Design and Performance Evaluation of Resilient Optical Path Networks That Adopt Spatially-Jointed Flexible Waveband Routing

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***Abstract*— We propose a survivable SDM optical network architecture that adopts dedicated path protection and spatially-jointed flexible waveband routing. With a proposed heuristics-based design algorithm that considers the limited number of flexible wavebands, we can achieve almost identical routing performance to conventional optical networks while reducing the hardware cost. Numerical simulations on several topologies elucidate that the number of flexible wavebands, equals to the degree of WSSs in the spatially-jointed switching mode, can be small. The total number of necessary WSSs is successfully reduced by 75%/91% relative to conventional SDM networks with core-wise/spatially-jointed switching nodes.**

Keywords—Flexible waveband routing, Spatially-jointed switching, Spatial-division multiplexing, Node architecture

I. Introduction

The standardization of the ITU-T flexible grid [1-3] and the following development of bandwidth-variable devices have enabled substantial channel capacity enhancements up to 400+Gbps. However, the continuous explosive traffic growth [4,5], accelerated by the outbreak of the Corona virus [5], exceeds recent optical fiber capacity enhancements which are approaching the theoretical limit [6]. Increasing the number of optical fibers on each link and using them in parallel will cope with explosion in traffic growth. Parallelism has been explicitly introduced with the recently developed spatial-division multiplexing (SDM) networks using multi-core/multi-mode fibers [7]; however we need to manage the multitude of cores/modes in each network. Thus the scalability of optical cross-connects (OXCs) to efficiently accommodate more fibers/cores/modes is a crucial issue. Conventional OXC nodes need wavelength selective switches (WSSs), whose degrees are equal to or higher than OXC port count and the number of WSSs used in an OXC is equal to its port count. Extremely high port count OXCs (100×100~) can be realized in theory, however massive interconnections between WSSs will be needed and the number of WSSs used will be greatly increased if we cascade WSSs (all of which have limited port counts) to fulfill the port count requirement.

As the number of paths will increase while the network topologies remain static, more paths will be routed together at each node. We proposed an OXC node architecture [8] that adopts a two-stage routing scheme; optical paths are bundled and routed as groups (flexible wavebands). Different from the conventional path hierarchy, any path group can form a flexible waveband regardless of center frequencies and bandwidths of paths. The path bundling operations are done by low port count WSSs acting as flexible demultiplexers. This OXC node architecture has been further improved to support SDM (spatial-division-multiplexing) realized using multi-core fibers (MCFs) with M uncoupled cores [9]. Greater cost-effectiveness and throughput were realized with the introduction of spatially-jointed switching; signals of multiple cores are switched together by a joint-switching WSS. A hardware scale analysis elucidated that the estimated OXC cost is reduced by over 50% for 4×4 and 21 core / MCF configuration [10]. Transmission experiments showed an OXC prototype with this configuration achieved the throughput of 2.15Pbps [11].

Survivability is one of the crucial goals of optical networks as they play a key role in our ICT society. Dedicated/shared path protection and restoration are simple but effective schemes to guarantee survivability [12,13]. Extensive studies have been done on conventional optical networks with path granularity switching [14-19]. On the other hand, reducing the hardware scale of optical nodes often relies on flexibility in the setting of routes for paths. Path routing is performed so that as many paths as possible go through the same or similar routes. Thus paths in an input core/fiber of a node tend to be routed to just a few output cores/fibers; multiple paths will be routed together as a bundle. Several optical network architectures with bundled path routing have been proposed so far; hierarchical optical path networks that introduce

This work is partly supported by NICT and NSF.

waveband routing [20-22], grouped routing networks [23,24], and fiber granular switching networks [25,26]. Our spatially-jointed flexible waveband routing nodes also take advantage of this strategy to realize substantial hardware scale reduction; however their flexible path grouping differentiate them from the other networks. The introduction of protection deteriorates the flexibility in routing; working and backup paths cannot share any node/link except for their end nodes. Therefore, we have to evaluate the performance degradation caused by route exclusion and confirm whether cost-effective nodes can achieve sufficiently high routing performance or not.

Motivated by the need for cost-effective implementation of resiliency to SDM optical networks, we propose survivable optical networks that adopt dedicated path protection and spatially-jointed flexible waveband routing. A design algorithm is developed for the proposed networks. Then, numerical simulations on several topologies confirm that the necessary number of flexible wavebands, which represents the trade-off between hardware scale and routing performance, will be still sufficiently small. The number of MCFs installed in a network to accommodate given path setup requests is adopted as a general metric for evaluating the routing performance of nodes. Spatially-jointed flexible waveband routing nodes successfully suppress the metric increment relative to conventional nodes, which need many WSSs, to 2%. The results also show that the spatially-jointed flexible waveband nodes reduce the total number of necessary WSSs in a network by 75%/91% relative to two different conventional nodes: core-wise switching nodes [27] and spatially-jointed switching nodes [7,28].

