State-of-the-Art and Future of Submarine Cable System Technology

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Abstract. The FASTER cable system has been developed as the first trans-pacific optical submarine cable system designed for digital-coherent transmission at the initial state. With this significant change for submarine cables, the design capacity is continuously being upgraded following the improvement of the state-of-the-art modulation format to maximize spectral efficiency even at the limited optical signal-to-noise ratio (OSNR). For the next generation, the novel technologies are expected to increase the capacity per cable under the conditions of limited feeding power and space in a cable. This report reviews some technologies from the current to the promising future submarine cable systems such as the introduction of space-division-multiplexing (SDM) technologies.

Keywords: Submarine cable, optical communication, digital coherent transmission.

1 INTRODUCTION

The demand for increasing the capacity of optical submarine cable systems for global communication is steadily growing. The traffic increase rate is maintained at around 40% per year for transpacific segments. To support the traffic growth, over 10 submarine cable systems have been built and operated following the technology evolutions. Nowadays, digital-coherent transmission technology is considered as the default for a transponder at the initial design stage of optical submarine cables. For example, in the FASTER cable system whose ready-for-service (RFS) launch was June 2016, the initial design capacity is 60 Tbit/s consisting of 6 fiber pairs (FP) x 100 ch x 100 Gbit/s utilizing wavelength-division-multiplexing (WDM) technology [1-3]. This trend never seems to change, so the higher capacity optical submarine cable system will be indispensable for future global communication. This paper reviews the evolution of telecommunication technology for submarine cable systems, explains the currently available state-of-the-art technologies, and finally describes the promising technologies that are expected to overcome some significant issues and be applicable for future optical submarine cable systems.

2 EVOLUTION OF SUBMARINE CABLES FOR COMMUNICATION

2.1 Transpacific Submarine Cable Systems

Table 1 shows the evolution of the once in-service transpacific submarine cable system for communication by RFS year, including those already retired. Typical cable length of transpacific systems is around 10,000 km. The "TPC-1" was the first telephone cable between Japan and the US, consisting of a coaxial cable, whose initial design capacity was just 128 phone lines. Assuming the bit rate of a phone line as 64 kbit/s, the initial design capacity has increased ~560 million times that of the original 50 years ago, leading to the introduction of FASTER.

Table 1. In-service transpacific submarine cable systems

System	RFS [Year]	Tech.	Ini. des. Rx	Ini. des. signals/FP [bit/s]	FP	Initial design capacity
TPC-1	1964	Coax.	-	-	-	128 lines*1
TPC-2	1976	Coax.	-	-	-	845 lines*2
TPC-3	1989	Regen.	DD	1 x 280M	2	560 Mbit/s
TPC-4	1992	Regen.	DD	1 x 560M	2	1.1 Gbit/s
TPC-5	1995	EDFA	DD	1 x 5G	2	10 Gbit/s
China-US	2000	EDFA	DD	8 x 2.5G	4	80 Gbit/s
PC-1	2001	EDFA	DD	16 x 10G	4	640 Gbit/s
Japan-US	2001	EDFA	DD	16 x 10G	4	640 Gbit/s
TGN-P	2002	EDFA	DD	64 x 10G	8	5.12 Tbit/s
TPE	2008	EDFA	DD	64 x 10G	4	2.56 Tbit/s
Unity	2010	EDFA	DD	96 x 10G	5	4.8 Tbit/s
FASTER	2016	EDFA	DC	100 x100G	6	60 Tbit/s
NCP	2018	EDFA	DC	N x 100G	7	80 Tbit/s

*1 Assuming the bitrate for a telephone line as 64 kbit/s, it will be 8.2 Mbit/s.
*2 Assuming the bitrate for a telephone line as 64 kbit/s, it will be 54 Mbit/s.
RFS: Ready for Service
Coax: Copper cable
Regen.: Regenerator as the repeater for the optical fiber cables
EDFA: Optical amplifier as the repeater for the optical fiber cables
Ini. des.: Initial design
Rx: Receiver
DD: Direct detection
DC: Digital coherent Displayed equations are centered and set on a separate line.

