodes using dense space division multiplexing technology and their potential for implementing high-capacity optical networks.

Keywords: space division multiplexing, optical node architectures, integrated wavelength selective switching technology

1. Introduction

Communication traffic continues to increase each year, and the total Internet traffic in Japan alone reached 5.4 Tbit/s in 2015, increasing by 50% in that year [1]. If we assume a 40% increase per year, we can predict that the volume will exceed 1 Pbit/s by the mid-2020s. The capacity of single-mode fiber (SMF) is estimated to be 100 Tbit/s. To overcome the capacity limitations of SMF, research is underway on transport technologies using dense space division multiplexing (DSDM) [2]. It is also expected that DSDM will similarly need to be used to handle high-volume traffic in the photonic nodes used to build optical transport networks [3].

The throughput of a photonic node S is given by the product of the number of degrees N, the number of cores M, the spectral efficiency η, and the desired bandwidth B. The relationships between the number of degrees, number of cores, spectral efficiency, and attainable throughput are shown in **Fig. 1**. The two main bands used for optical communication are the 1.55-µm band (C band) and the 1.58-µm band (L band), which together give a combined 10 THz of usable bandwidth. The solid line in the figure shows the relationship between spectral efficiency and the space division multiplicity (product of degrees and cores $N \cdot M$), to implement an optical node with a throughput of 1 Pbit/s, assuming a combined signal bandwidth of 10 THz for the C band and L band. Achieving 10-Pbit/s-class throughput using modulation with the multiplicity of polarization-division-multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) or greater, which would give a spectral efficiency of 5 bit/s/Hz or better, would give η of 5 to 6 bit/s/Hz. Therefore, with the desired bandwidth B = 10 THz, space division multiplexing (SDM) photonic nodes with the product of cores and degrees $N \cdot M$ of 150 to 200 would be needed. Thus, with eight degrees, photonic nodes using DSDM with more than 20 cores would be necessary. Wavelength selective switches (WSS) already used to build reconfigurable optical add/drop multiplexers (ROADM) have around 20 ports, but there are issues in using them for high-capacity DSDM photonic nodes.

This article gives an overview of the devices and methods necessary to implement photonic nodes with DSDM technology for high-capacity optical

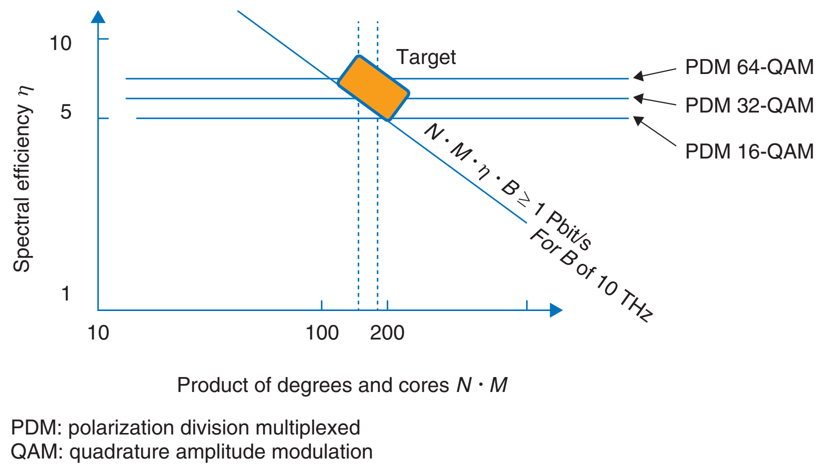
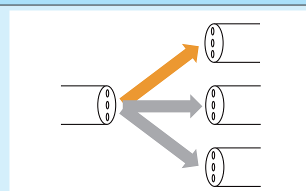
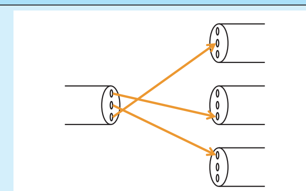


Fig. 1. Relationship between number of degrees/cores and spectral efficiency.

Table 1. Comparison of joint and independent spatial mode switching.

	(a) Spatial mode joint switching	(b) Spatial mode independent switching
Switch structure		
Switch function flexibility	No (Low)	Yes (High)
Switch granularity	No (All spatial modes together)	Yes (In spatial mode units)
Switch degree of freedom	No (No switching between spatial modes)	No (Switching between spatial modes)
Switched signal spatial mode coupling	Mode coupling/ No mode coupling	No mode coupling

networks.

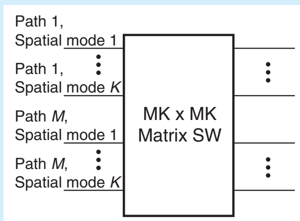
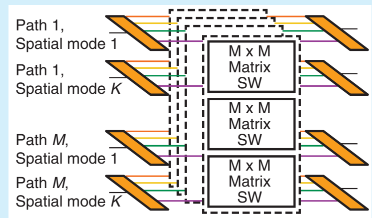
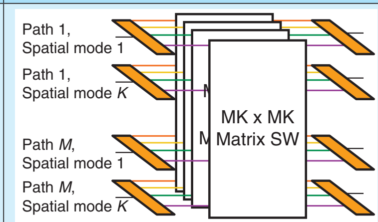
2. DSDM photonic node structure and SDM photonic networks

DSDM photonic nodes introduce a new degree of freedom in the spatial domain and with it, additional complexity to the node structure. For this reason, it is a challenge to implement a simple DSDM photonic node that provides the switching function necessary for an SDM photonic network.

2.1 Spatial mode switching types

DSDM photonic nodes can be broadly categorized into (a) spatial mode joint switching and (b) spatial mode independent switching, according to whether they can switch spatial modes independently or not (**Table 1**). SDM transmission methods include multi-core fiber (MCF), which involves multiple cores within a single optical fiber, and multi-mode fiber (MMF), which involves multiple waveguide modes propagating within a single core. We use *spatial* modes to refer to cores within MCF and *waveguide* modes within MMF. Spatial mode joint switching switches all spatial modes in a single optical fiber at once, outputting them to the same optical fiber. In contrast, spatial mode independent switching can independently select the output optical fiber for each

Table 2. Classification by switch granularity and degree of freedom.

		(a) Fiber XC	(b) Wavelength XC	
			(b)-1 No spatial mode switching	(b)-2 Spatial mode switching
Node structure				
Function flexibility	Switch freedom	Yes (Switching between spatial modes)	No (No switching between spatial modes)	Yes (Switching between spatial modes)
	Switch granularity	No (Spatial mode units)	Yes (Wavelength units)	Yes (Wavelength units)
	Signal level tuning	No (Cannot equalize deviation between wavelengths)	Yes (Can equalize deviation between spatial modes, wavelengths)	Yes (Can equalize deviation between spatial modes, wavelengths)
Switch scope (no. of switch elements)		$(MK)^2$	$W \cdot M^2K$	$W \cdot (MK)^2$

M: no. of paths; *K*: no. of spatial modes; *W*: wavelength multiplicity
SW: switch
XC: cross-connect

spatial mode.

When MMF is used, the spatial modes (waveguide modes) of the optical signal are coupled, so multiple modes are transmitted and received together, and the receiver must process the signal to separate these modes. All waveguide modes input to a single optical fiber are output from the fiber, so spatial mode joint switching is adequate. However, if MCF is used, coupling between spatial modes (cores) is weak, so optical signals from different transceiver nodes can be transmitted on each spatial mode. The use of spatial mode independent switching rather than joint switching for this yields finer switching granularity and more flexible switching control.

2.2 Switching methods according to switching granularity and degree of freedom

DSDM photonic node structures for spatial mode independent switching are listed in **Table 2**. They are classified according to whether they can switch wavelengths independently (wavelength independence) and whether they can switch between spatial modes. With SDM transmission, multiple optical signals with different wavelengths can be multiplexed and transmitted in each core or in each waveguide mode. DSDM photonic node structures can be classified as either (a) fiber cross-connect (fiber XC), which switches all wavelengths of the optical signal in a single spatial mode at once, or (b) wavelength cross connect (wavelength XC), which can switch wavelengths independently. Table 2 also lists wavelength XCs further classified into those that can or cannot switch signals between spatial modes. In these structures, the switching granularity gets finer moving from fiber XC to wavelength XC, and the degree of freedom in switching increases by enabling switching between spatial modes, providing greater flexibility in switching control.

Table 2 also indicates the signal level tuning and the scale (number) of switches needed to implement each node structure. The wavelength XC configuration with spatial mode switching ((b)-2) has very flexible switching control and is able to adjust levels to reduce disparity among both optical signal spatial modes and wavelengths in transmission paths and nodes. However, it requires more switch elements, so a simple node implementation is difficult to achieve.

Network control technologies such as software-defined networking (SDN)*1 are expected to advance in the future, and in line with this, network control techniques providing greater flexibility will be needed.

*1 SDN: A technological approach to control the operation of network devices centrally using software.

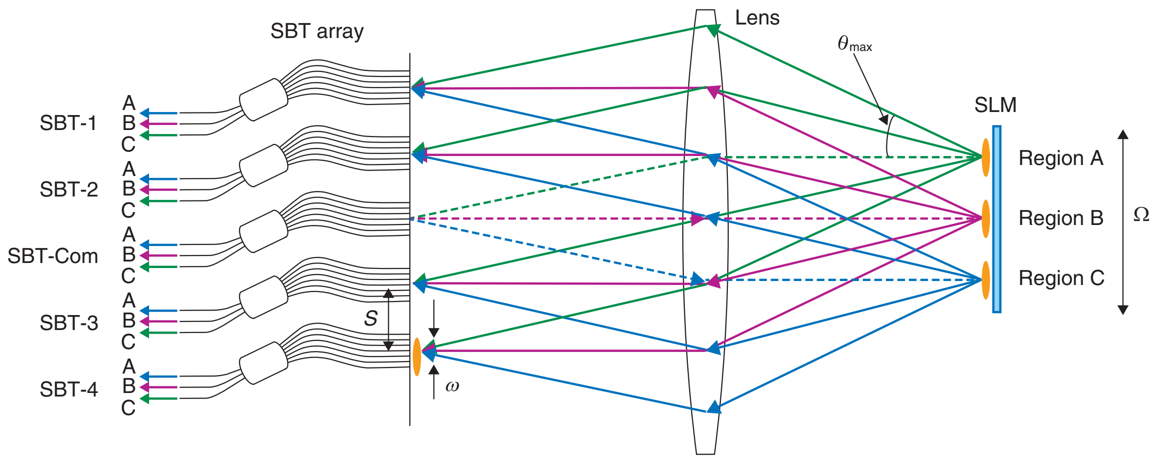


Fig. 2. Multiple-WSS integration on SPOC platform.

Research is underway at the NTT laboratories on wavelength XC as a DSDM photonic node structure that will enable more-flexible switching control, as it can switch independently between spatial modes.

To allocate network resources efficiently in a network using DSDM photonic nodes, the degree of freedom in the spatial domain must be considered. As SDM photonic networks are expanded, network capacity will need to be designed so as to optimize resource utilization. Wavelength domain resources on communication routes will have to be allocated in the network using conventional wavelength division multiplexing (WDM), but spatial domain resources will also have to be allocated. The transmission characteristics of the optical fiber medium (MCF or MMF) and photonic nodes are also conditions of signal capacity. Thus, optical fiber characteristics and photonic node structures are very important elements in SDM photonic networks.

3. DSDM photonic node switching devices

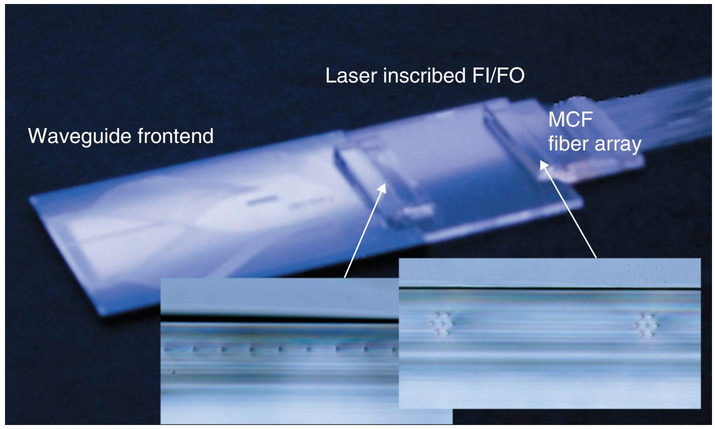
Multiple switching devices are used in a DSDM photonic node. SDM technology is expected to be used together with WDM communication to increase throughput, so a WSS able to switch by wavelength is needed. Thus, a structure with multiple WSS is needed in an SDM photonic network, and the increased footprint of node equipment could become a concern.

We are developing a spatial and planar optical circuit (SPOC) platform [4] combining waveguide optical systems*2 and spatial optical systems*3, which is an original optical system technology integrating multiple WSS in a single module.

A schematic diagram of an optical system integrating multiple WSS using the SPOC platform is shown in **Fig. 2**. The spatial beam transformer (SBT) circuit elements, positioned on optical waveguides, play an important role in integrating the multiple WSS. The SBT circuits are composed of a slab waveguide and an array waveguide with uniform lengths. When the light signal shown with pink arrows is input to the SBT circuit designated as SBT-Com in Fig. 2, it diverges in the plane of the slab waveguide and is output to the spatial optical system through the array waveguides. Here, the lengths of the array waveguides are the same, so the wavefront of the output optical signal is planar, with the direction shown by the pink dotted line. When the light signal is switched to the green input port, the output optical signal will be a planar wave in the direction of the green upwardly inclined dotted line. The optical signals arrive at a different position on the spatial light modulator (SLM), which is the switching engine, and are independently reflected in different directions. Finally, the signals are independently switched to any of the output ports and optically combined at the output

*2 Waveguide optical system: An optical system using optical waveguides, which are optical integrated circuit structures; used to implement highly integrated optical communication devices.

*3 Spatial optical system: An optical system using lenses and diffraction gratings; larger than waveguide optical systems, but capable of extremely high optical performance.



FI/FO: fan-in/fan-out

Fig. 3. Optical waveguide frontend in WSS for MCF.

SBT circuits.

We constructed a WSS for MCF [5] using this multiple-WSS integrated function. A photograph of the optical waveguide system on the SPOC platform is shown in **Fig. 3**. The MCF has a two-dimensional (2D) core arrangement, so to combine it with the planar optical waveguide, the two dimensions must be converted to one dimension. In this case, we fabricated a circuit to convert the core arrangement from 2D to 1D using 3D waveguide technology with an ultrashort pulse laser*4 and implemented a direct connection of the MCF to the waveguide circuits.

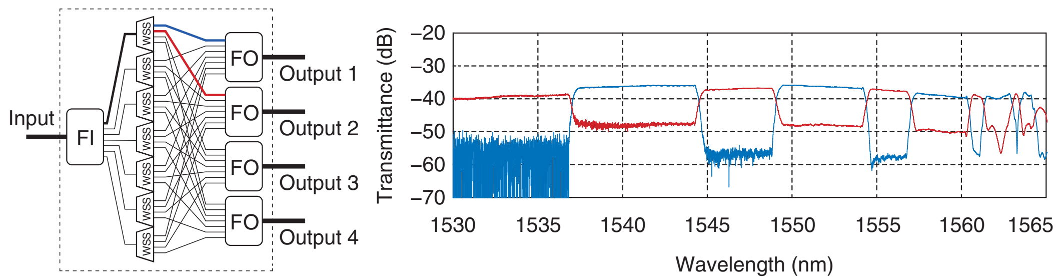
The switching spectra for each core of a 1 x 4 WSS for a 7-core MCF are shown in **Fig. 4**. Here, operation is configured as a flexible grid with different wavelength bands for wavelength channels on the first and seventh cores (see Fig. 4(a)), as two-way switching and attenuation with a 200-GHz channel width on the second (Fig. 4(b)) and third cores (Fig. 4(c)), and as switching to four different paths with a 50-GHz channel width on cores 4 to 6 (Fig. 4(d)).

Each of these examples implements wavelength selective switching operation, showing that the SPOC platform is effective for SDM node switches.

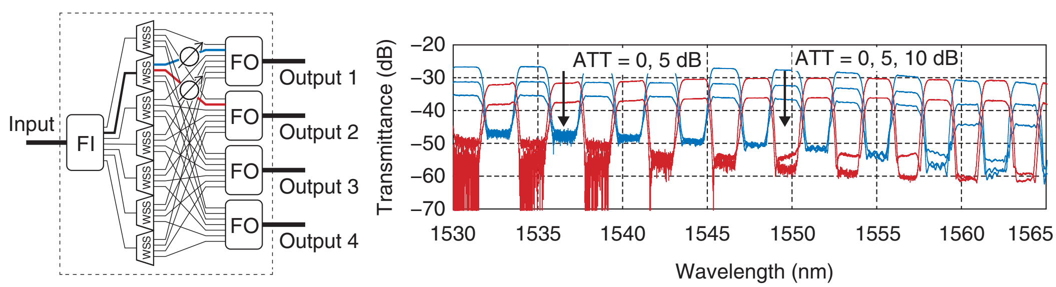
4. Future prospects

The SPOC platform is a key technology for making DSDM photonic nodes smaller. The NTT laboratories will receive support for contracted research from NICT (the National Institute of Information and Communications Technology) and other institutions and conduct research and development (R&D) through open innovation [6] to accelerate R&D on these elemental technologies.

*4 Ultrashort pulse laser: A laser that outputs light pulses with lengths in the range of femtoseconds to nanoseconds.



