Spatially-Jointed Flexible Waveband Routing Optical Networks Adopting Shared Path Protection

Ryuji Munakata
Department of Information and Communication Engineering
Nagoya University
Furo-cho, Chikusa, Nagoya,
464-8603 Japan
munakata.ryuji.m4@s.mail.nagoya-u.ac.jp

Yojiro Mori
Department of Information and Communication Engineering
Nagoya University
Furo-cho, Chikusa, Nagoya,
464-8603 Japan
mori@nuee.nagoya-u.ac.jp

Suresh Subramaniam
Department of Electrical and Computer Engineering
The George Washington University
800 22nd Street NW SEH 6570,
Washington DC, 20052 USA
suresh@gwu.edu

Masahiko Jinno
Department of Engineering and Design
Kagawa University
2217-20 Hayashi-cho, Takamatsu,
761-0396 Japan
jinno@eng.kagawa-u.ac.jp

Hiroshi Hasegawa
Department of Information and Communication Engineering
Nagoya University
Furo-cho, Chikusa, Nagoya,
464-8603 Japan
hasegawa@nuee.nagoya-u.ac.jp

***Abstract*—We propose a cost-effective and survivable space-division multiplexing optical network architecture that offers spatially-jointed flexible waveband routing (SJ-FWR) and shared path protection. A strategy to group backup paths by sharing frequency resources is developed to take advantage of the switching capability of SJ-FWR. We also show a network design algorithm based on the backup path grouping strategy. Numerical simulations on several network topologies elucidate that the number of fibers necessary is reduced by up to 25% compared to the dedicated path protection approach and a substantial hardware scale reduction is achieved relative to conventional networks with shared path protection.**

Keywords—optical node, space-division multiplexing, shared path protection, spatially-jointed flexible waveband routing

I. Introduction

The ceaseless Internet traffic increase continues with the penetration of cloud-based services including high-resolution video streaming and 5G/6G mobile communications [1,2]. The traffic growth has already exceeded the capacity enhancement of single-mode fiber (SMF) and now the capacity is approaching the theoretical bound [3,4]. In recent years, space-division multiplexing (SDM) technologies using multi-core fibers (MCFs) or multiple SMFs have been extensively studied as they are considered to be a key technology for further network capacity enhancement [5-7]. However, the high link parallelism in SDM networks necessitates high-port-count optical cross-connects (OXCs) to bridge the many cores of MCFs or SMFs set on each link. Present OXC nodes for SMF-based networks consist of multiple wavelength-selective switches (WSSs). Although a 1×95 WSS prototype has been reported [8], the port count of commercially available WSSs remains bounded to around 40 [9,10]. Port-count enhancement is still possible by cascading multiple WSSs; however, the number of necessary WSSs is super-linear to the OXC port count [11]. To resolve this problem, we proposed an OXC node architecture [12,13], where spatially-jointed flexible waveband routing (SJ-FWR) is realized by combing cost-effective joint-switching (JS) WSSs and delivery-and-coupling (DC) switches; JS-WSSs switch signals from multiple cores together and virtually bundle multiple paths, whereas DC switches route path bundles on a core basis. The OXC architecture can attain high routing flexibility while the hardware requirements are drastically reduced [14]. Moreover, transmission experiments show the OXC throughput of 2.15 Pbps [15].

Resiliency is another primary requirement for optical networks as they are now the infrastructure of our information society. A simple but effective scheme to guarantee resiliency is to introduce dedicated/shared path protection; for each path request, a pair of working and backup paths is established that are node and link disjoint except for the edge nodes [16-18]. The node and link disjoint condition severely limits the flexibility of path establishment. As indicated in the literature related to coarse granular routing [19,20], the establishment of redundant paths can severely degrade the routing performance in such networks. Therefore, we recently evaluated the routing performance of SJ-FWR optical networks that exploit dedicated path protection [21]. It was shown that SJ-FWR optical networks with dedicated path protection can almost match the routing performance of conventional WSS-based networks. Furthermore, a substantial reduction in the number of WSSs compared to conventional networks was verified. However, the introduction of dedicated path protection demands double the network resources relative to the baseline case where path protection is unused [21]. For the cost-effective accommodation of the ever-increasing traffic, we must suppress the network resources necessary for path redundancy. A straightforward approach to this problem is the introduction of shared backup paths; however, its effectiveness is unclear as SJ-FWR networks

This work is partly supported by JSPS, NICT, and NSF.

2022 12th International Workshop on Resilient Networks Design and Modeling (RNDM) | 978-1-6654-8677-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/RNDM55901.2022.9927712

have an unconventional switching mechanism, and additional switching flexibility will be needed to support frequency resource sharing between multiple backup paths.