The optical fiber communication has been introduced with TPC-3 as the first transpacific optical submarine cable system. A regeneration repeater was used so the signal quality was independent of the total transmission distance; however, the capacity had never changed from the initial design stage. TPC-5 was the first transpacific cable to introduce an erbium-doped fiber amplifier (EDFA) for the re-amplifying scheme with the initial design capacity of 10 Gbit/s (5 Gbit/s x 2FP) in 1995. With its larger capacity, the mainstream of international video broadcasting was shifted from satellites to submarine cables after the Atlanta Olympic games in 1996. Thanks to the physical characteristics of EDFA, it is independent of the modulation format of optical signals. Even though it has the drawback of noise accumulation being generated in EDF, it is possible to increase the design capacity by changing the signal modulation format, known as upgrading. This means that the evolution of the transponder increases the value of the deployed cable. In other words, the limitation is determined by the usable bandwidth of a repeater. For example, already deployed cables seem obsolete when a new generation cable is constructed with a wider bandwidth. This is because the operation and maintenance cost for submarine cables is not so different between the old and the newly deployed version. Therefore, the narrower bandwidth cable has relatively higher running costs. Even if the design lifespan of submarine cables is typically 25 years, the actual "business" lifespan tends to be shortened with traffic migration to a higher capacity cable because of the previously described reason. For example, the China-US cable as shown in Table 1 was retired in Dec. 2016 even16 years after RFS [4].

2.2 Technology Trend of Optical Submarine Cable

The repeatered system with EDFA is widely adopted currently. Figure 1 shows the historical evolution of the initial design capacity per one FP for transpacific optical submarine cable systems.

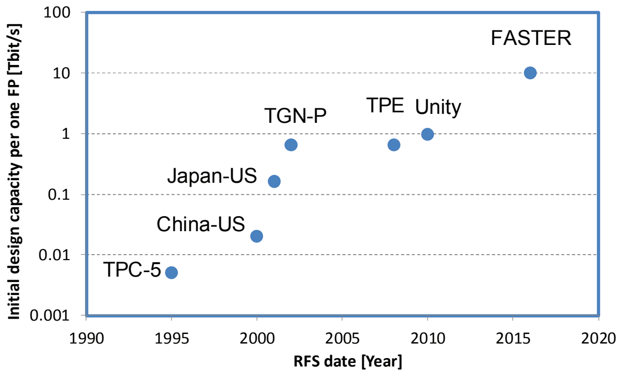

Fig. 1. Historical evolution of the initial design capacity per one FP for transpacific optical submarine cable systems.

The TCP-5 used a dispersion shifted fiber (DSF) cable designed for single channel transmission. After that, the non-zero DSF (NZ-DSF) cable was introduced for WDM transmission such as the Japan-US cable network, etc. Furthermore, the dispersion managed fiber (DMF) cable was introduced for dense WDM (DWDM) systems such as Unity. For these cable types, the direct-decision (DD) receiver was considered as the transmission method. On the other hand, the digital-coherent transmission technology was considered at the initial design stage for FASTER. This enables the cable to only consist of positive dispersion fibers (D+ fiber).

3 STATE-OF-THE-ART TECHNOLOGIES

This section explains the cutting-edge submarine cable technologies that are currently available. There are two types of application: that for new cable deployment, and that for the upgrading of already deployed cables by simply replacing the submarine line terminal equipment (SLTE).

3.1 +D fiber Transmission Line

The newly deployed cable can support digital-coherent transmission since the introduction of FASTER for transpacific cables. This change has led to the introduction of the dual-polarization (DP), phase and amplitude modulation to increase the spectral efficiency (SE). Compared to DSF, NZ-DSF and DMF cables, the +D fiber cable gives increments of accumulated dispersion monotonously, which contributes to the reduction of the signal quality degradation caused by the nonlinear effect such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM), etc. However, the quantity of accumulated dispersion becomes huge, e.g., it hits 200,000 ps/nm when the signal transmits over 10,000-km fiber with +20 ps/nm/km dispersion. For the digital coherent transmission, the dispersion is compensated by digital signal processing (DSP). Thanks to the development of the high-performance DSP, which had an ability to compensate such a huge dispersion, it has become possible to introduce +D fiber for transoceanic submarine cables. Moreover, the evolution of +D fiber is rapidly proceeded in terms of the larger effective area (A_{eff}) and lower attenuation. Compared to the standard single mode fiber (SSMF) whose A_{eff} is 80 μm^2, the ultra-low-loss 130 μm^2 fiber is used in FASTER [2]. Furthermore, the fiber with 0.152-dB/km attenuation has been commercialized recently [5]. The large A_{eff} fiber contributes to the reduction of the nonlinear effect, and low loss fiber is effective for increasing the signal-to-noise ratio (SNR) or extension of the repeater span, which gives a higher capacity or lower cost with fewer required numbers of repeaters. At R&D bases, as a loss of 0.1419 dB/km is reported with an A_{eff} of 147 μm^2, further improvement can be expected [6].

