Node Architecture and Design of Flexible Waveband Routing Optical Networks

Hiroshi Hasegawa, Suresh Subramaniam, and Ken-ichi Sato

***Abstract*—A novel coarse granular routing scheme for elastic optical networks is proposed in this paper, together with a node architecture and a network design algorithm. The proposed scheme allows any combination of optical paths to be routed together, and each bundle of paths, named "flexible waveband," is routed as an entity. The flexibility in bundled paths differentiates the proposed routing scheme from optical path hierarchies proposed so far and is especially appropriate for elastic optical path networks in which frequency bandwidths of optical paths are not necessarily uniform. Path bundling at each input port of a node is realized with a small port count flexible grid wavelength selective switch (WSS), while flexible waveband routing is done by other optical switches, i.e., two-stage routing. These WSSs are only responsible for the path bundling, and their degrees need not be changed even if the number of fibers connected to a node, i.e., node fiber degree, is changed. Moreover, the number of WSSs increases linearly as the node fiber degree increases. The proposed network design algorithm resolves the routing and frequency slot assignment problem while considering specific constraints imposed by the routing scheme. Numerical experiments on several real and regular topologies confirm that the routing performance degradation caused by the coarse granularity of the routing is small while the number of WSSs is substantially reduced.**

***Index Terms*—Elastic optical network; Flexible waveband; Node architecture; Optical cross-connect node; Routing and spectrum assignment.**

I. Introduction

The continuous increase of Internet traffic is being driven by the explosive use of video-based services. Further traffic expansion is expected due to higher-resolution videos such as 4K/8K, huge data transmission between data centers, mobile backhaul, including that for emerging 5G, and so on. Fiber capacity needs to be expanded to accommodate the growing traffic. Conventional DWDM transmission uses fixed channel frequency spacing on the ITU-T G.694 standardized grid (i.e., 25/50/100 GHz regularly spaced grids). Utilizing a fixed grid degrades frequency utilization efficiency and is a significant problem in the 400 Gbps/1 Tbps transmission envisaged. That is, very high bitrate channels cannot be accommodated with the currently most popular 50 GHz grid spacing, which wastes a lot of frequency resources. In order to enhance spectrum utilization efficiency, the elastic optical path network [1] is seen as a viable solution. It employs fine channel spacing and bandwidth assignment; multiples of 6.25 and 12.5 GHz, respectively. Further improvement in utilization efficiency is possible by adopting distance-adaptive modulation [2–5]. Unfortunately, even if the spectrum utilization efficiency is maximized by elastic optical network technologies, traffic growth is and will outpace possible fiber capacity enhancements. As a result, the number of optical paths in a network, and that of fibers on each physical link, will inevitably increase. Thus the large-scale ROADM/OXC is already being targeted [6]. To create large-scale OXCs (multidegree ROADMs) that utilize wavelength selective switches (WSSs), a large port count WSS is required. However, the highest port count commercially available at present is limited to 20+. Although several experimental benchtop prototypes [7,8] have been described as increasing the port count, it will be difficult to substantially and cost-effectively increase the commercially available port count (for example, 10 times) in the near future. This is because the port count increment needs more aerial beam manipulation adjustment operations, which will trigger substantial cost increments. A straightforward approach is to cascade several WSSs. If we use 1×9 WSSs, a two-stage architecture yields 1×81 WSSs; however, it requires 10 1×9 WSSs, and the loss is twice that of the basic WSS. This is not practical in terms of cost or loss.

