Core Selective Switch Based Branching Unit Architectures and Efficient Bidirectional Core Assignment Scheme for Regional SDM Submarine System

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Abstract: We propose core-selective-switch-based branching-unit architectures and an efficient bidirectional core-assignment scheme for regional space-division-multiplexing submarine systems. The architectures increase the number of reconfigurable cores and halve the number of multi-core fibers in branching cables.

1. Introduction

Among telecommunication network fields, submarine optical networks represent one field where spatial division multiplexing (SDM) technology is likely to be applied first. This is because submarine optical cable systems are designed under the constraints of limited cable space and power supply. It has been widely recognized nowadays that rather than increasing the signal-to-noise ratio for higher spectral efficiency, increasing the number of parallel single-mode fibers (SMFs) while sharing repeater power among them is a power-efficient approach to increasing the submarine cable capacity [1, 2]. There are two other important trends in submarine optical cable systems: the first trend is towards a higher-level requirement for connection reconfigurability in terms of failure recovery and adaptation to unforeseeable future traffic demands. Reconfigurability in submarine optical cable systems is achieved using branching units (BUs) that are placed along the trunk cable. Typical branching granularity of current regional submarine cable systems is the wavelength, which is achieved through a wavelength selective switch [3]. As the traffic demand of system owners increases and the number of SMF pairs increases in the context of submarine SDM, the appropriate branching granularity will shift from the wavelength to an SMF [1-3], which is the second trend. Traditionally, fiber switching in a BU is achieved using a pair of 1×2 fiber switches dedicated to an individual trunk SMF. Commercial submarine cable system supports fiber switching for up to 24 trunk SMF pairs per cable [2]. This trend has naturally led to multi-core fibers (MCFs) as a next step to increase further the submarine cable capacity.

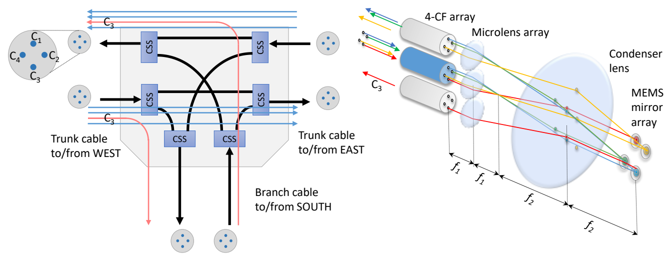
However, if the conventional BU architecture continues to be employed in SDM submarine systems, several problems will arise [4]. First, the required number of fiber switches in a BU will increase with the number of SMF pairs in the trunk cable and will consume the limited space in the BU. Second, since in the conventional BU architecture double the number of SMF pairs in the trunk cable is required in the branch cable, submarine systems employing such a BU architecture will be costly, especially if the branching cable is long and requires many repeaters. Third, if MCFs are introduced to submarine cables, the conventional BU architecture will require a fan-in fan-out (FIFO) device for each MCF to demultiplex cores spatially in an MCF into SMFs, which will incur additional cost and insertion loss.

In this paper, we propose BU architectures based on core selective switches (CSSs) [5], which represent a novel optical switch directly supporting MCFs, and an efficient bidirectional core assignment to address the above issues.

2. CSS Based BU Architectures

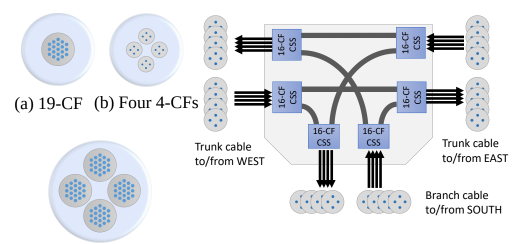
2.1. Basic Architecture of CSS-Based BU

Figure 1(a) shows the proposed BU architecture based on a 1×2 CSS, where the trunk cables and the branch cable comprise a pair of uncoupled four-core fibers (4-CFs). Note that an uncoupled 4-CF with a standard 125-μm cladding is expected to be the earliest commercialized SDM fiber due to its higher degrees of reliability and compatibility with the current SMF-based optical transmission technology [6]. We assume that cores in the 4-CF are numbered from C_1 to C_4. A 1×2 CSS is a one-input MCF and two-output MCF device where an optical signal launched into any core in the input MCF can be switched to a core that has the same core number of any of two output MCFs. The figure illustrates this by arranging three CSS pairs in a *route-and-select* configuration, where an optical signal transmitted through C_3 in the trunk 4-CF from the west is dropped to the branch 4-CF to the south. Figure 1(b) shows an implementation of the 4-CF 1×2 CSS. By placing a CSS pair on the branching side as well, the number of 4-CFs required for the branch cable remains the same as the number of 4-CFs required for the trunk cable, resulting in a significant cost savings. This BU architecture requires only six CSSs and no FIFO devices.



