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Impact of Connection Flexibility in Spatial Cross-Connect on Core Resource Utilization Efficiency and Node Cost in Spatial Channel Networks

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Abstract *Spatial bypassing and spectral grooming in a spatial channel network (SCN) achieve high resource utilization and cost-effectiveness. We show how spatial cross-connect architectures and the associated degree of connection constraints affect the required number of cores and the total node cost of an SCN. ©2022 The Authors*

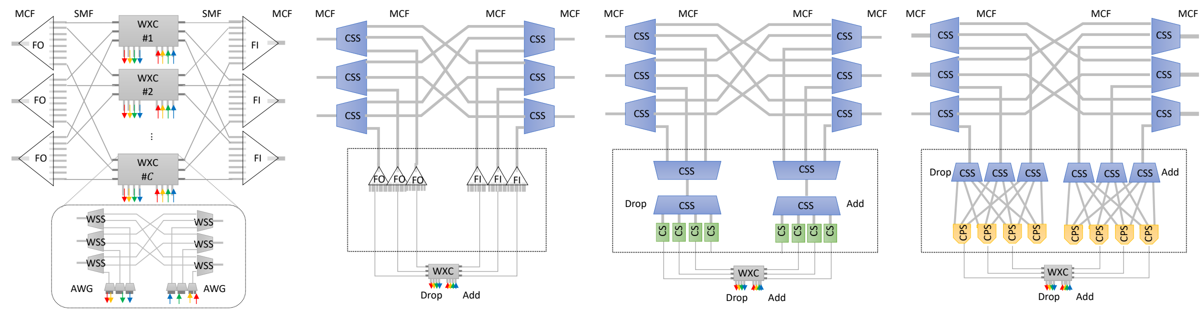
Introduction

The idea of a multigranular optical network with the coarsest granular fiber switching was already proposed at the end of the '90s [1]. As spatial division multiplexing (SDM) technology [2,3] began to gather much attention, some experimental demonstrations on multigranular (time, wavelength, and space) optical networks based on a multicore fiber (MCF) link and a high port count single-mode fiber (SMF) switch were reported [4-6]. The scalable and cost-effective spatial channel network (SCN) architecture was recently proposed [7-9], where the current optical layer evolves into wavelength division multiplexing (WDM) and SDM layers, and an optical node is decoupled into a spatial cross-connect (SXC) and a wavelength cross-connect (WXC) to form a hierarchical optical cross-connect (HOXC). SXCs and WXCs establish a spatial channel (SCh) and a wavelength channel (WCh), which are media channels in the SDM and WDM layers, respectively. A novel modular SXC architecture based on a core selective switch (CSS) [10-13] was also proposed. Here, a CSS provides the functionality to switch an optical signal launched into any core in the input MCF to a core that has the same core identifier of any output MCF.

One important benefit that the HOXC architecture will yield is a reduction in the total node cost by introducing potentially cost-effective coarse granular spatial switching in SXCs while maintaining a reasonably high spectral efficiency resulting from proper placement of WXCs in the network for spectral grooming. Members of our research group recently conducted a techno-economic simulation and showed that hierarchical spatial bypassing and spectral grooming in a CSS-based HOXC achieves both high resource utilization and cost-effectiveness at the total network traffic load of $\geq \sim 1$ Pb/s and higher [10].

In [10], the simplest SXC model is used, *i.e.*, CSSs are arranged in the route-and-select (R&S) configuration at the line side, and fan-in (FI) and fan-out (FO) devices are placed at the add/drop side. In this architecture, an input (output) port of an FI (FO) device is associated with a specific core number of the MCF heading in (coming from) a specific direction, which necessitates manual intervention when a connection change is requested. However, there is a wide variety of add/drop block architectures associated with connection flexibilities that are selected based on operator preference [15-19].

In this paper, we discuss how add/drop block architecture and the associated degree of connection constraint in SXCs affect the required number of cores per link and the total node cost in an SCN.



(a) Conventional stacked colored and directional WXC
(b) HOXC based on FC/D/CL SXC
(c) HOXC based on AC/ND/wC SXC
(d) HOXC based on AC/ND/CL SXC

Fig. 1: Optical node architectures that support multicore fiber links.

SDM Compatible Optical Node Architectures

Figure 1(a) shows the baseline stacked WXC architecture. In order to focus on SXC architectures, we assume WXCs that have the simplest colored and directional structure that employs 1×9 WSSs arranged in the R&S configuration and wavelength multiplexers and demultiplexers.