II. PRELIMINARIES

A. Assumptions

This paper assumes transparent optical path networks that adopt the ITU-T flexible grid [1]. The channel center frequency is on a grid with interval of 6.25GHz, and the frequency bandwidth is an integral multiple of 12.5GHz. Hereafter, the 12.5GHz width frequency assignment unit is called a frequency slot. Dedicated path protection is introduced for survivability; a pair of working and backup paths that share only their edges are established for each path setup request. Distance-adaptive modulation is not assumed; i.e. the modulation format will be common for paths of the same capacity regardless of their length. Neither wavelength conversion nor 3R regeneration is used.

Each link of a network consists of multi-core fibers (MCFs), either uncoupled M cores or M parallel single-mode fibers (SMFs), to represent optical transport with spatial

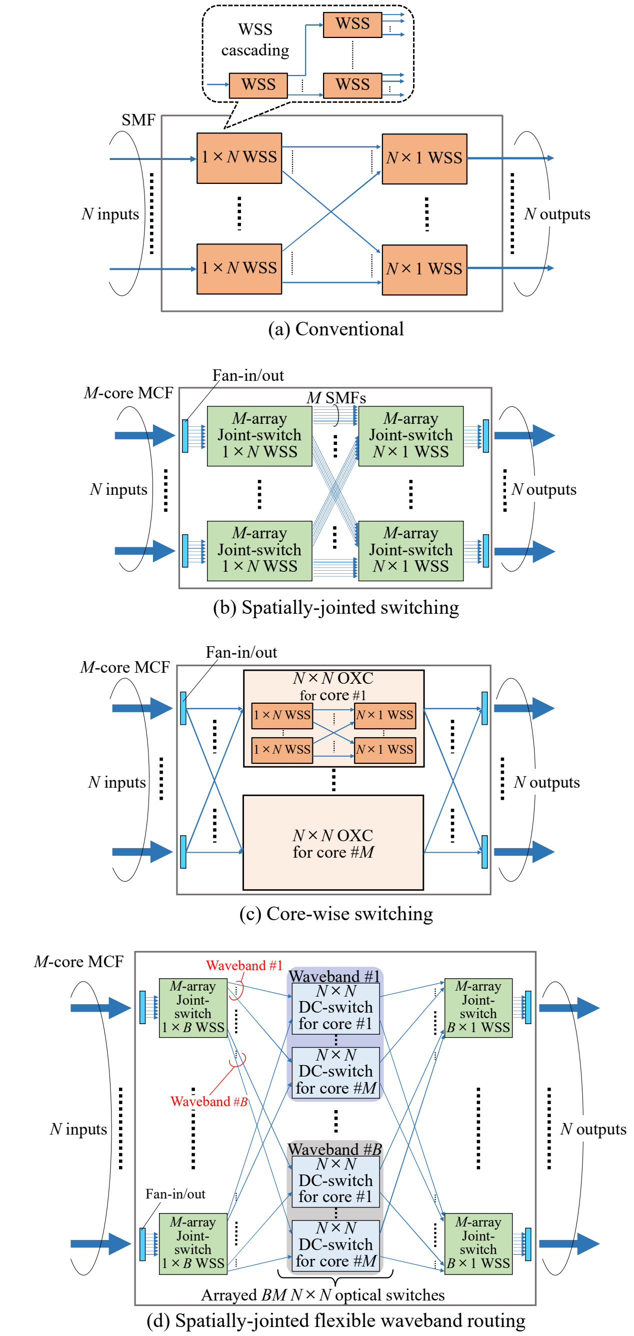


Fig. 2 $N \times N$ OXC node configurations.