Although the numbers of optical paths and fibers are expected to increase, the network topology is expected to largely remain the same. This fact encourages us to bundle optical paths that are routed to the same node. Historically, higher-order paths have been introduced as an effective solution, for example, in SDH/SONET networks. For the conventional fixed grid case, hierarchical optical path networks also have been studied where bundles of paths are defined as waveband paths. The existing studies range from node architectures [9–12] to design and control algorithms [13–15]. An essential difference between the conventional path hierarchy and optical path hierarchy lies in the so-called wavelength continuity constraint, which forces traversed waveband paths to occupy the same frequency range. This requirement often prevents the achievement of higher waveband path utilization. Waveband or wavelength conversion can improve frequency utilization efficiency [16]; however, only a few prototypes have been presented, and currently no cost-effective conversion

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device is available. Moreover, a few advances in efficient waveband path routing devices have been published [17,18]. An example of a waveband path routing device is the waveband selective switch [18], which monolithically integrates all devices, multiplexer(s), de-multiplexer(s), and switches on a PLC chip. Some proposals introduce a path hierarchy to elastic optical path networks [19]. Study [19] relies on the potentially greater cost-effectiveness of fixed-grid switching devices compared with flexgrid switching devices. Elastic optical paths are aligned within the passbands of the fixed grid switching devices, and the routing at nodes is done by these devices. However, optical paths cannot be located on guard bands between passbands and the separation into several passbands limits the room for optimization to suppress fragmentation in the frequency domain. Therefore, a novel coarse granular routing architecture that can efficiently manage elastic optical paths remains necessary; the routing constraint is any combination of paths, which may occupy noncontiguous and nonuniform frequency ranges, should be supported.

In this paper, we propose a coarse granular routing scheme named “flexible waveband routing.” A flexible waveband routing node first divides all the incoming optical paths on an input fiber into several groups. These path groups are then routed to different output fibers. The path groups are named “flexible wavebands.” The former operation is done by a flexgrid WSS and the latter by matrix switches. These WSSs use arrays of flexible bandpass filters. The WSS cascade conventionally needed to enhance port count is eliminated, so the filter narrowing effect, a typical impairment caused by WSSs, is suppressed. Numerical experiments on several topologies with a heuristic-based network design algorithm found that the number of path groups can be small (for example, four); hence we can utilize cost-effective low port count WSSs instead of the high port count cascaded WSSs required by the conventional routing scheme. Even for such small values, the fiber increment ratio to accommodate the same traffic, caused by the reduced routing capability, is just 3%–5%, while the number of WSSs is substantially reduced. The heuristic-based network design algorithm is also shown to be sufficiently efficient for the proposed flexible waveband networks where the above routing constraint exists. The results show that our coarse granular routing scheme is a viable approach to realizing cost-effective elastic optical path networks.

A preliminary version of this research was presented at an international conference [20].

II. Flexible Waveband Routing and Node Architecture

We assume elastic optical path networks (ITU-T G694.1) where the center frequencies of optical paths lie on a 6.25 GHz spaced grid [193.1 THz + $6.25n$ GHz (n: integer)] and bandwidths are multiples of 12.5 GHz [21]. However, the methodology in this paper can be directly applied to conventional fixed-grid networks whose channel center

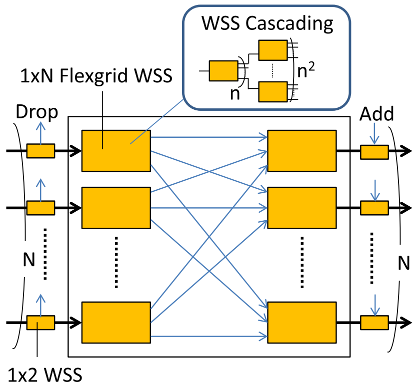


Fig. 1. WSS-based OXC node architecture.

frequencies are located on a fixed spacing grid [$193.1\ \mathrm{THz} + \{12.5, 25, 50, 100\}n$ GHz (n: integer)]. Figure 1 shows a typical OXC node architecture for elastic optical networks. The fine granular (6.25 GHz) switching is made possible by flexgrid: for example, liquid-crystal-on-silicon-based WSSs. As noted in the Introduction, higher degree nodes are difficult to realize due to the limitation on the WSS port count.

Figure 2 shows an example of a conventional definition of wavebands for the fixed-grid case. The available frequency band is divided into several ranges called “wavebands.” Because optical paths are always located on a regular spacing grid in the frequency domain, the maximum number of paths in a waveband is proportional to the bandwidth of that waveband. All paths in each waveband are always switched together and the definition of wavebands is usually common to all nodes. Thus, there is no congestion between any pair of waveband paths routed to the same fiber as long as their waveband indices are different.