(a)



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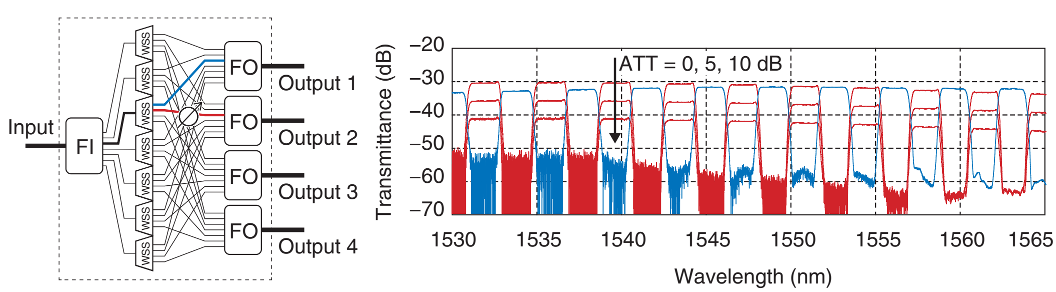
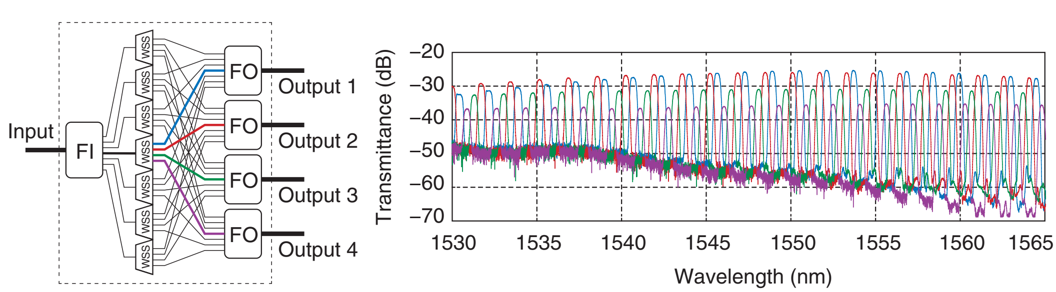


(c)



(d)

Fig. 4. Switching spectra examples from WSS for 7-core MCF.

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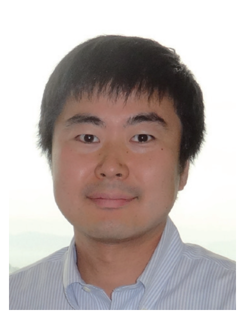

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Optical Amplification Technologies for Space Division Multiplexing

Hirotaka Ono

Abstract

Technologies that enable simultaneous optical amplification of spatially multiplexed optical signals are essential for a long-haul space division multiplexing (SDM) transmission system that employs a multi-core fiber and/or few-mode fiber. This article introduces optical amplification technologies that make it possible to construct a multi-core erbium-doped fiber amplifier (EDFA) and a few-mode EDFA for SDM transmission.

Keywords: multi-core fiber amplifier, few-mode fiber amplifier, erbium-doped fiber

1. Introduction

An optical amplifier is necessary for a long-haul space division multiplexing (SDM) transmission system that employs a multi-core fiber and/or a few-mode fiber as a transmission line. SDM optical amplifiers utilize an erbium-doped fiber (EDF) as the amplification medium in the same way as the optical amplifiers used in the current single-core and single-mode fiber transmission system. An important function of SDM optical amplifiers is simultaneous amplification of spatially multiplexed optical signals. Two kinds of optical amplifiers have mainly been studied in recent years in order to realize such a function. One is a multi-core erbium-doped fiber amplifier (MC-EDFA), which employs a multi-core EDF that has multiple erbium cores within a single fiber. The other is a few-mode erbium-doped fiber amplifier (FM-EDFA), which utilizes a few-mode EDF that is a kind of multi-mode fiber. A few-mode EDF supports several propagation modes used for signal transmission and restricts unusable higher-order modes.

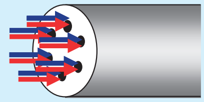
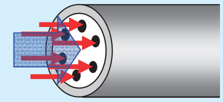
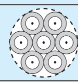
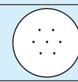
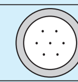
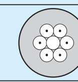
2. MC-EDFA

Table 1 categorizes MC-EDFAs in terms of pumping schemes and active fibers. There are two kinds of pumping schemes, namely core pumping and cladding pumping.

An MC-EDFA employing core pumping can employ optical components that are used for a conventional single-core EDFA. It provides high pumping efficiency and can also support conventional high-speed control to suppress the transient power caused by a change in the input signal power. The challenges to be met include integrating the optical components to reduce the total amplifier size, cost, and power consumption. Cladding pumping has the potential to achieve both low power consumption and downsizing by using an uncooled multi-mode pump laser diode (LD). Challenges include improving the pumping efficiency, developing optical components for launching the pump and multiple signal lights simultaneously, and devising a technique for adjusting the gain of several cores to achieve a pump power with high-speed control.

Four kinds of active fibers have already been reported for multi-core amplification: a bundle of reduced-cladding EDFs, a multi-core EDF with a single cladding, a multi-core EDF with a double cladding, and a multi-element EDF. The bundle and multi-element EDFs can utilize conventional mature fiber fabrication techniques, and the lengths of different EDFs can be adjusted to achieve a uniform gain. A drawback is the necessity of downsizing the cross-section of the amplification medium. The benefit of multi-core EDFs with single and double cladding lies

Table 1. Categorization of MC-EDFA in terms of pumping scheme and active fiber.

	Core pumping		Cladding pumping	
Pumping scheme	Multiplexed pump and signal lights launched into core 		All cores pumped by first cladding propagating pump light 	
Benefit	High pump efficiency and applicability of components and high-speed control used in conventional single-core EDFA		Possibility of reducing size, power consumption, and cost by employing uncooled multi-mode pump laser diode (LD).	
Challenge	Reducing size, cost, and power consumption		Improving pumping efficiency, developing pump/signal combiner, and achieving high-speed control	
Fiber	Single-core EDF	Multi-core EDF	Multi-core EDF	Single-core EDF
Structure	Bundle	Single cladding	Double cladding	Multi-element
				
Benefit	Applicability of conventional fabrication technology and adjustability of EDF length	Size and cost reduced by manufacturing several cores in one fiber fabrication operation		Applicability of conventional fabrication technology
Challenge	Reducing cladding diameter and suppressing crosstalk			
	Developing fiber bundling technique	Achieving uniform gain and noise figure between cores		

in the reduced cost, which is achieved by manufacturing several cores in one fiber fabrication operation. Another benefit of multi-core EDFs is that their cladding diameter is small compared with bundled and multi-element EDFs. Finding a way to achieve a uniform amplification characteristic for all the cores is a challenge for both multi-core and multi-element EDFs, and finding a way to suppress crosstalk is a common challenge for all active fibers.

2.1 Core-pumped MC-EDFA

A typical configuration of a core-pumped MC-EDFA is shown in **Fig. 1(a)**. Both the pump and signal lights are multiplexed with a wavelength division multiplexing (WDM) coupler and launched into an erbium-doped core through a fan-in (FI), and the amplified signals are output through a fan-out (FO). In this amplifier configuration, since the FI and FO can reverse the propagation direction of the signal lights, the propagation of the signal light in each core can be set in any direction. Setting the signal lights in two adjacent cores to propagate in opposite directions reduces the intercore crosstalk [1]. An MC-EDFA was constructed for long-haul transmission through 12-core fiber by employing this method. Its configuration is shown in **Fig. 1(b)**. This MC-EDFA utilizes the outer cores of a dual 7-core EDF. As shown in **Fig. 1(c)**, a gain of over 11.4 dB and a noise figure of less than 6.5 dB were achieved across the entire C-band when the signal lights of all the cores propagated in the same direction. The MC-EDFA was applied to SDM transmission with a capacity-distance product of 1 Ebit/s, and the results suggest its feasibility [2]. A bundle of reduced-cladding EDFs can also be used in this kind of SDM optical amplifier [3].

2.2 Cladding-pumped MC-EDFA

The configuration of a cladding-pumped MC-EDFA is shown in **Fig. 2(a)**. To improve pumping efficiency, we employed double-clad multi-core erbium/ytterbium-doped fiber (DCMC-EYDF). In this fiber, the pump absorption is sensitized by transferring energy from the ytterbium to erbium ions and suppressing the clustering of erbium ions, which results in improved pumping efficiency. Twelve erbium/ytterbium-doped cores were arranged in a hexagon as shown in the figure. The core pitch is 37.2 μm, and the first and second claddings and the coating diameters are 216, 284, and 356 μm, respectively. The pump source was a 976-nm multi-mode LD with a 125-μm-diameter multi-mode fiber pigtail. A schematic of the pump combiner is also shown in Fig. 2(a). The pump combiner consists of a multi-mode fiber with a tapered section and the double-clad 12-core fiber, whose cross-sectional design was the same as that of the DCMC-EYDF. A short section of the double-clad 12-core fiber was stripped of its low refractive-index

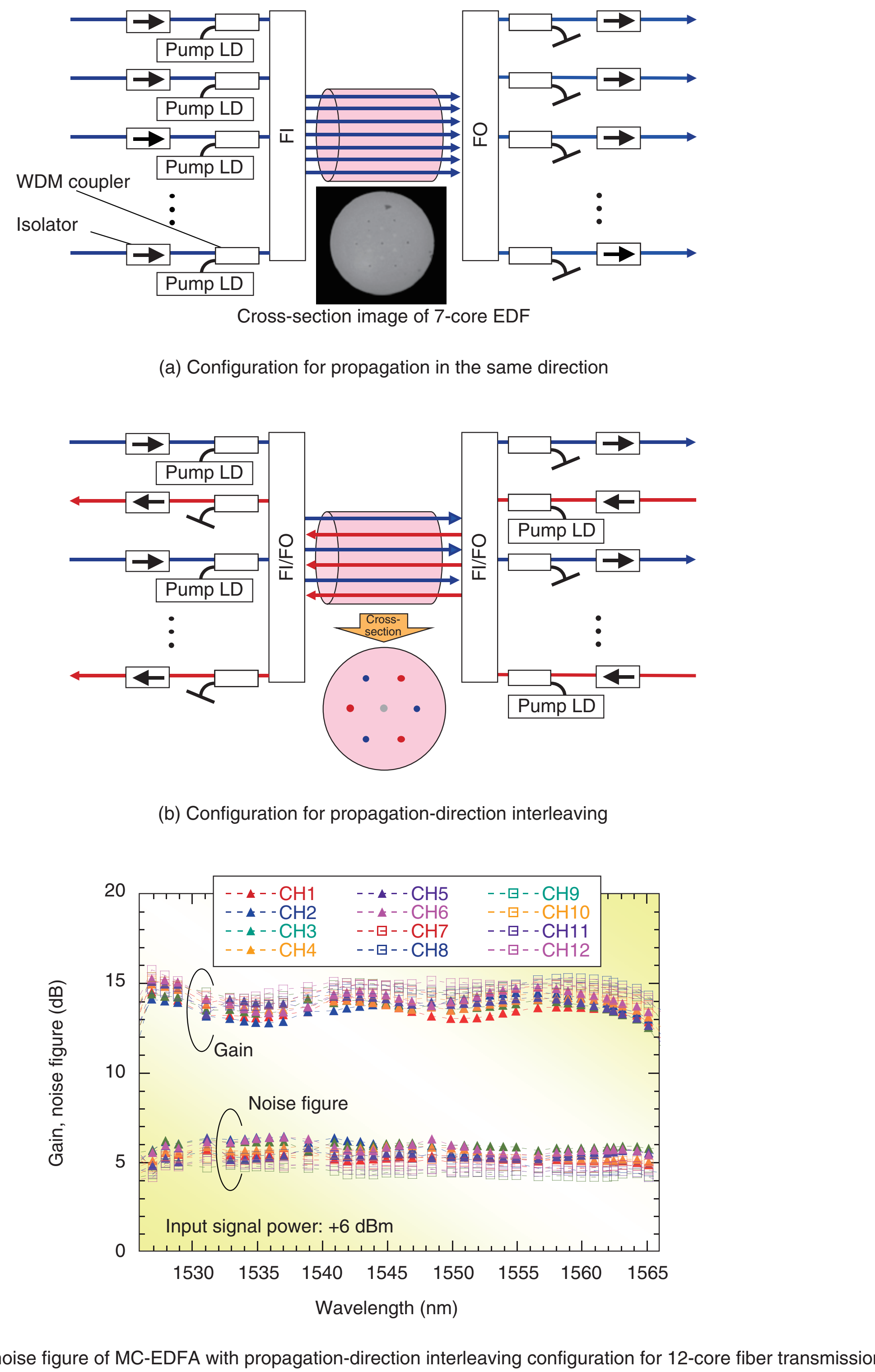
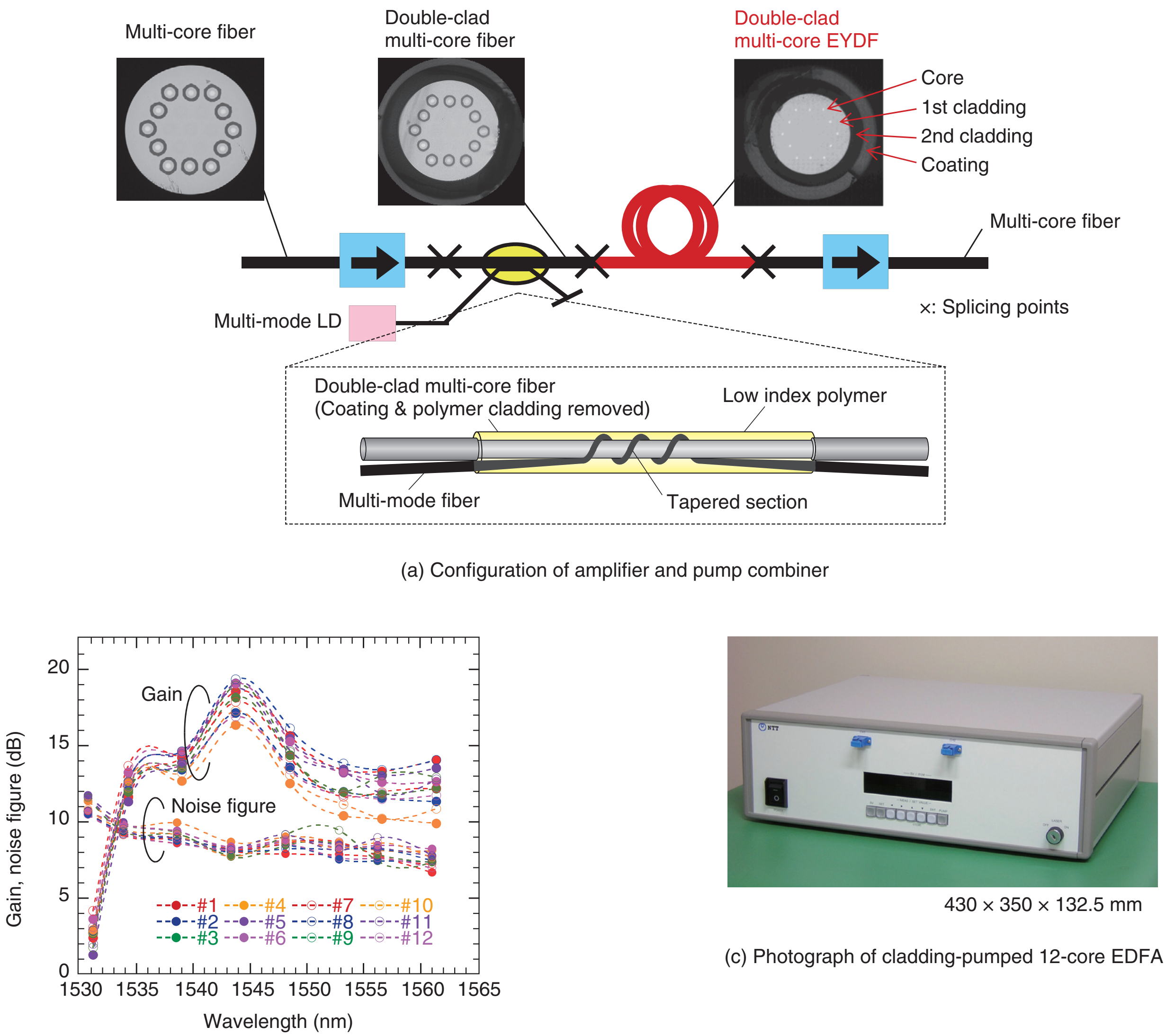


Fig. 1. Core-pumped MC-EDFA.

second cladding and coating, and the stripped section was rounded to form an optical contact with the tapered multi-mode fiber. The optical contact section was recoated with a low index polymer. This pump



(a) Configuration of amplifier and pump combiner

(b) Gain and noise figure

(c) Photograph of cladding-pumped 12-core EDFA

Fig. 2. Cladding-pumped MC-EDFA.

combiner was fusion-spliced to the DCMC-EYDF, which enables the pump light to couple to the first cladding of the DCMC-EYDF. Twelve-core isolators were located at the input and output ends of the amplifier to avoid laser oscillation.

The gain and noise figure of the cladding-pumped MC-EDFA are shown in **Fig. 2(b)**, and a photo of the device is shown in **Fig. 2(c)**. The input signal was an 8-channel WDM signal with a power of −14 dBm/ch, and the pump power was 3.4 W. The optical amplifier exhibited over 10-dB gain and less than an 8.7-dB noise figure for all 12 cores at wavelengths longer than 1534 nm. In this case, the electrical power consumption was about 10 W, while the sum of that of 12 conventional EDFAs was estimated to be 20 W at an ambient temperature of 65°C. This suggests that the cladding-pumped MC-EDFA successfully reduced the power consumption by about half that of the conventional optical amplifier.

The cladding pumping was also adopted in an SDM optical amplifier for a dense SDM (DSDM) transmission. A 32-core EDFA that employed a DCMC-EYDF was used in a DSDM transmission experiment as an optical amplifier repeater [4].