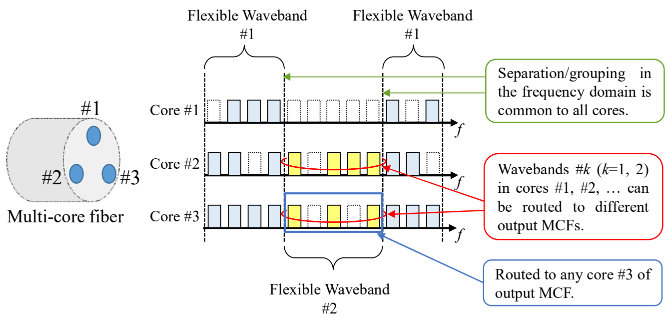


Fig. 3 Path bundling and routing for a MCF.
(e.g. $B = 2$)

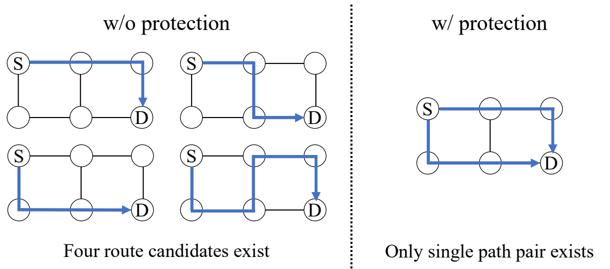


Fig. 1 Restriction of route selection by path protection.

Table 1. Numbers of devices necessary for a $N \times N$ (M-core MCF) / $MN \times MN$ (SMF) OXC with different node architectures [9].

		Conventional	Spatially-jointed 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	$1 \times (MK-1)$ WSSs	$2MN\left\lceil\frac{MN-2}{MK-2}\right\rceil$		$2MN\left\lceil\frac{N-1}{MK-2}\right\rceil$	$2MN$	
	$1 \times (K-1)$ JS-WSSs		$2N\left\lceil\frac{N-1}{K-2}\right\rceil$			$2N$
DC-type matrix switches	Size				$MN \times MN$	$N \times N$
	Number				B	MB

regular parallelism. We refer to such networks as MCF networks to distinguish them from conventional optical networks with SMF links. The following discussion is valid for spatial super-channels over multiple cores; however we restrict our attention to conventional channels/paths, which are accommodated in one of the cores for notational simplicity.

The survivability requested is achieved by the introduction of dedicated path protection. The route redundancy often restricts the flexibility in route selection (see Fig. 1). The routing performance of node architectures shown in Sec.II.B under the restriction will be compared using green-field design; networks are built from scratch to accommodate a given set of path setup requests. The number of fibers necessary is the primary performance evaluation metric and the hardware scale is the secondary metric.

B. *Spatially-Jointed Flexible Waveband Routing Optical Node Architecture*

Figure 2 shows express parts of optical nodes discussed in this paper. Common path-granular add/drop portions are assumed for all node architectures and hence omitted from Fig. 2. The add/drop portions are responsible for path insertion and termination along with power equalization among the multiple cores. A conventional WSS-based OXC node for SMF networks (Fig. 2(a)) assigns a WSS to each input/output SMF. Drawing an analogy to the conventional node, a node with spatially-jointed switching (JS) has been proposed for MCF networks (Fig. 2(b)) [7,28]. A $1 \times (MN-1)$ WSS is used as a $1 \times (N-1)$ JS-WSS for M-core joint-switching. Sharing the same JS-WSS by M cores makes the node more cost-effective than the conventional approach. An another node for MCF networks is shown in Fig. 2(c). This node consists of a set of small WSS-based OXCs; each of which is assigned to a different core. Routing performance was shown to almost match that the conventional WSS-based alternative [27].

Figure 2(d) shows the architecture that adopts spatially-jointed path grouping at JS-WSSs, followed by bundled path switching at distribute-&-coupling (DC) switches. Any combinations of paths can be grouped through appropriate WSS control; however, the switching must be common to all cores for each input MCF. We refer the bundled paths as flexible wavebands. Figure 3 describes an example of path bundling and routing. The frequency domains in all cores are commonly sliced by spatially-jointed switching and then each slice, a flexible waveband, is independently routed to the same core of an arbitrary selected output MCF. By taking advantage of the flexibility in route selection in mesh networks, paths to be similarly routed are accommodated to the same fiber. Then the number of wavebands, B, for each core can be small. Indeed, it has been shown that routing performance almost identical to the core-wise switching node (see Fig.2(c)) can be achieved with $B = 3$ [11]. However, equivalent routing performance for path-protected cases, which often significantly restricts the flexibility in route selection, has not been verified to date.

Table 2. Parameters of network topologies.

Network topology		5×5 regular mesh	Pan-European	USNET
# of nodes		25	19	24
# of links		40	37	43
Node Degree	Max.	4	7	5
	Min.	2	2	2
	Ave.	3.2	3.89	3.58
Max. # of shortest hops		8	8	6

Hardware scale analysis in terms of the numbers of WSSs and DC switches necessary is shown in Table 1. The degree of WSSs/JS-WSSs is assumed to be $1 \times (MK-1)/1 \times (K-1)$ as the degrees of WSSs and nodes can be different. The WSS cascading will be necessary if $MK - 1 < N$ and $K - 1 < N$ respectively for core-wise switching and spatially-jointed switching as necessary WSS degrees depend on the number of fibers connected to the nodes. On the other hands, the number of wavebands, B, is generally small and satisfies $MK - 1 \geq K - 1 \geq B$, and hence, no WSS cascading is not assumed for the proposed.

