Development and Future Outlook of High-capacity Optical Transmission Systems

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1. Introduction

This paper describes the development to date of high-capacity optical transmission systems that make full use of the low-loss and broad-bandwidth characteristics of optical fiber and discusses the outlook for new technologies driving a paradigm shift in the future. We take up, in particular, the terrestrial optical network and submarine cable system as typical high-capacity optical transmission systems[1], describe the historical development of each based on differences in system requirements such as installation envirnment and equipment configuration, and discuss future technical trends.

2. Progress and Future Outlook of Terrestrial Optical Transmission System

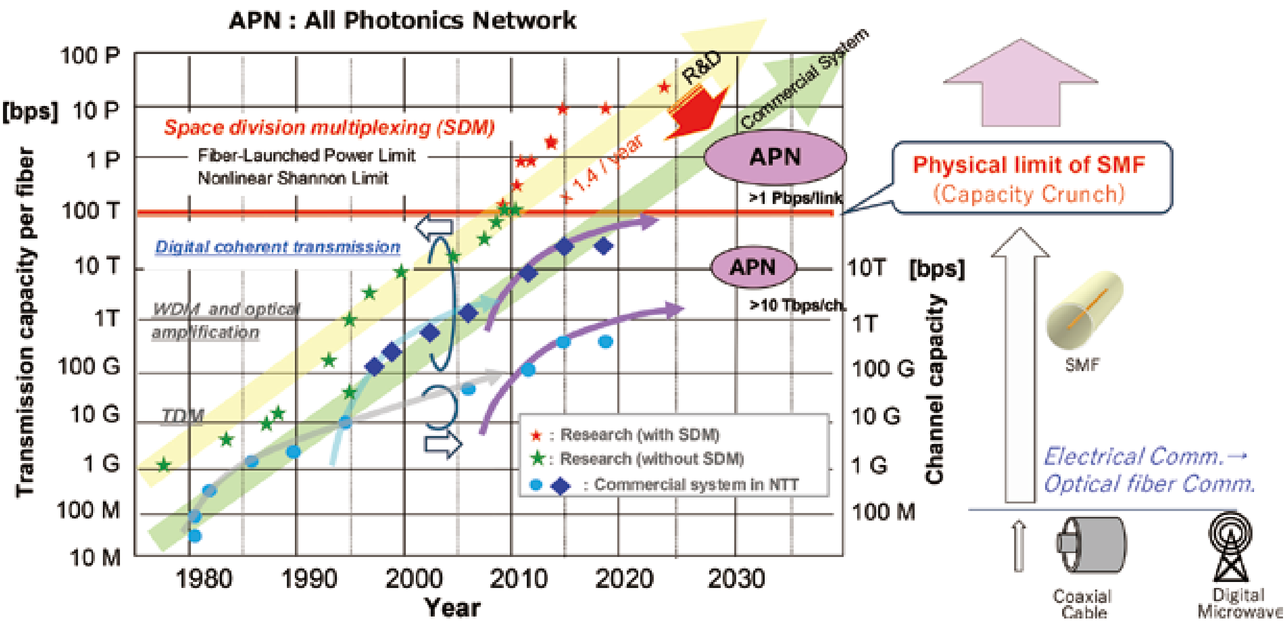
This section describes recent progress in the terrestrial optical transmission system, current technologies, and outlook for the future.

2.1 Expansion of Link Capacity in the Terrestrial Trunk Transmission System

Progress in the development of Japan's terrestrial trunk optical network are shown in Figure 1. Japan's first terrestrial trunk optical network was a 32 Mbit/s regeneration repeater system using multi-mode optical fiber (MMF) deployed for short hauls in 1981. Then, taking a global lead in the early deployment of fundamental technology using single-mode optical fiber (SMF), an optical fiber cable transmission network throughout Japan using SMF was completed in 1985 at Nippon Telegraph and Telephone Public Corporation. In the terrestrial optical network, the installation plan has been to increase capacity by using existing optical fiber cables and replacing repeater equipment while maintaining backward compatibility with repeater spacing in the existing system. Up to now, by overlaying many innovative and paradigm-shifting repeater transmission technologies, optical inline amplified transmission systems based on SMF has progressed by leaps and bounds increasing capacity by approximately six orders of magnitude over a 40-year period.

