# Architectures of Spatial Add/Drop Multiplexer and Cross-Connect for Spatial Channel Networks

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***Abstract*—Architectures of spatial channel add/drop multiplexers and spatial channel cross-connects for future spatial channel networks are compared from the viewpoints of connection flexibility and node complexity.**

***Keywords—spatial-division-multiplexing, spatial-channel network, spatial channel cross-connects, optical switch***

## I. Introduction

In this decade, substantial research efforts have been focused on achieving larger scale single-layer reconfigurable optical add drop multiplexers (ROADMs) or wavelength cross-connects (WXCs) toward the forthcoming space division multiplexing (SDM) era [1, 2]. We should note that such larger scale ROADMs/WXCs are designed to be used in single-layer wavelength division multiplexing (WDM) networks and to handle traffic demands only at fine wavelength granularity. However, if we consider that optical channels (OChs) having bit rates of 10-Tb/s and beyond that will be needed in the next few to ten years [3] will occupy almost the entire accessible spectrum in a single mode fiber (SMF), it is quite clear that for such a ultra-high capacity OCh, the wavelength switching layer is no longer necessary.

In this context, we recently reevaluated traditional hierarchical (or multiglandular) optical transport networks and proposed a spatial channel network (SCN) architecture [4-8]. In an SCN, the optical layer evolves into hierarchical WDM and SDM layers and an optical node is decoupled into a spatial cross-connect (SXC) and a conventional WXC to achieve a hierarchical optical cross-connect. This hierarchical architecture will support a wide variety of traffic demands from the wavelength level to spatial level in a cost-effective manner [4]. This architecture also yields prominent extension of the optical reach for spatially bypassed OChs that passes through low-loss SXCs and suffers less accumulated amplified spontaneous emission noise [4]. We also proposed two types of growable and reliable SXC architectures based on a single stage sub-matrix switch (MS) and a core selective switch (CSS). In an SCN, we define a spatial lane (SL) in an optical link between adjacent SXCs whose physical entities are single mode cores in parallel SMFs or/and parallel multi-core fibers (MCFs).

In this paper, we discuss detailed SXC and reconfigurable spatial add drop multiplexer (RSADM) architectures based on MSs and core selective switches (CSSs) from the viewpoints of connection flexibility and node complexity.

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## II. Basic SXC Architectures

### A. Clos Network Based Configuration

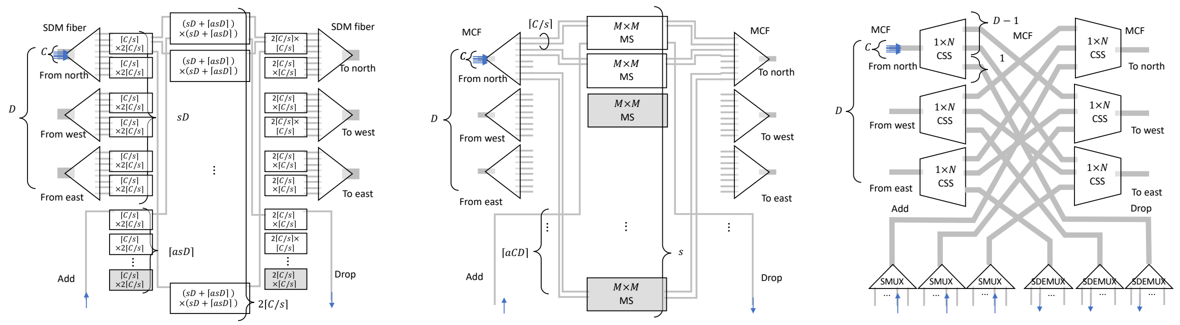
Fig. 1(a) shows an SXC architecture based on a Clos network. Here, $D$ input MCFs that support $C$ cores and $D$ output MCFs are connected to ingress and egress MSs via a $1 \times C$ spatial demultiplexer (SDEMUX) and a $C \times 1$ spatial multiplexer (SMUX). It is strict-sense non-blocking if the number of center MSs, $m$, is $\geq 2n-1$ where $n$ is the input port count of the ingress stage MS. The size of the ingress stage MS per MCF can be reduced by partitioning cores into $s$ core groups. In this architecture, we require a large number of MSs: $2(sD+\lceil asD \rceil)$ ingress/egress MSs with the size of $(\lceil C/s \rceil) \times (2\lceil C/s \rceil)$ and $2\lceil C/s \rceil$ center MSs with the size of $(sD+\lceil asD \rceil) \times (sD+\lceil asD \rceil)$ at the end of life (EoL), where $a$ is the add drop ratio [7].