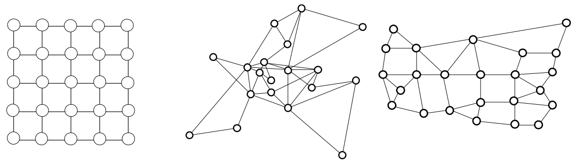
III. Design of Survivable SDM Networks That Adopt Spatially-Jointed Flexible Waveband Routing

In optical networks that adopt flexible waveband routing, path routing must be carefully handled as each input fiber is bounded in terms of the number of wavebands. Even for conventional fix-grid optical networks, the calculation of optimal assignment of route and wavelength is NP-complete. Thus the introduction of flexible grid and path grouping for the proposed node make the optimal routing and spectrum assignment extremely hard. A heuristics-based network design algorithm is proposed in this section that keeps the number of flexible wavebands, B, to a relatively small number even though the dedicated path protection reduces the room for route selection of paths.

For a path whose source and destination nodes, route, and frequency slot set are $\mathrm{s}, \mathrm{d}, \mathrm{r}, S$ respectively, we let $\mathrm{w}(\mathrm{s}, \mathrm{d}, \mathrm{r}, S)$ be the weighted sum of the number of hops h, that of newly established fibers f, and that of wavebands in which nodes are newly reserved g ; $\mathrm{w}(\mathrm{s}, \mathrm{d}, \mathrm{r}, S) = \alpha \mathrm{h} + \beta \mathrm{f} + \gamma \mathrm{g}$. The weighting values α, β, γ should be determined to satisfy $\beta > \max\{\alpha, \gamma\}$, since fiber increment must be avoided as much as possible. The design algorithm is summarized below.

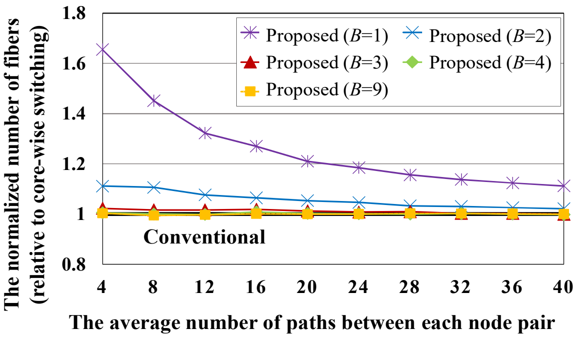
<Design Algorithm of Path-Protected Flexible Waveband Routing Optical Networks >

Step 1. For each node pair (s, d), find a set of route candidates $\mathrm{R}(\mathrm{s}, \mathrm{d})$ from s to d by the k-shortest route

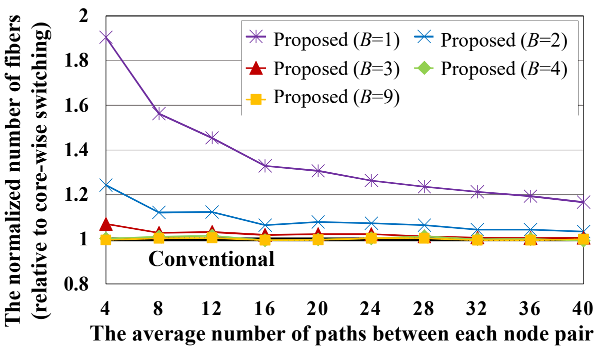


(a) 5 × 5 regular mesh (b) Pan-European (c) USNET

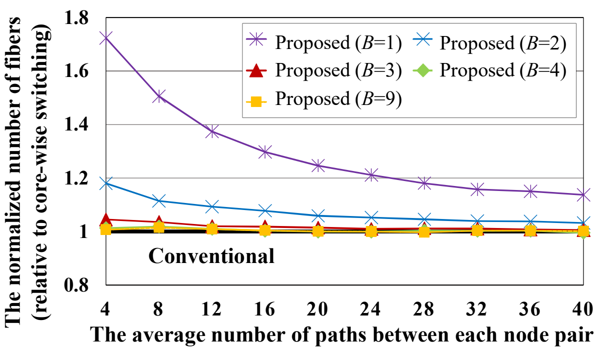
Fig. 4 Network topologies.