Additionally, this evolution leads to significant changes not only for the transmission capacity, but for the operation and maintenance works. In the case of cable repairment, it is required to insert additional cables whose length must be twice as long as the water depth. For example, if a cable fault happens at a water depth of 6,000 m, a 12-km cable at least must be inserted. This means that the accumulated dispersion is changed according to the length of the inserted cable. In the cable of NZ-DSF and/or DMF types, the transmission line is composed of at least 2 types of fiber, so the repair procedure depends on the type and the length of fiber at the faulty point with precise calculation of the accumulated dispersion. However, for the +D fiber cable, basically only one type of fiber is required to prepare the spare cable; additionally, the operator no longer has to pay heed to the change of the accumulated dispersion utilizing the DSP function in the transponder. This contributes to simplifying the operation and maintenance procedures.

3.2 Advanced Modulation Formats

As shown in Fig. 1, the initial design capacity has increased 10-fold from Unity to FASTER with the introduction of digital coherent transmission technology. Furthermore, it can achieve higher SE with the advanced modulation formats. This progress is applicable both to new cable systems and all of the already deployed cables such as DSF, NZ-DSF, DMF and +D fiber types. By upgrading the design capacity of the existing cable, the "business" lifespan of the cable can be extended. Especially, it is more effective to apply the format for +D fiber cables than the other fiber types. As +D fiber cables give smaller nonlinearity, they are suitable for the typical higher SE modulation format that is weak for nonlinear effects. In the case of FASTER, while the initially designed modulation format is dual-polarization (DP)-quadrature phase shift keying (QPSK) with SE of 2.5 bit/s/Hz between the Japan and US segment, the DP-8QAM (quadrature amplitude modulation) signals have been introduced in 37.5-GHz spacing with SE of 4.0 bit/s/Hz [2]. Additionally, at the MAREA for transatlantic cables with a length of 6,644 km, it has been reported that the SE of 6.21 bit/s/Hz is achievable with DP-16QAM, which indicates that it will contribute to the upgrading of the design capacity from the initial one of 160 Tbit/s/cable to 200 Tbit/s/cable [7]. Furthermore, recently the commercialization of the constellation shaping modulation format has proceeded which can approach the theoretical limit, the so-called Shannon limit [3,8]. Even these are offline processing, SE of 7.46 bit/s/Hz is confirmed at AEC-1 of transatlantic cables (5,523 km) with probabilistic constellation shaping (PS)-64QAM modulation [8]. Additionally, it has been confirmed that 5.5 bit/s/Hz is achievable with a Q-margin of 0.45 dB without the application of the nonlinear compensation function at the Taiwan to US segment of FASTER with 11,000 km [3]. Still, the decision about the availability of these SE should be defined by operators according to their policies in light of the communication sustainability and reliability.

3.3 C+L Band Transmission Technologies and Raman Amplification

One of the restrictions for submarine cables is the limited number of fibers in a cable, therefore the technologies to increase the transmission bandwidth is attractive. A typical submarine cable system is designed for C-band transmission, but recently, C+L band transmission has been introduced. For example, PLCN, which is under construction at this moment, will be the first transpacific system with C+L band transmission between Hong Kong and the US of over 12,917 km [9]. Roughly, L-band can support almost the same capacity as C-band, so the C+L band can be treated as virtually double the number of FPs compared to the C-band only system. However, as shown in the schematic view of Fig. 2, the C- and L-band must be separated in a repeater, so twice the number of EDFAs is required, and therefore it does not contribute to the reduction of power consumption per signal basically. Another case of L-band application is the hybrid type with Raman amplification. As shown in the actual case of ARBR (2,700 km with 4 FPs) between Argentina and Brazil, even though the initial design capacity is 12 Tbit/s per FP, the potential capacity can be extended to 44 Tbit/s per FP utilizing the 70 nm of C+L band transmission bandwidth [10,11].

