Technologies for Optical Submarine Cables: Past Present & Future

Yuichi Nakamura* and Hitoshi Takeshita
NEC Corporation, 1753 Shimonumabe, Nakahara-ku, Kawasaki, 211–8666, JAPAN
**yuichi_nakamura@nec.com*

Abstract: Optical submarine cables are critical infrastructures that carry more than 80% of the Internet traffic between continents. An overview of the technology used in past and present optical submarine cables is presented. © 2022 The Author(s)

1. Introduction

In the 21st century, information and communication technology has become a vital social infrastructure that provides a richer lifestyle and consistently superior services compared to the early telegraphs of the 19th century and the telephone lines and Internet connectivity of the 20th century. The emergence of the Internet in the 1990s has led to an ever-increasing need for communication and information transfer capabilities. In the present day, the demand for capacity expansion of communication systems is increasing year by year, with a compound annual growth rate (CAGR) of 26% in the global IP traffic base [1, 2]. It is therefore extremely important to expand communication systems so that we can accommodate the increasing communication traffic in the coming decades. Among communication systems, optical submarine cable systems are vital because they transfer the bulk of this huge amount of traffic. In some cases, the transmission distance exceeds 10,000 km for intercontinental connections [3–7]. Submarine optical cable systems must simultaneously address the conflicting demands for large communication capacity and ultra-long distance transmission capability, so the technical capabilities required to achieve this are significantly difficult. The introduction of cutting-edge technologies therefore tends to be prioritized ahead of other systems [8–10], and recent innovations such as open system [11] have been driven by major content providers willing to improve their services (computing, storage, communication, content delivery, etc.) faster than others. However, there are some circumstances in which signal transmission capability is not the only priority from the viewpoint of deployment. Specifically, optical submarine cable have been deployed on cable ships and laid down on the ocean floor, and these are distinctive and harsh environments in terms of the requirements for the reliability and lifetime of system design because there are limited opportunities for making repairs or replacements.

This paper provides an overview of the main features of optical submarine cables looking back on past technical innovations and discusses recent research aimed at meeting the capacity expansion demands over the next decade.

2. Background and establishment of optical submarine cable

The history of optical submarine cables begins with the first telegraph cable laid in Europe in 1840, which was soon followed by the first transatlantic telegraph cable in 1850. The transmission capacity at that time was less than 10 words per minute. In 1956, it became possible to construct a transatlantic submarine cable system using coaxial cables. The first such system was the TAT-1, which had a maximum transmission capacity of about 10 Mbps. Optical fiber transmission technology was developed in 1980, and once this technology was applied to submarine cable systems, the transmission distance and capacity expanded dramatically. The first application of optical fiber transmission technology to a transatlantic system was in 1988 with the TAT-8 system, which had a transmission capacity of 0.5 Gbps. During the same period, the transpacific cable TPC-3 was deployed. The signal wavelength used in both systems was in the 1.3-μm band [12]. The TAT-9 and TPC-4 systems that followed utilized the signal wavelength in the 1.55-μm band, which is the same as today. By changing the signal wavelength band, the transmission capacity was successfully doubled [13]. In the 1990s, wavelength division multiplexing (WDM) technology made it possible to deploy multiple transmission channels even with a single fiber. Currently, more than 100 wavelength channels per fiber are available. WDM technology has undergone a major evolution since the invention of the erbium-doped fiber amplifier (EDFA), which is an efficient optical repeater. Optical amplification technology was first implemented in TPC5-N optical submarine cables in 1995 [15]. The following year, in 1996, it was used for the transatlantic cables TAT-12 and TAT-13 [16]. These systems utilized both WDM and EDFA to provide 20-Gbps capacity over a transmission distance of 5,913 km. Although waveform distortion due to the non-linearity effect between multiple wavelength channels became a problem in long-haul transmission using WDM technology, this was soon resolved by devising an optical fiber transmission line with a chromatic dispersion (CD) design. This led to a method in which various species of optical fibers with normal and anomalous dispersion were combined to make the total CD zero and to maintain the local CD at non-zero [17].

3. Era of pursuing transmission efficiency enabled by digital coherent technology

Around 1980, which is the same time the EDFA was invented, research into long-haul transmission using coherent detection became active. However, the invention of EDFA was so great that it attracted much more attention than the coherent detection. For this reason, the coherent detection was not immediately put into practical use at that time. Since then, CMOS process and digital signal processing technology have advanced significantly, mainly in the computing field. By incorporating this technical innovation into the digital field, the combination of the old (analogue) coherent detection technology and the dramatically evolved digital technology underwent renewed research attention [18]. In 2000, such technology started being applied to terrestrial transmission systems [19]. Digital coherent technology, which is based on coherent detection and digital signal processing, made it possible to compensate for linear impairments such as the chromatic dispersion and polarization mode dispersion (PMD) in digital signal processing, thus doing away with the complicated CD design [20]. It also became possible to partially mitigate the signal distortion due to non-linear effects. Since such digital signal processing requires a huge amount of circuit resources, efficient circuit design for signal processing algorithms and circuit implementation is an important focus of research and development today. Polarization division multiplexing and multilevel phase modulation capability by using digital coherent technology has made it possible to improve spectrum utilization efficiency. The first such system was based on polarization multiplexing quadrature phase shift keying (PM-QPSK) [21], and additional spectrally efficient modulation formats have been actively researched and developed [5]. Though the output signal modulation format of the digital coherent transponders was fixed initially, it comes possible to select and output modulation formats from multiple options at present day.