(a) 5×5 regular mesh



(b) Pan-European



(c) USNET

Fig. 5 Variations of number of 4-core MCFs relative to core-wise switching networks.

algorithm. For each route candidate, $r_c \in \mathrm{R}(\mathrm{s},\mathrm{d})$, remove all links and intermediate nodes of r_c from the given topology. Find the shortest route $\overline{r_c}$ on the residual topology by Dijkstra's algorithm. If found, let $(r_c, \overline{r_c})$ be a route pair candidate. Let the set of all route pair candidates found for (s,d) be $\mathrm{P}(\mathrm{s},\mathrm{d})$. Sort all route pair candidates in $\mathrm{P}(\mathrm{s},\mathrm{d})$ in ascending order of the distance metric (total hop counts or length).

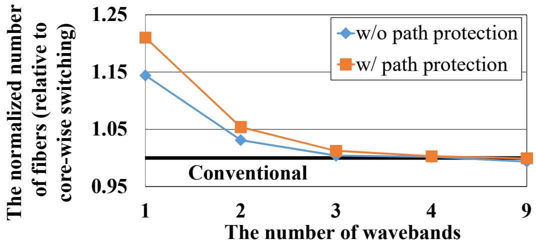
Step 2. In descending order of distance metric between source and destination node pairs, sequentially accommodate path establishment requests between node pairs. For each path accommodation, calculate $\mathrm{w}(\mathrm{s},\mathrm{d},\mathrm{r}_w,S_w) + \mathrm{w}(\mathrm{s},\mathrm{d},\mathrm{r}_b,S_b)$, where s and d are source and destination nodes, respectively, $(\mathrm{r}_w,\mathrm{r}_b) \in \mathrm{P}(\mathrm{s},\mathrm{d})$ is a route candidate pair, and (S_w,S_b) is a pair of frequency slot sets to be occupied by the path pair. Select the route pair minimizing $\mathrm{w}(\mathrm{s},\mathrm{d},\mathrm{r}_w,S_w) + \mathrm{w}(\mathrm{s},\mathrm{d},\mathrm{r}_b,S_b)$ and use the pair to establish a pair of working and backup paths. Install new fiber whenever necessary for path establishment.

IV. Routing Performance Evaluations

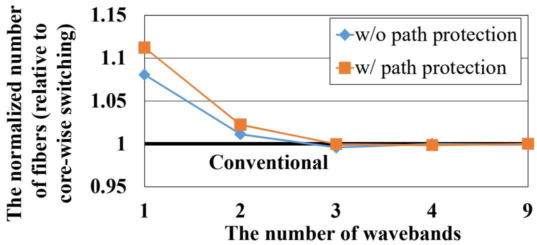
In order to verify the routing performance of the spatially-jointed flexible waveband routing nodes for path-protected scenarios, comparisons with the other nodes in Sec.II.B are performed below. The available frequency bandwidth is set to 4.4THz (=352 × 12.5GHz-width frequency slots) in the C-band. 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. Optical path capacities are equally selected from 100Gbps, 400Gbps, and 1Tbps occupying 4, 7 [29], and 15 [30] slots; i.e. each capacity is assigned with the probability of 1/3.

The benchmarking alternative is the conventional core-wise switching shown in Fig. 2(c) as its routing performance is comparable to that of the conventional route-&-select node and is slightly better than that of the spatially-jointed switching node [9]. For each pair of traffic intensity value and node architecture, the number of fibers in the network is calculated 10 times and the results are averaged. In addition to a 5×5 regular mesh topology, two real topologies are examined; Pan-European network [31] and USA (USNET) [32] which, respectively, consist of 19 nodes/37 links and 24 nodes/43 links. (see Fig.4 and Table 2). Considering the recent development of MCFs whose diameters are compatible to existing SMFs, the number of cores per fiber is set to M=4, 7 [33,34].

Figure 5 shows the results for networks whose links use 4-core MCFs. The fiber number increment relative to core-wise switching MCF networks is less than +25% for all topologies when the number of wavebands, B, is set to 2. As B increases, the gap between conventional core-wise switching and spatially-jointed flexible waveband routing MCF networks decreases. Figure 6 shows the dependency of relative number of 4-core MCFs on B for two cases, where the average numbers of paths for each node pair are 20 and 40. Slight performance degradation relative to the 5×5 mesh network is observed for Pan-European and USNET which might be due to the larger variation in node degree. However, the performance for B=3,4,9 is still equivalent to the conventional with core-wise switching. The fiber number increment at the highest traffic volume case is less than +0.6% for all topologies when B is set to 3. These results elucidate that spatially-jointed flexible waveband routing nodes achieve almost identical routing performance to conventional nodes while keeping the degree of JS-WSSs relatively small.