Up to the mid-90s, higher capacities were achieved by increasing the speed of a single-wavelength system through time-division multiplexing (TDM) using an intensity modulation direct detection system. In 1987, an F-1.6G system applying a 1.5-μm-band single-mode laser (single-wavelength, 1.6-Gbit/s

■ **Figure 1: Change in link capacity of terrestrial optical network and paradigm-shifting elemental technologies**



regenerative repeater system) was deployed, and in 1996, an FA-10G system using an erbium-doped fiber amplifier (EDFA) repeater (single-wavelength, 10-Gbit/s inline-amplified repeater system) was deployed. Then, in the 2000s, by applying wavelength-division multiplexing (WDM) and a broadband inline-amplified repeater system, even higher capacities were achieved through a 10-Gbit/s-channel-based WDM system with a 1-Tbit/s-class link capacity. In the existing terrestrial optical network, typical regenerative repeater spacing between main network nodes is 500–1,000 km with an optical inline-amplified repeater spacing of approximately 80–100 km. These optical inline-amplified repeaters amplify and transmit WDM optical signals while compensating for losses occurring within the optical fiber and optical devices. In the 2010s, advances were made in spectral efficiency and long-haul transmission in the WDM system through digital coherent technology making full use of multi-level digital modulation/demodulation signal processing technology. In 2013, a WDM optical network was deployed with a link capacity of 8 Tbit/s using 100-Gbit/s channels (polarization multiplexing, quadrature phase shift keying (QPSK) modulation), and from 2017 on, an inter-data-center network and long-haul WDM optical network were deployed with a 20-Tbit/s-class transmission capacity using 400-Gbit/s channels (multi-carrier 16 quadrature amplitude modulation (16-QAM)).

2.2 Higher Capacities through Multi-band WDM Transmission Technology

In terrestrial long-haul optical networks, the average number of fibers in one cable is several hundred, and for the time being, studies are underway to increase capacity by making effective use of existing SMF resources. Up to now, it's been mainly optical amplifier repeater systems using approximately 4.5 THz as a single EDFA optical amplifier band such as the C-band or L-band that have already been installed in commercial systems. However, given the significant advances made in spectral efficiency in recent years thanks to the practical application of digital coherent technology, it is becoming difficult to make significant improvements in spectral efficiency going forward. Furthermore, as a result of recent research and development, it has been found that there is a physical limit to SMF link capacity of around 100 Tbit/s (capacity crunch) in long-haul transmission as shown in Figure 1 due to factors such as signal distortion caused by an optical nonlinear effect and laser safety issues in terms of allowable fiber-launched power limits. Consequently, to achieve higher capacities in the 100-Tbit/s class using SMF from here on, studies are being conducted on the practical application of multi-band long-haul transmission technology using the C+L band (approximately 9 THz) and beyond to speed up WDM channel capacities and keep a certain number of wavelength channels per WDM system (about 100 ch). Two 1,000-km-class, 3-band optical amplifier repeater transmission experiments (80-km repeater span) [2, 3] have recently been reported as examples of transmission experiments with an over-100-Tbit/s-class link capacity that considers SMF allowable power limits and optical nonlinear effects such as spectral gain tilt caused by the inter-band stimulated Raman scattering effect.

