Spatial Channel Network (SCN): Introducing Spatial Bypass Toward the SDM Era

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Abstract: We review the spatial-channel network technology toward the spatial-division-multiplexing era from the viewpoints of network and node architectures, physical performance, network-resource utilization efficiency, and novel optical switches for modular and low-loss spatial cross-connects.

1. Introduction

Based on the extrapolation of recent compound annual growth rates of high-end router blades and other technologies used to generate and process data, the need for commercial 10-Tb/s optical interfaces working in 1-P b/s optical transport systems by around 2024 was recently predicted [1]. Since the optical-transport system capacity of 1-P b/s far exceeds the fundamental capacity limit of the conventional single mode fiber (SMF), there will be massive numbers of parallel SMFs and/or novel fibers with a new core structure, *e.g.,* uncoupled multi-core fibers (MCFs), between adjacent optical nodes. In addition, since optical channels having bit rates of 10-Tb/s and beyond will occupy almost the entire available spectrum in a conventional SMF, they will no longer require the wavelength switching layer. Considering the above-noted trend and recalling the introduction of an *optical bypass* when entering the wavelength abundant era in the early 2000s, we believe it would be natural to introduce a *spatial bypass* through a spatial channel cross-connect (SXC) rather than working on achieving larger-scale single-layer reconfigurable optical add drop multiplexers [2, 3] in the forthcoming massive space division multiplexing (SDM) era. According to these observations, a member of our research group recently reevaluated traditional hierarchical (or multi-granular) optical networks and proposed a spatial channel network (SCN) that employs a *spatial bypass* through a potentially cost-effective and low-loss SXC [4-10]. In this paper, we review the SCN technology from the viewpoints of network and node architectures and novel optical switches for modular, low-loss, and cost-effective SXCs.

2. SCN Architecture

Figure 1 shows an SCN architecture [4] where the SDM layer comprises SXCs and parallel spatial lanes (SLs), whose physical entities are single mode cores in SMFs and/or MCFs, and the wavelength division multiplexing (WDM) layer comprises wavelength cross-connects (WXCs) and frequency slots. An SXC and an overlying WXC form a hierarchical optical cross-connect (HOXC). The SXC performs SL level multiplexing and grooming and serves as the main switch in the HOXC. The WXC performs wavelength level multiplexing and grooming and serves as an edge switch in the HOXC. Following the definition of the optical multiplexing section (OMS) in a current optical transport network, which is defined between adjacent WXCs, a spatial multiplexing section (SMS) is defined between adjacent SXCs. In an SCN, a spatial channel (SCh) is defined as an ultra-high capacity optical data stream that is allowed to occupy the entire available spectrum of a core in an SMF or MCF. An SCh transports a single or multiple optical channels (OChs) that are spectrally aligned with the G.694.1 flexible grid paradigm as shown in Fig. 2. An SCh may include its in-band overhead information (SCh OH) such as source/destination node identification and is spatially

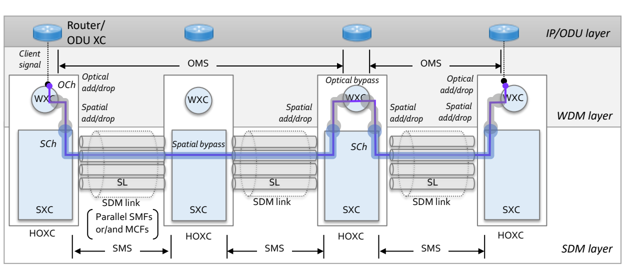

Fig. 1. Spatial channel network (SCN) architecture.

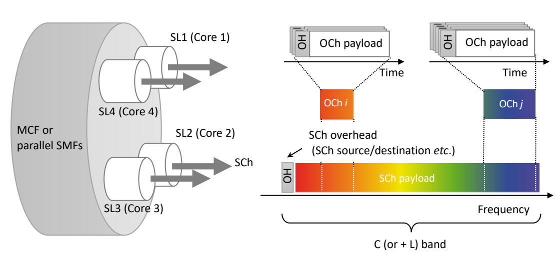

Fig. 2. Spatial channel (SCh) structure.