In this paper, we propose a cost-effective and survivable SJ-FWR optical network architecture that adopts shared path protection to attain complete resiliency against single node or link failure. Given that DC switches can merge multiple signals delivered from different input ports at an output port, backup paths from different input ports can be assigned to the same output port and then share the same wavelength/frequency slots on the next link. However, after the merger, this means that multiple backup paths sharing the same resource on a link cannot be assigned to different output ports on the following nodes; bundled routing is enforced until the drop. Routing and wavelength/frequency slot assignment of working and backup path pairs are processed under this constraint. Numerical simulations on several network topologies elucidate that the number of fibers is reduced by up to 25% compared to our previous work with dedicated path protection and hardware cost is reduced by 73% relative to conventional core-wise switching networks with shared path protection.

II. Preliminaries

We assume transparent SDM optical path networks whose links consist of multiple uncoupled M-core fibers [22] or multiple M-parallelized single-mode fibers (SMFs). Frequency assignment to paths follows the flexible grid decided by ITU-T [23]. The center frequencies of channels are located on a grid with a space of 6.25 GHz, and the channel bandwidth is an integral multiple of 12.5 GHz. Hereafter, the minimum frequency assignment unit, i.e., 12.5 GHz, is referred to as a frequency slot. For notational simplicity, frequency bandwidths of paths are independent of the path length; i.e., the modulation format will be common for the same-capacity paths regardless of their distances. However, the following discussion is valid for the case where distance-adaptive modulation is adopted. No wavelength conversion and 3R regeneration is assumed. Moreover, no spatial super-channel use is assumed; a channel/path is accommodated in one of the cores.

The survivability requirement is satisfied by introducing shared path protection. In Section III and Section IV, we briefly review the SJ-FWR node architecture and then propose our backup resource sharing scheme in SJ-FWR networks. For the performance evaluation in Section V, we conduct green-field design, i.e., a network is constructed from scratch to meet all path-setup requests. The number of fibers needed is the benchmark metric.

III. Node Architecture with Spatially-Jointed Flexible Waveband Routing

Figure 1 shows express portions of optical node architectures discussed below. In every case, the use of common add/drop parts is assumed and hence we omit them from Fig. 1. The add/drop parts insert and terminate arbitrary optical paths, and equalize the channel power over the frequency range and among the cores. Such functions can be realized by using simple 1×2 WSSs or 1×2 couplers with wavelength blockers.

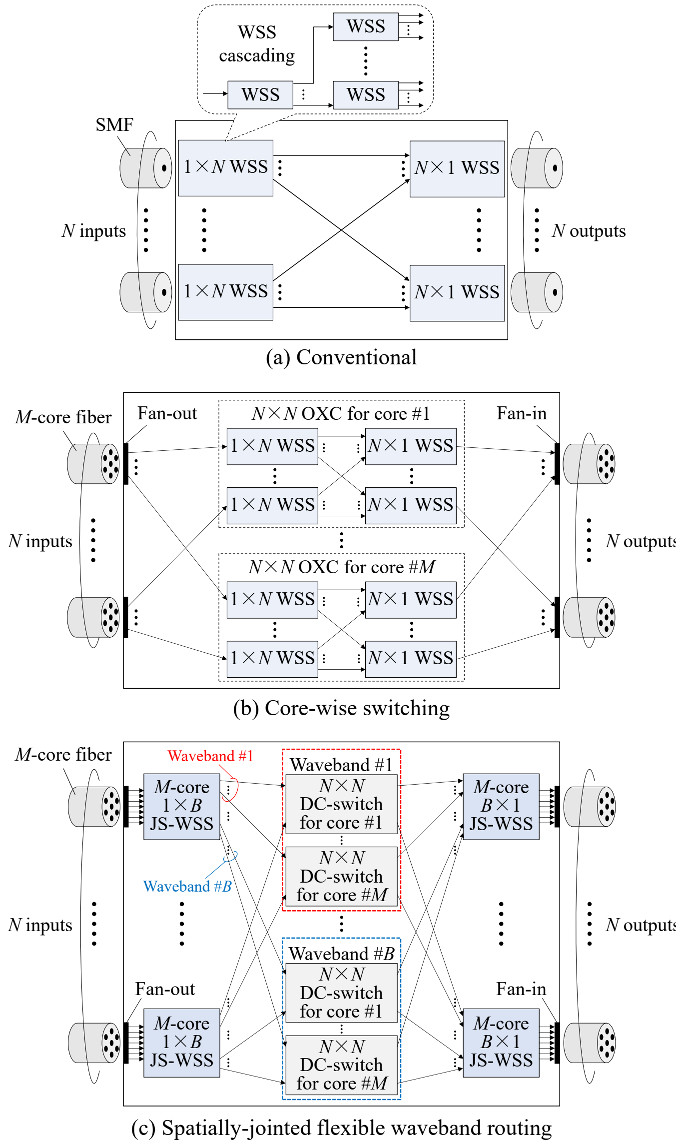


Fig. 1. OXC node architectures.

