NODE ARCHITECTURE AND DESIGN OF SPATIALLY JOINTED FLEXIBLE WAVEBAND ROUTING OPTICAL NETWORKS

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Abstract

A novel node architecture for spatial-division-multiplexing networks that adopts spatially jointed flexible optical path grouping followed by core-wise path group switching is proposed. Numerical experiments elucidate that almost ideal routing performance is realized while reducing WSS number by up to 54-73 %.

1 Introduction

The rapid and ceaseless traffic growth [1] encourages research for capacity expansion of optical networks. Historically, the introduction of WDM transmission substantially increased fibre capacity and cost-effectiveness as it shared expensive components including optical amplifiers among multiple wavelength paths. However, the fibre capacity expansion is becoming saturated and approaching the theoretical limit [2]. Aiming at further capacity expansion and cost-effectiveness, three important optical transport technologies that utilize spatial division multiplexing (SDM) are being studied; multi-core/multi-mode fibres [3-5], spatial joint switching by wavelength selective switches (WSSs) [6,7], and optical amplifiers that accept multi-core fibres [8,9]. Strategies for introducing all or some of these technologies for optical parallelism and the evaluation of their impact must be studied to realize smooth migration to future bandwidth-abundant optical networks

The increment in the number of fibres connected to a current optical cross-connect (OXC) node to cope with the traffic growth highlights the scalability issue of optical nodes; the number of WSSs in a node increases approximately in the square of node degree [10]. Thus reducing WSS number by the use of spatial joint switching would an attractive solution to resolve this difficulty [6]. However, if spatial joint switching is added to conventional WSSs, all MCF cores are connected to the WSS. While WSS degree is reduced approximately by "1/(# of cores)", we need to cascade such spatially joint switching WSSs (JS-WSSs) to compensate the degree reduction. Therefore, we need an efficient solution for the dilemma between the WSS sharing by spatial joint switching and the WSS number increment due to WSS cascading.

We have recently proposed an optical network architecture with novel routing strategy named flexible waveband routing (FWR) [11]. FWR nodes utilize WSSs as dynamic optical filters to bundle optical paths into several groups, which are called flexible wavebands, and dedicated optical switches are responsible for routing them. Its notable advantage is that WSS degree is kept small and constant regardless of node scale. Numerical simulations on several topologies elucidate that FWR substantially reduces the number of WSSs needed.

In this paper, we propose a novel node architecture which adopts spatially jointed FWR (SJ-FWR). SJ-FWR nodes set JS-WSSs at the input ports to realize spatially jointed grouping of optical paths in input MCFs. The optical switches then conduct core-wise switching of these path groups, flexible wavebands, to output MCFs. The novel spatially jointed path grouping combined with core-wise switching substantially reduces hardware scale. For example, the number of 1x41 WSSs, can also be used as 7-core 1×5 JS-WSSs, necessary to realize a 16×16 OXC for 7-core fibre networks, is reduced by 75%. Moreover, the degree of JS-WSSs is determined by the number of flexible wavebands in the multi-core fibre, so SJ-FWR resolves the difficulty in realizing high-degree JS-WSSs and also achieves better scalability. Numerical evaluations on several topologies elucidate that SJ-FWR matches the routing performance of spatial joint switching nodes.

2. Optical node architecture that adopts spatially jointed flexible wavebanding followed by core-wise switching

In this paper, we focus on optical networks whose links consist of multi-core fibres (MCFs) with uncoupled M cores to represent the optical transport with spatial regular parallelism. We refer to such networks MCF networks to distinguish them from conventional optical networks with single mode fibre (SMF) links. Although a generalization of the following discussion to spatial super-channels over multiple cores is straight-forward, we restrict our attention to conventional channels/paths which are accommodated in one

Table 1. Numbers of devices necessary for a K × K (MCF) / MK × MK (SMF) OXC with different node architectures

