European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Increase of Capacity with Bidirectional Transmission Using 4-core-or-more MCF and MC-EDFA in Submarine Systems

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Abstract We analytically demonstrate that bidirectional multicore transmission design with bidirectional MC-EDFA increases the capacity of submarine cables, by 5.0 times, compared to conventional SCF, for 3,000 km-long regional Asian systems using 6-core MCF and 2.3 times for 9,000 km-long transpacific systems using 4-core MCF.

Introduction

The amount of communication traffic in submarine systems is growing rapidly with annual increase rate of 30% [1]. Spatial-division multiplexing (SDM) is being researched as a candidate to satisfy such a demand in undersea communication systems [2]. Several techniques have been proposed to realize SDM, such as uncoupled multicore fibre (MCF) multi-mode fibre or coupled MCF. Uncoupled MCF has advantage of compatibility with the exiting equipment, whereas coupled MCF and multimode fibre would require a new generation of complex transceivers with MIMO signal processing.

Early trials of transmission over cabled uncoupled MCF have been reported to validate the fibre performance [3,4]. The tested fibres had standard cladding diameter of 125 µm, which enables compatibility with equipment used for standard single mode fibre production and cabling. The increase of the number of cores of MCF is required to increase the number of spatial channels and therefore the capacity; however, in standard cladding diameter this leads to reducing the core-to-core distance, eventually increasing crosstalk (XT) generated from the field coupling between adjacent cores and limiting the transmission. It has been shown that the optimum number of cores was 4 for standard diameter cladding and that this optimum was independent of the transmission distance [5]. This is also the number of cores of field-tested fibres [3,4].

However, this reported optimum [5] and reported design studies on multicore submarine systems [6] only consider unidirectional transmission in MCF to our best knowledge. Nonetheless, bidirectional transmission over MCF is known to reduce XT between adjacent cores with opposite direction of transmission [7-10], as the dominant factor of XT becomes Rayleigh backscattered light, which is lower.

Therefore, in this paper, we study analytically the design of multicore submarine systems, including both unidirectional and bidirectional transmission inside MFC, according to the schematic shown in Fig. 1, with feed power constraints. We show that bidirectional systems have higher capacity and that transmission over 6-core MCF enables the highest capacity for considered systems up to 6,000 km. We further consider the benefit of bidirectional MC-EDFA without fan-in fan-out (FIFO), which can mitigate the feed power limit, shown in Fig. 1(c). We also show the utilizing bidirectional MC-EDFA enables to increase capacity, especially in 6-core MCF systems or long transmission systems under the severe power limit.

Analysis of the SNR dependence on XT

In this section, we first discuss signal to noise ratio (SNR) for unidirectional and bidirectional transmission over a 2-core MCF to clarify the potential differences. As core pitch length has a direct influence on XT between cores, we investigate its influence and how it can be relaxed for bidirectional transmission, for which the XT penalty is lower.

Figure 2 shows the calculated dependence on core pitch length of the core-to-core XT and SNR of a 2-core MCF at a wavelength of 1550 nm in a 3,000 km-long-system; it also indicates the core pitch length between nearest cores for 4 to 8-core MCF geometries, with a one-ring core layout, except for 7-core MCF, as shown in Fig. 3(b). The cladding diameter is the standard size, 125 µm. The cladding thickness, *i.e.* the distance between

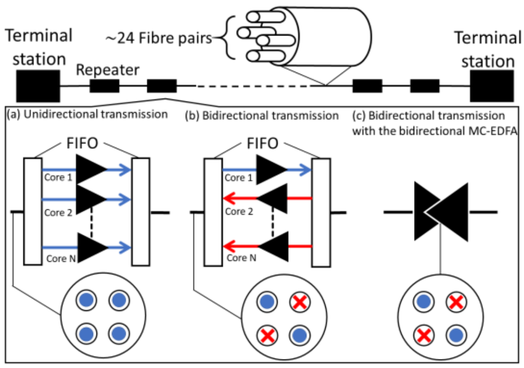

Fig. 1: Schematic of the submarine cable system and the amplifier configuration in (a) the unidirectional system, (b) the bidirectional system (c) the bidirectional system with the bidirectional MC-EDFA.

the outer core and the coating, is set to be 30 µm to avoid the excess loss due to the leakage of the light to the coating [11]. Here, we assume a trench-assisted MCF (TA-MCF), which suppresses the field overlap by a low refractive index area around core centre [12]. The core-to-core XT is calculated by the analytical solution of TA-MCF [13]. The core design is set to be compatible with the optical properties of standard single mode fibre [14]. The trench design is consistent with previous reports [5,15]. The bidirectional XT is estimated using the analytical solution [9], where the Rayleigh scattering coefficient is assumed to be -32 dB [16]. As shown in Fig. 2, the bidirectional XT is smaller than the unidirectional XT by more than 30 dB.