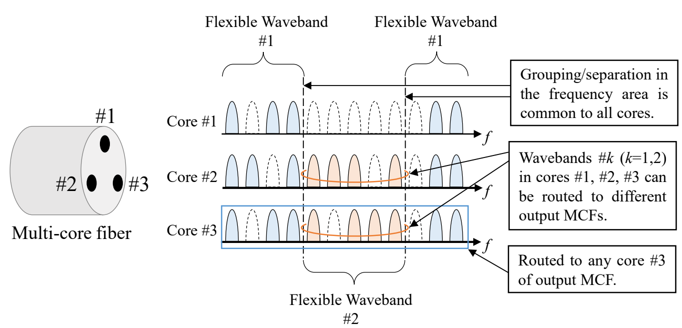


Fig. 2. Path grouping and routing in the spatially-jointed flexible waveband routing architecture (e.g. the number of flexible wavebands is 2).

Table 1. The necessary number of components for an $MN\times MN$ (SMF)/ $N\times N$ (M-core fiber) OXC with different node architectures [14].

		Conventional	Core-wise switching	SJ-FWR
Fiber type		SMFs	M-core fibers	M-core fibers
# of WSSs/JS-WSSs necessary	$1\times(MK{-}1)$ WSSs	$2MN\left\lceil\frac{MN}{MK-1}\right\rceil$	$2MN\left\lceil\frac{N}{MK-1}\right\rceil$	
	M-core $1\times(K{-}1)$ JS-WSSs			$2N$
DC-type matrix switches	Size			$N\times N$
	Number			MB

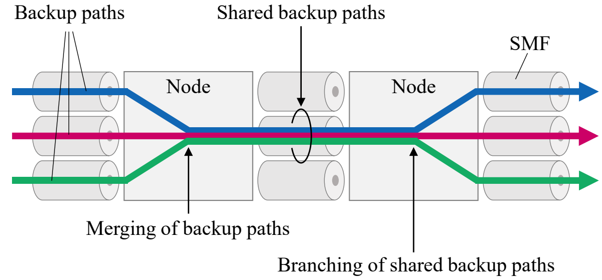
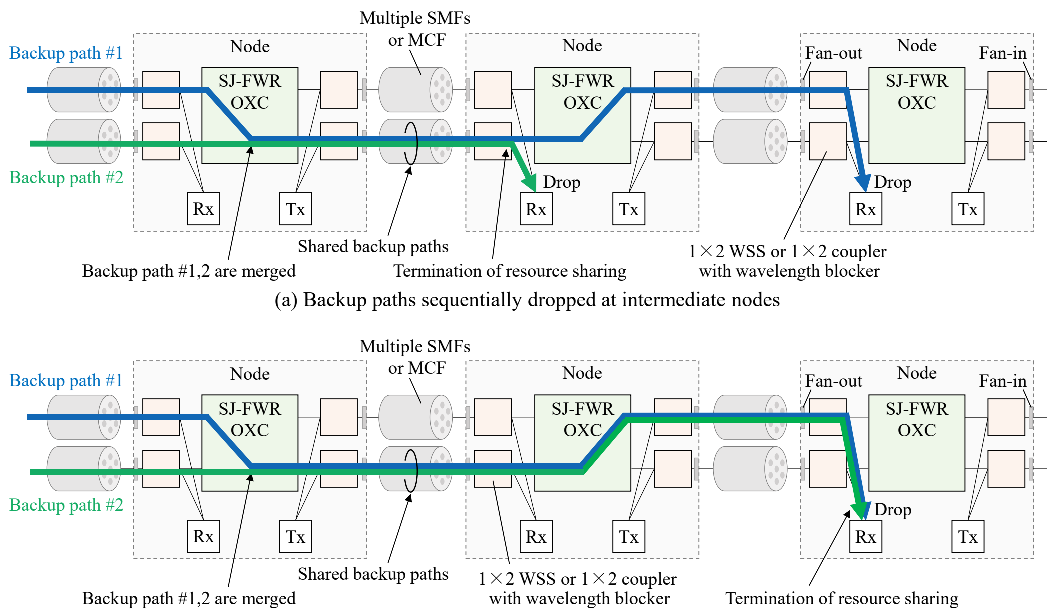


Fig. 3. Merging and branching of backup optical paths in conventional networks.



(a) Backup paths sequentially dropped at intermediate nodes

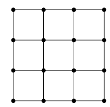
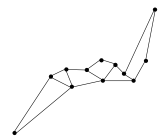
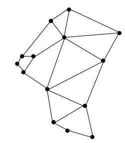
(b) Backup paths with the same destination nodes

Fig. 4. Backup paths sharing condition in the shared-path-protected spatially-jointed flexible waveband routing networks.