2.3 Higher Capacities through Spatial Multiplexing Transmission Technology

As a technology that can fundamentally avoid the capacity crunch in long-haul high-capacity optical transmission systems, the importance of space-division multiplexing (SDM) was promoted by the Extremely Advanced Optical Transmission Technologies (EXAT) Study Group established in 2008[4]. Since then, Japan has taken the lead in this field and various types of research and development represented in this special issue have been progressing on a global basis. Of particular interest here were transmission systems using multi-core fiber (MCF), and in the 2010s, the limits of long-haul high-capacity transmission systems were vigorously pursued and studied to both increase the number of cores per a single strand of optical fiber and suppress inter-core crosstalk. In particular, weakly coupled MCF based on single-mode cores that can suppress inter-core crosstalk by controlling the refractive index profile and core arrangement has the advantage of using conventional transmission equipment using digital coherent technology for SMF. To realize 12-core weakly coupled MCF with the same refractive index core profiles (homogeneous cores) while maintaining mechanical reliability of the fiber, the cladding diameter of the developed 12-core fiber was set to 250 μm or less, which is about two times larger than that of existing SMF. Using this 12-core fiber in conjunction with multi-band WDM transmission technology using the 11-THz band comprising the C-band and extended L-band as an optical amplifier band, the first 1 Pbit/s non-repeatered transmission experiment (50 km) was reported[5]. Then, in 2017, as part of a Japan-EU coordinated funded project called Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI), the world's first 1-Pbit/s inline-amplified unidirectional transmission experiment was reported extending over 200 km using low-inter-core-crosstalk 32-core MCF with a cladding diameter less than 250 μm[6]. This was achieved by suppressing inter-core crosstalk by a 32-core heterogeneous MCF structure having two types of refractive indices. To realize a low-power and compact multi-core optical amplifier, only the C-band was used as an optical signal bandwidth. The feasibility of 0.75 Pbit/s optical amplifier repeater transmission (1,200 km) in combination with a multi-level coded modulation system was also shown. In relation to ultra-high capacities, the further pursuit of limits made progress by combining mode-division multiplexing and multi-band transmission technology under conditions that exclude the cladding diameter limit of 250 μm. For a spatial multiplicity (number of modes × number of cores) of 100 or more, the world's first transmission experiment (11.3 km) exceeding 10 Pbit/s (10^{16} bit/s) was reported in 2017[7] and a transmission experiment

(13 km) achieving the world's highest capacity of 22.9 Pbit/s was reported in 2023[8].

Recently, with a view toward implementing SDM technology in the terrestrial optical network, studies have been progressing on 4-core weakly coupled MCF with the same 125-µm standard cladding diameter as that of SMF from the viewpoints of MCF mass production, international standardization, and suppressing inter-core crosstalk. In 2017, as part of NICT commissioned research (#170, #188), a multi-vendor interoperability experiment was conducted applying prototype 4-core fibers manufactured by multiple fiber vendors with common specifications along with multi-core-fiber amplifiers and multi-core connectors, and a 118-Tbit/s optical-amplifier-repeater (3 × 100 km) transmission experiment was reported[9]. Then, using the knowledge gained from those experiments, studies progressed on the design and mass production of 4-core fiber cable with standard cladding diameter toward the terrestrial optical network also as part of NICT commissioned research (#203)[10]. At present, standardization is proceeding at ITU-T including the issuing of SDM technical reports and international standardization is intensifying at IEC in relation to methods of evaluating and measuring multi-core connectors.

Furthermore,, on looking ahead to the implementation of future Pbit/s-class optical transmission systems, there will be a strong need for applying SDM for compact, integrated, and low-power optical network node equipment such as optical transmitters/receivers, optical amplifier repeaters, and optical switching nodes in addition to enhancing spatial efficiency in spatial multiplexing fiber as a transmission medium. For example, looking back at the history of WDM system introduction, about 10 years were needed from the world's first 1-Tbit/s-class WDM transmission demonstration experiment in 1996 to the full-fledged introduction and practical use of an economical 1-Tbit/s-class WDM system based on 10-Gbit/s channels in Japan in 2003 (Figure 1). The reason for this is that progress was made in the development of compact and low-power 10-Gbit/s-class transmitter/receiver equipment and optical switching nodes during this 10-year period due to the evolution of silicon integrated circuit technology and 10-Gbit/s-class optical transmitter/receiver circuit packaging technology and the introduction of multi-degree Reconfigurable Optical Add Drop Multiplexer (ROADM) nodes. Likewise, in the implementation of practical Pbit/s-class SDM systems, the study of compact, integrated, and low-power SDM optical network nodes will be extremely important in achieving economy in operations while extracting suitable performance from an SDM transmission medium such as MCF. In NICT commissioned research (#188, #170), studies focused on optical switching node integration technology based on SDM technology and on compact and low-power optical amplifier repeaters such as cladding-pumped multi-core optical amplifiers toward the realization of SDM photonic nodes with over-Pbit/s-class node throughput. A 3-node experimental network was configured using standard cladding diameter 4-core fiber and integrated wavelength selective optical switching nodes and an experiment demonstrating node throughput over Pbit/s was reported[11].