		Conventional	Spatial joint switching	Core-wise switching	Flexible waveband routing	Spatially jointed flexible waveband routing
Fiber type		SMFs	M-core MCFs	M-core MCFs	SMFs	M-core MCFs
# of JS-WSSs / WSSs necessary	1x(MN-1) WSSs	$2MK\left\lceil\frac{MK-2}{MN-2}\right\rceil$		$2MK\left\lceil\frac{K-1}{MN-2}\right\rceil$	$2MK$	
	1x(N-1) JS-WSSs		$2K\left\lceil\frac{K-1}{N-2}\right\rceil$			$2K$
DC-type matrix switches	Size				$MK\times MK$	$K\times K$
	Number				B	MB

of the cores for notational simplicity. We assume that add/drop portions are common to all node architectures and they are responsible for path insertion and termination and power equalization among multiple cores. Hence, the target of this paper is the development of compact and cost-effective express parts of optical nodes in MCF networks by taking advantage of a regular structure such that each link consist of nM cores (n: a positive integer).

Figure 1(a) shows a conventional WSS-based optical node for conventional networks. The number of output ports of a WSS must be equal to or larger than the number of output fibres of the node which necessitates massive fibre interconnection between the input and output sides. Analogous to this architecture, conventional 1 × (MN − 1) WSSs as 1 × (N − 1) JS-WSSs for M-core MCFs can derive a node architecture with spatial joint switching (See Fig. 1(b)). The constraint for this node is that all channels with the same wavelength in an input MCF must be switched to the same output MCF. The other architecture, shown in Fig. 1(c), adopts core-wise switching. A channel in core #i of an input MCF can be switched to core #i of any output MCF. However, it cannot be switched to the other cores. This node is realized by stacking small conventional OXCs.

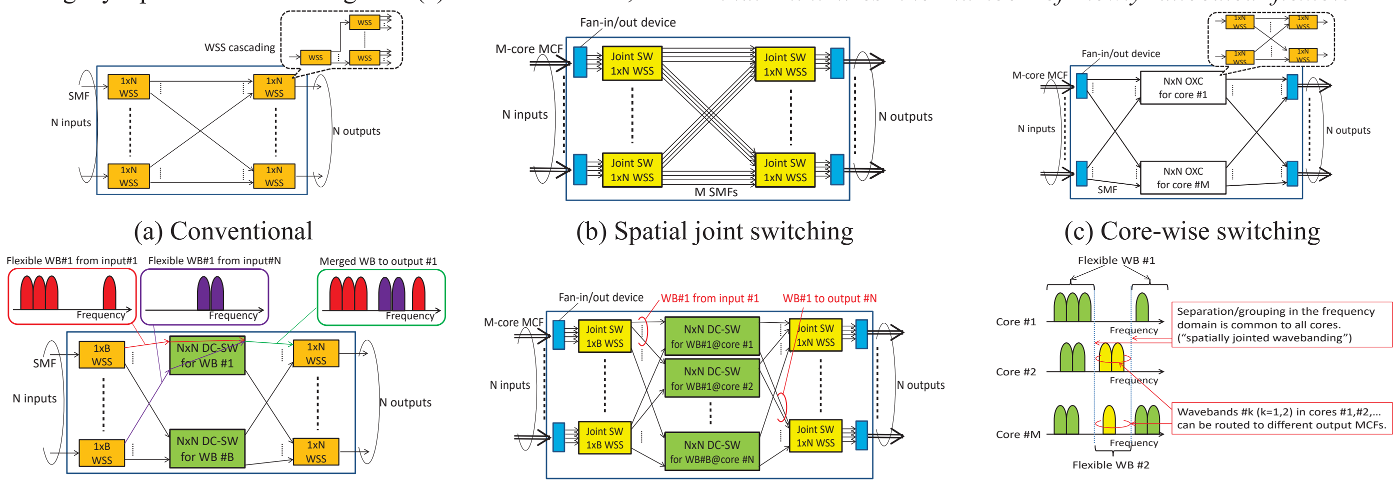
Figure 1(d) shows a flexible waveband routing node for conventional networks. This architecture combines dynamic path grouping by WSSs at the input side and path group routing by optical switches. Figure 1(e) shows SJ-FWR, it enables efficient routing in MCF networks. Optical paths incoming from an input multi-core fibre are grouped by a JS-WSS. The grouping operations are homogeneous among all cores of the MCF (See Fig. 1(f)). Each path group in a core is called a flexible waveband. These wavebands are routed by distribute-&-coupling type matrix switches. A dedicated matrix switch is assigned to each core, and hence, switch degree is kept small.