Fig. 1 (a) shows the conventional WSS-based OXC node adopted by present SMF-based networks [24]. This OXC sets a WSS at each input and/or output SMF. In order to form a high-port-count OXC, we need WSS cascading because the maximum port count of commercially available WSSs is around 40. Consequently, the number of necessary WSSs increases super-linearly against the OXC port count [11]. This difficulty can be relaxed by the introduction of the core-wise switching OXC node architecture shown in Fig. 1 (b). Because each link can consist of multiples of M cores/SMFs, this OXC is configured by stacking M relatively small sub-OXCs, where each sub-OXC is dedicated to a different core. The literature shows that the routing penalty of adopting core-wise switching OXC is almost negligible compared to conventional WSS-based OXC [25]. The number of WSSs will equal or exceed the total number of cores connected to the OXC. Therefore, considering the saturation of fiber/core capacity, the number will increase in proportion to the exponential traffic growth. Fig. 1(c) shows the SJ-FWR OXC node architecture that consists of JS-WSSs and DC switches [12,13]. A $1\times(MK{-}1)$ WSS can be converted into an M-core $1\times(K{-}1)$ JS-WSS by grouping sets of M adjacent ports [26]. A JS-WSS delivers signals in different cores in the input port group to the same output port group if they share the same wavelength. For the proposed SJ-FWR OXC, we set a JS-WSS at each input MCF. Multiple JS-WSSs can be used in parallel for each input MCF to increase the number of cores [14]. Arbitrary combinations of paths can be bundled as the use of JS-WSS conforms to the flexible grid; however, the separation of frequency bands must be common to all cores for each input MCF. Each path group is called a flexible waveband. An example of path grouping and routing in the SJ-FWR architecture is shown in Fig. 2. The frequency areas in all cores are commonly separated by JS-WSS, and each waveband can be switched to the same core of a freely chosen output MCF.

Table 1 summarizes the hardware scale, the number of necessary WSSs and DC switches, for the different OXC architectures. The number of M-core fibers connected to the OXC of each input/output is N. We assume that the WSSs and JS-WSSs have degrees of $1\times(MK{-}1)$ and $1\times(K{-}1)$, respectively; K, M, and N are determined independently. We need to cascade WSS if $MK-1<MN$ and $MK-1<N$ for conventional WSS-

Table 2. Tested network topologies.

				
Network topology		4×4 regular-mesh	Japan	German
# of nodes		16	12	14
# of links		24	17	23
Node degree	Max.	4	4	6
	Min.	2	2	2
	Ave.	3	2.83	3.29

based and core-wise switching OXC, respectively. In contrast, as the number of wavebands B is typically small for JS-WSS, $MK - 1 \geq K - 1 \geq B$. Hence, SJ-FWR OXC do not need WSSs cascading. Although SJ-FWR OXC needs DC switches in addition to JS-WSSs, DC switches can cost-effectively be implemented using planar-lightwave-circuit or silicon-photonics technologies [27,28].

IV. Shared Path Protection for Spatially-Jointed Flexible Waveband Routing Networks

A. *Frequency Resource Sharing among Multiple Backup Paths in SJ-FWR Networks*

It has been proven that SJ-FWR networks and conventional WSS-based networks have almost identical performance when dedicated path protection is employed [21]. Dedicated path protection requires establishing a pair of working and backup paths for each setup request, where resources are exclusively reserved for each path. On the other hand, shared path protection allows us to allocate the same frequency resource to multiple backup paths; in typical conventional cases, we merge and branch these backup paths at some nodes (See Fig.3). In SJ-FWR networks, however, branching wastes the limited wavebands assigned to each input fiber whereas no restriction is imposed on the merging operation. Considering these asymmetric features stemming from the switching capability of DC switches, we adopt a strategy such that backup paths sharing frequency resources at some links will not be directed to different output fibers at the following nodes. The resource sharing is terminated only when backup paths are dropped at nodes (See Fig.4). Merging of backup paths is encouraged to pursue better resource sharing efficiency.