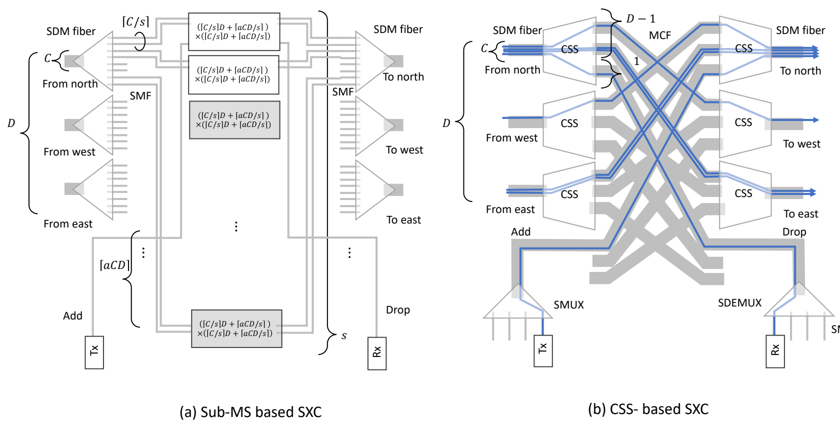

Fig. 3. Spatial channel cross-connect (SXC) architectures.

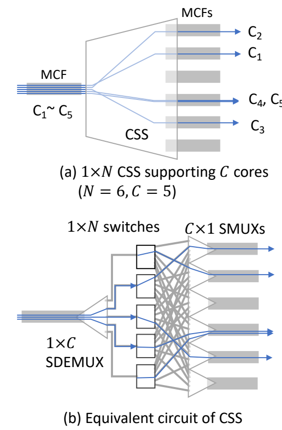

Fig. 4. CSS functionality and its equivalent circuit.

routed end to end as a single entity through SXCs bypassing the overlying WDM layer. If there is an insufficient amount of traffic between a source/destination pair, the corresponding OCh shares an SCh with other low-capacity OChs that have different source/destination pairs for better spatial resource utilization.

3. SXC Architectures

If we employ the traditional approach, a possible SXC architecture would be based on an $N \times N$ optical matrix switch (MS) connected in parallel with the secondary MS with optical splitters and optical 2×1 switches or $N \times M$ MSs configured to achieve a Clos network. Both of these are strictly non-blocking, however, their requirements for MSs are challenging. Even if we do not take the add/drop traffic into account, the former requires two ultra-high port count optical MSs in the order of $CD \times CD$ where C is the number of single mode cores per link and D is the node degree, while the latter requires large numbers of moderate size ($\sim C \times 2C$) MSs in the order of $2(C + D)$. In order to address the above problem in traditional SXCs, we proposed two types of growable and reliable SXC architectures as shown in Fig. 3 based on a sub-matrix switch (sub-MS) and a core selective switch (CSS), respectively. Both of these are designed to reduce the node complexity at the expense of introducing a reasonable connection constraint. A sub-MS is a small MS formed by dividing a full-sized MS into s sub-MSs, which can be achieved through commercially available MS technology. On the other hand, a CSS is a novel optical device as shown in Fig. 4 that is an SDM counter part of the conventional wavelength selective switch (WSS). A $1 \times N$ CSS supporting C cores comprises functionalities of a $1 \times C$ spatial demultiplexer (SDEMUX), $1 \times N$ switches, and $C \times 1$ spatial multiplexers (SMUXs). CSSs should be used in the route-and-select configuration in order to achieve a low-loss SXC, which will yield the added value of extending the optical reach for *spatially bypassed* OChs [4, 6].

A sub-MS based SXC architecture virtually divides an SCN that supports C SLs into s sub-SCNs and enables non-blocking connectivity in each sub-SCN while requiring fewer moderate-sized MSs. Fault-independent path protection can be achieved by choosing the working and backup SChs link and sub-MS disjoint each other. Similar to current WSS-based WXCs, there could be a wide variety of CSS-based SXC architectures in terms of add-drop part design. Figure 5 shows an SXC architecture example where a transceiver can be connected to any core of any direction so long as no transceiver is already connected to a core with the same core index. This connectivity can be expressed as *any-core access* and *non-directional* with *core contention*, while the connectivity of the SXC shown in Fig. 3(b) can be expressed as *fixed-core access* and *directional*. In order to achieve *any-core access* connectivity, we need another new optical switch called a *core selector* (CS), which is an SMF-input, MCF-output $1 \times C$ optical switch as show in Fig. 6. Although both the sub-MS-based and CSS-based SXCs have limited SL change capabilities, the techno-economic analysis presented in [7] showed that this limited capability exerts little influence on the total number of assigned SLs in unprotected and $1 + 1$ protected SCNs, while the architectures themselves yield significant total node cost reduction.