(a) Average # of paths between each node pair = 20



(b) Average # of paths between each node pair = 40

Fig. 6 Dependency of relative number of 4-core MCFs on number of wavebands *B* on 5×5 regular mesh.

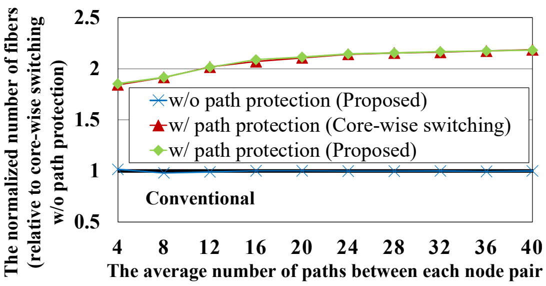


Fig. 7 Variations of number of 4-core MCFs on 5×5 regular mesh relative to core-wise switching networks w/o protection (*B*=4).

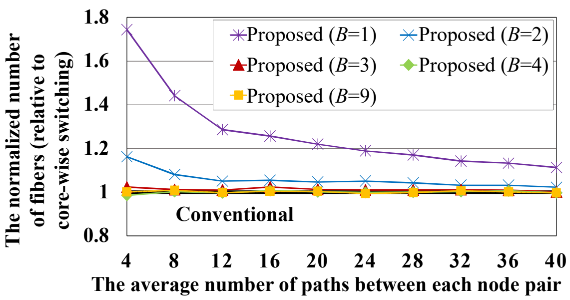


Fig. 8 Variations of number of 7-core MCFs on 5×5 regular mesh relative to core-wise switching networks.

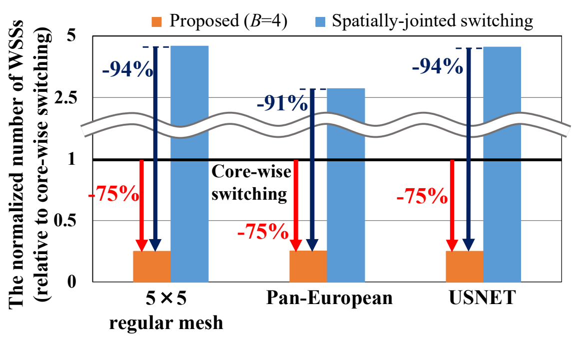


Fig. 9 Number of 1×20 WSSs/4 –core 1×4 JS-WSSs necessary at the highest traffic intensity relative to that of core-wise switching networks.

Figure 7 compares the number of MCFs relative to that of conventional without path protection. The number of wavebands, *B*, is set to 4. The ratios for conventional and proposed with protection are less than 2 when the traffic intensity is minimum as the capacity of MCF networks is large enough to accommodate all working and backup paths even when each link consists of a single MCF. The ratios slowly increase to 2+ due to the doubled number of paths and the possible detouring of backup paths. However the ratios saturate in the high traffic intensity area which shows that *B*=4 will realize almost ideal routing performance in the 5×5 regular mesh. The same trends were observed in the other topologies.

Figure 8 shows, for the 5×5 regular mesh, the variation of relative number of 7-core MCFs. Although the fiber capacity was enhanced, similar trend was observed. Spatially-jointed flexible waveband routing is still efficient for the path protected case if waveband number $B \geq 3$.

The relative number of WSSs necessary at the highest traffic intensity on each topology is shown in Fig. 9. The number for spatially-jointed switching node is also shown in this figure. The number of MCF cores is set to 4, and 1×20 WSSs/4-core 1×4 JS-WSSs are assumed. The number of wavebands, *B,* is set to 4. While the spatially-jointed flexible waveband routing node needs only one WSS for each MCF, the core-wise switching node needs one WSS for each core of the MCF. Thus the ratio between these two nodes will be determined by the number of cores. On the other hand, the JS-WSSs have small degree as the degree of the original WSS is divided by the number of cores of the MCF. For the spatially-jointed switching nodes, WSSs are inevitably cascaded to fulfill the port-count requirement, and hence, it needs more WSSs than the core-wise switching nodes. Although the spatially-jointed flexible waveband routing nodes only need relatively small port count JS-WSSs, they need DC space switches for waveband routing; however, DC space switches can be cost-effectively implemented with planar-lightwave-circuit technologies or silicon-photonics technologies [35,36]. For all topologies, the reduction ratio reaches 75% (relative to core-wise switching nodes) and 91% (relative to spatially-jointed switching nodes).