The gain and noise figure of the cladding-pumped MC-EDFA with a DCMC-EYDF degraded in the

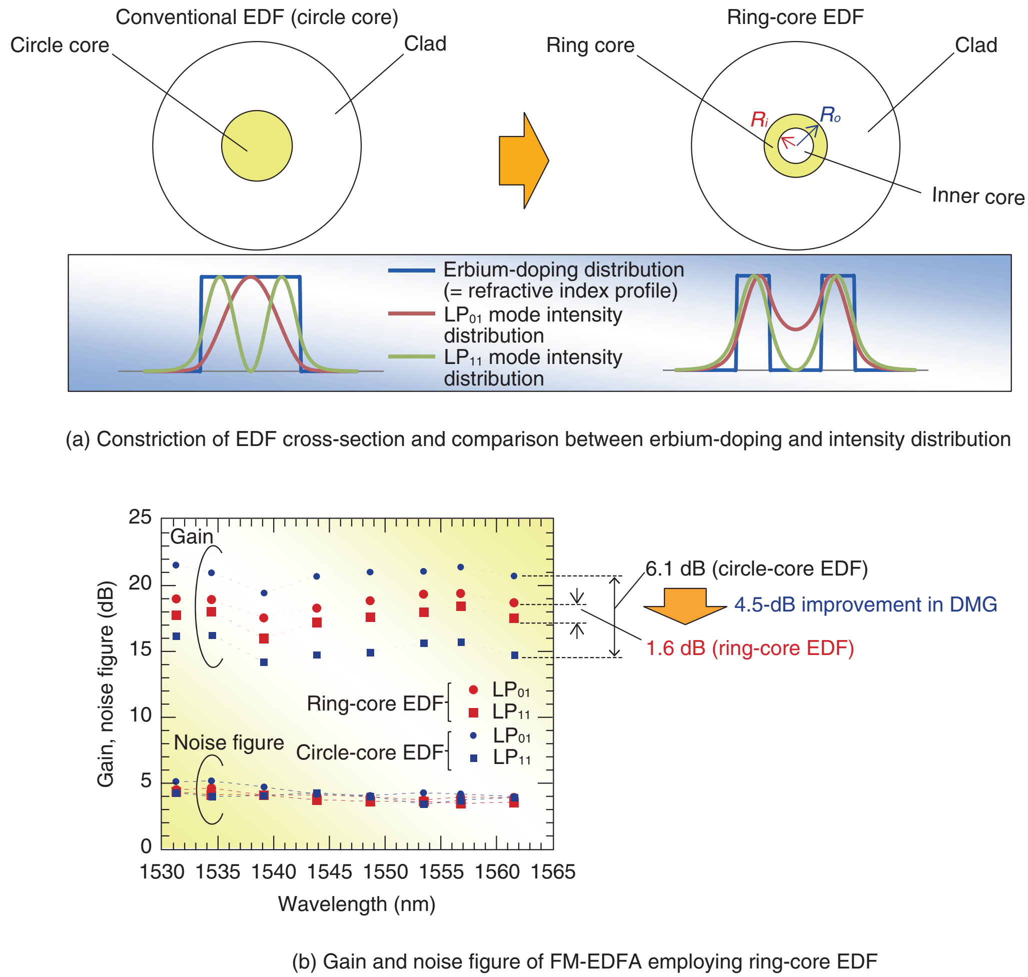


Fig. 3. FM-EDFA.

shorter wavelength region because of the strong absorption of the erbium ions in the EDF. Further study is necessary to improve the uniformity of the gain and the noise characteristics if we are to use the entire C-band for amplification.

3. FM-EDFA

One issue with FM-EDFAs is the differential modal gain (DMG) needed to minimize the differences between the signal-to-noise ratios of all the transmitted signals and thus maintain signal quality. To reduce the DMG in FM-EDFAs, it is important to reduce the difference between two overlap integrals, namely that for the excited erbium ion area and the intensity distribution of the fundamental mode signal and that for the excited erbium ion area and the intensity profile of higher-order signals. For this purpose, the doping of erbium ions with a ring profile and the use of a reconfigurable pump mode have been reported [5, 6]. Disadvantages of these techniques are that the former complicates the EDF fabrication process, and the latter introduces an additional loss for the pump power.

Another approach was taken in an NTT study, which involves employing a ring-core erbium-doped fiber (RC-EDF) with a ring-shaped index profile. As shown in **Fig. 3(a)**, the optical signals of LP_{01} and LP_{11} modes at the RC-EDF have a similar intensity distribution, in which the overlap integral for both the LP_{01} and LP_{11} mode signals have similar values, resulting in a reduction of the DMG. Our approach has advantages over other approaches in that it maintains a simple fabrication process with uniform erbium doping and eliminates the need for lossy additional pump adjustment. The FM-EDFA with an

RC-EDF whose parameters were optimized successfully exhibited a small DMG of 1.6 dB, which is 4.5 dB smaller than that for an FM-EDFA with a conventional circular core (**Fig. 3(b)**). The FM-EDFA with the RC-EDF was also used for a long-haul mode-division-multiplexing transmission as an optical amplifier repeater, which confirmed its feasibility [7].

4. Future work

In upcoming research, we will investigate advanced amplification technologies for gain and output control in SDM optical amplifiers.

This study was undertaken as part of a collaborative project with Fujikura Ltd., Osaka Prefecture University, Shimane University, and Chitose Institute of Science and Technology.

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Research and Development of Next Generation Optical Fiber Using Multiple Spatial Channels

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Abstract

The capacity of conventional single-mode fiber (SMF) that is widely used in the existing optical communication network is expected to be limited to around 100 Tbit/s. Therefore, next generation optical fiber such as multi-core and/or multi-mode fiber has been investigated in order to overcome the limited capacity of SMF and to utilize multiple spatial channels to realize space division multiplexing (SDM). We introduce in this article the recent progress achieved in SDM fiber.

Keywords: optical fiber, space division multiplexing, multi-mode multi-core

1. Introduction

The capacity of conventional single-mode fiber (SMF) is expected to be around 100 Tbit/s, and therefore, next generation optical fiber that can accommodate traffic at more than 100 Tbit/s is needed for future optical communications systems. Optical communications systems have been developed in line with the low loss and wideband characteristics of SMF and the evolution of transmission technology. Network capacity has greatly increased because of wavelength division multiplexing (WDM) technology, which can transmit multiple signals with different wavelengths in an optical fiber.

Digital coherent transmission using a multi-level modulation format has recently been studied as a way to improve spectral efficiency since the operational wavelength window is limited in terms of the loss characteristics of SMF and the amplification bandwidth of erbium-doped fiber amplifiers. Although a very high signal-to-noise ratio is required when a complex modulation format such as quadrature amplitude modulation is used to achieve high spectral efficiency, the input power into the fiber is severely limited by nonlinear effects or the fiber fuse phenomenon. That is why the capacity of SMF is predicted to be limited to around 100 Tbit/s for telecom networks.

However, Internet traffic has been increasing at a rate of 30–50% per year, and innovative technology will be required in order to accommodate such a large amount of traffic in the future. One promising solution to this capacity crunch is to use a spatial channel by developing a space division multiplexing (SDM) fiber. In this article, we report the recent progress achieved in SDM fiber as the next generation optical transmission line for ultra-large-capacity systems.

2. Recent research on SDM fiber

SDM technology involves the transmission of multiple signals in parallel in the same way as WDM technology. SDM uses spatial channels, for example, by using multiple cores in multi-core fiber (MCF). Generally speaking, parallel transmission using multiple SMFs is also considered to be SDM transmission, but we would like to focus on SDM technology using SDM fiber, where multiple spatial channels exist in an optical fiber.

The proposed SDM fiber is illustrated in **Fig. 1**. SMF has a core in the cross section. In contrast, MCF

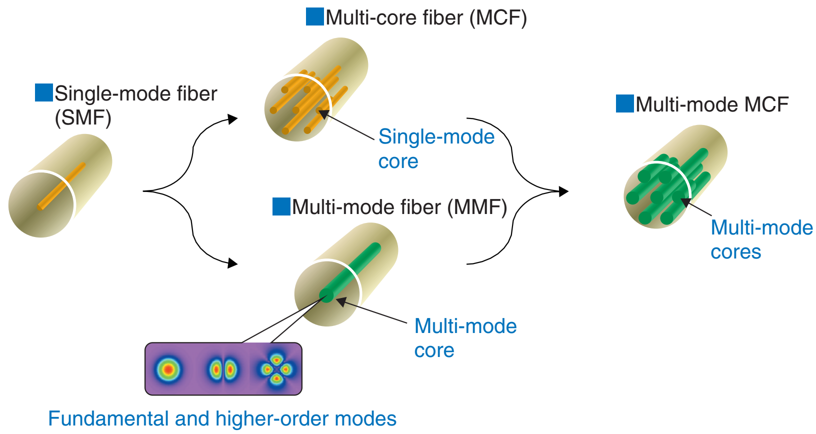

Fig. 1. Schematic diagram of SDM fibers.

has multiple cores, and multiple signals can be transmitted through the multiple cores. Multi-mode fiber (MMF) has a relatively larger core than that of SMF, and multiple modes can propagate in this core. Because each propagation mode can be treated as an individual transmission channel, multiple signals can be transmitted through the multiple modes. The parallel transmission scheme using multiple modes is called mode division multiplexing (MDM). Multi-mode MCF, which is MCF with multi-mode cores, has also been investigated as a way to perform MDM transmission in each core [1–5].

The important parameters that should be taken into account when designing SDM fiber are listed as follows.

- The number of spatial channels
- Optical characteristics of each spatial channel
- Mechanical reliability of optical fiber

It is preferable to have as many spatial channels as possible to increase the capacity, and better (or comparable) optical characteristics for each spatial channel than those of SMF are desired in order to achieve higher transmission capacity per spatial channel.

In addition to the optical characteristics, mechanical reliability of the fiber is also an important aspect for telecom networks. The failure probability is one factor that affects the mechanical reliability of the fiber. This refers to the probability that the fiber will break if it is stretched or bent. Therefore, the fiber should be properly designed in order to achieve a sustainable network infrastructure. In general, the failure probability increases as the fiber cladding diameter increases. NTT clarified that 250 µm is the maximum cladding diameter to provide mechanical reliability comparable to that of SMF [1] and also investigated the SDM fiber design to maximize the number of spatial channels within the limited cross section of the fiber. NTT defines DSDM (dense space division multiplexing) transmission as the system that can support more than 30 spatial channels [3]. The design considerations for different kinds of SDM fiber and fiber arrangements proposed so far are introduced in the next section.

3. MCF technology

The relationship between the number of cores and the cladding diameter of the proposed MCFs is shown in **Fig. 2**. MCF tends to have a larger cladding diameter than that of SMF (125 µm). This is because it requires a larger cross section to deploy more cores. As explained in the previous section, the cladding diameter is limited to a certain value because of the mechanical reliability. Therefore, deploying cores as closely together as possible inside the fiber is effective. However, there is a lower limit of the core pitch in terms of the inter-core crosstalk value, which should be sufficiently low to prevent interference of the transmitted signals.

Cross sections of the proposed MCFs are shown in **Fig. 3**. Various core arrangements such as hexagonal-lattice [6–8], circular [9, 10], square lattice [11], or a combination of these core arrangements [12, 13] have been proposed. The trench-assisted refractive index structure has been used for each core profile in order to reduce the inter-core crosstalk. The use of a heterogeneous core structure is also considered to be a way to reduce crosstalk. In the heterogeneous MCF

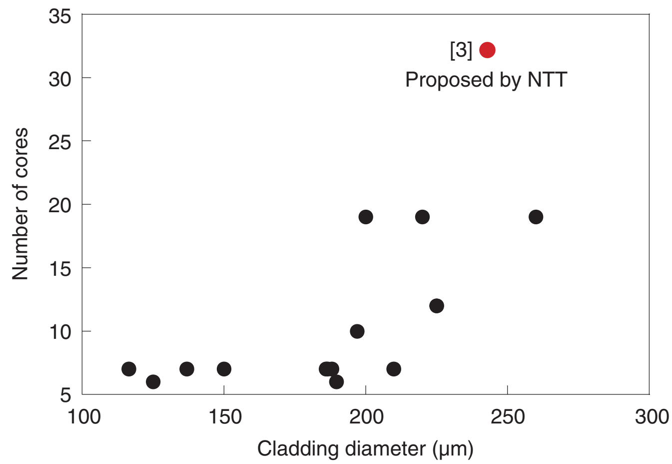

Fig. 2. Relationship between number of cores and cladding diameter of MCFs.

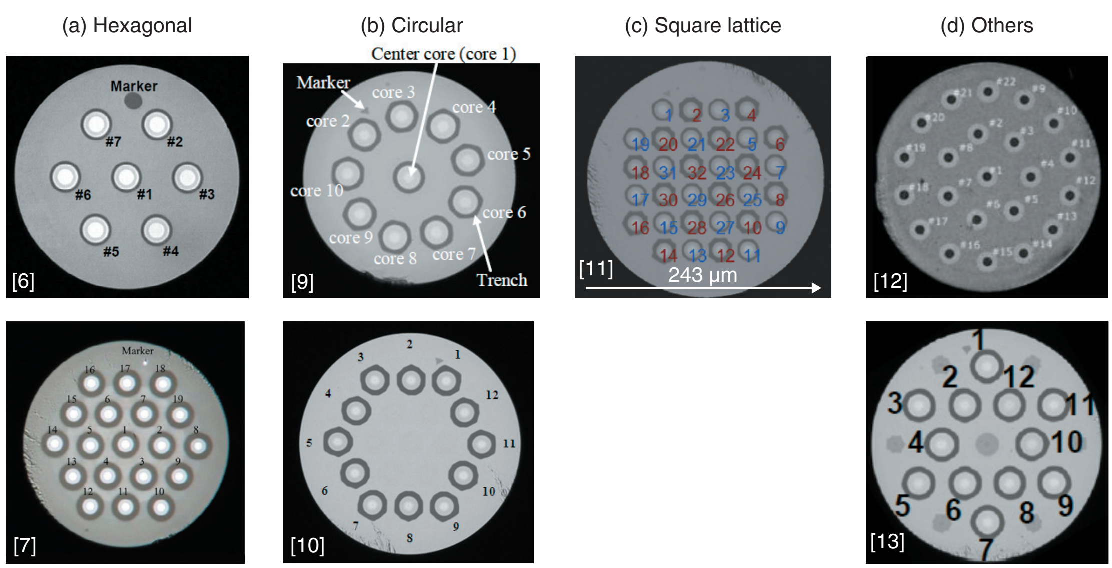

Fig. 3. Cross sections of MCFs.

design, the index profile of the adjacent core is designed to be different, which can effectively reduce the crosstalk because the propagation constant of the mode in the adjacent core is different. NTT successfully developed a 32-core fiber with a cladding diameter of less than 250 μm by using an MCF design technique that combined a square lattice core arrangement, trench-assisted core profile, and a heterogeneous MCF design. This work was supported by the EU-Japan coordinated research and development (R&D) project known as SAFARI (Scalable And Flexible optical Architecture for Reconfigurable Infrastructure).

Designing MCF with optical properties comparable to those of the SMF is also an important issue. For example, investigations have been carried out on MCF with 125-μm-diameter cladding MCF and with optical characteristics conforming to ITU-T* recommendations on fiber optics in regard to mode field diameter, chromatic dispersion, macrobending loss, and other factors.

* ITU-T: The Telecommunication Standardization Sector of the International Telecommunication Union.

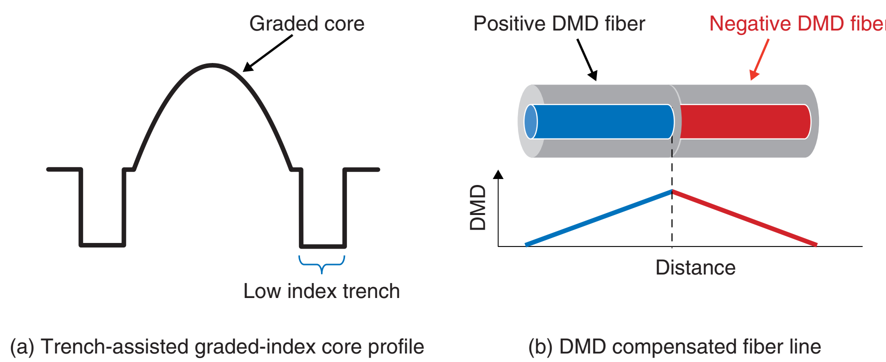

Fig. 4. Trench-assisted graded core MMF.

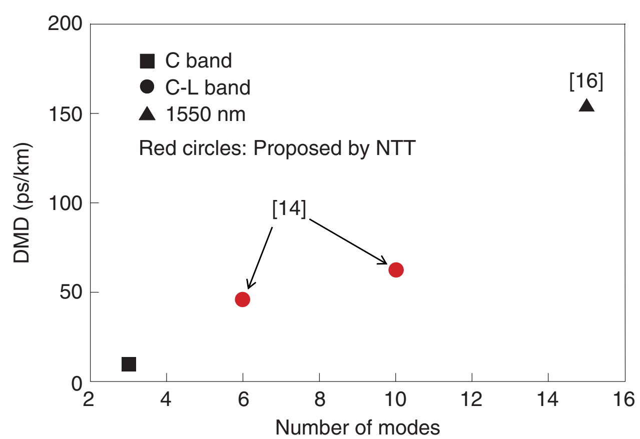

Fig. 5. Relationship between number of modes and DMD value of low DMD fiber.