B. *Design Algorithm of Shared-Path-Protected SJ-FWR Networks*

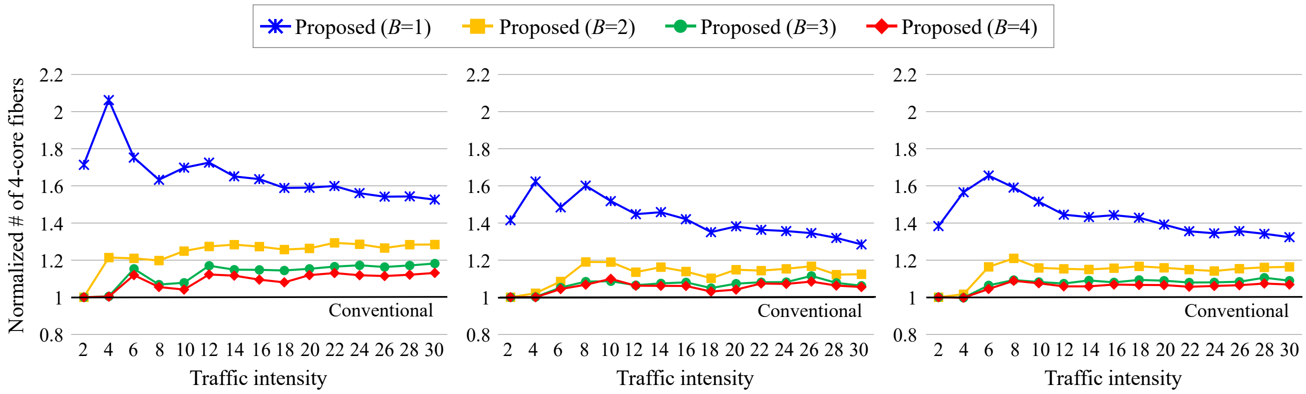
Even the simplest optical network design problem, the optimal routing and wavelength assignment in conventional fixed-grid optical networks is categorized as being NP-complete [29]. The design of SJ-FWR networks includes not only the more complicated routing and spectrum assignment problem but also the path grouping is subject to given waveband number. Thus, we must rely on an efficient sequential-heuristics-based network design algorithm to find sub-optimal solutions. Even with the complexity of the design, a heuristics-based algorithm has succeeded in finding sub-optimal SJ-FWR networks without path protection and with dedicated path protection [12,21]. Therefore, in what follows, we propose a variant of our heuristics-based algorithm; it encourages backup resource sharing by means of merging operations.

A path setup request is represented by a vector (s,d,r,S) with source node s, destination node d, route r, and frequency slot set S. For a working path, we define $W_w(s,d,r,S) = \alpha h + \beta f + \gamma g$, where h, f, and g are, respectively, the number of hops, that of newly established fibers, and that of wavebands in which nodes are newly reserved; α, β, and, γ denote weighting values. Since adding costly fibers should be avoided, the weighting values α, β, γ(≥ 0) are decided so that the condition $\beta > \max\{\alpha, \gamma\}$ is satisfied. For a backup path, let the weighted sum be $W_b(s,d,r,S) = \alpha h + \beta f + \gamma g - \delta b$, where b is the number of slots that are successfully shared with existing backup paths following the condition given in Section IV.A and a positive weighting value δ is used to encourage backup resource sharing. The proposed design algorithm is outlined below.

<SJ-FWR Network Design Algorithms that Employ Shared Path Protection>

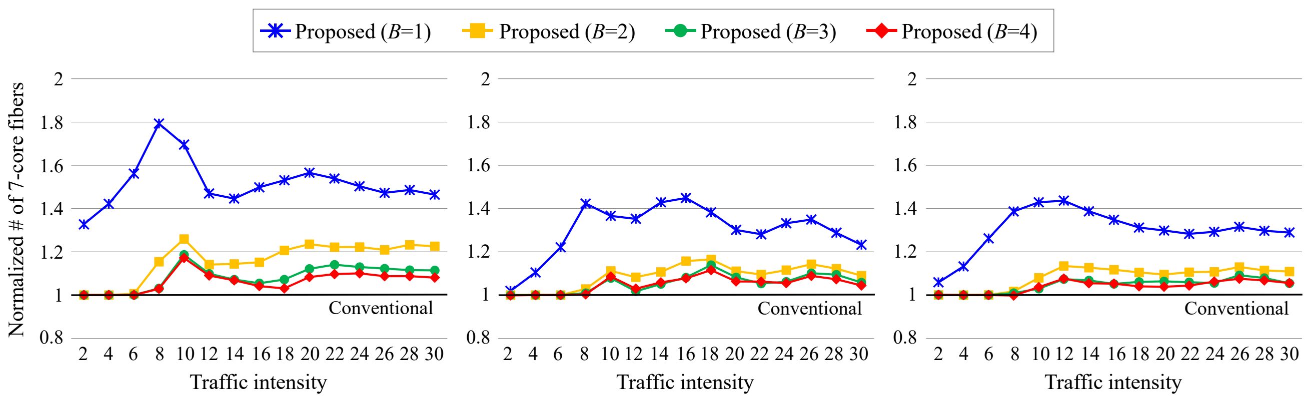
Step 1. Regarding each node pair (s,d), find a set of route candidates R(s,d) connecting s with d by the k-shortest path algorithm. For each candidate, $r_c \in$ R(s,d), eliminate all links and intermediate nodes that are used by r_c from the given network topology. Find the route $\overline{r_c}$ on the reformed topology by applying the k-shortest path algorithm. If $\overline{r_c}$ is found, (r_c,$\overline{r_c}$) is listed as a route-pair candidate. Collect all route-pair candidates and let the set of them for (s,d) be P(s,d). Sort all route-pair candidates in P(s,d) in ascending order according to the distance metric, i.e., total hop counts or link length.

Step 2. Sort all path setup requests in descending order of distance metric. Then, paths are established on a path basis. For each path establishment, calculate $W_w(s,d,r_w,S) + W_b(s,d,r_b,S)$, where $(r_w,r_b) \in$ P(s,d) is one of the route candidate pairs. Select the route pair that minimizes $W_w(s,d,r_w,S) + W_b(s,d,r_b,S)$ and establish a pair of working and backup paths. Add new fibers as necessary for each path established.