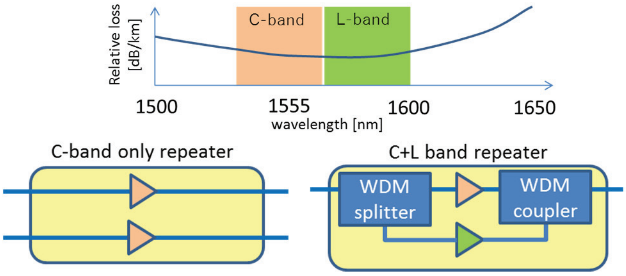

Fig. 2. Schematic view of C-band only and C+L band repeaters.

4 RESTRICTIONS FOR OPTICAL SUBMARINE CABLES

Submarine cable systems have particular restrictions compared to terrestrial ones. In this section, the two main limitations are explained.

4.1 Power Feeding Limitation for Submarine Cable

First, there is only one type of power supply for optical submarine cables. In the case of a typical point-to-point configuration, the electrical power is supplied from both ends of the cable by the power feeding equipment (PFE) in the cable landing station (CLS). For the transpacific cables, it supplies electrical power to 100 repeaters. The electric potential difference is mainly determined by the power consumption of repeaters and power loss at cables. The voltage of each side of the cable is set to be positive and negative half that of the required electric potential difference. For example, when the required potential difference is 15 kV, the voltage of each side is set to be +7.5 kV and -7.5 kV, respectively. So, the voltage in the middle point becomes virtual earth of 0 V, the same as ground (earth) shown in Fig. 3, even if the conductor is not electrically connected to the ground. This configuration is a remedy for cable fault types called shunt faults. When the conductor of a cable is partly exposed in the water caused by scratch, the faulty point is forced to be grounded (earthed) as 0 V. It means that it becomes impossible to supply power from the initially assigned PFE to the repeaters that are located on the far side of the faulty point. To repair this situation, the PFE on the other side of the cable increases the output power to provide sufficient power to the repeater. If a shunt fault happens near the shore, all of the required power must be supplied from one side. It seems like a single-end feeding that needs twice the power as that of the normal setting. Therefore, typically the maximum voltage for PFE is specified as twice the voltage for the normal setting. Note that the maximum voltage of current commercialized PFE is 15 kV, so a limited number of EDFAs can be activated. Especially, the transatlantic and/or transpacific cables must be equipped with a large number of repeaters, so the usable power is relatively small for each repeater, and accordingly, the number of implementable FPs is limited. The other design is to reduce the power of the pump laser or to use fewer numbers of repeaters to increase the supportable number of FPs; however, the achievable OSNR will be decreased, and accordingly, the ultimate capacity per FP becomes smaller.

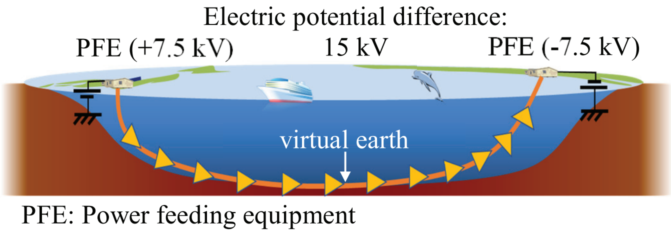

Fig. 3. Schematic view of double-end feeding for a submarine cable.

The cable capacity with the utilization of dual-polarization (DP) transmission is restricted by the Shannon limit as shown in Eq. (1):

$$C = N \times B \times 2log_2(1 + SNR) \quad (1)$$

where *C* is the maximum capacity in theory, *N*, *B* and *SNR* are the number of FP, bandwidth and signal-to-noise ratio (SNR), respectively. The *SNR* is related to OSNR in the optical fiber communication field, so usually：

$$OSNR = P_{sig}/P_{ASE} \quad (2)$$

P_{sig} and P_{ASE} are the power per signal within the signal bandwidth of BW_{sig} and amplified spontaneous emission (ASE) noise power density, respectively. The noise power density is defined with the bandwidth BW_{noise}. In the case of the bandwidth of P_{sig} and P_{ASE} are equalized, the *OSNR* can be treated as *SNR*. The P_{sig} can be assigned by the output power setting of the repeater; on the other hand, the P_{ASE} depends on span loss, which also means gain, noise figure (NF) of the repeater, and the number of repeaters. Therefore, the OSNR is decreased as the number of repeaters increases, so the theoretical maximum capacity becomes smaller for longer distances.