4. MMF technology

We can increase the number of spatial channels by increasing the number of modes per core as well as increasing the number of cores. Reducing the inter-modal crosstalk and differential group delay is also important in the MMF design. However, the propagation modes in multi-mode cores can easily convert to another mode due to structural perturbation in the event of a splice point or fiber bending. Optical multiple-input multiple-output (MIMO) has been proposed to deal with this issue, and signal processing has been investigated in order to compensate for the crosstalk.

However, the complexity of signal processing increases as the differential mode delay (DMD) increases. Low DMD fiber has been proposed to reduce the complexity of MIMO processing, and we have investigated trench-assisted graded-index core MMF to reduce the DMD and control the number of propagation modes, as shown in **Fig. 4(a)** [14]. We successfully adjusted the DMD value by accurately controlling the index profile of the graded core, and we designed the optical properties (e.g., bending loss) of all propagation modes to have a comparable value to that of conventional SMF by optimizing the trench structure. A DMD compensated fiber line has also been proposed, where two kinds of fibers with positive and negative DMD values are used (**Fig. 4(b)**). This technique is similar to that used in a chromatic dispersion compensation line; thus, we can flexibly control the total DMD value by changing the length ratio of the two kinds of fiber [15].

The relationship between the number of modes and the DMD value of the proposed low DMD fiber is plotted in **Fig. 5**. NTT succeeded in developing MMF with 10 modes and a DMD of less than 100 ps/km. Although MMF with up to 15 modes has been reported

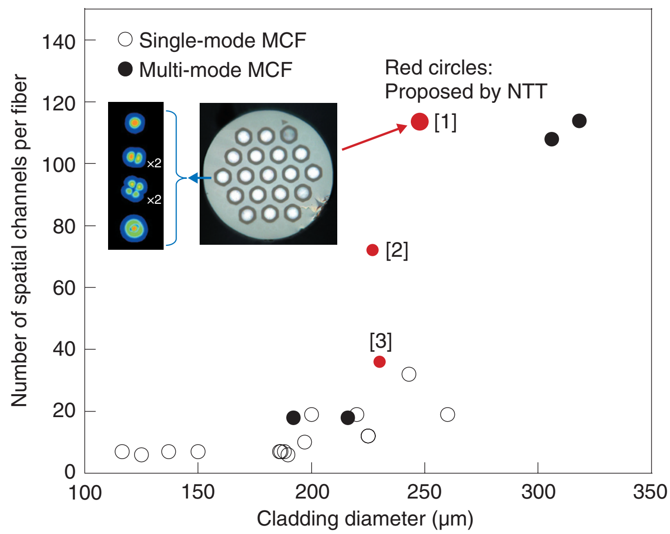

Fig. 6. Relationship between number of spatial channels as a function of cladding diameter of reported single-mode MCFs and multi-mode MCFs.

[16], our fiber has been designed to achieve the low DMD characteristics over a broad wavelength range from the C to L band. Thus, the current WDM technology can be incorporated with MDM technology with our fiber. We have also investigated a technique for utilizing the higher-order mode in MMF for long-haul transmission by exciting a specific higher-order mode to reduce the fiber nonlinearity.

5. Multi-mode MCF technology

The use of either MCF or MMF technology makes it possible to achieve a few dozen spatial channels, but many more spatial channels may be needed in order to accommodate the huge amount of traffic expected in the future. Multi-mode MCF has been investigated as a way to greatly increase the number of spatial modes in the fiber. For example, *n*-core fiber with *m*-mode cores exhibits m × n spatial channels. The number of spatial channels as a function of the cladding diameter of reported single-mode MCFs and multi-mode MCFs is shown in **Fig. 6**. Multi-mode MCF can realize a larger number of spatial channels compared to that of single-mode MCF, and multi-mode MCFs with more than a hundred spatial channels have been proposed [1, 4, 5]. NTT realized a 6-mode 19-core fiber with 114 spatial channels and a cladding diameter of less than 250 μm and achieved the highest reported spatial density while maintaining comparable mechanical reliability to that of SMF [1].

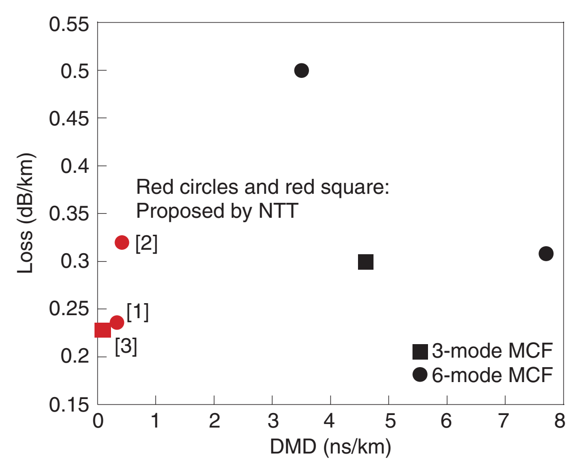

Fig. 7. Relationship between loss and DMD of proposed multi-mode MCFs.

The relationship between the loss and DMD of the proposed multi-mode MCFs is shown in **Fig. 7**. Our multi-mode MCF has a low DMD value, which is achieved by employing the trench-assisted graded-index core profile as we mentioned [1–3]. We also achieved loss characteristics comparable to SMF for all spatial channels. As a result, we successfully developed SDM fiber with more than a hundred spatial channels and with optical properties and mechanical reliability comparable to SMF.

6. Conclusion

In this article, we briefly reviewed the recent progress in the development of SDM fibers with multiple spatial channels, for example, MCF and MMF. We will continue our R&D in order to introduce SDM fiber and achieve a petabit-per-second transmission system in the latter half of the 2020s.

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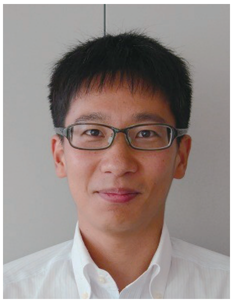

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Multi-core Fiber Connector Technology for Low-loss Physical-contact Connection

Yoshiteru Abe, Kota Shikama, and Shuichiro Asakawa

Abstract

The NTT laboratories have been researching and developing connection technology for multi-core fiber, which is expected to be the transmission medium in future high-capacity transmission systems. In this article, we introduce a multi-core fiber connector that achieves physical-contact connection with low loss, and a pluggable fan-in/fan-out device connecting multi-core fiber and single-core fiber.

Keywords: multi-core fiber, optical connector, fan-in/fan-out

1. Introduction

Optical fiber connection technology is essential to construct and operate an optical communication network. Fusion splicing and optical connectors are the prevailing methods used for optical fiber connections. Fusion splicing permanently connects the optical fibers by melting them with an arc discharge. Optical connectors detachably connect the optical fibers.

Establishment of optical fiber connection technology is necessary for multi-core fiber (MCF), which is expected to be used as the transmission medium in future high-capacity transmission systems. To connect MCFs with low loss, it is essential to precisely match the axis rotation angle of the optical fibers, which is unnecessary when aligning single-core fiber (SCF). The general-purpose conventional fusion splicer that aligns the optical fiber by observing it from solely a lateral view cannot adjust the rotating position of the MCF cores. In contrast, another commercially available fusion splicer achieves low-loss connection of the MCF by showing the fiber end with a mirror, which enables us to adjust the rotating position of the core.

The optical connector needs an alignment mechanism with a repeatable accuracy of less than 1 μm for an insertion loss of 0.1 dB at the mated core of single-mode fibers. With the conventional simplex optical connector, the external force acting on the optical connector does not affect the optical fibers at the connection point because the butt-jointed ferrules are floated inside the plug housings. The floating mechanism is achieved by enabling the rotation of the optical fiber axis.

However, when we connect the MCFs with the conventional connector, the floating mechanism degrades the rotational angle alignment. It is therefore difficult to achieve low-loss connection of MCF with the conventional connector. The NTT laboratories have been promoting research and development (R&D) of MCF connection technology aimed at achieving a level of performance equivalent to that of the conventional optical connectors used with SCFs. A fan-in/fan-out (FI/FO) device is also required that couples each core of the MCF optically with individual SCFs to construct the transmission system with the MCF. In this article, we describe the simplex MCF connector, multiple MCF connector, and FI/FO device.

2. Simplex MCF connector

Precise alignment of the MCF's rotational angle θ_z is required to achieve a low-loss connection of all the cores of the MCF (**Fig. 1**). Here, conventional simplex connectors such as a single-fiber coupling (SC)

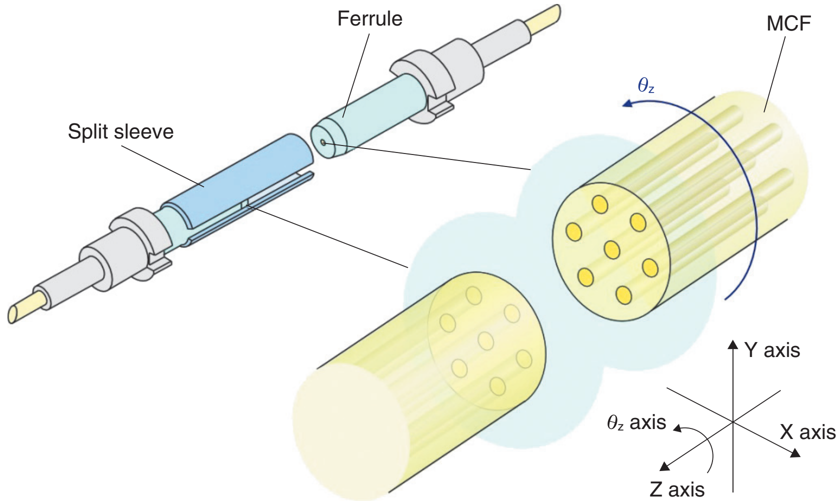


Fig. 1. Basic structure of simplex MCF connector.

connector have clearance between the flange and the plug, enabling the mated ferrules to be floated inside the plug housing. The clearance enables us to rotate the fiber within ± 2 degrees and degrades the rotational angle alignment. Therefore, when we connect the MCFs with the conventional connector, it is difficult to achieve low-loss connection with good repeatability for the outer cores of the MCF.

To achieve precise rotational angle alignment for the MCF, we have studied a simplex MCF connector that enables us to adjust the rotational angle of the ferrule when assembling the connector and to narrow the rotational angle range of the ferrule when connecting the connector. Our MCF connector components are shown in **Fig. 2(a)**. The plug frame, flange, and stop ring are unique to the MCF connector. The other parts are the same as those used in the conventional SC connector. The plug frame has two key guides. The stop ring has guides to rotate the ferrule, and these guides fit the key guide.

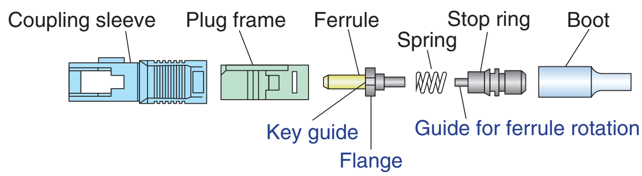
A schematic diagram of the rotation structure is shown in **Fig. 2(b)**. As the stop ring rotates around the plug frame, the ferrule housing the MCF also rotates along with the stop ring. In this configuration, the rotational angle can be aligned precisely by monitoring the MCF facet with a microscope after the MCF is fixed to the ferrule. Then the stop ring is fixed to the plug housing with an adhesive at an optimum angle.

We tested the repeatability of the connection loss for the MCF connector using 7-core MCF with a core pitch of 50 μm. The variation between maximum and minimum losses was about 0.1 dB. This result indicates that the MCF connector suppresses the variation of the rotation angle to less than 1.1 degrees. We also measured the connection losses of the fabricated MCF connector at a wavelength of 1.55 μm. The connection loss was sufficiently small at < 0.2 dB with an average value of about 0.1 dB. We confirmed that the measured connection loss values were the same as those of the conventional simplex SCF connector.

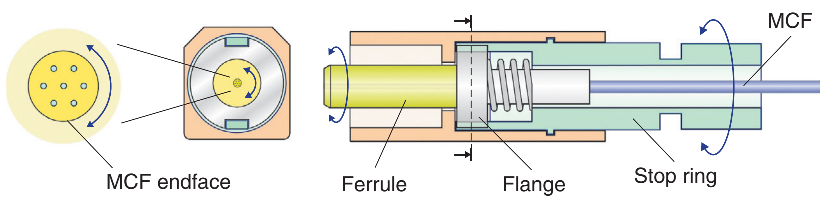
Simplex SCF connectors such as SC or MU (miniature universal coupling) connectors employ a physical-contact (PC) connection that is in direct contact with the fiber endface, which is done by pressing the ferrule with the polished convex spherical end. The PC connection obtains high return loss by reducing Fresnel reflection at the connection point and also makes it possible to achieve high-power durability by eliminating organic substances such as adhesive at the connection point.

The MCF connector must achieve the PC connection not only at the center core but also at the outside cores. To do this, the MCF connector has a larger contact area between the mated fiber endfaces compared to the SCF connector. For the MCF connector, we clarified the relation between the fiber end shape and the compression force required for the PC connection. We found that the end shape changes in a complex manner when applying the compression force to the ferrule and MCF simultaneously.

We established the design method for the PC connection of MCF using a finite element method simulation with a three-dimensional asymmetric geometry model that conforms to the actual endface structure



(a) Components of simplex MCF connector



(b) Configuration for rotation alignment of MCF

Fig. 2. Simplex MCF connector.

[1]. We have designed and fabricated 7-core MCF connectors using our design method. All the cores of the fabricated MCF connectors provided a high return loss of more than 45 dB, which verifies the PC connection.

3. Multiple MCF connector

The MCF enables us to increase the core density of a fiber cable in a long-haul transmission or to reduce the number of fibers in a datacenter optical link. To construct such a system using the MCFs, we need optical connectors for both single and multiple MCFs. The conventional multiple SCF connector achieves the multi-fiber connection by coupling the mechanically transferable (MT) ferrule accommodating the multi-fiber array with two guide pins. The multiple MCF connector also employs the MT ferrule in order to obtain the same performance and operability as the conventional multiple SCF connector.

The basic structure of our devised multiple MCF connector is shown in **Fig. 3(a)**. The configuration that mates the MT ferrules using the two pins is the same as that of the conventional MT connector. The conventional MT connector fixes the fibers to the micro-hole of the MT ferrule with adhesive. Our multiple MCF connector separates the fixed portion of the fibers from the MT ferrule. That is, the fibers are fixed at the fixing component rather than at the ferrule.

We devised the new configuration for PC connection of multiple MCFs. However, the difference in the protrusion length of the MCFs from the MT ferrule and the angle error of the polished fiber end make it difficult to achieve PC connection of multiple MCFs. We found that the PC connection of the MCF array could be achieved by using the elastic compression force of a fiber at the unfixed portion generated when the mated MCFs are pressed together [2].

A photograph of the fabricated quadruple-MCF connector for 7-core MCF is shown in **Fig. 3(b)**. On the MT ferrule endface, the cores of the four MCFs are aligned to have the same arrangement. The average insertion loss of the fabricated connectors was less than 0.3 dB. The result indicates that our multiple MCF connector has the same insertion loss as the multiple SCF connector. The return losses exceeded 45 dB, which confirmed that all the connection points achieved PC connections.

4. FI/FO

A FI/FO device that couples each core of the MCF optically with individual SCFs is essential to construct a transmission system that uses MCF. The NTT laboratories have studied a bundled fiber FI/FO device that realizes a closely packed core arrangement of an MCF by utilizing individual SCFs. The bundled fiber FI/FO device enables us to achieve a pluggable connection by accommodating the bundled fibers in connector housings.

The basic configuration of the FI/FO device is

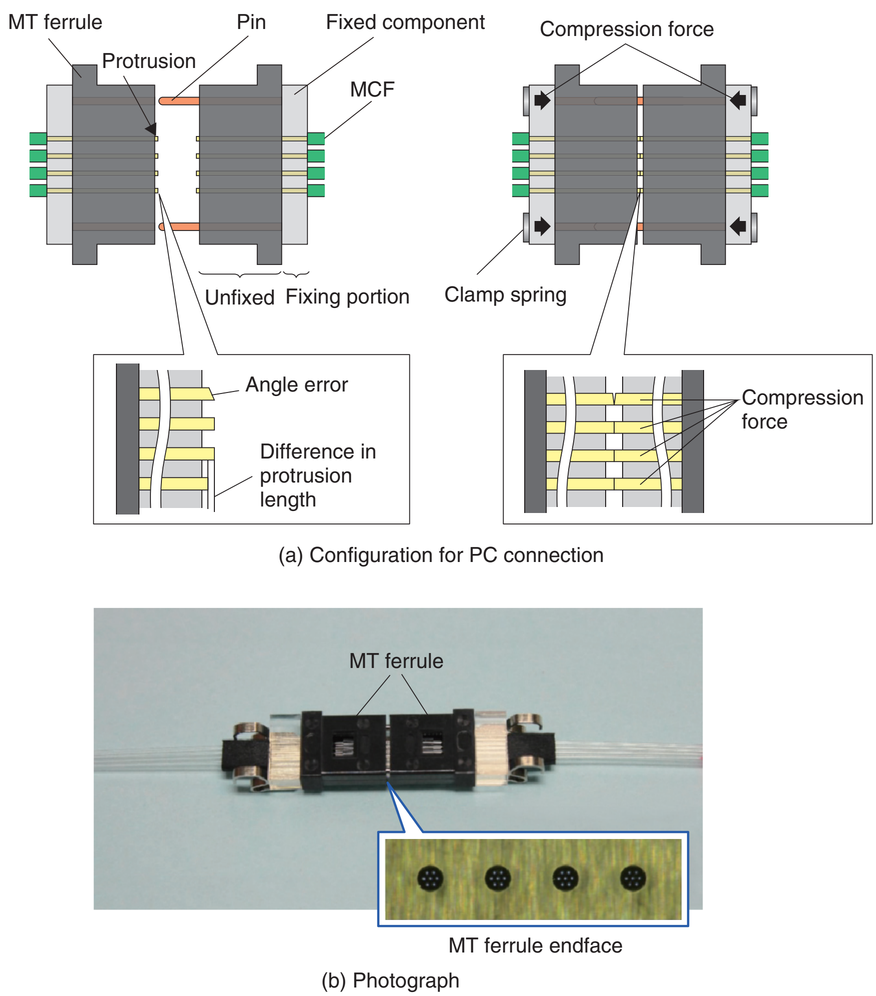


Fig. 3. Multiplex MCF connector.

shown in **Fig. 4**. It employs two ferrules and a split sleeve. The MCF is inserted into the micro-hole of one of the ferrules. The SCFs required for the MCF core arrangement are inserted into the micro-hole of the other ferrule. The inserted SCFs are then fixed in place with adhesive. The portion of the SCFs inserted into the ferrule has the same cladding diameter as the core pitch of the MCF. The core arrangement of the bundled fibers at the ferrule end is made to correspond to the hexagonal closely packed core arrangement of the MCF by inserting individual SCFs into the circular hole, as shown in Fig. 4(b). Because the FI/FO device utilizes the same plug and adapter as the simplex MCF connector, the rotation of the ferrule via the stop ring enables us to match the core arrangement of the MCF and SCFs.