Figures 1(b), 1(c), and 1(d) show HOXC architectures based on the CSS. There is currently no commercially available CSS, however, free-space based 1×8 CSS prototypes supporting bundled three 5-core fibers per link [8] and a 19-core fiber (19-CF) per link [9] were recently reported. Figure 1(b) shows a CSS-based HOXC architecture with the simplest add/drop block in the SXC. In this architecture, CSSs are arranged in the R&S configuration and add-and drop MCF ports of CSSs are connected to FI and FO devices to provide SMF ports each dedicated to a specific core in a specific direction for the underlying WDM layer. Core-contention, which is described below, does not occur at any part in this architecture. We refer to this connection flexibility as *fixed core access, directional, and contention-less* (FC/D/CL).

One way to achieve *any core access* (AC) and *nondirectional* (ND) connectivity at the add/drop block of an SXC is to introduce two pairs of CSSs connected back-to-back whose client-side ports are attached to a core selector (CS) as shown in Fig. 1(c). Here, a CS is a novel spatial switch that provides the functionality to connect a core of the input SMF to any of *C* cores in the output MCF [12]. The add/drop block enables any WXC port to be connected to any client-side port of the SXC and any client-side port to be connected to any SXC line degree unless core contention occurs at the back-to-back connection of the CSSs, all without requiring manual intervention. We refer to this connection flexibility as AC and ND *with contention* (AC/ND/wC).

In order to eliminate the core-contention constraint in the add/drop block to achieve highly flexible end-to-end SCh provisioning by efficiently utilizing spatial resources in an SCN is to introduce another type of novel spatial switch, a core and port selector (CPS), as shown in Fig. 1 (d). Here, a CPS has an input SMF, multiple output MCFs, and provides a functionality to connect a core of an input SMF to any core of any output MCF. This type of add/drop block enables any WXC port to be connected to any client-side port of the SXC and any client-side port to be connected to any SXC line degree while avoiding core contention. We refer to this connection flexibility as AC, ND, and CL.

Tab. 1: Traffic model.

Traffic load (Pb/s)		Base bit rate	2 x	3 x	4 x	5 x
0.2	Bit rate (Tb/s)	0.2	0.4	0.6	0.8	1
	# of FSUs	1	2	3	3	4
0.4	Bit rate (Tb/s)	0.4	0.8	1.2	1.6	2
	# of FSUs	2	3	5	6	7
0.8	Bit rate (Tb/s)	0.8	1.6	2.4	3.2	4
	# of FSUs	3	6	9	11	14
2	Bit rate (Tb/s)	2	4	6	8	10
	# of FSUs	7	14	20	26	33
3.2	Bit rate (Tb/s)	3.2	6.4	9.6	12.8	16
	# of FSUs	11	21	32	42	52
4	Bit rate (Tb/s)	4	8	12	16	20
	# of FSUs	14	26	39	52	65
Distribution (%)		0.36	0.26	0.18	0.12	0.08

Tab. 2: Node cost model.

Device	1x9 WSS	1x11 CSS (2x19CF/port)	1x8 CSS (2x19CF/port)	CS (2x19CF/port)	1x4 CPS (2x19CF/port)
Relative cost	1	0.90	0.86	0.11	0.15

Network, Traffic, and Node Cost models

We conduct SCN technoeconomic simulations for network model NSF15 (15 nodes, 23 links, and maximum node degree of 4).

We employ a mixed bit rate static traffic model, in which the bit rate required by each demand is an integer multiple of the base bit rate, and the proportion of demand at a certain bit rate decreases with the bit rate as shown in Tab. 1. Here, each bit rate is accompanied by the necessary number of 50-GHz width frequency slot units (FSUs) to accommodate a Nyquist WDM signal that comprises subchannels employing a modulation format of 32-Gbaud dual-polarization 16-quadrature amplitude modulation. Here, we assume that a core in an MCF provides 96 FSUs. The distribution in the last row of Tab. 1 shows the ratio of the traffic for each bit rate to the total traffic load shown in the leftmost column. We assume a uniform demand distribution for all the source/destination node pairs in the network.

Based on the cost analysis of optical devices comprising each optical node architecture in Fig. 1, we employ the cost model as shown in Tab. 2. In order to accommodate traffic loads up to 4 Pb/s, we assume CSSs that use a bundle of two 19-CFs for each input / output port, which support 38 cores per port [12,13]. Correspondingly, the MCF port of CS and 1×4 CPS is also configured by bundling two 19-CFs.

RSWA Problem and Heuristic

The routing and SDM/WDM multilayer resource assignment (RSWA) problem is to output the following.

- A spatial topology comprising intermediate WXCs connected by SChs needed to transport the set of demands,
- the route and core allocation for each SCh,

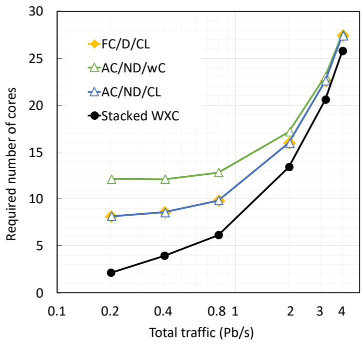


Fig. 2: Required number of cores N_c.