While the ultimate performance of submarine cables is determined by Eq. (1) and (2), the existence of nonlinear effect cannot be disregarded with the introduction of digital coherent transmission. So, the characteristics of optical submarine cables should be defined by the generalized OSNR (GOSNR) that includes the nonlinear effect as follows [12]:

$$GOSNR = P_{sig}/(P_{NL} + P_{ASE}) \quad (3)$$

where P_{NL} is the noise caused by the nonlinear effect. Additionally, Generalized SNR (GSNR) is also proposed which is independent of signal bandwidth [29]:

$$GSNR = GOSNR - 10\log_{10}(BW_{sig}/BW_{noise}) \quad (4)$$

As described previously, the +D fiber type cable gives smaller P_{NL} than the other types such as DSF, NZ-DSF and DMF, and this is one of the main reasons why +D fiber can have higher potentials than the other types in terms of the capacity.

Conventionally, the optical submarine cable is procured for both wet and dry plants including SLTE at the same time. Therefore, it is common sense to use the Q-factor to show signal quality as the criteria for acceptance of the system. In addition to this condition, FASTER has adopted another criterion defined by OSNR for the first time in the world [2]. Furthermore, there is a new trend of using the GOSNR (or GSNR) as the criteria instead of the Q-factor [13]. The background to this trend is that recently the style of procurement has changed to the so-called "Open cable", which is contracted for wet plants only. It is advantageous because operators can choose SLTE freely. However, it also means no SLTE introduction at the initial stage, so it is impossible to define the criteria with Q-factor for acceptance. Therefore, there are some difficulties to be resolved, for example, how to confirm the reliability of estimated GOSNR (or GSNR) before making a contract, and how to measure GOSNR (or GSNR) after construction, etc. Currently, the GN-model is used for the estimation of GOSNR (or GSNR) at the design stage [14], while the measured nonlinear coefficient can be correlated with the value of the fiber specification that is obtained by the transmission performance of an actual real-time transponder [13]. The result contributes to the strategy of the cable system acceptance test.

4.2 Limitation of Fiber Counts for Submarine Cables

Another constraint for optical submarine cables is the implementable number of fibers, which is significantly less compared to terrestrial cables and/or unrepeatered systems. As shown in Table 1 and the case of MAREA, the number of FPs is equal to or less than 8. This restriction is related to the limitation of the power supply described in the previous section. Even if it is difficult to define the limitation of implementable fiber counts per cable, the cable capacity can reach several 100 Tbit/s per cable considering these limitations such as GOSNR, power supply and fiber counts [12].

5 POLICY AND TECHNOLOGIES FOR NEXT GENERATION

5.1 Maximum Power Operation for Double-End Feeding

The normal setting for PFE is typically half that of the required electric potential difference on both ends to repair shunt faults at double-end feeding configuration. In other words, these PFEs have potentials to support double the capacity utilizing maximum power even in normal situations, if accepted by operators. However, as this configuration is quite weak for shunt faults, it means that communication can fail suddenly. To make matters worse, the cable cannot be used until the completion of the cable repairment. Therefore, this operational policy will be one of choices if the operator has robustness with diversity using the other cables. Note that the repair period for a submarine cables will take a few weeks or more [15]. So, it is important for operators to keep in mind the estimated duration for recovery.

5.2 Shared Pumping for Multiple EDFA with Multicore Fiber (MCF) of Space-Division-Multiplexing (SDM) Technologies

Related to the issues described previously, it is important to reduce the power consumption per FP or channel. To provide the same gain for all of the WDM channels, each EDFA has a gain flattening filter (GFF) at the output side of EDF. However, The GFF reduces the total output power because the transmission profile of GFF is designed to highly attenuate around the higher gain band to equalize the power or OSNR among all WDM channels. Recently, however, it is considered to be one of the causes of wasted energy. So, a novel configuration is proposed to increase capacity that utilizes a higher number of fiber cores with narrow bandwidth EDFA [16,17]. The attractive point of Ref. [16] is the introduction of multicore fiber (MCF) as a method of space-division multiplexing (SDM) technologies. In that report, WDM signals are transmitted via a 12-core fiber with 12 EDFAs in parallel whose pump light power is provided and shared from a pump laser output of 800 mW. As a result, it is confirmed that 105.1 Tbit/s signals successfully transmit over 14,350 km of a 12-core fiber transmission line. The drawback of this proposal is that the required number of cores becomes 12 times, so it seems difficult to install in a submarine cable just by utilizing the multiple conventional single core single-mode fibers (SC-SMF). Therefore, the introduction of MCF is feasible with the reduction of the fiber counts. Moreover, the multiple parallel EDFA can be replaced by multicore-EDFA (MC-EDFA) as explained in the following section.