### B. Sub-MS Based Configuration

We recently proposed an SXC architecture based on $s$ sub-MSs as shown in Fig. 1(b) [4, 5], which is designed to reduce the complexity of the Clos network at the expense of introducing a reasonable connection constraint. In this architecture, cores in an MCF are partitioned into $s$ core groups and each core group is accommodated in a different sub-MS with the size of $(\lceil C/s \rceil D+\lceil aCD/s \rceil) \times (\lceil C/s \rceil D+\lceil aCD/s \rceil)$. Here, a core that belongs to a core group can only be connected to a core in a different direction or a transceiver that belongs to the same core group. We refer to these constraints on the sub-MS based SXC as *partial any-core access* (partial AC), *non-directional* (ND), *contention-less* (CnL), and *partial lane change* (partial LC). Instead, this architecture achieves growability in terms of SLs and supports fault independent protection by choosing working and backup routes to be SDM link disjoint and sub-MS disjoint [7].

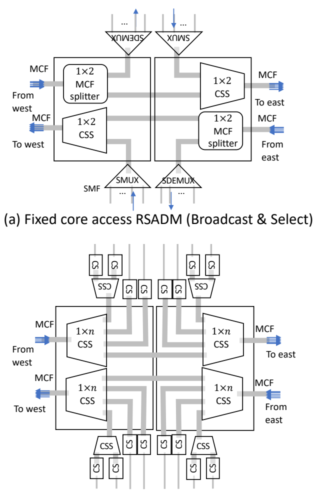
### C. CSS-Based Configuration

Fig. 1(c) shows another SXC architecture designed to address the node complexity problem by introducing a novel spatial optical switch referred to as a CSS. A CSS in an SCN provides functions equivalent to those provided by a wavelength selective switch (WSS) in a current WDM network. It has an input MCF and $N$ output MCFs where each MCF has $C$ cores in its cladding [4, 6]. Optical signals propagated through cores of the input MCF are spatially demultiplexed,




(a) Conventional SXC architecture based on Clos network (b) SXC architecture based on single stage sub-matrix switches (c) SXC architecture based on core selective switches

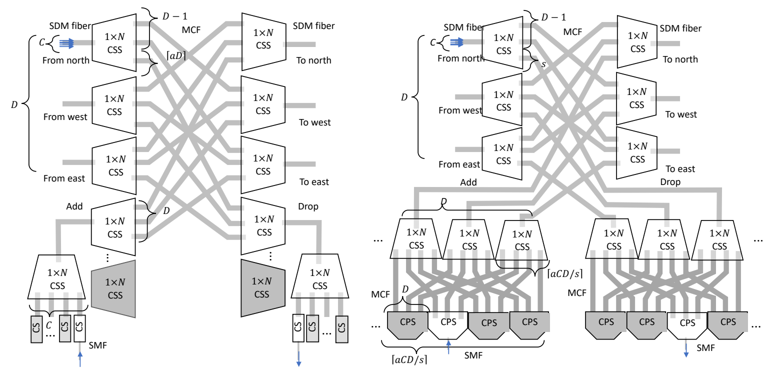
Fig. 1. Spatial channel cross-connect (SXC) architectures.




(a) Fixed core access RSADM (Broadcast & Select)

(b) Any core access RSADM (Route & Select)

Fig. 2 Reconfigurable spatial add drop multiplexer (RSADM) architectures.




(a) Any core access and non-directional SXC architecture with core contention

(b) Any core access, non-directional, and contention-less SXC architecture

Fig. 3. Flexible SXC architectures based on CSS.

routed, and spatially multiplexed into its designated output MCFs. In this SXC architecture, CSSs are arranged in the route and select configuration instead of broadcast and select (B&S) configuration to avoid the splitting loss of a $1 \times N$ MCF splitter ($\sim 1/N$) [4, 6]. A line-side CSS used in this architecture is a $1 \times D$ CSS whose $D - 1$ ports are for through signals and the remaining port that is linked to an SDEMUX (SMUX) is for local drop (add) signals. In this architecture, an unused input port on an SMUX can be connected to an unused core with the index associated to the SMUX input port on the egress MCF to which the SMUX is linked. This architecture provides *fixed core access* (FC), *directional* (D), CnL, and *non-LC* (NLC) features. Hereafter, we refer to this architecture as the SMUX-type. The required number of CSSs and associated mirrors for this architecture are $2D$ and $2CD$, respectively [7].