The insertion loss measured using the fabricated FI/FO device for 7-core MCF was sufficiently small at less than 0.3 dB, with an average value of 0.12 dB. The return losses exceeded 45 dB, which confirmed that all the connection points achieved PC connections. With the configuration of the FI/FO device as shown in Fig. 4(a), we can change the sectional shape of the ferrule hole to a hexagon (Fig. 4(c)) or a square to achieve a FI/FO device that corresponds to various types of MCF with different numbers of cores and core arrangements from those of the 7-core MCF.

5. Future prospects

In this article, we described connection technology that includes a simplex connector, multiple connector, and FI/FO device for MCF, which is expected to be the transmission medium in future high-capacity

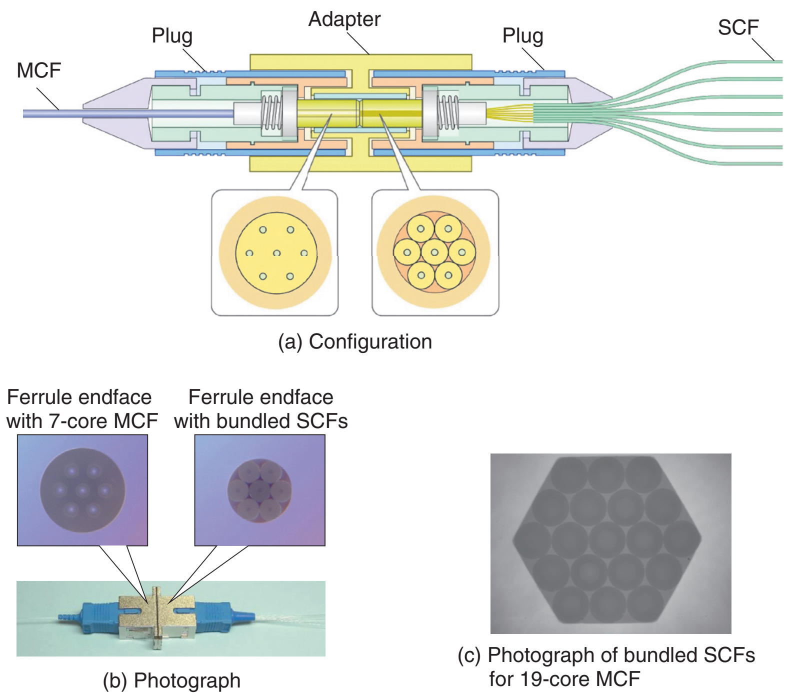


Fig. 4. FI/FO device.

transmission systems. R&D on MCF connection technology is steadily progressing and will enable us to achieve the same performance as the connection technology for SCF. Meanwhile, further efforts are necessary to achieve the reliability and mass production required for practical use of MCF connection technology. We will continue to promote R&D for future ultra-high-capacity transmission systems.

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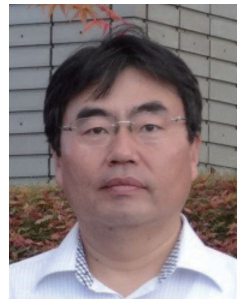

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Activity Report of ITU-T Focus Group on IMT-2020

Yoshinori Goto

Abstract

In 2015, the ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) established the Focus Group on IMT (International Mobile Telecommunication)-2020 (FG IMT-2020) to study the non-radio part of IMT-2020. The FG worked until December 2016 and produced key concepts such as the network slice and network softwarization components constituting the IMT-2020 system. This article presents the activities of FG IMT-2020.

Keywords: network slice, network softwarization, fronthaul

1. Introduction

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) established the Focus Group on IMT (International Mobile Telecommunication)-2020 (FG IMT-2020) in April 2015 in a decision taken by Study Group 13 (SG13), which is the parent group of FG IMT-2020 as well as the lead study group on the non-radio part of IMT. The FG carried out its activities until December 2016. The FG was mandated to examine new network technologies, which were originally studied under the topic of future networks, for possible application in future mobile networks. In the latter half of the FG's study period, new approaches were investigated such as prototyping new technologies and collaborating with open source communities as a way to promote standardization activities. This attempt was a unique feature of this FG, and it prompted the ITU-T to consider further actions to be taken at higher levels such as the World Telecommunication Standardization Assembly (WTSA).

2. History of FG IMT-2020's activities

Technologies examined in FG IMT-2020 were rooted in the study of future networks, which had been a topic of study in SG13 since 2009. When study on future networks began, these networks were a high-level concept without tangible and implementable technologies. Nevertheless, SG13's activities resulted in ITU-T Recommendation Y.3001, which described the objectives and design goals in 2011.

As the concept of IMT-2020 attracted interest from industry, the experts working on future networks began to consider how their achievements might contribute to the realization of IMT-2020. SG13 had a technical background in future networks and was also responsible for studying the non-radio part of IMT. This background and also the increased interest in IMT-2020 led SG13 to establish FG IMT-2020 at its meeting in April 2015.

Standards development groups in the private sector play major roles in the standardization of mobile networks. The 3rd Generation Partnership Project (3GPP) is the most prominent group in this area. Institutions such as ITU-T that set de jure standards play a more limited role. This means that this FG may not be successful by simply taking the conventional approach to standardization without considering a standardization strategy.

The conventional standardization approach usually starts with gathering requirements, and then drawing a high-level architecture and making detailed technical specifications. In contrast, this FG took a new approach that began with a gap analysis of existing standardization work to find technical areas where

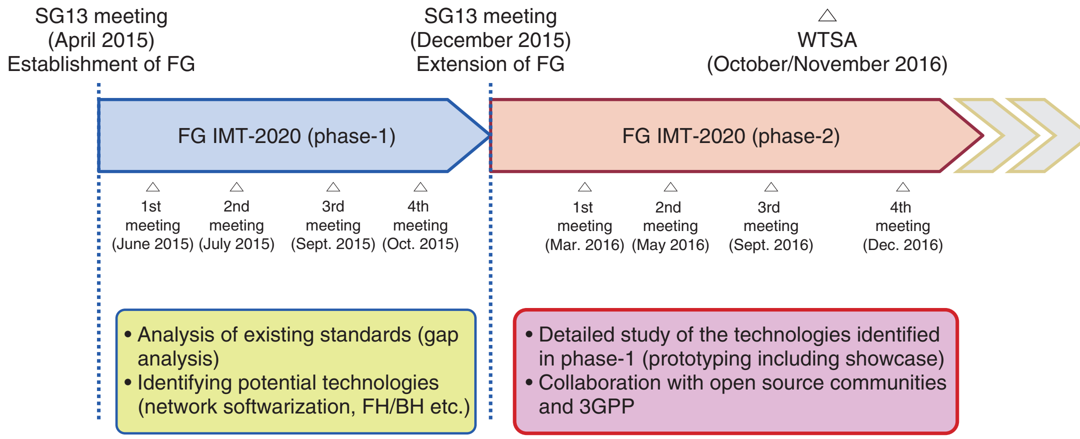

Fig. 1. History of FG IMT-2020.

ITU-T had a competitive advantage. In the more than two years of work done by the FG, this period (from June 2015 to October 2015) is referred to as phase-1. This author served as vice-chair of SG13 and along with other members played a leading role in building a consensus to create a ToR (Terms of Reference) document describing the direction of phase-1 of the FG.

The phase-1 FG concluded its activities in October 2015 and produced a deliverable, which is the major output of an FG as defined in ITU-T Recommendation A.7. The deliverable of this FG describes the candidate technologies such as network softwarization, FH/BH (fronthaul/backhaul), information centric networking and content centric networking (ICN/CCN), as well as proposed directions for further study in ITU-T. With this conclusion of the phase-1 FG, SG13 decided to extend the FG into phase-2, which was mandated to study details of identified technologies and to conduct prototyping activities (**Fig. 1**).

3. Technical study

Studies were carried out on the various technical elements of IMT-2020. These are described in more detail in this section.

3.1 Architecture

The network slice is a technology that was newly introduced in FG IMT-2020 discussions. The first challenge of the FG is to determine how to define the architecture of this virtual concept of a network slice. At the beginning of the phase-2 study, the FG tried to draw a typical architectural diagram containing functional blocks and reference points. The efforts continued until the second phase-2 meeting (May 2016), but the FG did not produce an architectural diagram that was satisfactory to the FG experts.

Faced with the slow progress and the difficulty of drawing an architectural diagram, the chair and vice-chairs considered that once a simplified diagram that was agreeable to the experts was produced, the discussion on further details could be accelerated. Therefore, at the meeting in September 2016, the meeting attendees worked on producing a minimal agreeable diagram.

In this discussion, an idea centered on the concept of a network slice was proposed. The network slice architecture consists of two different aspects. One is the network provider which owns all the network resources and provides the necessary elements of the resources at the request of the slice users. The other is the slice instance that is actually produced by the slice users and offered for actual services to the end users. Consequently, the different natures of a slice meant that a specific architecture would be necessary for each case.

In the FG, the former aspect was called a network slice blueprint, and the latter was called a network slice instance (**Fig. 2**). The network slice blueprint consists of all resources and functions of data, control, services, and other elements that are used as foundations of network slice instances. The orchestrator combines the necessary resources and functions to produce a network slice instance. There are two cases of network slice instances based on whether the application is included in the slice—for example,

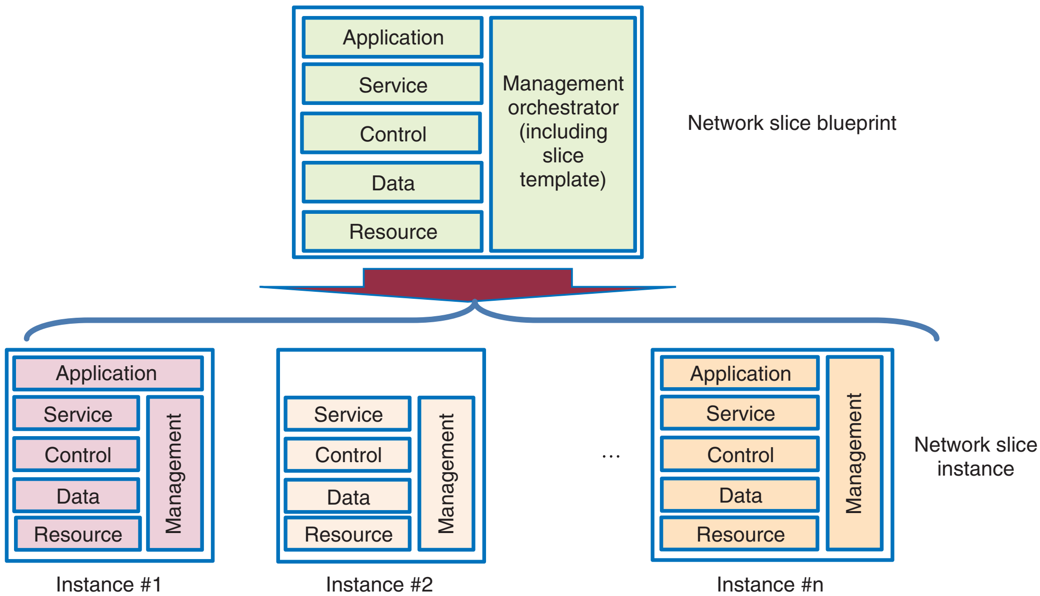

Fig. 2. Concept of network slice.

an application provided by the slice user—or not included—for example, when only connectivity is provided by the slice user.

There was a general agreement that the network slice instance does not include its own orchestrator since the orchestrator does not play any operation role inside the slice. However, it was pointed out that multi-layered slicing is possible, for example, in an FMC (fixed mobile convergence) slice combining a mobile slice and a fixed slice, and that the orchestrator in the slice could play certain roles in such cases.

In contrast to the architectural diagram discussed in 3GPP, which was drawing a physical entity diagram, the diagram drawn in the FG was created from the viewpoint of the hierarchical structure of a network slice blueprint and instance. There was no contradiction between the two kinds of diagrams; however, further study is needed to clarify the relationship between these two.

3.2 Network softwarization

Network softwarization (**Fig. 3**) is one of the major results of FG IMT-2020 for which Japanese experts actively contributed. This subject is strongly connected to the architecture discussion, and it includes the major characteristics of the network slice.

The IMT-2020 system consists of a radio access network, mobile packet core, and other components. In cases where the network slice provides applications by itself, IMT-2020 includes the datacenter. All the elements mentioned above are referred to as resources in the concept of network softwarization. The network slice is considered as a collection of resources. It was discussed whether the user equipment would be considered as a resource consisting of a slice. This point was not clarified due to a lack of sufficient use case studies. A future study will reveal this point as potential use cases are studied in depth.

3.3 Fronthaul

The fronthaul is a link between the baseband unit (BBU), which generates baseband signals, and the remote radio head (RRH), which emits radio signals. Fronthaul technology improves the quality of a radio access network by utilizing multiple base stations in a collaborative manner, although it requires a high level of time and frequency synchronization among the base stations.

The consensus of the experts of the FG at the beginning of phase-1 was to use RoF (radio over fiber) technology for the fronthaul, which is expensive but considered to be a promising and technically reliable approach. However, the Japanese experts proposed a packet based approach as an alternative. Because of the expected cost effectiveness of a packet based approach, the majority of the members shifted their support in favor of the Japanese proposal. Among packet based approaches, Ethernet based methods

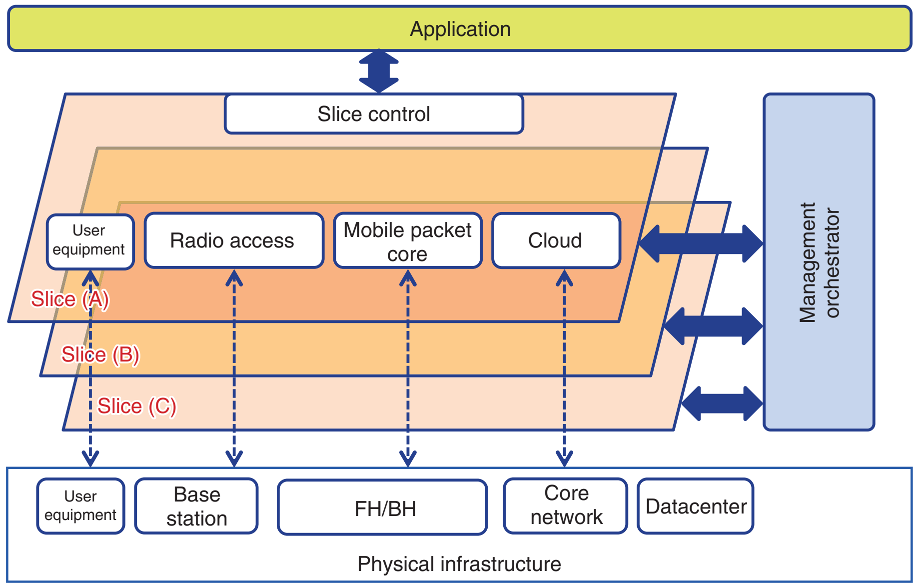

Fig. 3. Concept of network softwarization.

have been the most intensively developed and discussed. At the FG meeting in May 2016, China Mobile demonstrated a prototype product based on its proposed technology to the IEEE* 1914 Working Group. Additionally, a Chinese manufacturer presented FlexEthernet as a solution to achieve time and frequency synchronization.

Many researchers participating in this FG had been studying software-defined networking technology but were having difficulty in testing their ideas in an end-to-end network system without technical knowledge or the facilities of a radio access network, which is an important component of mobile networks. A solution called OpenAirInterface was introduced as a useful tool to construct a base station using off-the-shelf products. This solution uses open source software to achieve a BBU and RRH on a personal computer. Certain models of commercial user equipment products can be connected for this purpose, and many participants of the FG were interested in learning how to use this solution to set up their own test environment.

3.4 Other technologies

ICN/CCN is network technology that enables more efficient distribution of content. ICN/CCN caches the content and transcodes it adaptively in response to network conditions. In FG IMT-2020, prototyping activities and use cases, which were primarily from the US, were introduced. The FG considered ICN/CCN to be a potentially useful technology but thought that there was room for improvement to increase the possibility of identifying/caching relevant content before it was selected as an actual solution to be deployed. The FG also noted that one of the key factors in the development of IMT-2020 is determining how to address the increasing volume of traffic, particularly video traffic. In this sense, potential use of ICN/CCN technology should be considered.