Figure 3 shows the proposed node architecture for flexible waveband routing. This network node consists of $1 \times B$ flexgrid WSSs and B matrix switches. Optical paths from an incoming fiber are first divided into a limited number ($\leq B$) of groups, and these groups are then distributed to up to B output ports of the WSS (see Fig. 4). The WSS is used as a dynamic waveband demultiplexer. At each output port of each matrix switch, arriving flexible wavebands

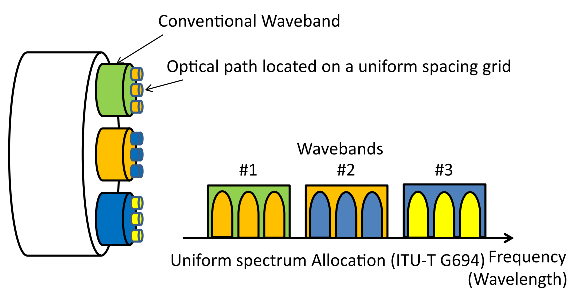


Fig. 2. Relationship among fiber, conventional waveband, and optical path on the fixed grid.

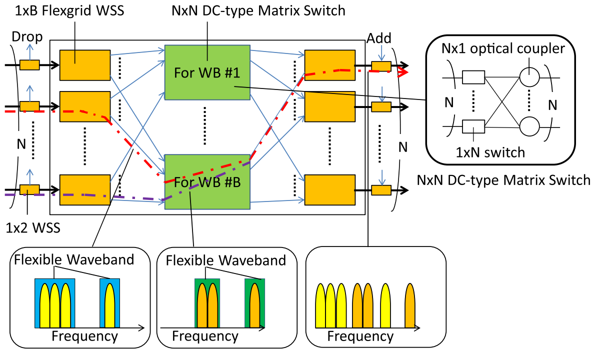


Fig. 3. Proposed node architecture for flexible waveband routing.

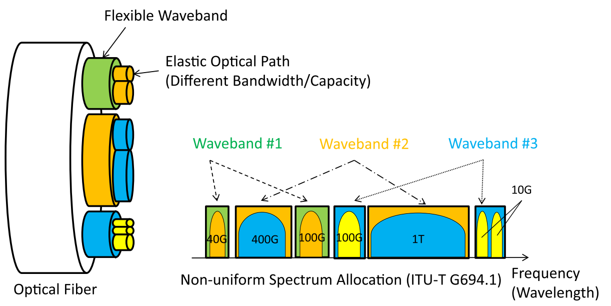


Fig. 4. Relationship among fiber, flexible waveband, and elastic optical path.

from all input ports are merged. Accordingly, each switch must be capable of switching optical signals incoming from multiple input ports to an output port. Several types of optical switches are available such as 3D MEMS-based optical space switches, high-speed SOA/PLZT switches, and so on, but these are not necessary to realize this switching operation, as it can be realized, for example, by delivery and coupling (DC) switches. Their integration on a PLC chip has already been demonstrated [22], and the results are now commercially available. This switch also can be realized by using independent $1 \times N$ optical switches [23] and $1 \times N$ optical couplers (see Fig. 3). Throughout this paper, we call the $N \times N$ switching component, consisting of N $1 \times N$ switches and N $1 \times N$ couplers, the $N \times N$ DC-type matrix switch. Finally, at each outgoing fiber, path sets from the corresponding outputs of matrix switches are combined by a $1 \times B$ WSS, which can be replaced by an optical coupler if B is sufficiently small (e.g., $B = 4$). Due to the dynamic and fine granular bandwidth flexible capability of WSSs, a flexible waveband can be any set of elastic optical paths and can dynamically adapt to path addition and removal to/from that waveband. The flexible bandwidth allocation to wavebands, which is specific for each fiber, is different from the conventional fixed bandwidth waveband, and an additional constraint is imposed such that no pair of wavebands routed to an output fiber can overlap (Fig. 5). We name this constraint the "waveband collision constraint."