The numbers of WSSs necessary to realize a K × K (for M-core MCF links) / MK × MK (for SMF links) OXC with these architectures are shown in Table 1. As the number of cores/fibres connected to each node will be large in future networks that need SDM, the conventional and joint-switching architectures necessitate WSS cascading to increase WSS port count, which substantially enlarges the number of WSSs necessary. While the core-wise switching node needs more WSSs than the joint-switching one, the WSS port count needed is lower (i.e. 1 × K). The physical degree of a centre node in Fig. 2, i.e. the number of nodes adjacent to the centre node, is 8 and we assume that each link from/to the centre node consists of two 7-core MCFs/14 SMFs. Then the degree of the OXC at the centre node must be 16 × 16 for MCFs and 112 × 112 for SMFs. We assume that 1 × 41 WSSs/ 1 × 5 JS-WSSs are available. As the proposed architecture eliminates WSS cascading, the number of 1 × 5 JS-WSSs in a 16 × 16 node with 7-core MCF is reduced by 75% from the spatial joint switching node.

We have developed a sequential-heuristic-based network design algorithm that is aware of the spatially jointed wavebanding. Due to the space limitation, we summarize the algorithm.

<Design algorithm for spatially jointed waveband routing optical networks>

Sort given path setup demands in descending order of their length/hop counts. Then pick up a demand that has not been processed yet and find a pair of route and wavelength/frequency slot set that minimizes the number of fibres to must be newly installed to satisfy the demand. If multiple pairs minimize the fibre number, select the pair that minimizes the number of newly allocated flexible



(a) Conventional (b) Spatial joint switching (c) Core-wise switching

(d) Flexible waveband switching (e) Spatially jointed flexible waveband switching (Proposed) (f) Spatially jointed flexible wavebanding

Fig. 1. Node architectures

wavebands at nodes traversed. Establish the path on the selected route and wavelength/frequency slot set. Repeat this path accommodation procedure until all path setup demands are processed.

3 Routing performance evaluation

This section compares the routing performance of the proposed node architecture and conventional architectures for several topologies. The ITU-T flexible grid [12] is assumed and the available frequency bandwidth is set to 4.4THz in the C-band. The bandwidth is divided into 352 12.5GHz-width frequency slots. Traffic demand is given by a set of optical path setup demands whose source and destination nodes are selected randomly following a uniform distribution. The intensity of traffic is represented by the average number of optical paths between each node pair. Three optical path capacities are assumed; 100Gbps, 400Gbps, and 1Tbps which occupy, respectively, 4, 7, and 15 [13] slots. For each path setup demand, one of the three capacities is equally selected; i.e. the probability assigned to the selection of each capacity is 1/3.

Two conventional node architectures are compared; core-wise switching (Fig. 1(b)) and spatially joint switching (Fig. 1(c)). The latter is a special case of the proposed node architecture with $B = \infty$ where B is the maximum number of wavebands in a core. For each pair of traffic intensity value and node architecture, the number of fibres in a network is calculated 20 times and the results are averaged. In addition to a 5x5 regular mesh topology, three real topologies are adopted; USA (USNET) [14], Pan-European (COST239) [15], and Japan (JPN25) [16,17] which, respectively, consist of 24 nodes and 43 links, 19 nodes and 37 links, and 25 nodes and 43 links (See Fig.3). Considering the compatibility to networks, the number of cores per fibre is set to $M = 4$ [4] and 1x20WSSs / 4-core 1x4 JS-WSSs are used.