V. Conclusions

A SDM optical network architecture that assures survivability was proposed; it adopts dedicated path protection and spatially-jointed flexible waveband routing. A heuristics-based design algorithm was also proposed to reduce the fiber number and limit the number of flexible wavebands needed as well. Numerical simulations on several topologies showed that it almost matches the routing performance of conventional optical networks. The necessary number of flexible wavebands to achieve the performance was sufficiently small, and hence, the degree of WSSs in the spatially-jointed switching mode will be small. As a result, the hardware scale, total number of WSSs in a network, was successfully reduced by 75%/91% relative to conventional core-wise/spatially-jointed switching nodes.

REFERENCES

[1] ITU-T Recommendations, G694.1, 2012.

[2] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," IEEE Communications Magazine, vol. 47, no.11, pp. 63-73, Nov. 2009.

[3] H. Takara, K. Yonenaga, and M. Jinno, "Spectrally-efficient elastic optical path networks toward 1 Tbps era," Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, USA, pp. 1-3, Mar. 2012.

[4] https://www.cisco.com/c/dam/m/en_us/network-intelligence/service-provider/digital-transformation/knowledge-network-webinars/pdfs/1213-business-services-ckn.pdf (accessed: Jun. 11th 2021).

[5] https://www.soumu.go.jp/main_content/000699741.pdf (in Japanese)

[6] A. D. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear shannon limit," IEEE/OSA Journal of Lightwave Technology, vol. 28, no. 4, pp. 423-433, Feb. 2010.

[7] D. M. Marom, P. D. Colbourne, A. D'errico, N. K. Fontaine, Y. Ikuma, R. Proietti, L. Zong, J. M. Rivas-Moscoso, and I. Tomkos, "Survey of photonic switching architectures and technologies in support of spatially and spectrally flexible optical networking [invited]," IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 1, pp. 1-26, Jan. 2017.

[8] H. Hasegawa, S. Subramaniam and K. Sato, "Node Architecture and Design of Flexible Waveband Routing Optical Networks," IEEE/OSA Journal of Optical Communications and Networking, vol. 8, no. 10, pp. 734-744, Oct. 2016.

[9] H. Hasegawa, S. Subramaniam, and M. Jinno, "Node architecture and design of spatially jointed flexible waveband routing optical networks," European Conference on Optical Communication (ECOC), Dublin, Ireland, pp. 1-4, Sep. 2019.

[10] T. Kuno, Y. Mori, S. Subramaniam, M. Jinno, and H. Hasegawa, "High-throughput and high-port-count optical cross-connents using flexible waveband routing," International Conference on Optical Network Design and Modeling (ONDM), Barcelona, Spain, pp. 1-6, May 2020.

[11] T. Kuno, Y. Mori, and H. Hasegawa, "A 2.15 Pbps throughput optical cross-connect with flexible waveband routing," International Conference on Photonics (ICP), Kota Bharu, Malaysia, pp. 28-29, May 2020.

[12] J.-P. Vasseur, M. Pickavet, and P. Demeester, Network Recovery: Protection and Restoration of Optical, SONET-SDH, IP, and MPLS, Morgan Kaufmann Publishers, 2004, (ISBN 0-12-715051-x).

[13] D. Zhou and S. Subramaniam, "Survivability in optical networks," IEEE Network, vol.14, no. 6, pp. 16-23, Nov./Dec. 2000.

[14] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh networks. part I - protection," Proc., IEEE INFOCOM, vol. 2, pp. 744-751, Mar. 1999.

[15] E. Bouillet, G. Ellinas, J.-F. Labourdette, and R. Ramamurthy, Path Routing in Mesh Optical Networks, John Wiley & Sons Ltd, 2007, (ISBN 978-0-470-01565-0).

[16] A. Dacomo, S. De Patre, G. Maire, A. Pattavina, and M. Martinelli, "Design of static resilient WDM mesh networks with multiple heuristic criteria," Proc., IEEE INFOCOM, vol.3, pp. 1793-1802, Jun. 2002.

[17] W. D. Grover, Mesh-Based Survivable Networks: Options and Strategies for Optical, MPLS, SONET and ATM Networking, Prentice Hall PTR, 2003, (ISBN 0-13-494576-x).

[18] J. Tapolcai and T. Cinkler, "On-line routing algorithm with shared protection in WDM networks," International Conference on Optical Network Design and Modeling (ONDM), Budapest, Hungary, pp. 351-364, Feb. 2003.