## III. RSADM Architectures

### A. FC RSADM

In the same way that WSSs were first introduced to a simple two-degree ROADM in WDM networks, the first application of CSSs in SCNs would be a simple two-degree RSADM as shown in Fig. 2(a). Instead of ingress CSSs in Fig. 2(a), simple $1 \times 2$ MCF splitters can be used to form a B&S configuration. This is because the insertion loss of a $1 \times 2$ MCF splitter ($\sim 3$ dB) may be comparable to that of a $1 \times 2$ CSS.

### B. AC RSADM

The AC functionality, which corresponds to the *colorless* functionality in current ROADMs achieved by employing a wavelength tunable transponder, can be introduced into an RSADM by implementing an additional novel optical device, the core selector (CS) [7], and increasing the number of add ports (drop ports) in an egress (ingress) CSS by $\lceil aC \rceil$ as shown in Fig. 2(b). A CS has an input SMF and an output MCF with $C$ cores in its cladding. It can be achieved by employing very simple free-space optics comprising a condenser lens and a micro-electro-mechanical system mirror. The implementation is expected to be very similar to that of a commercially available SMF-based $1 \times N$ optical switch. In this architecture, the input (output) port of an unused CS can be connected to an unused core on the egress (ingress) MCF to which the CS is attached. The number of add (drop) ports per direction can be expanded by cascading an additional CSS at an add (drop) port.

## IV. Flexible CSS-Based SXC Architectures

### A. AC ND CC CSS-Based SXC

Introducing client-side ingress (egress) CSSs with $D$ output ports and aggregation (distribution) CSSs with $C$ output ports each attached to a CS as shown in Fig. 3(a) allows us to connect a transmitter (receiver) to (from) any core of any egress (ingress) MCF unless core-contention occurs in the aggregation

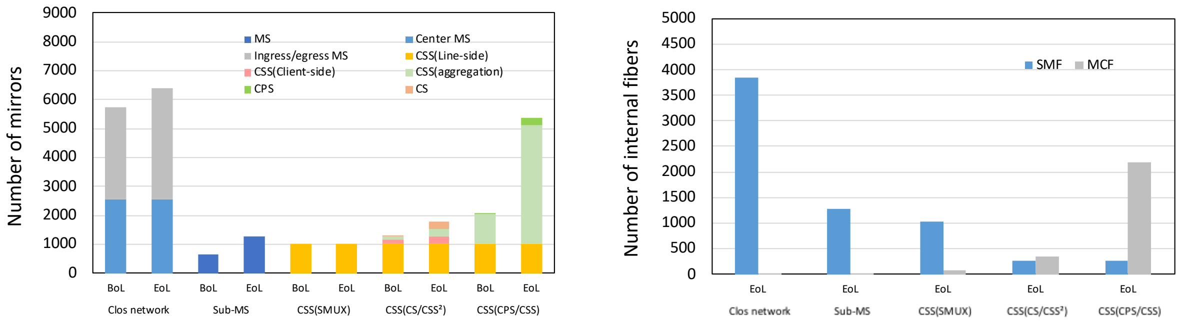



Fig. 4. Optical layer evolution scenarios toward SDM era.

(distribution) CSS. We refer to this architecture as the CS/CSS$^2$-type and categorize its connectivity as AC, ND, *core-contention* (CC), and NLC. The required number of line-side CSSs, client-side and aggregation CSSs, and CSs at the EoL are $2D$, $4\lceil aD \rceil$, and $2C\lceil aD \rceil$, respectively.

### B. AC ND CnL CSS-Based SXC

One way to eliminate the CC constraint to achieve highly automated end-to-end light-path provisioning is to introduce another novel optical device, the core/port selector (CPS) [7]. A CPS has an input SMF and $N$ output MCFs with $C$ cores in its cladding and can be achieved using simple free-space optics very similar to that of a CS. Fig. 3(b) shows a CPS/CSS-type SXC architecture that provides AC, ND, and CnL functionality where $1 \times (\lceil aCD/s \rceil)$ CSSs and $1 \times D$ CPSs form a $D \times \lceil aCD/s \rceil$ CSS for CnL add/drop ports. Although the architecture enables an input (output) port of an unused CPS to be connected to any unused core on any egress (ingress) MCF, it does require a large number of aggregation (distribution) CSSs as shown in Fig. 3(b).