(a) 4×4 regular-mesh network (b) Japan network (b) German network

Fig. 5. The normalized number of necessary 4-core fibers relative to conventional WSS-based networks.



(a) 4×4 regular-mesh network (b) Japan network (b) German network

Fig. 6. The normalized number of necessary 7-core fibers relative to conventional WSS-based networks.

V. Numerical Simulations

We perform numerical simulations to evaluate the routing performance and hardware cost of the SJ-FWR network with shared path protection. The available frequency range is assumed to be 4.8 THz in the extended C-band; i.e., 384 12.5 GHz frequency slots are used. Traffic demand is given by a set of optical path establishment requests, where the source and destination nodes are randomly and uniformly distributed. We parameterize the traffic intensity expressed as the average number of optical paths between each node pair. We assume the use of three types of optical paths; 100 Gbps, 400 Gbps, and 1 Tbps that occupy 4, 7, and 15 slots [30,31], respectively. As stated in Section II, the modulation format is common for the same-capacity paths regardless of their distances. The occurrence probability of each path is 1/3.

We use the routing performance and hardware cost of the conventional WSS-based network that adopts shared path protection as the baseline. This network has no restriction on the merger or branching of backup paths; i.e., merging and branching can be performed in express or add/drop portions. For each scenario, the number of fibers and the hardware cost are calculated 20 times and the obtained results are averaged. The topologies tested are a 4×4 regular-mesh network, Japan nationwide network [32], and German nationwide network [33]; as shown in Table 2, the Japan network consists of 12 nodes and 17 links whereas the German network consists of 14 nodes and 23 links. The number of MCF cores is set to 4 and 7 in consideration of commercially available devices.

Figure 5 plots the number of necessary fibers versus traffic intensity, where the number of cores of each MCF is set to 4. When the traffic intensity is small, the number of fibers fluctuates. This is because the results are normalized by conventional WSS-based networks. When the number of wavebands B is 2, the fiber increment is less than 30% for all network topologies. The gap against the conventional WSS-based network decreases as B increases. The increase in the number of fibers at the highest traffic intensity examined is less than 7% in the Japan network and the German network when B is 4. As for the 4×4 regular-mesh network, the increment of the number of fibers at the highest traffic intensity examined is around 13% if B is set to 4.

Figure 6 shows the results obtained by using 7-core fibers, where the simulation conditions are common to Fig. 5 except for the number of cores. The number of fibers is increased by 6%

for the Japan network and 5% for the German network in the case where the traffic intensity is 30 and B is 4. As for the 4×4 regular-mesh network, the increment in the number of fibers at the highest traffic intensity examined is 8% if B is 4. The fiber increment tends to be smaller compared to the use of 4-core fibers because increasing the number of cores reduces the number of fibers used.

Figure 7 illustrates the number of necessary fibers, where the results are normalized by those of conventional networks without path protection in the German network. Here, 4-core fibers are used and the number of wavebands B is 4. When the traffic intensity is small, shared path protection and dedicated path protection yield almost the same performance. This is because the MCF-network capacity is sufficiently large to establish all working and backup paths even though backup paths are not shared. On the other hand, the number of fibers obtained by introducing shared path protection is reduced by 20-25% compared to dedicated path protection case in the high traffic intensity region. As indicated in Fig. 5 and Fig. 6, although the increase in the number of fibers is not negligible (~10%), the introduction of shared path protection still contributes to the network resource reduction. We observed the same tendency in the other topologies and with the use of 7-core fiber.

Figure 8 shows the backup resource sharing ratio versus traffic intensity in the German network, where 4-core fiber is used. The backup resource sharing ratio of SJ-FWR is smaller by 13-20% compared to the conventional equivalent because the proposed network design does not branch shared paths. This deterioration with backup resource sharing stems from the constraint in SJ-FWR and results in an increment in fibers used; the improvement in node architecture and the enhancement in backup resource sharing will contribute to reducing the number of fibers.

Figure 9 shows the number of necessary WSSs in OXC at the highest traffic volume scenario for each topology. The number of MCF cores is 4, and the use of 1×20 WSSs or 4-core 1×4 JS-WSSs are assumed. The number of wavebands, B, is set to 4. An SJ-FWR OXC needs only one JS-WSS for each input/output MCF. On the other hand, the conventional WSS-based OXC needs to cascade multiple WSSs if the OXC port count exceeds that of WSS. Thus, it needs more WSSs in the high traffic intensity region. The number of WSSs necessary for the core-wise switching OXC is also shown in Fig. 9. The core-wise switching OXC necessitates, at least, one WSS for each core of the input/output MCF. Although the SJ-FWR OXC additionally needs DC switches for waveband routing, DC switches offers outstanding advantages in terms of mass-production. For all topologies examined, the reduction ratio is 90-93% relative to the conventional WSS-based OXC and 73-79% relative to the core-wise switching OXC.