The application of satellite communications technology was presented at the FG in September 2016. Satellite communications is relevant for the backhaul in mobile networks. Many developing countries still lack fiber backbone networks, so satellite communications could play a bigger role in such cases. Signal attenuation caused by weather conditions such as rain and clouds reduces the reliability of satellite communications; therefore, satellite communications plays a supplementary role where the terrestrial fiber network is available. However, some plans are being made to deploy a number of smaller satellites in the relatively low orbits (about 1000 km above earth) rather than in the conventional geostationary orbit. This type of satellite network features low latency as well as global coverage. New use cases will be developed.

* IEEE: Institute of Electrical and Electronics Engineers

Table 1. Structure of SG13 and relationship with FG IMT-2020.

SG13			FG IMT-2020 Working Group	
WP	Title	Question	Working Group	Document
1	IMT-2020 Networks & Systems	Q.6: Quality of service (QoS) aspects including IMT-2020 networks	QoS	
		Q.20: IMT-2020: Network requirements and functional architecture	Requirements & architecture	Terms and definitions for ITU-T IMT-2020
				Requirements of IMT-2020 from network perspective
				Framework of IMT-2020 network architecture
		Q.21: Software-defined networking, network slicing and orchestration	Softwarization	Report on the application of network softwarization to IMT-2020
			E2E management	IMT-2020 network management requirements
				Network management framework for IMT-2020
		Q.22: Upcoming network technologies for IMT-2020 and future networks	ICN/CCN	Report on the application of ICN to IMT-2020
		Q.23: Fixed-mobile convergence including IMT-2020	FMC	Requirements of IMT-2020 fixed and mobile convergence
				Unified Network Integrated Cloud on FMC
2	Cloud Computing & Big Data	Q.7 (DPI), Q.17 (cloud requirements), Q.18 (cloud architechture), Q.19 (cloud management)		
3	Future Network Evolution & Trust	Q.1 (innovation services), Q.2 (NGNe), Q.5 (developing countries), Q.16 (knowledge & trust)		

DPI: deep packet inspection
E2E: end to end
FMC: fixed mobile convergence
NGNe: Next Generation Network evolution
WP: Working Party

4. Future plan

WTSA-16, which is the highest level meeting in the ITU-T, was held in October and November 2016. WTSA recognized that IMT-2020 will be one of the most important subjects over the next four years and therefore adopted a new resolution to promote IMT-2020 related activities based on the outcomes of FG IMT-2020. IMT related work including IMT-2020 is coordinated by SG13 as a mission of the lead study group on this subject. SG13 also organized a dedicated working party to draft questions for particular subjects of IMT-2020 (**Table 1**). The FG IMT-2020 produced nine deliverables. These deliverables are assigned to the relevant questions and will be used as base documents for further development.

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He received a B.E. and M.E. in applied physics from Tohoku University, Miyagi, in 1992 and 1994. He joined NTT Basic Research Laboratories in 1994. He has been researching and developing cable television systems, Internet protocol television (IPTV), and machine-to-machine technology. He has been engaged in the standardization work for IPTV in ITU-T as a member of the IPTV Focus Group and Global Standards Initiative since 2006. He has also served as Rapporteur of Question 11 of ITU-T SG9, Questions 5 and 25 of ITU-T SG13, and Question 21 of ITU-T SG16. He has been a vice-chair of ITU-T SG13 since 2013. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Case Studies of Wireless LAN Problems

Abstract

This article describes cases studies of problems occurring in wireless LANs (local area networks). This is the fortieth article in a series on telecommunication technologies. This contribution is from the EMC Engineering Group, Technical Assistance and Support Center, Maintenance and Service Operations Department, Network Business Headquarters, NTT EAST.

Keywords: wireless LAN, Wi-Fi, access point

1. Introduction

The increasing popularity of mobile terminals equipped with wireless local area network (LAN) functions has driven the installation of wireless LAN access points (APs) in both indoor and outdoor locations and the creation of Internet connection environments in all sorts of places. In line with this trend, NTT EAST has made its 5th-generation home gateway compliant with the new IEEE802.11ac*1 wireless networking standard and has been expanding its communication services using wireless LAN such as by launching FLET'S HIKARI (optical broadband) services capable of gigabit-class communications. Services in a variety of formats are also expanding such as Wi-Fi*2 access for apartment buildings and Wi-Fi access for corporate use.

However, communication faults can occur as a result of insufficient signal strength, signal interference, incompatible communication protocols, and other factors. Finding ways of recovering from faults quickly and improving service quality has consequently become a matter of urgency.

In this article, we introduce recent case studies of wireless LAN problems handled by the Technical Assistance and Support Center.

2. Case study 1: Wi-Fi access for an apartment building

In this section, we describe a problem a customer had with Wi-Fi access for an apartment building and explain how it was rectified.

2.1 Overview and report

Wi-Fi access for apartment buildings is an Internet connection service via wireless LAN targeting a building of 4 to 12 units. In this service, any room in the building should be able to connect to wireless LAN via radio signals transmitted from shared APs installed outdoors. In this case study, a report was received that an AP connection could not be made from an indoor location, so an investigation was carried out.

2.2 Results of investigation and causes of fault

We considered the possibility that the signal strength of wireless LAN was insufficient, so we checked the manner in which the antennas were installed. We found some cases in which antennas were installed at a height midway between the first and second floors or on the ceilings of balconies, as shown in **Fig. 1**, and we surmised that the signals in such cases were not strong enough to reach indoors. The indoor signal-strength distribution measured with a wireless LAN tester [1] (a product developed by the Technical Assistance and Support Center and

*1 IEEE802.11ac: A wireless networking standard developed by the Institute of Electrical and Electronics Engineers (IEEE).

*2 Wi-Fi: A technology for wireless LAN with devices based on the IEEE 802.11 standards. Wi-Fi is a registered trademark of Wi-Fi Alliance.

Fig. 1. Antenna installation formats (examples of inappropriate installation).

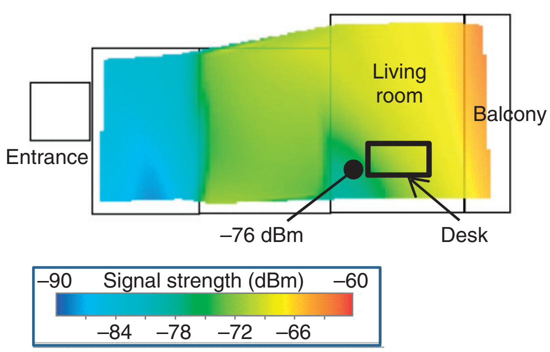


Fig. 2. Signal-strength distribution (before relocating antenna).

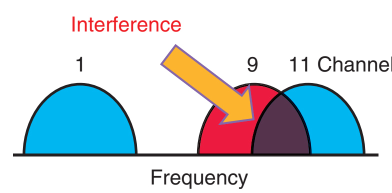


Fig. 3. Channel interference in 2.4-GHz band.

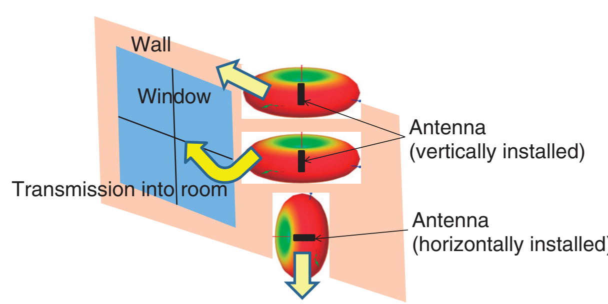


Fig. 4. Antenna signal transmission.

awarded a 2016 NTT EAST President's Commendation) is shown in **Fig. 2**. It was found that the signal strength in the living room where the customer was using wireless LAN was –76 dBm, which we considered to be insufficient.

Furthermore, considering that wireless LAN channel interference might be occurring, we measured the channel interference with the wireless LAN tester and found that channels 9 and 11 were indeed interfering with each other as shown in **Fig. 3**.

We surmised that the causes of the fault were insufficient indoor signal strength due to an inappropriate antenna installation format and interference of wireless LAN signals due to inappropriate channel allocation to the AP.

2.3 Proposed method

Since radio signals are more able to permeate through windows than walls, installing an antenna on the balcony side rather than the entrance side of a unit would make it easier for indoor terminals to receive signals. Signals from a Wi-Fi antenna are strongly transmitted in the direction perpendicular to the antenna direction as shown in **Fig. 4**. To therefore transmit radio signals efficiently into a room, the

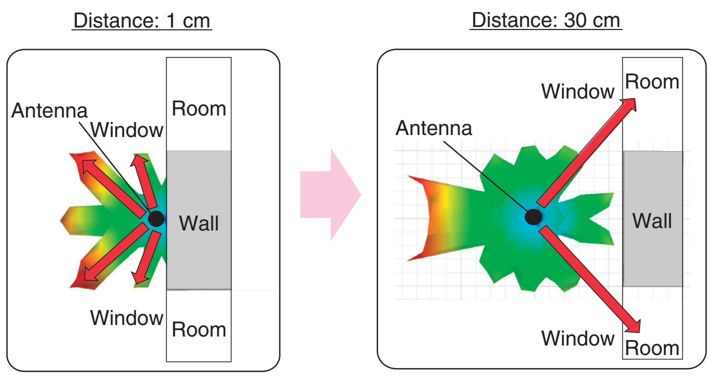


Fig. 5. Antenna transmission characteristics in 2.4-GHz band (simulation).

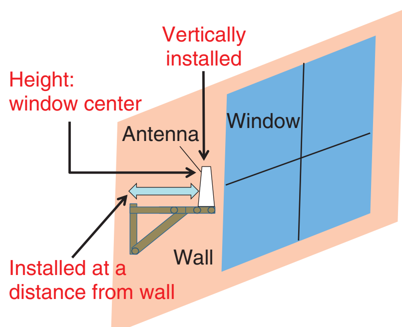


Fig. 6. Optimal antenna installation format.

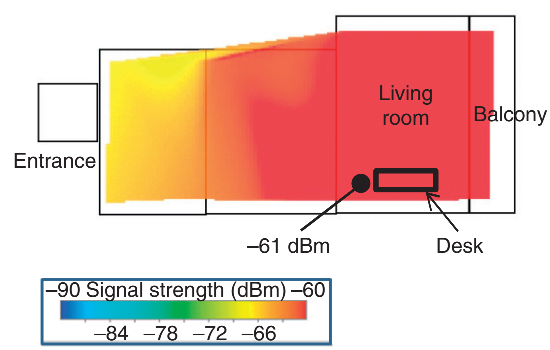


Fig. 7. Signal-strength distribution (after relocating antenna).

antenna should be vertically installed at a height aligned with the center of the window frame. Moreover, installing the antenna away from walls can secure a line-of-sight toward rooms, thereby achieving more efficient transmission of radio signals into rooms, as shown in **Fig. 5**.

Therefore, an optimal antenna installation format would be the one shown in **Fig. 6**. That is, the antenna should be vertically installed at a height corresponding to the center of the window and at a distance from the wall. The indoor signal-strength distribution after changing the antenna installation format is shown in **Fig. 7**. The signal strength in the living room was now –61 dBm, reflecting a 15 dB improvement compared with that before antenna relocation.

Finally, allocating wireless LAN channels 1, 6, and 11 as shown in **Fig. 8** can prevent the occurrence of interference.

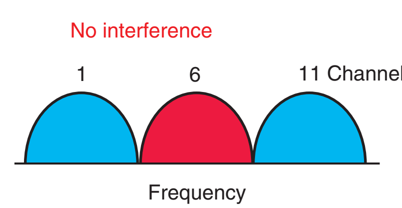


Fig. 8. Optimal channel allocation in 2.4-GHz band.

3. Case study 2: Wi-Fi access service for corporate use

The second case study involved a problem a customer had with Wi-Fi access for corporate use. We describe the problem and the countermeasure in this section.

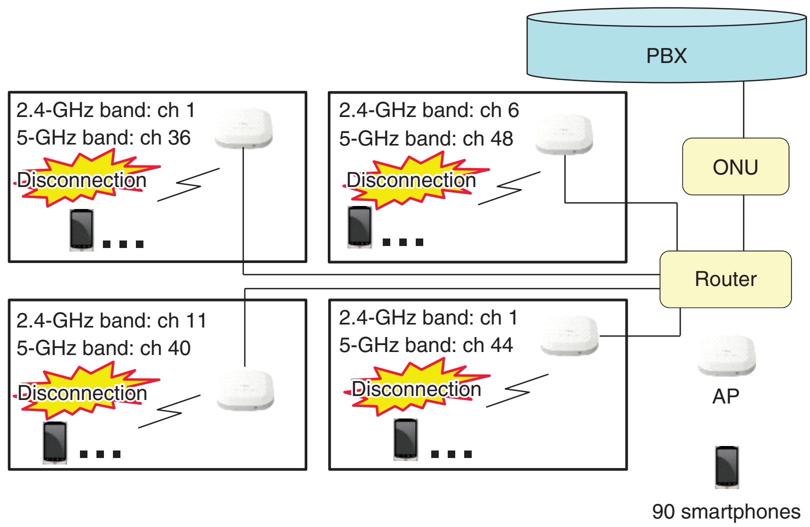


Fig. 9. Equipment setup.

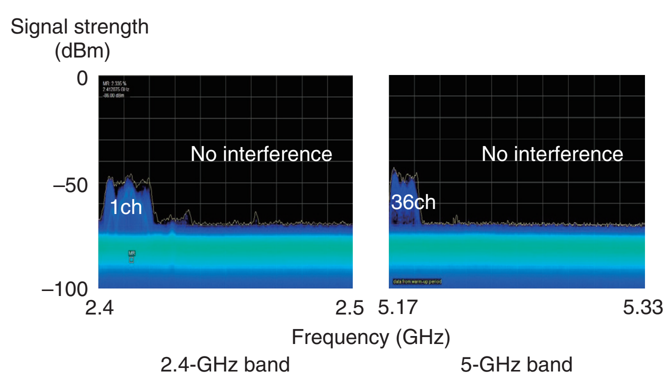


Fig. 10. Results of measuring radio-signal condition.

3.1 Overview and report

Wi-Fi access for corporate use is an Internet connection service via wireless LAN targeting corporate customers. This service delivers AP units to the customer, who then installs them at various indoor locations. There were four AP units (one per room) installed in the customer's office with each AP connected to a router, ONU (optical network unit), and PBX (private branch exchange), as shown in **Fig. 9**. 90 smartphones that could connect to these APs had been used. The customer reported that disconnections occurred.

3.2 Results of investigation and causes of fault

We used a spectrum analyzer to measure the radio-signal condition in both the 2.4-GHz and 5-GHz bands in a room where disconnections had occurred. The results of these measurements are shown in **Fig. 10**. Other than Wi-Fi signals, no interfering signals could be observed.

Next, using AirMagnet (a generally available wireless LAN analysis tool), we measured the protocol on the radio signal in a room where disconnections had occurred. The results are shown in **Fig. 11**. These results revealed that no Block Ack message (acknowledgment that data were received) was returned from the terminal after a data transmission from the AP when a disconnection had occurred (using smartphone A), which resulted in the resending of Block Ack Request messages from the AP. To troubleshoot

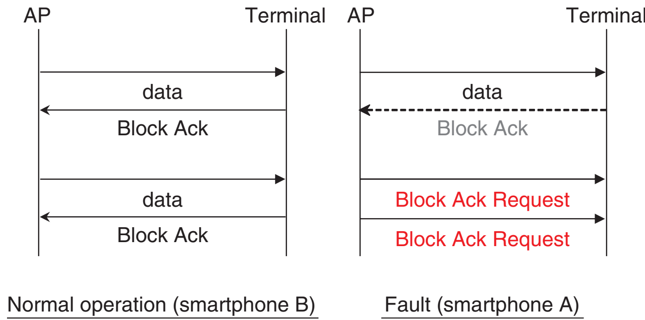


Fig. 11. Results of measuring protocol (case study 2).

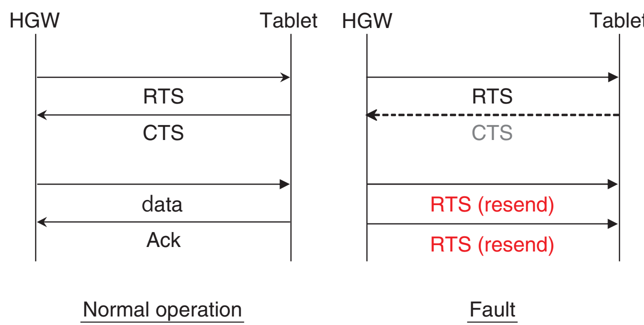


Fig. 12. Results of measuring protocol (case study 3).

this result, we used smartphone B and found that the protocol had no problem in the order of data→Block Ack→data and so on.

We therefore surmised that the cause of the disconnection when using smartphone A was that Block Ack messages that should have been transmitted in reply to data packets from the AP were somehow missing.

3.3 Proposal to the customer

We confirmed that smartphone A was outside the scope of this system's operational guarantee, so we proposed to the customer that smartphone A be replaced with a smartphone unit for which normal operation was guaranteed.

4. Case study 3: Home gateway (HGW) equipped with a wireless LAN function

The final case study involves a problem that occurred in a HGW.

4.1 Overview and report

A customer using a tablet terminal and a HGW equipped with a wireless LAN function reported that an application download would stop 2 to 3 seconds after starting.

4.2 Results of investigation and causes of fault

We measured the signal strength, channel interference, and interfering signals with a wireless LAN tester in the room, but found that no signal attenuation, channel interference, and interfering signals could be observed at the time of the fault.

We then measured the protocol for the radio signals. A download would normally be completed in the order of RTS (Request To Send)→CTS (Clear to Send)→data→Ack (acknowledgment that data were received), as shown in **Fig. 12**. However, at the time of the fault, the AP would resend RTS repeatedly, while no CTS would be returned from the terminal.