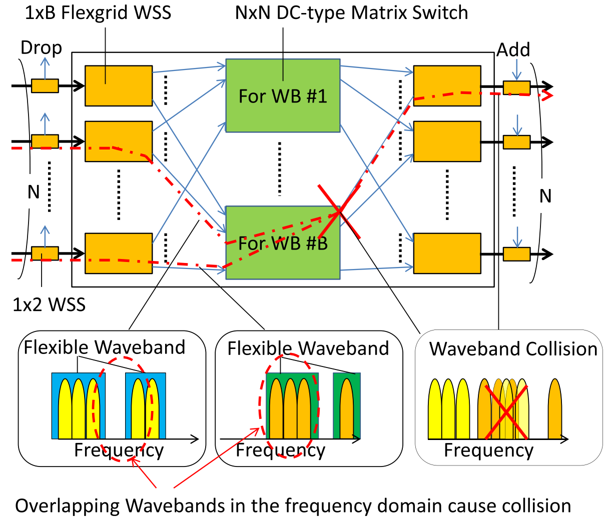


Fig. 5. Collision between flexible wavebands.

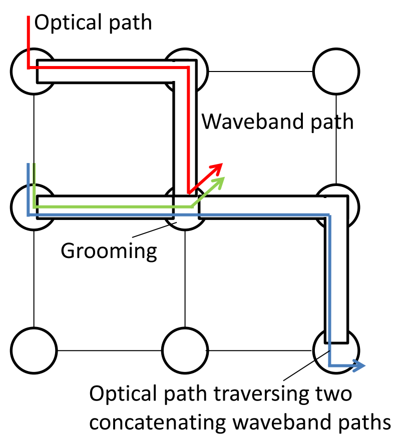


Fig. 6. Hierarchical path routing on a 3×3 regular mesh network.

In conventional hierarchical optical networks, each optical path is carried by a sequence of concatenated waveband paths where the source node of the first waveband path and the destination node of the last waveband path coincide with those of the optical path (Fig. 6). Optical path accommodation to waveband paths can be changed through grooming; optical paths incoming from terminating waveband paths are bundled into several groups and routed to outgoing waveband paths. There is a severe constraint in that the waveband paths carrying the optical path must occupy the same frequency range to satisfy the wavelength continuity constraint for the path, which substantially reduces the fiber utilization ratio [16]. Moreover, paths can be added/dropped only at nodes where waveband paths are started or terminated. If the number of paths routed in parallel exceeds the waveband capacity, we need multiple waveband paths routed together, which implies some redundancy. On the other hand, the flexible wavebands

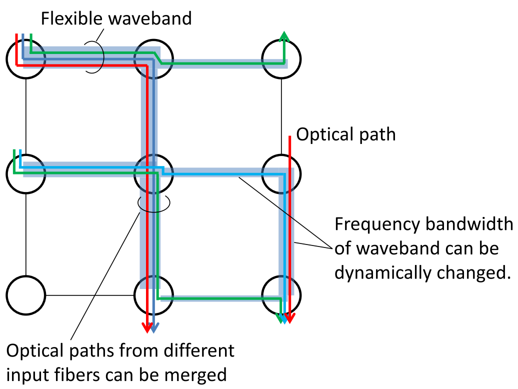


Fig. 7. Flexible waveband routing on a 3×3 regular mesh network.