5.3 Uncoupled-core MCF and Coupled-core MCF

The MCF is regarded as a possible candidate for an applicable technology for optical submarine cable systems in terms of its energy and space-saving efficiencies. The MCFs are categorized into two groups: uncoupled MCF (UC-MCF) and coupled-core MCF (CC-MCF), depending on the quantity of crosstalk (XT) between cores. The first advantage of UC-MCF is the easier upgradability from the current conventional SC-SMF based system. With the minimized XT, it can be treated as multiple SC-SMFs virtually. To reduce the XT, each core is surrounded by a lower refractive index layer [18,19]. It contributes to the application of the conventional transponder without any modification, so it seems easier to realize.
one of the topical merits of CC-MCF is lower attenuation. For example, the attenuation of 0.158 dB/km is achieved even if its cladding diameter is the standard size of 125 μm for a 4-core fiber [20]. The value of attenuation is approaching the value of SC-SMF with a pure-silica core that is commonly used for submarine cable systems, so it is

effective for system design in terms of maintaining the repeater span, etc. Furthermore, it is indicated that CC-MCF gives lower nonlinearity compared to SC-SMF that has equivalent A_{eff}, as confirmed by the transmission experiment [21]. This means that CC-MCF may contribute to the increase in GOSNR or reduction of the number of repeaters.

5.4 Multicore EDFA

Regardless of the multi-fiber or MCF cases, the required number of EDFAs in a repeater is increased as a function of the number of cores. Because of the space limitation in a repeater, it is required to minimize the size of an EDFA unit. From this perspective, multicore EDFA (MC-EDFA) is attractive to decrease the number of EDFs and then amplify multiple cores with one MC-EDF. The low XT characteristics have been confirmed and the applicability for transoceanic distance transmission is demonstrated experimentally [22-25]. Moreover, the cladding pump MC-EDFA (CP-MC-EDFA) method is proposed to excite multiple cores at once [24-27]. First, it has a further space saving efficiency utilizing some optical components that can handle multiple cores at once. Additionally, it contributes to reduction of the power consumption per core with the introduction of double cladding MC-EDF and a multimode laser diode (LD) for a pump laser instead of multiple single mode pump LDs. The drawback is the difficulty in increasing the excitation efficiency because of the huge difference of the mode field diameters between MM-LD and each core of MC-EDFA. Basically, the excitation efficiency is increasing as a function of the length of CP-MC-EDFA. Typically, the length of EDF is longer for L-band than C-band, therefore, in the case of cladding pumping, L-band CP-MC-EDFA is intrinsically energy efficient [25]. It is confirmed that 50 x 256 Gbit/s can be transmitted over 5,040 km of a 7-core fiber with CP-7C-EDFA [26]. To increase the excitation efficiency, it is proposed to recycle the remaining pump lightwave from output to input of CP-MC-EDFA [27,28]. It is reported that the pump power can be decreased by 14% compared to the no-recycling case at the same output power condition [27], and the other report shows that a 32% reduction in power consumption is observed in the same gain condition [28]. Regarding these results, CP-MC-EDFA is expected to be a possible means of reducing the power consumption of a repeater.

6 SUMMARY

This paper reviewed the evolution of transpacific communication cables, current cutting-edge technologies and promising technologies for future optical submarine cable systems. The typical design lifespan of submarine cable systems is as long as 25 years, so technical evolution is progressed for new cables and for already deployed cables with new type fibers and advanced modulation format in parallel. The main issues are limitation of power feeding for submarine cables and space for a cable and a repeater. So, MCF and MC-EDFA of SDM technologies are expected to overcome these limitations. It seems that the traffic demands will never abate for global networking; therefore, the technical evolution will continue into the future for optical submarine cable systems.