Optical submarine cable systems have evolved further by using digital coherent technology in addition to conventional WDM technology. For example, the FASTER submarine cable, which connects a distance of 9,000 km between Japan and the United States, currently has the transmission capacity of 60 Tbps when it goes into operation, which is equivalent to about 2,000 times the transmission capacity per fiber of the first WDM optical submarine cable system. Recent developments have included advanced modulation techniques approaching the Shannon theoretical limit [22]. For example, upgrading to transponders with probabilistic shaping modulation technique, which relies on the non-uniform symbol distribution of the constellation in higher-order phase modulation, has shown potential for increasing the existing optical submarine cable system capacity [5, 23]. Until this development, the transmission capacity per wavelength channel was determined at run time and could not be upgraded to increase capacity after the deployment.

4. Beyond the capacity limitation of conventional single-core single-mode fiber

The main challenge going forward is that increasing the capacity of optical transmission systems using conventional WDM technology is likely to reach the Shannon limit [24]. Therefore, to continue supporting global traffic growing at the CAGR of 26%, we need a disruptive technology that differs from the conventional WDM and digital coherent technology. Optical submarine cable systems are expected to reach the theoretical limit fastest because the signal multiplexing density is equal to or greater than that of terrestrial systems, and the transmission distance is much longer. Capacity expansion by increasing the number of fiber pairs (FP) has been investigated, which is one option for spatial division multiplexing (SDM) technology. However, considering cost optimization [25] as well as limitations to installation space [26] and power supply [27], this is not a long-term solution but rather a temporary workaround. For example, power supply equipment located on land cannot supply the submarine cable system with a voltage higher than 15 kV, so the number of FPs needs to be 30 or less [27], thus limiting the possibilities for increasing their number. SDM technology, which multiplexes spatial channels (the fiber itself, fiber core, and optical mode), is one of the leading candidates for fundamentally solving the problem of increasing the capacity of optical transmission systems [28–33]. In fact, there are currently plans to use SDM technology in commercial systems [3, 4].

MCF core counts of up to 100 have been reported [29]. Uncoupled-core (UC) MCF-based transmission systems with limited inter-core crosstalk are more compatible with the conventional SMF-based transmission systems than coupled-core (CC) MCF-based transmission systems. Indeed, the world's first multicore optical submarine cable (shown in Fig. 1), which applies a 4-core UC-MCF to the design of a commercial SMF-based submarine cable, has already been achieved [34]. Bidirectional transmission technology is an example of active use of the MCF features not found in the SMF [35–38]. As shown in Fig. 2, inter-core crosstalk can be cancelled out in bidirectional transmission using UC-MCF, resulting in longer reach than equivalent unidirectional transmission SMF- and MCF-based systems. In contrast, coupled core (CC) MCFs have dense cores with intentionally high crosstalk. These systems have the advantage of being able to transmit optical signals over long distances due to the small nonlinear signal distortion [32]. The CC-MCF based transmission system is thus expected to achieve both large-capacity and ultra - long-distance transmission. The transponders in these systems need to have multi-input multi-output (MIMO) functionality, and real-time reception has recently become possible thanks to using field programmable gate arrays (FPGA) [39]. In multimode multiplexing, one core handles multiple mode signals, and reports have shown that 15-

mode multiplexing can achieve 1 Pbps per fiber [40]. In addition, by combining the multimode multiplexing with MCF, it is possible to achieve a larger transmission capacity: studies have reported 10-Gbps transmission capacity using 6-mode 19-core fiber [30] and 228 SDM channels using 3-mode 39-fiber [31].

5. Conclusion

This paper described the early days of optical submarine cables, the present trends, and future prospects to give an overview of the research and development of various signal transmission technologies required for meeting the explosively increasing demand of communication traffic. Research and development related to optical fiber transmission lines will continue in the future to break free of the capacity limitation of the conventional single-mode single-core fiber.