3. Progress and Future Outlook of Optical Submarine Cables

This section describes the progress made in optical submarine cables, current technologies, and their future outlook based on SDM technology from the viewpoints of space and power limitations unique to this type of cable.

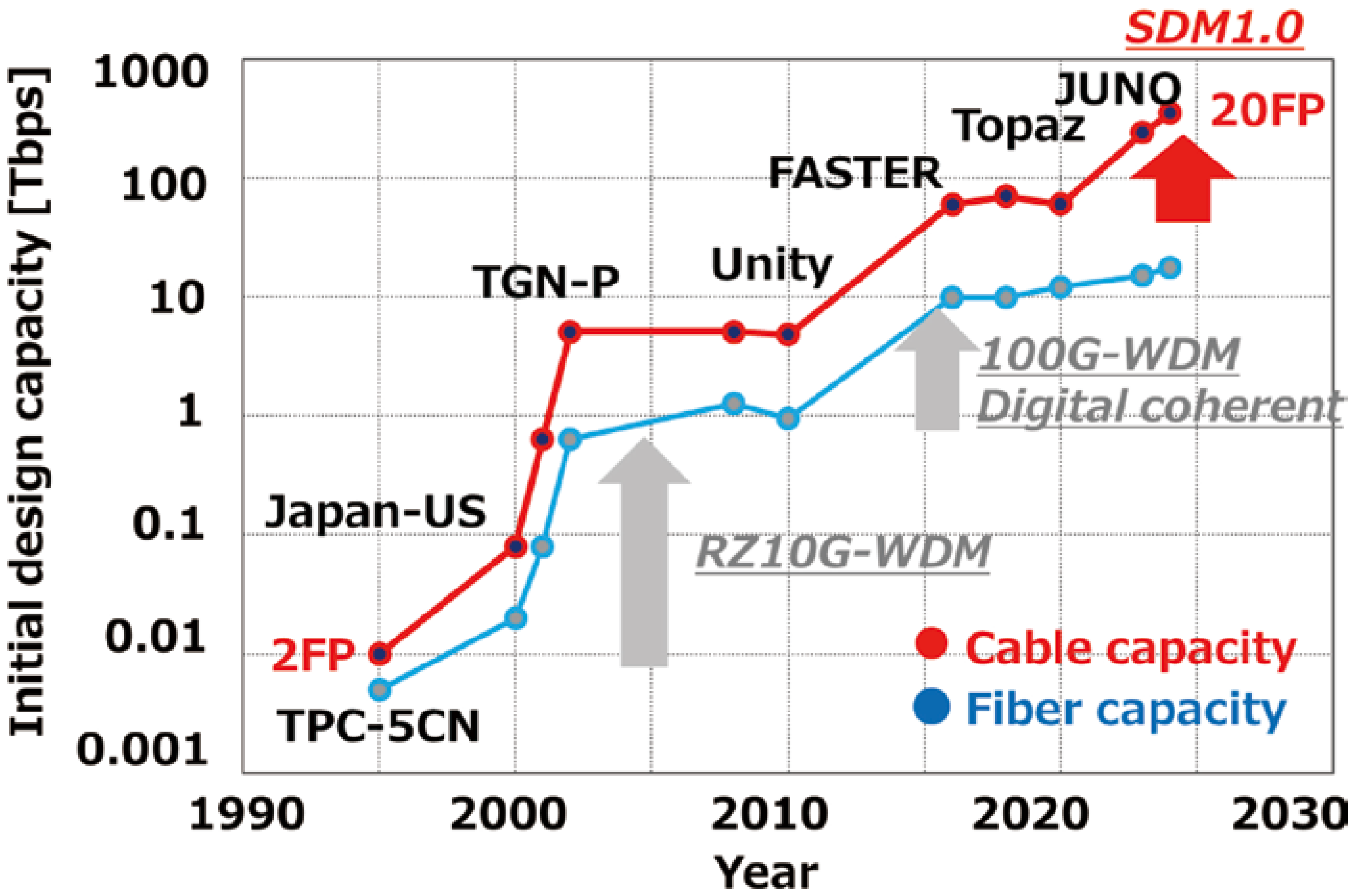
3.1 Change in Capacity per Fiber

Optical submarine cable systems have progressed in the order of parallelization and multi-level modulation through faster data rates of optical signals and bandwidth expansion the same as terrestrial systems. Change over time in fiber capacity and cable capacity of main transpacific optical submarine cables is shown in Figure 2. The signal data rate of 280 Mbit/s for single-wavelength optical submarine cable commercialized in 1989 was increased by approximately 8 times to 5 Gbit/s in the TPC-5 optical amplifier repeater system in 1995. Continuing on, a data rate of 10 Gbit/s and 100 WDM were achieved by expanding the bandwidth of optical amplifiers, applying WDM technology, and applying dispersion-managed soliton transmission technology using chirped Gaussian RZ signals that constitute a steady solution of the dispersion-compensated nonlinear optical transmission line[12]. In this way, total capacity jumped all at once by 200 times to 1 Tbit/s—this system was commercialized globally from the end of the 1990s to the middle of the 2010s[13]. Next, in the digital coherent system, spectral efficiency improved through polarization multiplexing and QAM multi-level modulation, and at present, fiber transmission capacity has expanded by approximately 20 times to 20 Tbit/s.