[19] H. Hasegawa, Y. Taniguchi, K. Sato, A. Jirattigalachote, P. Monti, and L. Wosinska, "Design strategies for survivable Grouped Routing Entity (GRE)-based optical networks," International Conference on the Design of Reliable Communication Networks (DRCN), Budapest, Hungary, pp.148–154, Mar. 2013.

[20] J. Yamawaku, A. Takada, W. Imajuku, and T. Morioka, "Evaluation of amount of equipment on single-layer optical path networks managing multigranularity optical paths," IEEE/OSA Journal of Lightwave Technology, vol. 23, no. 6, pp. 1971-1978, 2005.

[21] I. Yagyu, H. Hasegawa, and K. Sato,"An efficient hierarchical optical path network design algorithm based on a traffic demand expression in a cartesian product space," IEEE Journal on Selected Areas in Communications, vol. 26, no. 6, pp. 22-31, Aug. 2008.

[22] O. Turkcu and S. Subramaniam, "Optical waveband switching in optical ring networks," Proc. IEEE INFOCOM, pp.1-9, Mar. 2010.

[23] Y. Taniguti, Y. Yamada, H. Hasegawa, and K. Sato "Coarse granular optical routing networks utilizing fine granular add/drop," IEEE/OSA Journal of Optical Communications and Networking, vol. 5, no. 7, pp. 774-783, Jul. 2013.

[24] Y. Terada, Y. Mori, H. Hasegawa, and K. Sato, "Highly spectral efficient networks based on grouped optical path routing," OSA Optics Express, vol.24, no.6, pp.6213-6228, 2016.

[25] M.-E. Ganbold et al., "Assessment of optical node architectures for building next generation large bandwidth networks," IEICE Transactions on Communications, vol. 25E103-B, no.6, pp.679-689, Jun. 2020.

[26] M. Jinno, K. Yamashita, and Y. Asano, "Architecture and feasibility demonstration of core selective switch (CSS) for spatial channel network (SCN), OptoElectronics and Communications Conference (OECC) and International Conference on Photonics in Switching and Computing (PSC), Fukuoka, Japan, pp. 1-3, Jul. 2019.

[27] F.-J. Moreno-Muro, R. Rumipamba-Zambrano, P. Pavón-Marino, J. Perelló, J. M. Gené, and S. Spadaro, "Evaluation of core-continuity-constrained ROADMs for flex-grid/MCF optical networks," IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 11, pp. 1041-1050, Nov. 2017.

[28] L. E. Nelson, M. D. Feuer, K. Abedin, X. Zhou, T. F. Taunay, J. M. Fini, B. Zhu, R. Isaac, R. Harel, G. Cohen, and D. M. Marom, "Spatial superchannel routing in a two-span ROADM system for space division multiplexing," IEEE/OSA Journal of Lightwave Technology, vol. 32, no. 4, pp. 783-789, Feb. 2014.

[29] Optical Internetworking Forum, Technology options for 400G implementation, OIF-Tech-Options-400G01.0, Jul. 2015.

[30] F. Fresi, "Self-adaptation technique for bandwidth-variable transponders," Photonics in Switching (PS), Florence, Italy, pp. 157-159, Sep. 2015.

[31] N. Wauters and P. Demeester, "Design of the optical path layer in multiwavelength cross-connected networks," IEEE Journal on Selected Areas in Communications, vol. 14, no. 5, pp. 881-892, Jun. 1996.

[32] A. Nag and M. Tornatore, "Optical network design with mixed line rates," Optical Switching and Networking, no. 6, pp. 227-234, 2009.

[33] K. Nakajima, P. Sillard, D. Richardson, M. Li, R. Essiambre and S. Matsuo, "Transmission media for an SDM-based optical communication system," IEEE Communications Magazine, vol.53 no.2, pp.44-51, Feb. 2015.

[34] T. Mizuno, H. Takara, A. Sano, and Y. Miyamoto, "Dense space-division multiplexed transmission systems using multi-core and multi-mode fiber," IEEE/OSA Journal of Lightwave Technology, vol.34, no. 2, pp.582-592, Jan. 2016.

[35] M. Koga, A. Watanabe, T. Kawai, K. Sato, and Y. Ohmori, "Large-capacity optical path cross-connect system for WDM photonic transport network," IEEE Journal on Selected Areas in Communications, vol. 16, no. 7, pp. 1260-1269, Sep. 1998.

[36] T. Watanabe, K. Suzuki, and T. Takahashi, "Silica-based PLC transponder aggregators for colorless, directionless, and contentionless ROADM," Optical Fiber Communication Conference (OFC), Los Angeles, USA, pp. 1-3, Mar. 2012.