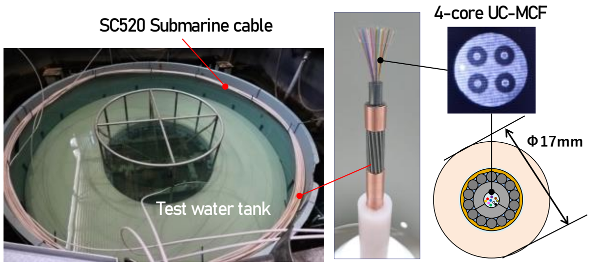

Fig. 1 4-core uncoupled multicore optical submarine cable.

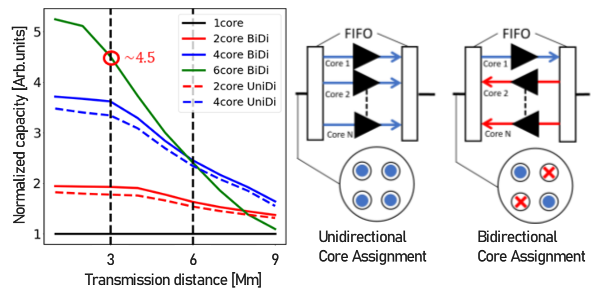

Fig. 2. Bidirectioanl core assignment.

Acknowledgements: This work was partially supported by "The research and development of innovative optical network technologies for supporting new social infrastructure" (JPMI00316) of the Ministry of Internal Affairs and Communications, Japan and the commissioned research of National Institute of Information and Communications Technology (NICT) Grant Number 0020103.

6. References

[1] VNI Global Fixed and Mobile Internet Traffic Forecasts, Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html
[2] Submarine Telecoms Forum, Available: https://issuu.com/subtelforum/docs/stf_industry_report_issue_8
[3] Google Cloud Blog, Available: https://cloud.google.com/blog/products/infrastructure/a-quick-hop-across-the-pond-supercharging-the-dunant-subsea-cable-with-sdm-technology?hl=en
[4] NEC Press Release, 2017, Available: https://www.nec.com/en/press/201706/global_20170622_01.html
[5] H. Bissessur, OFC 2013, OTh4C3
[6] V. Kamalov et al, ECOC 2017, Th.2.E.5
[7] NEC Press Release, 2022, Available: https://www.nec.com/en/press/202207/global_20220721_01.html
[8] V. Kamalov et al., OFC 2018, Th4D.5
[9] R. Ryf et al., ECOC 2016, Th.3.C.3
[10] G. Rademacher, JLT Vol. 37, No.2, Jan. 15, pp.425-432
[11] E. R. Hartling et al., JLT. Vol. 39, No. 3, Feb. 1, 2021, pp. 742–756
[12] N. S. Bergano, "Undersea Communication Systems," Ch. 4, Optical Fiber Communications VB: Systems and Networks, I. P. Kaminow, T. Li and A. E. Wilner, Eds., 2008.
[13] P. Winzer et al., Opt. Exp., Vol. 26, No. 18, 2018, pp.24190-24239
[14] K. Fukuchi, OFC 2018, ThX5
[15] I. Morita et al., OECC 2010, 6B2-4
[16] P. Trischitta et al., IEEE Commun. Mag., Vol. 34, No.2, 1996, pp.24-28
[17] Y. Yano et al., ECOC 1998, pp.261-262
[18] K. Kikuchi, , JLT, Vol. 34, No. 1, 2016, pp.57-179
[19] Y. Aoki et al., IEEE Commun. Mag., Vol. 5, Issue 2, 2012, pp.S50-S57
[20] M. Arikawa et al., JOCN 2012, Vol. 4, Issue 11, pp.B161-B167
[21] K. Fukuchi et al., OFC 2015, TuB.3
[22] T. Nakamura et al., ECOC 2015, Th.2.2.2
[23] S. Zhang et al., OFC 2018, M1G.3
[24] T. Morioka, OFC 2017, Th1C.3
[25] R. Dar et al., JLT, Vol. 36, No. 18, 2018, pp.3855-3865
[26] M. Kobiki et al., OECC 2019, WC2-2
[27] E. Mateo et al., SubOptic 2019, OP8-4.
[28] B. J. Puttnam et al., OFC 2019, Th4.B.1
[29] K. Mukasa, OECC 2019, TuC3-3
[30] D. Soma et al., ECOC 2017, Th.PDP.A.1
[31] J. Sakaguchi et al., ECOC 2018, Mo3G.1
[32] R.Ryf et al., ECOC 2017,M.2.E.1
[33] D. Soma et al., ECOC 2018, Mo3G.2
[34] H. Takeshita et al., JLT, DOI: 10.1109/JLT.2022.3195190
[35] D. Soma et al., ECOC 2022, Th1D.2
[36] K. Maeda et al., OECC 2020, VP56
[37] H. T akeshita et a., OECC 2022, TuC1.2
[38] S. Tateno et al., ECOC 2022, Mo4D.3
[39] S. Beppu et al., ECOC 2021, F3B.4
[40] G. Rademacher et al., ECOC 2020, Th3A-3