VI. Conclusions

We proposed a resilient and cost-effective SDM optical network architecture; it adopts SJ-FWR and shared path protection to assure survivability against single node or link failure. We also proposed a backup path sharing strategy based on the switching capability of DC switches which supports flexible wavebands. Extensive network simulations showed that

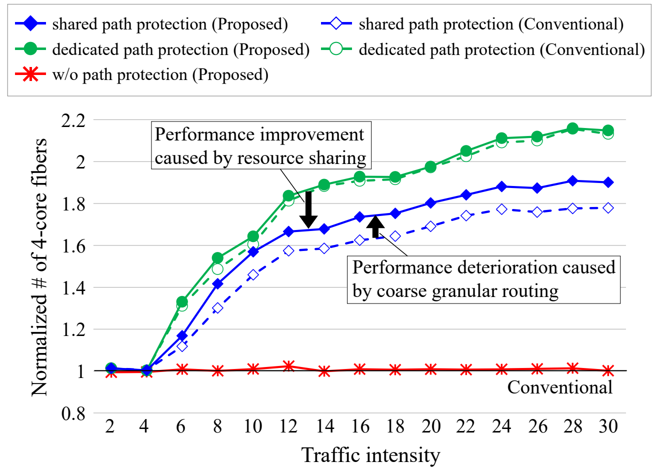


Fig. 7. The normalized number of necessary 4-core fibers in the German network relative to conventional WSS-based networks without protection (B=4).

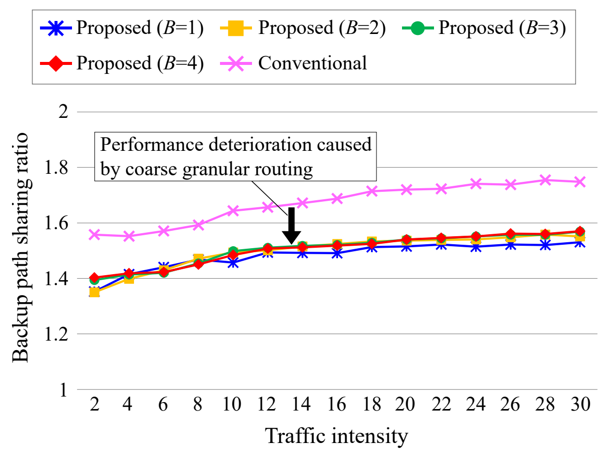


Fig. 8. Backup resource sharing ratio in the German network, where 4-core fiber is used.

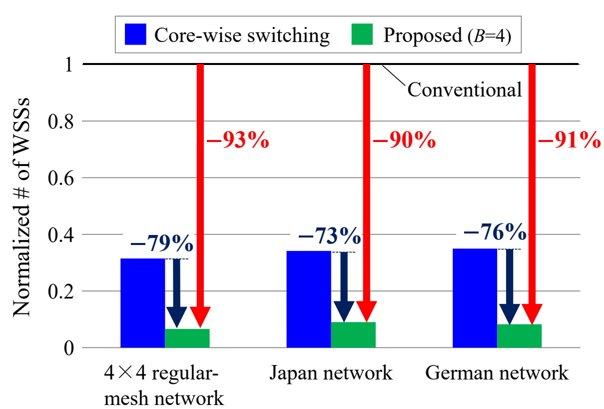


Fig. 9. The normalized number of necessary 1×20 WSSs/ 4-core 1×4 JS-WSSs at the highest traffic intensity relative to conventional WSS-based networks.

the reduction in the number of fiber can reach 25% relative to the dedicated protection cases and the hardware cost was successfully reduced by 73% relative to conventional core-wise switching networks with shared path protection.

REFERENCES

[1] Cisco Systems, Inc, "Visual networking index: forecast and trends, 2017-2022," White paper, 2019.

[2] Ministry of internal affairs and communications, "Telecommunications division data communication section", Jul., 2021. [Online]. Available: http://www.soumu.go.jp/main_content/000761096.pdf (accessed: May 8th, 2022, in Japanese).

[3] R. Essiambre and R. W. Tkach, "Capacity trends and limits of optical communication networks," *Proc. of the IEEE*, vol. 100, no. 5, pp. 1035-1055, May 2012.

[4] P. J. Winzer, "Scaling optical fiber networks: challenges and solutions," *OSA Optics and Photonics News*, vol. 26, no. 3, pp. 28-35, Mar. 2015.

[5] G. Li, N. Bai, N. Zhao, and C. Xia, "Space-division multiplexing: the next frontier in optical communication," *OSA Advances in Optics and Photonics*, vol. 6, no. 4, pp. 413-487, Dec. 2014.