3.2 Expansion of Cable Capacity by SDM

In commercial optical submarine cables, the capacity that can be transmitted by a single optical fiber is almost saturated, so parallelization by SDM is considered to be an effective approach to expanding capacity by several tens of times as required for next-generation systems. Unlike schemes such as increasing the data rate or modulation level that require more optical power to increase S/N, SDM can expand capacity on the basis of multiplicity. Examining change in cable capacity in Figure 2, it can be seen that the number of fibers and total capacity are increasing from the 2020s on despite the near saturation in fiber capacity. The number of fibers has increased by 10 times from 1995 to the present, and here, SDM technology based on single-core optical fiber is called SDM 1.0. However, due to space limitations in submarine cable with diameters under 2 cm, the number of fibers that can be accommodated in a cable is limited to about 50 (or 25FP = 25

■ **Figure 2: Change in fiber capacity and cable capacity of main transpacific optical submarine cables**



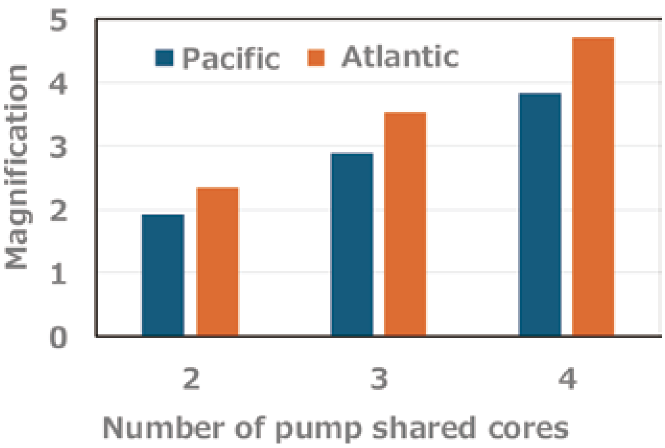
fiber pairs), so research and development is proceeding around the world on SDM 2.0 based on MCF having high spatial efficiency.