Acknowledgment

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References

1. KDDI Corporation, "FASTER Cable System is Ready for Service, Boosts Trans-Pacific Capacity and Connectivity," [Online]. Available: https://global.kddi.com/company/news/detail/faster-cable-system-is-ready-for-service-boosts-trans-pacific-capacity-and-connectivity.html, (2016).
2. Kamalov, V., Jovanovski, L., Vusirikala, V., Mateo, E., Inada, Y., Ogata, T., Yoneyama, K., Pecci, P., Seguela, D., Rocher, O., Takahashi, H., "FASTER Open Submarine Cable," ECOC2017, Th2E.5, (2017).
3. Kamalov, V., Jovanovski, L., Vusirikala, V., Zhang, S., Yaman, F., Nakamura, K., Inoue, T., Mateo, E., Inada, Y., "Evolution from 8QAM Live Traffic to PS 64-QAM with Neural-Network Based Nonlinearity Compensation on 11000 km Open Subsea Cable," OFC2018, PDP, Th4D.5, (2018).
4. FCC, [Online]. Available: https://docs.fcc.gov/public/attachments/DA-16-1221A1.pdf, (2016).
5. Yamaguchi, H., Yamamoto, Y., Hasegawa, T., Kawano, T., Hirano, M., Koyano, Y., "Ultra-Low Loss and Large Aeff Pure-Silica Core Fiber Advances," SubOptic2016, EC07, (2016).
6. Tamura, Y., Sakuma, H., Morita, K., Suzuki, M., Yamamoto, Y., Shimada, K., Honma, Y., Sohma, K., Fujii T., Hasegawa, T., "Lowest-ever 0.1419-dB/km Loss Optical Fiber," in Proc. Opt. Fiber Commun. Conf. (OFC2017), Th5D.1 (2017).
7. Infinera Corporation, "Infinera Breaks Real-time Subsea Spectral Efficiency Records with 6.21 b/s/Hz on 6,644 km MAREA Trans-Atlantic Cable," [Online]. Available: https://www.infinera.com/wp-content/uploads/pr-infpspectral-efficiency-records-marea-trans-atlantic-cable.pdf, (2018).
8. Cho, J., Chen, X., Chandrasekhar, S., Raybon, G., Dar, R., Schmalen, L., Burrows, E., Adamiecki, A., Corteselli, S., Pan, Y., Correa, D., McKay, B., Zsigmond, S., Winzer, P.J., Grubb, S., "Trans-Atlantic Field Trial Using High Spectral Efficiency Probabilistically Shaped 64-QAM and Single-Carrier Real-Time 250-Gb/s 16-QAM," Journal of Lightwave Technology, Vol. 36, No. 1, pp. 103-113, (2018).
9. Pacific Light Data Communication Co., Ltd., [Online]. Available: http://pldcglobal.com/.
10. Seaborn Networks, [Online]. Available: https://www.seabornnetworks.com/seaborn-networks-systems/arbr/.
11. Xtera, [Online]. Available: https://www.xtera.com/2018/05/01/seaborn-selects-cl-band-design-arbr-serve-needs-icp-community/, (2018).
12. Mateo, E., Inada, Y., Ogata, T., Mikami, S., Kamalov, V., Vusirikala, V., "Capacity Limits of Submarine Cables," SubOptic2016, TH1A.1, (2016).
13. Mateo, E., Nakamura, K., Inoue, T., Inada, Y., Ogata, T., "Nonlinear Characterization of Fiber Optic Submarine Cables," ECOC2017, Th2E4, (2017).
14. Poggiolini, P., Bosco, G., Carena, A., Curri, V., Jiang, Y., Forghieri, F., "The GN-Model of Fiber Non-Linear Propagation and its Applications," Journal of Lightwave Technology, Vol. 32, No. 4, pp. 694-721, 2014.