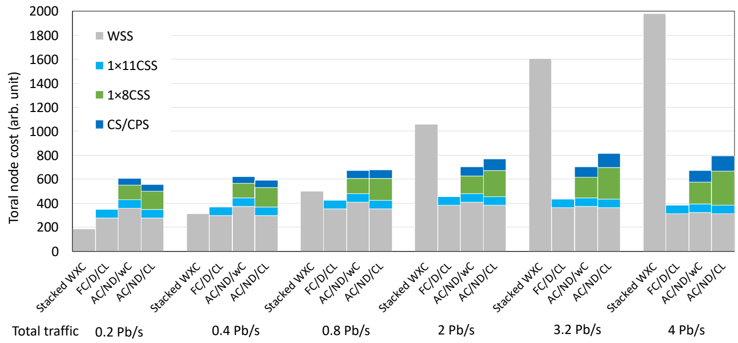


Fig. 3: Total node cost C_n.

- the route and spectrum allocation for each WCh in the spatial topology,
- network dimensioning including numbers of required cores, line-side 1×11 CSSs, client-side 1×8 CSSs, CSs, CPSs, and WXCs,

with the objective of:

- minimizing the required number of cores, N_c, of the most congested link in the network.

subject to the following constraints.

- Along with each SCh, a core for each link must not overlap that of other SChs,
- each core comprising an SCh must have the same core number,
- along with each WCh, FSUs must be contiguous to each other, must be the same for each link on the route, and must not overlap with those of other WChs, and
- for an AC/ND/wC SXC (Fig. 1(c)), SChs accommodated in the same add/drop CSS must not be allocated the same core number.

We developed a heuristic RSWA algorithm that has the following five steps[14]: (1) select a limited number of nodes as grooming nodes (GNs), (2) calculate *k*-shortest routes, (3) using a bin-packing heuristic, classify demands between a source/destination pair packed in a *frequency bin* when frequency filling ratio *h* exceeds the threshold into those carried end-to-end by a dedicated express SCh, and others into those carried by local SChs while being groomed by WXCs, (4) establish express SChs, and (5) establish local SCh(s), place WXCs, and establish a WCh.

Simulation Results and Discussions

In Fig. 2, simulation results of N_c as a function of the total traffic load in network T_{nw} are shown for the node architectures shown in Figs. 1(a)-1(d) (for short, we refer to them as stacked WXC, directional HOXC, HOXC with contention, and contention-less HOXC, respectively). Here, 6 of 15 nodes are selected as GNs, frequency filling ratio *h* is 80%, and the allowable number of frequency grooming is 3. In the area where T_{nw} does not exceed 0.8 Pb/s, N_c for the three HOXCs is much higher than that for the stacked WXC because a large amount of backhaul traffic from a non-GN to a GN requires many SChs and therefore consumes many cores. HOXC with contention always requires more cores than directional and contention-less HOXCs, *e.g.,* ~1.5x at 0.2 Pb/s, to allocate different core numbers for SChs accommodated in the same add (drop) CSS. As T_{nw} increases, N_c of the three HOXCs approaches that of the stacked WXC because traffic demands become efficiently packed into an express SCh. The difference in N_c between the HOXCs with and without contention becomes insignificant (<1% at 4 Pb/s) because increasing the number of cores used for existing SChs increases the chance of finding a feasible core that avoids the contention.

Simulation results of total node cost C_n are shown in Fig. 3 along with the cost breakdown of its components. Cost C_n of the stacked WXCs is the lowest in most cases until T_{nw} exceeds 0.8 Pb/s, but after that it increases more rapidly than those for HOXCs and becomes 4 times that of the directional HOXC at 4 Pb/s. HOXC with contention is slightly more expensive than that for the contention-less HOXC at a low traffic load because a higher number of WXCs is required to avoid contention. However, C_n of the HOXC with contention becomes 16% less than that for the contention-less HOXC at 4 Pb/s, due to a more gradual increase in the number of add/drop CSSs.

Conclusions

Simulation results show that (1) introducing any-core-access and nondirectional features does not compromise the cost advantage of the CSS-based HOXC over the conventional stacked WXC. The results also show that (2) the HOXC with contention requires more cores than the contention-less HOXC at a low traffic load (~1.5x at 0.2 Pb/s); however, the difference becomes negligible (< 0.1%) at a high traffic load of 4 Pb/s while it requires a 16% lower node cost.

Acknowledgements

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