The possibility of transoceanic transmission by SDM was first reported in 2012 by a transmission experiment using 7-core fiber and 7-core EDFA[14], and in the following year, the possibility of optical submarine cable exceeding a capacity-distance product of 1-exabit/s × km with a fiber capacity of more than 140 Tbit/s was demonstrated[15]. At present, the research and development of 4-core fiber with a standard cladding diameter of 125 µm[13] and associated standardization activities are actively proceeding, and in the OCEANS project commissioned by the Ministry of Internal Affairs and Communications (MIC) toward early implementation of SDM 2.0 with optical submarine cable, prototype 1.7-cm-diameter optical submarine cable (16FP including 4-core fiber) was fabricated and a 62.9-Tbit/s, 9,150-km transpacific transmission test was conducted[16]. Furthermore, in the TPU transpacific submarine cable system scheduled for commercialization in 2025, the plan is to introduce 2-core fiber, which is part of the results of the OCEANS project, in the Taiwan—submarine branch—Philippines interval of approximately 840 km as the first MCF commercial system.

3.3 Cable Capacity Limitations Accompanying Power Limitations

In addition to space limitations, a limiting condition peculiar to optical submarine cable is power. Since the electrical resistance of the conductor within a submarine cable is approximately 0.8 Ω/km, 8 kV would be lost as heat over 10,000 km assuming a power supply current of 1 A. The electric power of power feeding equipment at a landing station is presently 16–18 kV, and since power excluding the power consumed by cable resistance must be distributed to more than 100 repeaters, it is no exaggeration to say that power limitations determine total system capacity. In SDM 1.0, pump sharing that makes EDFA pump laser diodes (LDs) redundant and excites two EDFAs with one pump LD was introduced so that the number of fibers could be increased while suppressing consumed power. However, further expansion of capacity will require an increase in the number of pump-shared cores. Figure 3 shows the magnification of maximum cable capacity with respect to a reference value versus number of pump-shared cores for transatlantic (7,000 km) and transpacific (9,000 km) systems both using 4-core fibers. The reference capacity used here is 500 Tbit/s (24FP) for the transatlantic optical submarine cable and 350 Tbit/s (20FP) for the transpacific optical submarine cable. Other system parameters include a power supply voltage of 18 kV, power supply current of 1 A, cable resistance of 0.8 Ω/km, and a pump LD voltage of 2.5 V. Span length is increased to 80 km and the number of repeaters is reduced through the use of ultra-low-loss optical fiber (loss α = 0.15 dB/km). With the present number of pump-shared cores, the transatlantic system and transpacific system can achieve a capacity 2.4 times (1.18 Pbit/s) and 1.9 times (670 Tbit/s) the reference capacity, respectively, based on 2-core fiber. It should be noted here that increasing capacity in a transoceanic optical submarine cable is difficult even in the case of 4-core fiber since power limitations prevent the number of effective cores from being increased. As shown in Figure 3, increasing cable capacity here requires that the number of pump-shared cores be increased to 3–4 for 4-core fiber, in which case capacity magnification would be estimated to be 4.7 times (2.4 Pbit/s) for the transatlantic system and 3.8 times (1.3 Pbit/s) for the transpacific system. If the plan is to increase the number of cores even further toward higher capacities through the use of randomly coupled multi-core fiber that is expected to have many cores in the future, fundamental changes will have to be made such as an increase in the power supply and the use of high-voltage-resistant cables and repeaters, so there is a tradeoff between economy and high capacity.

Figure 3: Capacity magnification versus number of pump shared cores in 4-core fiber



4. Conclusion

In this paper, we described the progress made toward higher capacities in the terrestrial and submarine optical transmission systems and the future outlook for ultra-high-capacity systems through spatial multiplexing. Up to now, various types of research and development based on spatial-multiplexing optical transmission technology led by Japan have been actively promoted toward over-petabit-class link capacities beyond the physical limits of existing SMF. With a view to the implementation of high-capacity optical transmission systems using spatial-multiplexing optical transmission technology, the international standardization of 4-core fiber with standard cladding diameter is progressing and the commercial introduction of 2-core fiber for optical submarine cable is scheduled for 2025. Development targets toward "Extremely Advanced Optical Communication Systems" as put forward by the EXAT Study Group established in 2008 have been significantly moved up, and going forward, we can expect ongoing implementation of high-capacity optical transmission infrastructures through more progress in related technologies.

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