Figure 4 shows the result for the 5×5 mesh network. Fibre number increment (<+10%) is observed if the number of wavebands B is set to 2. However, the performance of the proposed architecture matches that of the original spatial joint switching node if the number of wavebands B is 3, 4, and 8. The core-wise switching is slightly (<4%) better than the joint switching at the highest traffic volume. Figures 5 shows the results for the three real topologies. Slight performance degradation relative to the 5×5 mesh network is observed in Pan-European and Japan which could be caused by the larger variation in node degree. However, the performance for $B = 3, 4, 8$ is still equivalent to that of the original spatial joint switching node. Although core-wise switching slightly better than joint switching and the proposed as observed in the above evaluation, considering the hardware scale difference shown in Table 1, the proposed architecture is most successful in resolving the trade-off between the cost-effectiveness and the routing performance on diverse situations. Indeed, bar graphs in Figs. 4 and 5 elucidate the number of WSSs reduced by 54-73% at the highest traffic volume.

4 Conclusion

A novel node architecture for spatial-division-multiplexing networks was proposed. The proposed architecture combines spatially jointed flexible optical path grouping realized by WSSs in the spatial joint switching mode and core-wise switching operation. With a tailor-made network design algorithm, sufficiently high routing performance is achieved even if WSS degree is kept low. In addition to sharing WSSs among multiple cores, the use of low-degree WSSs without cascading enables substantial hardware scale reductions which is not possible with conventional spatial-division-multiplexing optical nodes.

5 Acknowledgements

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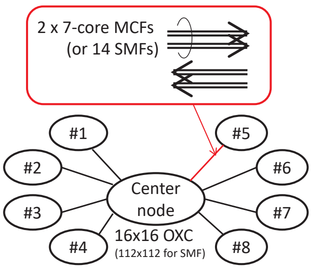


Fig. 2. 16x16 (for 7-core MCFs) / 112x112 (for SMFs) OXC at centre node.

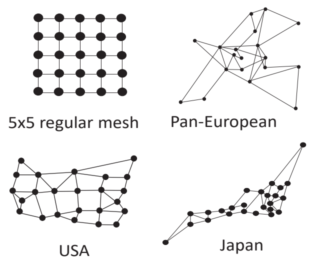


Fig. 3. Network topologies.

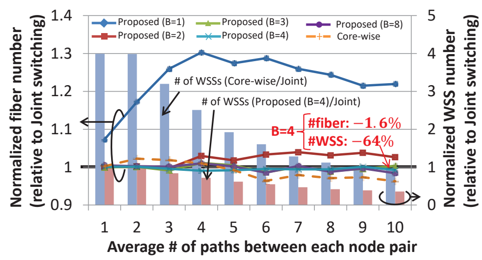
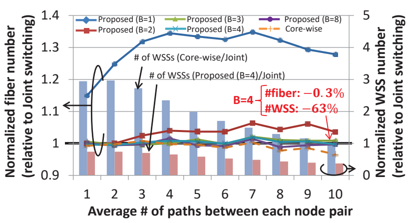
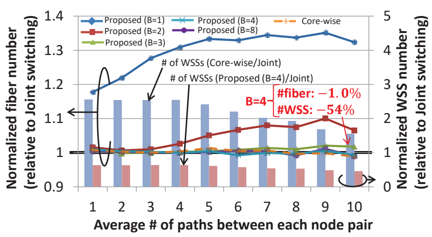


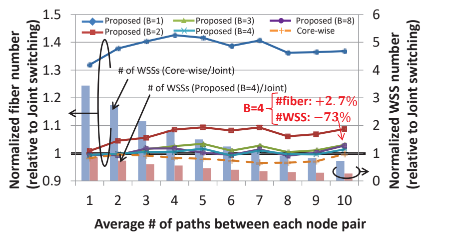
Fig. 4. Variation of normalized fibre/WSS numbers on the 5x5 regular mesh topology.



(a) USA



(b) pan-European



(c) Japan

Fig. 5. Variation of normalized fibre/WSS numbers on real topologies.