(a) BU architecture supporting 4 cores per direction (b) 1 × 2 CSS configuration

Fig. 1. Basic CSS based BU architecture.



(c) Four 19-CFs (d) BU architecture supporting 16 cores per direction

Fig. 2. High-core count CSS based BU architecture.

2.2. *High-Core-Count CSS-Based BU*

So far, a 1×8 CSS prototype supporting five cores per port has been reported, in which the CSS exhibits low insertion loss (1.2 dB~2.7 dB) and low polarization dependent loss (< 0.25 dB) over an ultrawide wavelength range (1480 nm to 1630 nm) [5]. Considering that commercial submarine cable systems support up to 24 trunk SMF pairs, it will be most likely required that ten or more cores be supported by a CSS in a BU. A straightforward way to increase the core count in a CSS is to employ a high-core count MCF, for example, a 19-core fiber as shown in Fig. 2(a), which may enable us to achieve a BU supporting four 4-CFs as shown in Fig. 2(d). Another way is to use several 4-CFs as a bundle and collimate/demultiplex beams emitted from it all at once using a single microlens as shown in Fig. 2(b). A further increase in the number of cores is expected by using both schemes together as shown in Fig. 2(c), where 19 4-CFs, 76 cores in total, can be accommodated based on calculation.

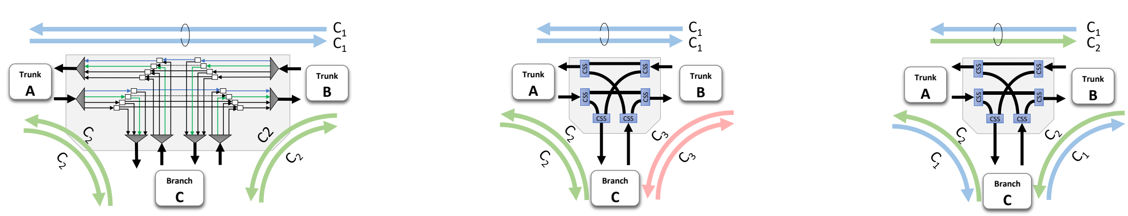
2.3. *CSS-Based BU Architecture Employing Broadcast-and-Select Configuration*

Reliability is an essential requirement in submarine cable systems. One way to enhance the CSS-based BU reliability is to employ a *broadcast-and-select* configuration by replacing ingress 1×2 CSSs with passive 1×2 MCF splitters. Note that the 1×2 MCF splitter should be specially designed so that both output ports provide horizontal flipping in the core position to restore the flipping that occurs in the egress CSS.

3. Efficient Bidirectional Core Assignment

3.1. *Estimation of Minimum Required Number of Cores*

Consider a submarine network topology where a single BU is implemented between three landing stations. Assume that (i) there exist bidirectional spatial channel (SCh) connection requests between any two stations and (ii) SMF pairs or an MCF pair are used to accommodate them. An SCh is an optical channel in the SDM layer that is constructed by connecting cores in each SDM link on a route. For the conventional BU architecture shown in Fig. 3(a), the required minimum number of cores, N_{min}, to establish all SChs is two if cores with the same core numbers are assigned in both directions by convention (*same core assignment*). If the CSS-based BU architecture and the conventional *same core assignment* are employed, N_{min} increases to three to avoid the core contention that



(a) Conventional BU with *same core assignment* (b) CSS-based BU with *same core assignment* (c) CSS-based BU with *different core assignment*

Fig. 3. Required minimum number of cores for conventional and CSS-based BUs.