Then we calculated SNR using Gaussian noise model, including the generalized signal droop effect in a long-haul system with constant output power amplifiers [17,18]. The repeater amplifier configuration is assumed to be the same of the previous studys [19,20], in which each core is separately amplified by EDFAs using FIFO device even if the bidirectional transmission, as schematically shown in Fig. 1(a-b). We assume 100 channels at 32GBd with 37.5 GHz spacing on the C band, 4dB noise figure regardless of gain, and FIFO XT of -40 dB [10]. The span length and span input power are optimized to maximize SNR for each core pitch length. As our goal in this part is to investigate the influence of the fibre geometry on SNR, we do not set constraints on system power, which is done in the last part for system design.

In the case of the unidirectional transmission, the SNR is strongly limited by XT for the core pitch lengths corresponding to more than 5-core MCF, illustrating the well-known result that 4-core MCF design seems optimal in standard cladding diameters [5,15,21]. However, for bidirectional transmission, denser core packing in standard cladding diameter, such as pitches corresponding to 6-core and 7-core designs still offer high SNR; thus, bidirectional transmission may not only reduce XT but also change the optimal fibre configuration for system design.

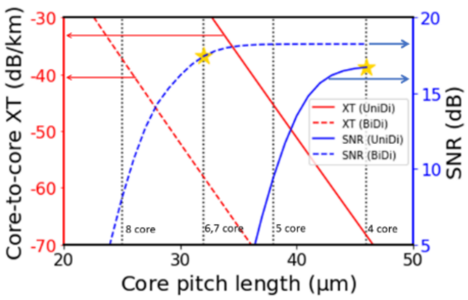

Fig. 2: The core-to-core XT and SNR as a function of core pitch length in the unidirectional (UniDi) and bidirectional (BiDi) transmission.

Capacity for XT limited MCF transmission

In order to analyse the influence of bidirectional transmission over multicore submarine system design, we first consider a simple XT limited design, with a relatively short distance of 3,000 km, *e.g.* an Asian regional system, where again for simplicity we do not consider power feeding constraints; this point is addressed in the next part. We consider the XT influence from the perspective of the capacity per fibre pair C as the Shannon limit given by $C \propto M\, log_2\,(1 + \mathrm{SNR})$, where M is the spatial multiplex term. C shows the trade-off relation between number of cores and SNR because the increase of the number of cores extends M and reduces SNR owing to the large XT influence; this implies the existence of an optimal number of cores to maximize capacity.

Figure 3(a) shows the capacity normalized by SCF as a function of the number of cores at the system total length L of 3,000 km. Again, span length and signal optical power are optimized to maximize capacity.

On the one hand, in the case of the unidirectional transmission, the maximum capacity is achieved with a 4-core MCF and the capacity decrease rapidly above 4 cores. Indeed, the SNR is largely degraded by XT for more than 4 cores as shown in Fig. 2. On the other hand, Fig. 3(a) shows that the capacity with the bidirectional transmission is significantly increased for 6-core MCF. Although the core pitch of 5-core MCF and 7-core MCF had a comparable influence on XT as shown in Fig. 2, the performance of systems based on an odd number of cores is not optimal for bidirectional transmission as all adjacent cores cannot be assigned to counter directions in this geometry, as shown in Fig. 3(b) [10]. For 8-core MCF the increase of XT becomes too large to benefit from bidirectional assignment.

Therefore, Fig.3(a) shows that 6-core MCF with bidirectional transmission has the highest potential of increase of capacity in XT limited systems. Notably, this is a different optimum from the 4-core design, which is restricted to

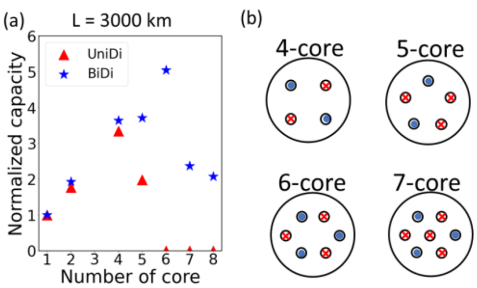

Fig. 3: (a)Normalized capacity as a function of numbers of cores in, (b) MCF design and signal direction allocation.

unidirectional transmission [5].