## V. Comparison of SXC Architectures

Figs. 4(a) and 4(b) show the required total numbers of switching mirrors and internal fibers for the SXC architectures described in the previous section. Here, we use $D = 8$, $C = 64$, $a = 0.25$, and $s = 4$. The figures show that the strict-sense non-blocking connectivity in the Clos-network based SXC architecture is at the expense of a larger number of switching mirrors, internal SMF wiring, and consequently a higher node cost when compared to sub-MS based or CSS-based SXC architectures, which have a limited LC capability and some other connectivity constraints. Since it was shown in [7] that the limited LC capability requires a non-significant increase in the required number of SLs (1% to 12% increase for incremental traffic demand depending on network topology), the few percent increase may be acceptable for a less expensive node cost in sub-MS based or CSS-based SXC architectures.

The SXC requiring the fewest switching mirrors is the sub-MS based SXC at the beginning of life and the SMUX-type CSS-based SXC at the EoL. In the latter, an input (output) port of an SMUX (SDEMUX) is tied to a specific core in a specific direction, so each SMUX (SDEMUX) should have input (output) SMF ports for all $C$ cores. This is why it requires a large number of SMFs comparable to the former despite its smaller amount of internal MCF wiring.

While the CS/CSS$^2$-type SXC architecture achieves AC and ND connectivity, it requires CSs, client-side CSSs, and aggregation (distribution) CSSs. The total number of required switching mirrors at the EoL increases by 40% and the required number of internal fibers is reduced to 55% when compared to the SMUX-type CSS-based SXC. The CS/CSS-type SXC is able to eliminate the CC observed in the CS/CSS$^2$-type CSS and the total numbers of switching mirrors and internal fibers are still less than those for Clos-network based SXCs.

## VI. Conclusions

In this paper, we discussed a wide variety of SXCs toward the forthcoming SDM era, from the viewpoints of connection flexibility and node complexity. The answer to which SXC architectures will achieve techno-economical validity in future SCNs depends on many factors such as traffic patterns (dynamic or incremental), fiber types (parallel SMFs or MCF), and the maturity of support technologies (optical amplifiers, optical switches, SMUX, etc.) in future SCNs. There is no clear technological forecast to these factors at this time. Therefore, our answer must be conditional at this moment. Whichever SXC architecture that will be put to practical use, there is no doubt that future SCNs will require high capacity, cost-effective, and low-loss SXCs.

## References

[1] D. M. Marom, *et al.*, "Survey of photonic switching architectures and technologies in support of spatially and spectrally flexible optical networking," J. Opt. Commun. Netw., vol. 9, no. 1, pp. 1-26, 2017.

[2] R. Hashimoto, *et al.*, "First demonstration of subsystem-modular optical cross-connect using single-module 6 × 6 wavelength-selective switch," J. Lightw. Technol., vol. 36, no. 7, pp. 1435-1442, 2018.

[3] P. J. Winzer and D. T. Neilson, "From scaling disparities to integrated parallelism: A decathlon for a decade," J. Lightwave Technol., vol. 35, no. 5, pp. 1099-1115, 2017.

[4] M. Jinno, "Spatial channel network (SCN): Opportunities and challenges of introducing spatial bypass toward massive SDM era," J. Opt. Commun. Netw., vol. 11, no. 3, pp. 1-14, 2019.

[5] M. Jinno, T. Kodama, and T. Ishikawa, "Feasibility demonstration of spatial channel networking using SDM/WDM hierarchical approach for peta-b/s optical transport," J. Lightw. Technol., DOI: 10.1109/JLT.2020.2972367, 2020.

[6] M. Jinno, T. Kodama, and T. Ishikawa, "Five-core 1×6 core selective switch and its application to spatial channel networking," Proc. OFC 2020, M3F. 3.

[7] M. Jinno, "Spatial channel cross-connect architectures for spatial channel networks," IEEE Journal of Selected Topics in Quantum Electronics, DOI: 10.1109/JSTQE.2020.2975660, 2020.