We surmised from these results that the non-return of the CTS message from the terminal to the AP caused the AP to repeatedly resend RTS messages, thereby stopping data transmission from the HGW and bringing the download to a halt.

4.3 Countermeasure

We checked the operating system (OS) of the tablet terminal and found that it was an old version. We therefore updated the OS to the latest version, and confirmed that a download was completed.

5. Conclusion

In this article, we introduced recent case studies of wireless LAN problems handled by the Technical Assistance and Support Center. With the proliferation of various types of wireless LAN services, the causes of faults in these services are becoming increasingly diverse. The EMC Engineering Group of the Technical Assistance and Support Center endeavors to achieve prompt resolution of faults related to wireless LAN and to contribute to the smooth provision of communication services. To this end, it is actively engaged in technology dissemination activities through technical support, development, and technical seminars.

Reference

[1] K. Okamoto et al., “Introduction of Wireless LAN Tester toward Smooth Provision of Wi-Fi Services,” IEICE Communications Society Magazine (B-plus), No. 25, pp. 38–43, Summer 2013 (in Japanese).

Event Report: Science Plaza 2016 at NTT Basic Research Laboratories

Norio Kumada

Abstract

Science Plaza 2016, an open-house event hosted by NTT Basic Research Laboratories, was held at NTT Atsugi R&D Center on November 23, 2016. Under the banner "Frontier Science: Open Door to the Future," Science Plaza was aimed at disseminating our latest research accomplishments to various groups of people inside and outside of NTT as well as gathering diverse opinions. This event was held jointly with NTT Device Innovation Center, NTT Device Technology Laboratories, and NTT Communication Science Laboratories.

Keywords: NTT Basic Research Laboratories, Science Plaza, open-house event

1. Purpose of Science Plaza

At NTT Basic Research Laboratories (BRL), we are engaged in research aimed at creating new principles and concepts that overcome the limitations of existing network technology and developing basic technologies that pave the way to future innovation. At Science Plaza 2016, our aim was to introduce to a wide audience the results of the cutting-edge research being carried out not only at BRL, but also at NTT Device Innovation Center (DIC), NTT Device Technology Laboratories (DTL), and NTT Communication Science Laboratories (CSL). This event was chiefly targeted at undergraduate and postgraduate students and corporate researchers.

2. Science Plaza overview

The event included lectures, poster exhibitions, and laboratory tours, which are briefly introduced here.

2.1 Lectures

At Science Plaza 2016, the lectures were divided into morning and afternoon sessions. The morning session started with an opening address delivered by BRL director, Tetsuomi Sogawa (**Photo 1**). This was followed by three lectures: Frontier Research in Quantum Electronic Optical Properties and Functional Materials (BRL), Groundbreaking New Device Research (DIC/DTL), and Communication Science as a Bridge Between Humans and Information (CSL). After that, Dr. Akira Fujiwara (Senior Distinguished Scientist, BRL) held a symposium called Ultimate

Photo 1. Opening address by BRL Director, Tetsuomi Sogawa.

Photo 2. Symposium by Dr. Akira Fujiwara (Senior Distinguished Scientist, BRL).

Photo 3. Special lecture by Dr. Hiroshi Amano (Nagoya University).

Electronics Using Nano-devices (**Photo 2**). This symposium lecture covered the prior development of silicon devices, the current state of research into silicon nano-devices at BRL, and the prospects for future development aimed at practical applications.

In the afternoon session, the 2014 winner of the Nobel Prize in Physics, Dr. Hiroshi Amano (Director, Center for Integrated Research of Future Electronics, Institute of Materials and Systems for Sustainability, Nagoya University), was invited to deliver a special lecture entitled Illuminating the World by LEDs (**Photo 3**). In this lecture, Dr. Amano talked about what happened immediately after the Nobel prize was announced, the problems he encountered in the research and development of blue light emitting diodes, the factors behind his eventual success, and the prospects for future development.

The lecture theater was filled to capacity in both the morning and afternoon lecture sessions, and the lectures were followed by lively question and answer sessions.

2.2 Lab tours

We held lab tours to show the attendees around facilities such as the clean room and laboratories where our research actually takes place, and to allow them to experience some of our latest research achievements (**Photo 4**). There were a total of ten tours (three from BRL, six from DIC/DTL, and one from CSL), each of which was run twice. All the tours were fully booked (with ten guests each), making a total of 200 participants in the lab tours. These tours

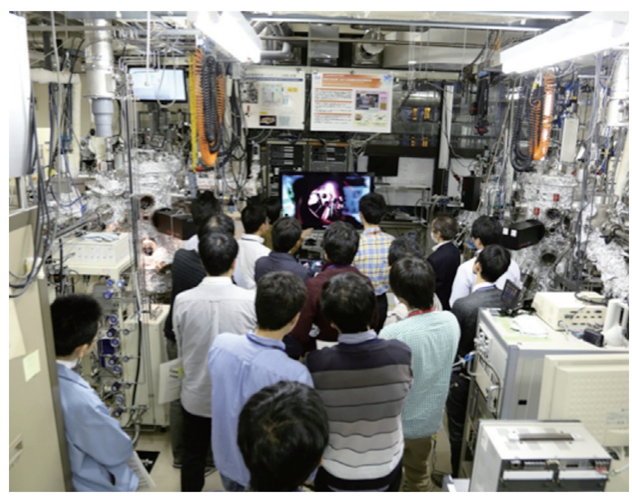


Photo 4. Lab tour.

were very well received, and the feedback questionnaires included responses such as “I don’t often get the chance to visit commercial laboratories. This was a really educational experience.”

2.3 Poster exhibition

We put on an exhibition of posters illustrating 52 research projects, including 13 from the joint research institutes, and the researchers involved in these projects were introduced directly to the exhibition visitors (**Photo 5**). The exhibition started with an overview of each research project and went on to describe in detail

Photo 5. Poster exhibition.

the originality and impact of the research and its future prospects, including an in-depth discussion of the research.

After all the lectures, exhibitions, and announcements were finished, we rounded off the event with an evening social gathering in the exhibition hall. This gave us a chance to get to know the visitors better and continue with the discussions on our research.

2.4 Conclusion of Science Plaza 2016

Science Plaza 2016 was attended by 198 visitors from universities, research institutes, private companies, NTT Group companies, and other organizations. We are really grateful to everyone who attended this event. The questionnaires filled in by those who attended the poster exhibition and lab tours will provide valuable feedback for the next Science Plaza.

Norio Kumada

Senior Research Scientist (Distinguished Scientist), Quantum Solid-State Physics Research Group, Physical Science Laboratory, NTT Basic Research Laboratories.

He received a B.S., M.S., and Ph.D. in physics from Tohoku University, Miyagi, in 1998, 2000, and 2003. He joined NTT Basic Research Laboratories in 2003. He has since been engaged in the study of highly correlated electronic states formed in semiconductor heterostructures. He was a visiting researcher at CEA Saclay, France, during 2013–2014. He was appointed as a Distinguished Scientist of NTT in 2010. He received the Young Scientist Award of the Physical Society of Japan in 2008 and the Young Scientists' Prize from the Minister of Education, Culture, Sports, Science and Technology in 2012. He is a member of the Physical Society of Japan.

One-petabit-per-second Fiber Transmission over a Record Distance of 200 km—Paving the Way to Realizing 1000-km Inline Optical Amplified Transmission Systems within C Band Only

1. Introduction

NTT has demonstrated ultralarge capacity inline optical amplified transmission of 1 petabit (1000 terabits) per second (Pbit/s) over a 205.6-km length of 32-core optical fiber in collaboration with the Technical University of Denmark, Fujikura Ltd., Hokkaido University, the University of Southampton, and Coriant GmbH.

This sets a new world record for the transmission distance of 1-Pbit/s capacity over a single strand of optical fiber within a single optical amplifier bandwidth (C band), which is half the bandwidth used in the previous experiment (**Fig. 1**). The present achievement indicates that the transmission of 1 Pbit/s—a capacity equivalent to sending 5000 high-definition television videos each two hours long in a single second—is potentially possible over 1000 km, which is approximately the distance between major cities in both Japan and Europe.

Part of this research utilized results from the EU-Japan coordinated research and development project on Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI) [1] commissioned by the Ministry of Internal Affairs and Communications of Japan and EC Horizon 2020.

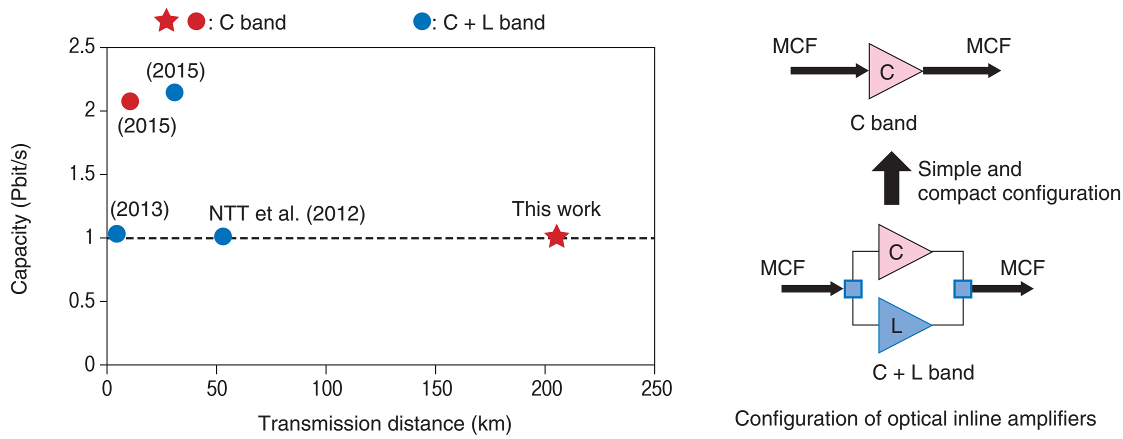
2. Experiment and results

The use of 32-core multi-core fiber (MCF), which we have successfully prototyped for a long length of over 50 km [2], a fan-in/fan-out (FI/FO) device to couple light into the MCF, and new digital coherent optical transmission technology made it possible to achieve the high-capacity optical transmission rate of 1 Pbit/s. We accomplished this by exploiting dense space and wavelength division multiplexing (DSDM and DWDM) over long distances. The 32-core MCF used in the experiment utilized a new arrangement of cores that greatly reduces inter-core light leakage that otherwise degrades performance [2]. In addition, we used the wave properties of light (phase and polarization) to apply multi-dimensional coding to polarization division multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) digital coherent technology to improve the long-distance transmission performance in each core.

The experimental results are shown in **Fig. 2**. We achieved 31.3-Tbit/s capacity per core (= 680 Gbit/s per wavelength x 46 wavelength channels), and using the 32-core MCF, we recirculated and amplified the signals over four spans of the 51.4-km fiber, demonstrating that signal transmission of an aggregate 1-Pbit/s capacity was possible over 205.6 km.

The Q-factor indicates the transmission quality of the PDM 16-QAM signals. Because the Q-factor was uniform, it showed that high quality transmission with small variations between cores and low error was possible. In 2012, we reported on an experiment in which we achieved a world-first 1-Pbit/s capacity over 52.4 km [3]. In comparison, these new results demonstrate a distance about four times longer at

This sets a new world record for the transmission distance of 1-Pbit/s capacity over a single strand of optical fiber within a single optical amplifier bandwidth (C band), which is half of that in previous record-breaking experiments.



MCF: multi-core fiber

Fig. 1. The achievement in petabit-per-second-class transmission.

- All 1473 channels with a 680-Gbit/s PDM 16-QAM signal format were transmitted over 205.6 km without eight-dimensional coded modulation.
- Total capacity of 1 Pbit/s/fiber (= 32 cores x 46 wavelengths x 680 Gbit/s) was achieved.

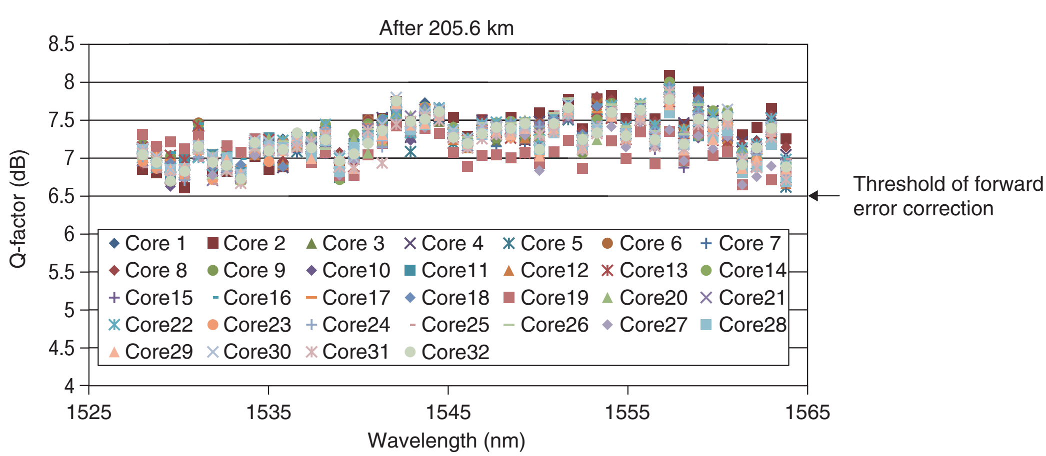


Fig. 2. Transmission performance of 1 Pbit/s over 205.6 km.

205.6 km, which is the world's longest distance for over petabit-per-second capacity transmission.

Moreover, by applying a digital signal processing technique called multi-dimensional coded modulation, the capacity per wavelength is reduced by 25% to 510 Gbit/s. Nevertheless, we demonstrated that the transmission distance can be increased to over 1000 km. As a result, with one optical fiber, we showed that there is a possibility for ultrahigh capacity equivalent to 0.75 Pbit/s using just the 5 THz bandwidth of the C band, and 1.5 Pbit/s using the 10 THz bandwidth provided by the combined C and L bands, with a potential transmission distance over 1000 km.

3. Technological features and roles

Here, we describe the technology that was applied to achieve the 1-Pbit/s transmission over a record distance.

3.1 Thirty-two-core MCF transmission line

The MCF we used in this experiment was jointly designed and prototyped by the Technical University of Denmark, Fujikura, and Hokkaido University. The fiber has a new structure (single-mode heterogeneous-core MCF) with 32 cores incorporating several types of cores, each with different properties [2]. The characteristic of this fiber is that two kinds of cores with slightly different refractive indices are arranged in a square lattice pattern. With this structure, even if the number of cores is increased to 30 or more, the crosstalk between adjacent cores can be greatly reduced [2], making it possible to realize long-distance DSDM transmission [4]. NTT and Coriant evaluated the long distance characteristics of the 51.4-km MCF transmission line with the 32-core MCF and FI/FO devices prototyped by Fujikura, the University of Southampton, and NTT. As a result, we confirmed that all cores had low crosstalk and low loss characteristics over the entire C band, which is a requirement for a 32-core MCF transmission line suitable for transmission over a 1000-km distance.

3.2 Multi-dimensional coded 16-QAM technique

In recent large-capacity optical communications, instead of the intensity modulation signal transmitted using binary states of either ON or OFF, a highly efficient PDM-QAM digital coherent signal has been used that realizes a large number of signal states created by using the wave properties (phase and polarization) of light. Such multi-level QAM signals can achieve a highly efficient ultrahigh speed optical signal by associating a plurality of bits of digital signals with a plurality of optical signal states encoded using the phase and polarization of light. However, the drawback is that when we increase transmission efficiency by increasing the number of multi-levels, the transmission distance sharply decreases. In addition, signal quality degrades by the crosstalk that arises in MCF transmission.

In this case, NTT reduced the number of multi-levels of the QAM signal from 32 in the conventional report [3] to 16 and applied a wideband digital-analog conversion technique [5] to the digital coherent signal using highly efficient error correction coding. As a result, we successfully transmitted a capacity of 680 Gbit/s per wavelength (1 Pbit/s per fiber) over a 205.6-km distance, the longest distance for petabit-per-second capacity transmission. Furthermore, by applying the eight-dimensional encoded 16-QAM technique [6] and by improving the allocation method of the digital signal and the optical signal state, the transmission quality can improve compared with the normal QAM code. With the same 16-level QAM, the transmission rate will be reduced to 510 Gbit/s per wavelength, but by doing this, we showed that it has the potential to extend the transmission distance to possibly over 1000 km.

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External Awards

Postgres PRIZE Award
Winner: Masahiko Sawada, NTT Open Source Software Center (NTT Software Innvation Center)
Date: March 17, 2017
Organization: PgConf.Russia 2017

For "Built-in Sharding Update and Future."
Published as: M. Sawada, "Built-in Sharding Update and Future," PgConf.Russia 2017, Moscow, Russia, Mar. 2017.

Young Researcher's Award
Winner: Chihiro Kito, NTT Access Network Service Systems Laboratories
Date: March 24, 2017
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE)

For "Loss Distribution Field Measurement of PON Branches with End-reflection Assisted Brillouin Analysis."
Published as: C. Kito, H. Takahashi, K. Toge, S. Ohno, and T. Manabe, "Loss Distribution Field Measurement of PON Branches with End-reflection Assisted Brillouin Analysis," Proc. of the IEICE General Conference 2016, B-13-15, Fukuoka, Japan, Mar. 2016.

Young Researcher's Award
Winner: Kohki Shibahara, NTT Network Innovation Laboratories
Date: March 24, 2017
Organization: IEICE

For "Spectrally-efficient Super-Nyquist Transmission by Multi-stage Successive Interference Cancellation."
Published as: K. Shibahara, A. Masuda, S. Kawai, and M. Fukutoku, "Spectrally-efficient Super-Nyquist Transmission by Multi-stage Successive Interference Cancellation," Proc. of the IEICE General Conference 2016, B-10-62, Fukuoka, Japan, Mar. 2016.