6 References

[1] ‘Cisco VNI’, http://www.cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/index.html, accessed 22 April 2019.

[2] Winzer, P. -J., ‘Scaling Optical Fibre Networks: Challenges and Solutions,’ OSA Optics & Photonics News,’ 2015, 26 (3), pp. 28-35.

[3] Koshiba, M., Saitoh, K., Kokubun, Y. ‘Heterogeneous multi-core fibres: proposal and design principle,’ IEICE Electronics Express, 2009, 6 (2), p. 98-103.

[4] Matsui, T., Sakamoto, T., Goto, Y., Saito, K., Nakajima, K., Yamamoto, F., and Kurashima, T. , ‘Design of 125 um cladding multi-core fibre with full-band compatibility to conventional single-mode fibre,’ ECOC2015, Sep. 2015, paper We.1.4.5.

[5] Takenaga, K., Matsuo, S., Saitoh, K., Morioka, T., Miyamoto, Y., ‘High-Density Multicore Fibres,’ OFC2016, Mar. 2016, paper, W1F.1.

[6] Nelson, L. E., Feuer, M. D., Abedin, K., Zhou, X., Taunay, T. F., Fini, J. M., Zhu, B., Isaac, R., Harel, R., Cohen, G., Marom, D. M., ‘Spatial Superchannel Routing in a Two-Span ROADM System for Space Division Multiplexing,’ IEEE/OSA Journal of Lightwave Technology, 2014, 32 (4), pp.783-789.

[7] Marom, D. M., Blau, M., ‘Switching solutions for WDM-SDM optical networks,’ IEEE Communications Magazine, 2015, 53 (2), pp. 60-68.

[8] Abedin, K. S., Taunay, T. F., Fishteyn, M., DiGiovanni, D. J., Supradeepa, D. J., Fini, V.R. J. M., Yan, M. F., Zhu, B., Monberg, E. M., Dimarcello, F.V., `Cladding-pumped erbium-doped multicore fibre amplifier,' OSA Optics Express, 2012, 20 (18), pp. 20191-20200.

[9] Takeshita, H., Matsumoto K., Yanagimachi, S., Taillandier de Gabory, E. Le, ‘Improvement of the Pump Recycling Ratio of Turbo Cladding Pumped MC-EDFA with Paired Spatial Pump Combiner and Splitter,’ OFC2019, Mar. 2019, paper Th1B.2.

[10] Iwai, Y., Hasegawa, H., Sato, K., ‘A large-scale photonic node architecture that utilizes interconnected OXC subsystems,’ OSA Optics Express, 2013, 21 (1), pp. 478-487.

[11] Hasegawa, H., Subramaniam, S., Sato, K., ‘Node architecture and design of flexible waveband routing optical networks,’ IEEE/OSA Journal of Optical Communications and Networking, Oct. 2016, 8 (10), pp. 734-744.

[12] ‘Spectral grids for WDM applications: DWDM frequency grid,’ ITU-T Recommendation G.694.1, Feb. 2012.

[13] Fresi, F., ‘Self-Adaptation Technique for Bandwidth-Variable Transponders,’ Photonics in Switching, 2015, paper THIII2.3.

[14] Gieselman, S. F., Singhal, N. K., Mukherjee, B., ‘Minimum-Cost Topology Adaptation for an IPS's Mesh Network,’ OFC/NFOEC, Mar. 2005, paper OTuP3.

[15] Wauters, N., Demeester, P., ‘Design of the optical path layer in multiwavelength cross-connected networks,’ IEEE Journal on Selected Areas in Communications, Jun. 1996, 14 (5), pp. 881-892.

[16] Sakano, T., Tsukishima, Y., Hasegawa, H., Tsuritani, T., Hirota, Y., Arakawa, S., Tode, H., ‘A study on a photonic network model based on the regional characteristics of Japan,’ IEICE Tech. Rep., 2013, vol. 113, pp. 1-6 (in Japanese).

[17] http://www.ieice.org/~pn/jpn/jpnm.html (in Japanese), accessed 22 April 2019.