15. The International Cable Protection Committee, “Submarine Cables and BBNJ,” [Online]. Available: http://www.un.org/depts/los/biodiversity/prep-com_files/ICC_Submarine_Cables_&_BBNJ_August_2016.pdf, (2016).
16. Turukhin, A., Sinkin, O.V., Batshon, H. G., Zhang, H., Sun, Y., Mazurczyk, M., Davidson, C. R., Cai, J.-X., Bolshtyansky, M. A., Foursa, D. G., Pilipetskii, A., “105.1 Tb/s Power-Efficient Transmission over 14,350 km using a 12-Core Fiber,” OFC2016, Th4C.1, (2016).
17. Turukhin, A., Sinkin, O.V., Batshon, H. G., Mazurczyk, M., Patterson, W. W., Wolter, G., Bolshtyansky, M. A., Foursa, D. G., Pilipetskii, A., “Power-Efficient Transmission Using Optimized C+L EDFAs with 6.46 THz Bandwidth and Optimal Spectral Efficiency,” ECOC2018, Mo4G.4, (2018).
18. Hayashi, T., Taru, T., Shimakawa, O., Sasaki, T., Sasaoka, E., “Uncoupled multi-core fiber enhancing signal-to-noise ratio,” Optics Express, Vol. 20, No. 26, pp. B94-B103, (2012).
19. Gonda T., Imamura K., Sugizaki R., Kawaguchi Y., Tsuritani T., “125 µm 5-core fibre with heterogeneous design suitable for migration from single-core system to multi-core system,” ECOC2016, W.2.B.1, (2016).
20. Hayashi, T., Tamura, Y., Hasegawa, T., Taru, T., “125-µm-cladding Coupled Multi-core Fiber with Ultra-low Loss of 0.158 dB/km and Record-low Spatial Mode Dispersion of 6.1 ps/km$^{1/2}$,” OFC2016, PDP, Th5A.1, (2016).
21. Ryf, R., Fontaine, N. K., Chang, S. H., Alvarado, J. C., Huang, B., Antonio-Lopez, J., Chen, H., Essiambre, R. J., Burrows, E., Tkach, R. W., Amezcua-Correa, R., Hayashi, T., Tamura, Y., Hasegawa, T., Taru, T., “Long-Haul Transmission over Multi-Core Fibers with Coupled Cores, “ ECOC2017, M2E1, (2017).
22. Takahashi, H., Tsuritani, T., de Gabory, E. L. T., Ito, T., Peng, W. R., Igarashi, K. ,Takeshima, K., Kawaguchi, Y., Morita, I., Tsuchida, Y., Mimura, Y., Maeda, K., Saito, T., Watanabe, K., Imamura, K., Sugizaki, R., Suzuki, M., “First Demonstration of MC-EDFA-Repeatered SDM Transmission of 40 x 128-Gbit/s PDM-QPSK Signals per Core over 6,160-km 7-core MCF,” ECOC2012, PDP, Th.3.C.3, (2012).
23. Igarashi, K., Tsuritani, T., Morita, I., Tsuchida, Y., Maeda, K., Tadakuma, M., Saito, T., Watanabe, K., Imamura, K., Sugizaki, R., Suzuki, M., “1.03-Exabit/s.km Super-Nyquist-WDM Transmission over 7,326-km Seven-Core Fiber,” ECOC2013 PDP, PD3.E.3, (2013).
24. Takeshima, K., Tsuritani, T., Tsuchida, Y., Maeda, K., Saito, T., Watanabe, K., Sasa, T., Imamura, K., Sugizaki, R., Igarashi, K., Morita I., Suzuki, M., “51.1-Tbit/s MCF Transmission over 2,520 km Using Cladding Pumped 7-core EDFAs,” OFC2015, W3G.1, (2015).
25. Tsuchida, Y., Maeda, K., Watanabe, K., Takeshima, K., Sasa, T., Saito, T., Takasaka, S., Kawaguchi, Y., Tsuritani, T., Sugizaki, R., “Cladding Pumped Seven-Core EDFA Using an Absorption-Enhanced Erbium Doped Fibre,” ECOC2016, M.2.A.2, (2016).
26. Kawaguchi Y., Tsuritani, T., “Ultra-Long-Haul Multicore Fiber Transmission Over 5,000 Km Using Cladding Pumped Seven-Core EDFA,” OECC2017, 3-1K-3, (2017).
27. Takasaka, S., Maeda, K., Kawasaki, K., Yoshioka, K., Sugizaki, R., Tsukamoto, M., “Cladding Pump Recycling in 7-core EDFA,” ECOC2018, We1E3, (2018).
28. Takeshita, H., Matsumoto K., de Gabory, E. L. T., “Transmission of 200Gbps PM-16QAM Signal Through 7-Core MCF and MC-EDFA Using Novel Turbo Cladding Pumping Scheme for Improved Efficiency of the Optical Amplification,” ECOC2018, We2.35, (2018).
29. Mateo, E., Inoue, T., Nakamura, K., Mikami, S., Inada Y., Ogata, T., “Linear Vs Nonlinear Submarine Systems,” SubOptic2019, OP8-3, (2019).