5. Architecture and Prototyping of Free-Space-Based CSS

A CSS could be built by using discrete commercially available optical devices arranged as shown in Fig. 4(b); however, it may be bulky and expensive. One way to achieve a compact and low-cost CSS would be employing free space optics. Figure 7 shows the free-space based architecture of a 1 × 6 CSS that supports 5-core MCFs. The CSS comprises two-dimensionally arranged input and output MCFs with collimating lenses (focal length f_1), a condenser lens (focal length f_2), and two-dimensionally arranged switching mirrors. Five beams launched from each core of an input MCF

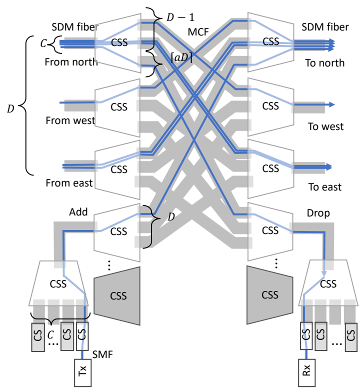

Fig. 5. CSS-based SXC architecture (*any-core access* and *non-directional* with *core-contention).*

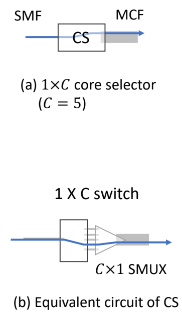

Fig. 6. CS functionality and equivalent circuit.

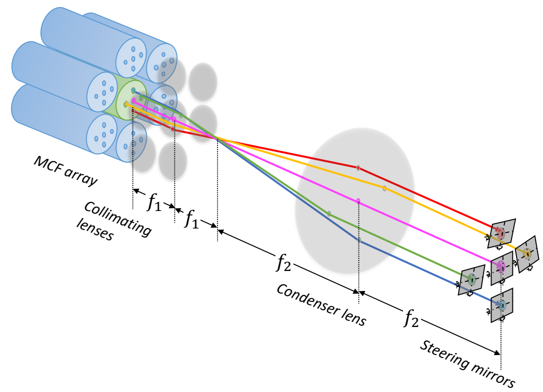

Fig. 7. Free-space based CSS.

converge to the same spot at the focus of the collimating lens at different angles. A condenser lens focuses each beam onto a different switching mirror according to its angle. By controlling the tilt of each mirror in two angular dimensions, a beam from any core of the input MCF can be connected to a core with the same index of any output MCF. We recently designed and prototyped a compact 5-core 1×6 CSS that incorporates an integrated input and output MCF array with spatial multiplexer/demultiplexers and a liquid crystal on silicon spatial light modulator [8,9]. Using the CSS prototype, we demonstrated spatial channel networking including spatial bypassing and spectral grooming of a 900-Gb/s spatial channel. It should be noted that since in practical SXC applications there is most likely no need to change seamlessly the switching area. Arrayed micro-electro-mechanical-system mirrors, which provide the polarization-independent beam steering with a larger steering angle, can be used as 2D switching elements.

6. SCN Networking Demonstration

In order to demonstrate the feasibility of spatial channel networking, we constructed a SCN testbed that comprises two types of low-loss HOXC prototypes based on sub-MSs and CSSs employing commercially available discrete optical devices [10]. Four HOXCs are connected to four-core MCFs to form a ring SCN. Bit-error-rate performance measurements for OChs confirmed that the proposed HOXCs enable spatial channel networking including spatial add-drop and spectral grooming, spatial bypassing with SL change, and spatial-channel protection with no optical signal-to-noise ratio penalty.

7. Conclusions

We reviewed the SCN architecture and its enabling technology as a possible facilitator for a reliable and cost-effective optical layer toward the forthcoming SDM era.

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