[6] T. Mizuno and Y. Miyamoto, "High-capacity dense space division multiplexing transmission," *Optical Fiber Technology*, vol. 35, pp. 108-117, Feb. 2017.

[7] Y. Awaji, "Review of space-division multiplexing technologies in optical communications," *IEICE Transactions on connunications*, vol. E102-B, no. 1. pp. 1-16, Jan. 2019.

[8] K. Suzuki, Y. Ikuma, E. Hashimoto, K. Yamaguchi, M. Itoh, and T. Takahashi, "Ultra-high port count wavelength selective switch employing waveguide-based I/O frontend", in *Optical Fiber Communication Conference (OFC)*, Los Angeles, USA, paper Tu3A.7, Mar. 2015.

[9] LUMENTUM, "TrueFlex twin 1×35 wavelength selective switch (Twin 1×35 WSS)," [online]. Availbable: https://www.lumentum.co.jp/ja/products/trueflex-twin-1x35-wavelength-selective-switch (accessed: May 8th, 2022).

[10] InLC Tecnology, "TLC series flexible grid WSS," [online]. Available: http://inlct.com/tlc-series-flexible-grid-wss/ (accessed: May 8th, 2022).

[11] M. Niwa, Y. Mori, H. Hasegawa, and K. Sato, "Tipping point for the future scalable OXC: What size MxM WSS is needed?," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 1, A18-A25, Jan. 2017.

[12] H. Hasegawa, S. Subramaniam, and M. Jinno, "Node architecture and design of spatially jointed flexible waveband routing optical networks," *in European Conference on Optical Communication (ECOC)*, Dublin, Ireland, poster, Sep. 2019.

[13] T. Kuno, Y. Mori, S. Subramaniam, M. Jinno, and H. Hasegawa, "Design and evaluation of a reconfigurable optical add-drop multiplexer with flexible wave-band routing in SDM networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 14, no. 4, pp.248-256, Apr. 2022.

[14] T. Kuno, Y. Mori, S. Subramaniam, M. Jinno, and H. Hasegawa, "High-throughput and high-port-count optical cross-connents using flexible waveband routing," in *International Conference on Optical Network Design and Modeling (ONDM)*, Barcelona, Spain, paper S6.4, May 2020.

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

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

[17] J.-P. Vasseur, M. Pickavet, and P. Demeester, *Network recovery: protection and restoration of optical, SONET-SDH, IP, and MPLS*, Morgan Kaufmann Publishers, 2004.

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

[19] Y. Yamada, H. Hasegawa, and K. Sato, "Hierarchical optical path network design algorithm considering waveband protection," *IEEE Journal of Lightwave Technology*, vol. 27, no. 24, pp. 5736-5748, Dec. 2009.

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

[21] R. Munakata, Y. Mori, S. Subramaniam, M. Jinno, and H. Hasegawa, "Design and performance evaluation of resilient optical path networks that adopt spatially-jointed flexible waveband routing," in *International Conference on Optical Network Design and Modeling (ONDM)*, paper NPR.1, Gothenburg, Sweden, Jul. 2021.

[22] M.-J. Li and T. Hayashi, "Advances in low-loss, large-area, and multicore fibers," in *Optical Fiber Telecommunications VII*, A. E. Willner, Ed., pp.19-45, Academic Press, 2019.

[23] *Spectral grids for WDM applications: DWDM frequency grid*, ITU-T Recommendations G694.1, 2012.

[24] S. L. Woodward, M. D. Feuer, and P. Palacharla, "ROADM-node architectures for reconfigurable photonic networks," in *Optical Fiber Telecommunications VIB*, I. P. Kaminow, T. Li, and A. E. Willner, Eds., pp. 686-696, Academic Press, 2013.

[25] F.-J. Moreno-Muro *et al*., "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.

[26] D. M. Marom *et al*., "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.

[27] 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.

[28] T. Watanabe, K. Suzuki, and T. Takahashi, "Silica-based PLC transponder aggregators for colorless, directionless, and contentionless ROADM," in *Optical Fiber Communication Conference (OFC)*, Los Angeles, USA, paper OTh3D.1, Mar. 2012.

[29] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: an approach to high bandwidth optical WAN's," *IEEE Transactions on Communications*, vol.40, no.7, pp.1171–1182, Jul. 1992.

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

[31] F. Fresi, "Self-adaptation technique for bandwidth-variable transponders," in *International Conference on Photonics in Switching (PS)*, Florence, Italy, pp. 193-195, Sep. 2015.

[32] Technical Committee on Photonic Network, "Announcement of Japan Photonic Network Model," [online]. Available: https://www.ieice.org/cs/pn/eng/jpnm_en.html (accessed: May 8th, 2022).

[33] K. Christodoulopoulos, I. Tomkos, and E. A. Varvarigos, "Elastic bandwidth allocation in flexible OFDM-based optical networks," *IEEE/OSA Journal of Lightwave Technology*, vol.29, no.9, pp.1354-1366, May 2011.