Young Researcher's Award
Winner: Hajime Katsuda, NTT Network Innovation Laboratories
Date: March 24, 2017
Organization: IEICE

For "A Study of Weighting Combining for CSI Estimation in SIC Process."
Published as: H. Katsuda, S. Ohmori, and K. Akabane, "A Study of Weighting Combining for CSI Estimation in SIC Process," Proc. of the IEICE General Conference 2016, B-5-157, Fukuoka, Japan, Mar. 2016.

Young Researcher's Award
Winner: Hiroki Kawahara, NTT Network Innovation Laboratories
Date: March 24, 2017
Organization: IEICE

For "Proposal of SDM Node to Enable Path Assignment in Any Wavelength/Core/Direction Port (1) - Proposal of SDM Node Architecture -."
Published as: H. Kawahara, A. Sawara, H. Yamamoto, S. Kawai, M. Fukutoku, Y. Miyamoto, K. Suzuki, and K. Yamaguchi, "Proposal of SDM Node to Enable Path Assignment in Any Wavelength/Core/Direction Port (1) - Proposal of SDM Node Architecture -," Proc. of the IEICE Society Conference 2016, B-10-55, Sapporo, Hokkaido, Japan, Sept. 2016.

Young Researcher's Award
Winner: Keita Yamaguchi, NTT Device Technology Laboratories
Date: March 24, 2017
Organization: IEICE

For "MxN Optical Switch by Holographic Phase Modulation."
Published as: K. Yamaguchi, M. Nakajima, Y. Ikuma, K. Suzuki, J. Yamaguchi, and T. Hashimoto, "MxN Optical Switch by Holographic Phase Modulation," Proc. of the IEICE General Conference 2016, C-3-54, Fukuoka, Japan, Mar. 2016.

Young Researcher's Award
Winner: Yusuke Muranaka, NTT Device Technology Laboratories
Date: March 24, 2017
Organization: IEICE

For "100-Gbps Optical Packet Switching with Ultralow-power Label Processor and Optical Switch."
Published as: Y. Muranaka, T. Segawa, S. Ibrahim, T. Nakahara, H. Ishikawa, and R. Takahashi, "100-Gbps Optical Packet Switching with Ultralow-power Label Processor and Optical Switch," Proc. of the IEICE Society Conference 2016, C-4-7, Sapporo, Hokkaido, Japan, Sept. 2016.

Young Researcher's Award
Winner: Takahiko Shindo, NTT Device Technology Laboratories
Date: March 24, 2017
Organization: IEICE

For "High Modulated Output Power of 9.0 dBm with L-band SOA Assisted Extended Reach EADFB Laser (AXEL)."
Published as: T. Shindo, W. Kobayashi, N. Fujiwara, Y. Ohiso, K. Hasebe, H. Ishii, and M. Itoh, "High Modulated Output Power of 9.0 dBm with L-band SOA Assisted Extended Reach EADFB Laser (AXEL)," Proc. of the IEICE Society Conference 2016, C-4-26, Sapporo, Hokkaido, Japan, Sept. 2016.

Best Presentation Award
Winner: Yoji Yamato, NTT Software Innovation Center
Date: March 31, 2017
Organization: The 5th IIAE International Conference on Industrial Application Engineering 2017 (ICIAE2017)

For "Proposal of Vital Data Analysis Platform Using Wearable Sensor."
Published as: A. Watanabe, Y. Matsuo, K. Watanabe, K. Ishibashi, and R. Kawahara, "Proposal of Vital Data Analysis Platform Using Wearable Sensor," Proc. of ICIAE2017, pp. 138–143, Kitakyushu, Fukuoka, Japan, Mar. 2017.

Papers Published in Technical Journals and Conference Proceedings

Entanglement Assisted Classical Communication Simulates "Classical Communication" without Causal Order

S. Akibue, M. Owari, G. Kato, and M. Murao

arXiv:1602.08835 [quant-ph], February 2016.

Phenomena induced by the existence of entanglement, such as nonlocal correlations, exhibit characteristic properties of quantum mechanics distinguished from classical theories. When entanglement is accompanied by classical communication, it enhances the power of quantum operations jointly performed by two spatially separated parties. Such a power has been analyzed based on the gap between the performances of joint quantum operations implementable by local operations at each party connected by classical communication with and without the assistance of entanglement. In this work, we present a new formulation for joint quantum operations connected by classical communication beyond special relativistic causal order but without entanglement and still within quantum mechanics. Using the formulation, we show that entanglement assisting classical communication necessary for implementing a class of joint quantum operations called separable maps can be interpreted to simulate "classical communication" that does not respect causal order. Our results reveal a new counter-intuitive aspect of entanglement related to spacetime.

Semi-automated Verification of Security Proofs of Quantum Cryptographic Protocols

T. Kubota, Y. Kakutani, G. Kato, Y. Kawano, and H. Sakurada

Journal of Symbolic Computation, Vol. 73, pp. 192–220, April 2016.

This paper presents a formal framework for semi-automated verification of security proofs of quantum cryptographic protocols. We simplify the syntax and operational semantics of quantum process calculus qCCS so that verification of weak bisimilarity of configurations becomes easier. In addition, we generalize qCCS to handle security parameters and quantum states symbolically. We then prove the soundness of the proposed framework. A software tool, named the verifier, is implemented and applied to the verification of Shor and Preskill's unconditional security proof of BB84. As a result, we succeed in verifying the main part in Shor and Preskill's unconditional security proof of BB84 against an unlimited adversary's attack semi-automatically; i.e., it is automatic except for giving user-defined equations.

Reducing Dense Virtual Network for Fast Embedding

T. Mano, T. Inoue, K. Mizutani, and O. Akashi

Proc. of INFOCOM 2016 (the 35th Annual IEEE International Conference on Computer Communications), April 2016.

Virtual network embedding has been intensively studied for a decade. The time complexity of most conventional methods has been reduced to the cube of the number of links. Since customers are likely to request a dense virtual network that connects every node pair directly ($|E| = O(|V|^2)$) based on a traffic matrix, the time complexity is actually $O(|E|^3 = |V|^6)$. If we were allowed to reduce this dense network into a sparse one before embedding, the time complexity could be decreased to $O(|V|^3)$; the time gap can be a million times for $|V| = 100$. The network reduction, however, combines several virtual links into a broader link, which makes the embedding cost (solution quality) much worse. This paper analytically and empirically investigates the trade-off between the embedding time and cost for the virtual network reduction. We define two simple reduction algorithms and analyze them with several interesting theorems. The analysis indicates that the embedding cost increases only linearly with exponential decay of embedding time. Thorough numerical evaluation justifies the desirability of the trade-off.

A Mobility-based Mode Selection Technique for Fair Spatial Dissemination of Data in Multi-channel Device-to-device Communication

H. Kuribayashi, K. Suto, H. Nishiyama, N. Kato, K. Mizutani, T. Inoue, and O. Akashi

Proc. of the 2016 IEEE International Conference on Communications, Kuala Lumpur, Malaysia, May 2016.

Wireless communication devices have spread widely in our society. However, they usually depend heavily on communication infrastructure, leaving them vulnerable to disasters or congestion of base stations. In these situations, a method to send out data without the support of infrastructure is required. Data transmission by device-to-device (D2D) communication is a reliable method that does not rely on infrastructure. In this paper, we aim to improve the data dissemination using D2D transmission by applying the concept of assigning "modes" to devices according to their own mobility. In our study, we assume a multi-channel environment, where devices will be allocated different amounts of frequency channels according to their modes. We propose a mode selection function that uses velocity information of the devices to assign modes. By using this function, it is possible to allocate more frequency channels to devices of high mobility, so that they can transmit their data to more devices as they move through a wide area. By mathematical analysis, we evaluated the fairness of disseminated data density among devices of various velocities, and the obtained results indicate the effectiveness of the proposed method for improving the efficiency of data dissemination.

Acceleration of Network Reachability Tests against a Huge Number of Hypercube Queries

R. Chen, T. Inoue, T. Mano, K. Mizutani, H. Nagata, and O. Akashi

Proc. of the 36th IEEE International Conference on Distributed Computing Systems, pp. 743–744, Nara, Japan, June 2016.

This paper proposes a novel windowing algorithm for network verification. Unlike existing windowing algorithms, our algorithm runs on a compressed data structure because the search space has to be represented in a compressed form due to the space complexity.

Security of Six-state Quantum Key Distribution Protocol with Threshold Detectors

G. Kato and K. Tamaki

Scientific Reports, Vol. 6, 30044, July 2016.

The security of quantum key distribution (QKD) is established by a security proof, and the security proof puts some assumptions on the devices consisting of a QKD system. Among such assumptions, security proofs of the six-state protocol assume the use of a photon number resolving (PNR) detector, and as a result, the bit error rate threshold for secure key generation for the six-state protocol is higher than that for the BB84 protocol. Unfortunately, however, this type of detector is demanding in terms of the technological level compared to the standard threshold detector, and removing the necessity of such a detector enhances the feasibility of the implementation of the six-state protocol. Here, we develop the security proof for the six-state protocol and show that we can use the threshold detector for the six-state protocol. Importantly, the bit error rate threshold for the key generation for the six-state protocol (12.611%) remains almost the same as the one (12.619%) that is derived from the existing security proofs assuming the use of PNR detectors. This clearly demonstrates the feasibility of the six-state protocol with practical devices.

Efficient Virtual Network Optimization across Multiple Domains without Revealing Private Information

T. Mano, T. Inoue, D. Ikarashi, K. Hamada, K. Mizutani, and O. Akashi

IEEE Transactions on Network and Service Management, Vol. 13, No. 3, pp. 477–488, September 2016.

Building optimal virtual networks across multiple domains is an essential technology for offering flexible network services. However, existing research is founded on an unrealistic assumption that providers will share their private information including resource costs. Providers, as well known, never actually do that so as to remain competitive. Secure multi-party computation, a computational technique based on cryptography, can be used to secure optimization, but it is too time consuming. This paper presents a novel method that can optimize virtual networks built over multiple domains efficiently without revealing any private information. Our method employs secure multi-party computation only for masking sensitive values; it can optimize virtual networks under limited information without applying any time-consuming techniques. It is solidly based on the theory of optimality and is assured of finding reasonably optimal solutions.

Experiments show that our method is fast and optimal in practice, even though it conceals private information; it finds near optimal solutions in just a few minutes for large virtual networks with tens of nodes. This is the first work that can be implemented in practice for building optimal virtual networks across multiple domains.

Towards Low-delay Edge Cloud Computing through a Combined Communication and Computation Approach

T. G. Rodrigues, K. Suto, H. Nishiyama, N. Kato, K. Mizutani, T. Inoue, and O. Akashi

Proc. of the 2016 IEEE 84th Vehicular Technology Conference, Montreal, Canada, September 2016.

There are many applications which cannot be executed by mobile devices due to their limitations in memory, processing, and battery, among others. One solution to this would be offloading heavy tasks to cloud servers at the edge of the network, in a service model called edge cloud computing. The main Quality of Service requirement of this model is a low service delay, which can be achieved by lowering transmission delay and processing delay. Works in literature focus on either one of those two types of delay. This paper, however, argues that an approach which combines transmission and processing technologies to lower service delay would be more efficient. This idea is defended by an analysis of the service model and existing stochastic modeling of the edge cloud computing system. We conclude that a dual-focus approach would be the only way of truly minimizing the service delay, therefore being the desired method to improve Quality of Service. We conclude by laying the foundation for a future model that follows such a concept.

Statistical Estimation of the Names of HTTPS Servers with Domain Name Graphs

T. Mori, T. Inoue, A. Shimoda, K. Sato, S. Harada, K. Ishibashi, and S. Goto

Computer Communications, Vol. 94, pp. 104–113, November 2016.

This work develops a novel framework called Service-Flow map (SFMap), which estimates names of HTTPS servers by analyzing precedent domain name graph (DNS) queries/responses in a statistical way. The SFMap framework introduces the domain name graph, which can characterize the highly dynamic and diverse nature of DNS mechanisms. Such complexity arises from the recent deployment and implementation of DNS ecosystems, i.e., canonical name tricks used by CDNs (content delivery networks), the dynamic and diverse nature of DNS TTL (Time To Live) settings, and incomplete and unpredictable measurements due to the existence of various DNS caching instances. First, we demonstrate that SFMap establishes good estimation accuracies and outperforms a state-of-the-art approach. We also aim to identify the optimized setting of the SFMap framework. Next, based on the preliminary analysis, we introduce techniques to make the SFMap framework scalable to large-scale traffic data. We validate the effectiveness of the approach using large-scale Internet traffic.

An Efficient Framework for Data-plane Verification with Geometric Windowing Queries

T. Inoue, R. Chen, T. Mano, K. Mizutani, H. Nagata, and O. Akashi

Proc. of 2016 IEEE 24th International Conference on Network Protocols, Singapore, Singapore, November 2016.

This paper presents a novel framework of data-plane verification, which flexibly checks the inconsistency with great efficiency. For the purpose of generality, our framework formalizes a verification process with three abstract steps; each step is related to 1) packet behaviors defined by a configuration, 2) operator intentions described in a policy, and 3) the inspection of their relation. These steps work efficiently with each other on the simple quotient set of packet headers. This paper also reveals how the second step can be regarded as the windowing query problem in computational geometry. Two novel windowing algorithms are proposed with solid theoretical analyses. Experiments on real network datasets show that our framework with the windowing algorithms is surprisingly fast even when verifying the policy compliance; e.g., in a medium-scale network with thousands of switches, our framework reduces the verification time of all-pairs reachability from ten hours to ten minutes.

Overlapping of /o/ and /u/ in Modern Seoul Korean: Focusing on Speech Rate in Read Speech

T. Igeta, S. Hiroya, and T. Arai

Journal of the Korean Society of Speech Sciences, Vol. 9, No. 1, pp. 1–7, March 2017.

Previous studies have reported on the overlapping of F1 and F2 distribution for the vowels /o/ and /u/ produced by young Korean

speakers of the Seoul dialect. However, few studies have examined whether speech rate influences the overlapping of /o/ and /u/. In the current study, we examined whether speech rates affect overlapping of /o/ and /u/ in read speech by male and female speakers. For female speakers, discriminant analysis showed that the discriminant rate became lower as the speech rate increased from slow to fast. Thus, this indicates that speech rate is one of the factors affecting the overlapping of /o/ and /u/. For male speakers, on the other hand, the discriminant rate was not correlated with speech rate, but the overlapping was larger than that of female speakers in read speech. Moreover, read speech by male speakers was less clear than by female speakers. This indicates that the overlapping may be related to unclear speech by sociolinguistic reasons for male speakers.

Online MVDR Beamformer Based on Complex Gaussian Mixture Model with Spatial Prior for Noise Robust ASR

T. Higuchi, N. Ito, S. Araki, T. Yoshioka, M. Delcroix, and T. Nakatani

IEEE/ACM Transactions on Audio, Speech, and Language Processing, Vol. 25, No. 4, pp. 780–793, April 2017.

This paper considers acoustic beamforming for noise robust automatic speech recognition. A beamformer attenuates background noise by enhancing sound components coming from a direction specified by a steering vector. Hence, accurate steering vector estimation is paramount for successful noise reduction. Recently, time–frequency masking has been proposed to estimate the steering vectors that are used for a beamformer. In particular, we have developed a new form of this approach, which uses a speech spectral model based on a complex Gaussian mixture model (CGMM) to estimate the time–frequency masks needed for steering vector estimation, and extended the CGMM-based beamformer to an online speech enhancement scenario. Our previous experiments showed that the proposed CGMM-based approach outperforms a recently proposed mask estimator based on a Watson mixture model and the baseline speech enhancement system of the CHiME-3 challenge. This paper provides additional experimental results for our online processing, which achieves performance comparable to that of batch processing with a suitable block-batch size. This online version reduces the CHiME-3 word error rate (WER) on the evaluation set from 8.37% to 8.06%. Moreover, in this paper, we introduce a probabilistic prior distribution for a spatial correlation matrix (a CGMM parameter), which enables more stable steering vector estimation in the presence of interfering speakers. In practice, the performance of the proposed online beamformer degrades with observations that contain only noise or/and interference because of the failure of the CGMM parameter estimation. The introduced spatial prior enables the target speaker's parameter to avoid overfitting to noise or/and interference. Experimental results show that the spatial prior reduces the WER from 38.4% to 29.2% in a conversation recognition task compared with the CGMM-based approach without the prior, and outperforms a conventional online speech enhancement approach.

Human Perception of Sub-resolution Fineness of Dense Textures Based on Image Intensity Statistcs

M. Sawayama, S. Nishida, and M. Shinya

Journal of Vision, Vol. 17, No. 4, April 2017.

We are surrounded by many textures with fine dense structures, such as human hair and fabrics, whose individual elements are often finer than the spatial resolution limit of the visual system or that of a digitized image. Here we show that human observers have an ability to visually estimate subresolution fineness of those textures. We carried out a psychophysical experiment to show that observers could correctly discriminate differences in the fineness of hair-like dense line textures even when the thinnest line element was much finer than the resolution limit of the eye or that of the display. The physical image analysis of the textures, along with a theoretical analysis based on the central limit theorem, indicates that as the fineness of texture increases and the number of texture elements per resolvable unit increases, the intensity contrast of the texture decreases and the intensity histogram approaches a Gaussian shape. Subsequent psychophysical experiments showed that these image features indeed play critical roles in fineness perception; i.e., lowering the contrast made artificial and natural textures look finer, and this effect was most evident for textures with unimodal Gaussian-like intensity distributions. These findings indicate that the human visual system is able to estimate subresolution texture fineness on the basis of diagnostic image features correlated with subresolution fineness, such as the intensity contrast and the shape of the intensity histogram.