Capacity estimation of multicore submarine cable systems

In this part, we investigate the benefit of bidirectional transmission design in comparison to unidirectional for multicore submarine systems. Therefore, we consider system constraints like power feeding and cable diameters, as illustrated on Fig. 1, and we simulate different system lengths from 1,000 km to 9,000 km. We consider feed power limit using the basic system model in submarine cables [22, 23]. We set upper limit of fibre pairs, the cable supply voltage, and the cable resistance to be 24, 15 kV, and 1 Ω/km [4]. The FIFO insertion loss is assumed to be 1 dB for one set. We calculate the maximal capacity, optimizing system parameters of span length, launched power, and number of fibre pair under the constraints of the considered system.

Figure 4(a) shows the capacity normalized by the result of SCF, for different lengths, considering MCF and amplifiers connected through FIFO devices. The values of optimized span length range between 40 and 60 km. Simulation results show that bidirectional transmission enables to increase the capacity for all considered cases of MCF in the studied distance range. Especially, a bidirectional 6-core MCF system design offers the most capacity for the Asian regional systems of length of 3,000 km, specifically a 4.5 times larger capacity than in the case of SCF. Notably, the 6-core MCF design can only be used with bidirectional transmission due to its denser core geometry. Figure 4(a) also shows the influence of the feed power limit becomes dominant in longer distances, which results in a capacity reduction. This impacts even more the 6-core MCF design, which uses more amplifiers. Indeed, 4-core MCF based systems offer more capacity for transoceanic distances of more than 6,000 km.

In further investigations for the capacity increase, we consider the use of bidirectional MC-EDFA. Although some early works report cladding pump design [24,25] with technical challenges [26], here we focus on the benefit of removing FIFO between MCF and MC-EDFA [4]; thus, we assume a core pumping design with integrated optics for pump combiner and for isolators. We want to investigate how this system can mitigate the feed power limit with FIFO-less configuration in bidirectional systems.

Figure 4(b) shows the result assuming bidirectional MC-EDFA repeaters without FIFO. The maximal capacity of a 3,000 km-long system with 6-core MCF is increased by 10% with such repeaters, resulting in 5.0 times larger capacity than a SCF system. This increase is due to the improvement of SNR and of the energy efficiency with a FIFO-less structure. For a 6,000 km-long transatlantic system, 4-core and 6-core MCF system designs offer comparable capacity, so system cost consideration is required, which is left for future work. Finally, for a transpacific 9,000 km class systems, the highest capacity is obtained with bidirectional 4-core MCF system, up to 2.3 times higher than for SCF system; it is namely increased by 51% compared to the unidirectional 4-core MCF transmission system. Indeed, the influence of the bidirectional MC-EDFA reducing loss due to FIFO is promising for such long-haul system under severe feed power limit.

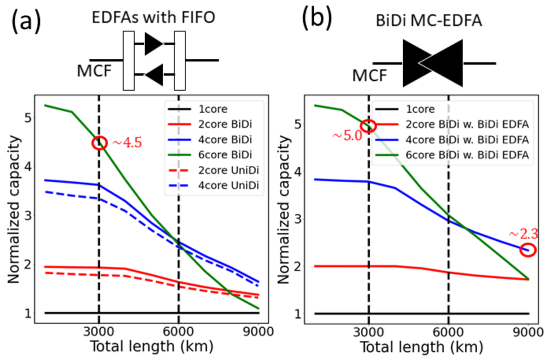

Fig. 4: Normalized capacity as a function of total length in (a) the conventional EDFA system and (b) the bidirectional MC-EDFA system.

Conclusions

In this study, we have demonstrated the increase of capacity of multicore submarine systems using bidirectional transmission. We have shown that bidirectional transmission enables an optimum design based on 6-core MCF in standard cladding diameter for regional Asian systems in the range of 3,000 km, as XT is reduced, and it offers 5.0 times the capacity of SCF systems. For transpacific systems in the range of 9,000 km, the power constraints lower the optimal number of cores and bidirectional transmission with 4-core MCF and EDFA offer the maximum capacity of 2.3 times compared to SCF, *i.e*. 51% more than a unidirectional 4-core MCF design.

Acknowledgements

These research results were partly obtained from "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 from the commissioned research of National Institute of Information and Communications Technology (NICT) Grant Number 0020103.

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