Table 1. Required Minimum Number of Cores

		Conventional BU	CSS-based BU	
		Same core assignment	*Same core assignment*	*Different core assignment*
N_{min}	for even M	$M^2/4$	$(M^2+2M-4)/4$	$M^2/4$
	for odd M	$(M^2-1)/4$	$(M^2+2M-3)/4$	$(M^2-1)/4$

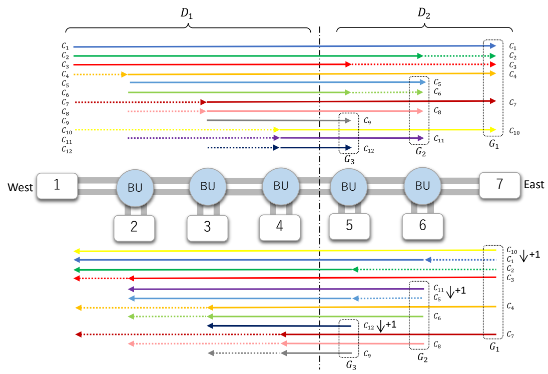


Fig. 4. Bidirectional core assignment heuristic.

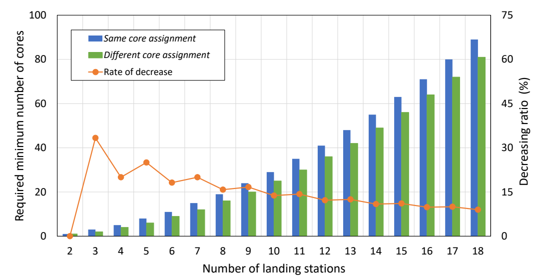


Fig. 5. Required minimum number of cores.

may occur by sharing a branch MCF between eastward and westward SChs (Fig. 3(b)). This issue can be addressed by selecting the appropriate core numbers that are different for each direction (*different core assignment*) as shown in Fig. 3(c). The N_{min} value for a submarine cable system with M landing stations to accommodate SCh connection requests between any two stations is analytically calculated and summarized in Table 1. We confirm that N_{min} is consistent with the results obtained by solving a static core assignment problem that considers the core-continuity and non-core overlapping constraints using integer linear programming (ILP) for M up to eight.

3.2. Bidirectional Core Assignment Heuristic

We developed a bidirectional core assignment heuristic for submarine cable systems employing a CSS-based BU that is applicable to a larger number of landing stations. The objective of the heuristic is to minimize the number of cores needed to establish full-mesh SCh connections. The core-continuity and non-core overlapping constraints are imposed, but the constraint of assigning the same core to both directions is not imposed. Taking a submarine cable system with seven landing stations as shown in Fig. 4 as an example, we describe how the core assignment heuristic works to establish bidirectional SChs. Assume that both trunk and branch cables comprise an MCF pair having cores numbered C_1, C_2, ... In this heuristic, a network is divided into two domains D_1 and D_2, and core assignment is conducted first for inter-domain connection requests in the uplink, and then for intra-domain connection requests. Since all SChs for inter-domain connection requests are established through the link between the domains, they must be assigned different cores to satisfy the non-core overlapping constraint. It should be noted that the 12 cores assigned at this stage equal the required minimum number of cores given by $(M^2-1)/4$. We search the available cores in ascending order of the core number and serve connection requests from lower-numbered stations to higher-numbered stations first. Then, cores are assigned to intra-domain connection requests using the *same core assignment* strategy, while reusing cores. Our next task is to establish SChs in the downlink using the 12 cores used for the uplink while avoiding core contention in the branch MCF. This can be achieved by (i) grouping all cores into sets of cores used by spatial channels destined for a station that is not the source of any SCh (See G_1 to G_3 in Fig. 4) and (ii) establishing downlink SChs while assigning cores in the same core group with the core number shifted by 1. Figure 5 shows the required minimum number of cores as a function of the number of landing stations, which is obtained by the core assignment heuristic. We confirm that the heuristic provides the same results as the ILP and analytical solutions.

4. Conclusions

We proposed CSS-based BU architectures and an efficient bidirectional core assignment heuristic that have the potential to increase the number of reconfigurable cores and halve the number of MCFs in branching cables in regional SDM submarine systems.

Acknowledgements

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