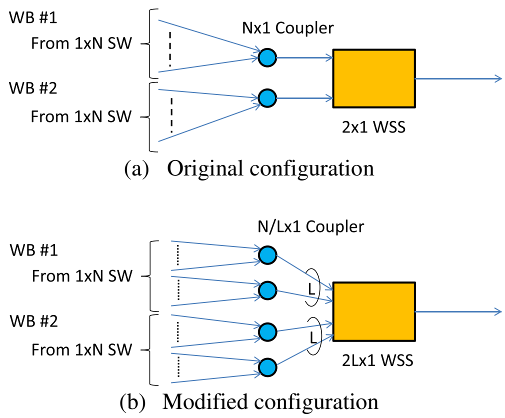


Fig. 8. Coupling loss reduction at output side when the number of wavebands B is 2.

of the proposed flexible waveband routing optical networks enable fully flexible waveband reconfiguration in terms of paths carried and frequency bandwidth (see Fig. 7). There is no limitation on the sites of path addition/termination. The new restriction unique to the proposed flexible waveband networks is that the number of outgoing fibers to which optical paths in an incoming fiber can be routed is bounded.

The number of $1 \times B$ WSSs necessary to realize a conventional $N \times N$ ($N > B$) route and select type node OXC is $2N(N-1)/B$, which is almost proportional to N^2, while a $N \times N$ proposed node needs $2N$ in addition to B matrix switches. Each input port of the $N \times N$ proposed node is preceded by a $1 \times B$ WSS and B optical switches. Numerical experiments will elucidate that B will be a small number (e.g., $B = 4$) and the use of such small degree WSSs will greatly enhance the cost effectiveness. Moreover, the elimination of WSS cascades reduces the impairments caused by traversing WSSs, i.e., the filter narrowing effect: for example, suppose a large-scale OXC that adopts the route-and-select configurations and cascaded WSSs in two stages at each port. An optical path traversing this OXC suffers from four times more impairment and optical loss at WSSs.

The scalability of the proposed node architecture depends on that of DC-type matrix switches. Monolithically integrated matrix switches [24,25] and DC-type matrix switches [22] have been developed so far. Recent developments in silicon photonics technologies make it possible to realize small-sized switches [26,27]. By combining these switches with other components, more compact switching that offers greater scalability will be possible in the near future. Another important objective of the switch configuration improvement is to resolve the optical coupling loss issue at DC-type switches, i.e., $\log_{10}N$ (+ excess loss) dB, where N is the degree of the switch. A straightforward method for loss reduction will be the use of lower degree couplers and higher degree WSSs at the output side, as shown in Fig. 8. Suppose that WSSs at the output side are $1 \times LB$ (L: a positive integer) instead of using $1 \times B$ WSSs in the original configuration in Fig. 8(a), then the degrees of optical couplers included in DC switches will be $1/L$ of the original case [Fig. 8(b)]. If the total optical loss cannot be acceptable, some EDFAs will be inserted just after WSSs at input sides used for waveband demultiplexing. Such additional EDFAs, other than pre-/post-amplifiers, must be compactly implemented (for example, by adopting pump sharing among multiple EDFAs); however, this paper omits further discussion because the amount of additional hardware such as EDFAs will depend on parameters of available products (WSSs, couplers, EDFAs, etc.). The optical loss at the DC-type matrix switch portion can be substantially improved by the use of more compact switches while keeping the routing capability to a sufficient level. This point is discussed in another paper [28], and an implementation as a prototype is shown in [29]. The detail of these papers will be discussed elsewhere.

Remark: A preliminary version of this two-stage routing strategy was originally proposed for fixed-grid networks [30]. In that study, the number of selectable outgoing fibers was defined for each physical link, i.e., a bundle of fibers to an adjacent node. Due to this constraint, the previous proposal was unable to adapt to nonuniform path distributions. Another difficulty is that WSS degree will be proportional to the physical degree of the node, i.e., the number of adjacent nodes. Existing network topologies generally include high degree nodes: for example, Paris in the pan-European network [31], which results in the need for excessively high degree WSSs. Given these weakness, we designed the proposed routing scheme with sufficient flexibility to cope with different traffic situations. Numerical experiments verify its performance improvement over the previous method.

III. Design of Flexible Waveband Routing Networks

To verify the performance of flexible waveband routing, we propose the following heuristic algorithm for the static network design problem. Here the general objective is to minimize the hardware needed to accommodate a given traffic demand, i.e., the number of necessary optical paths and their capacities for each node pair. Full

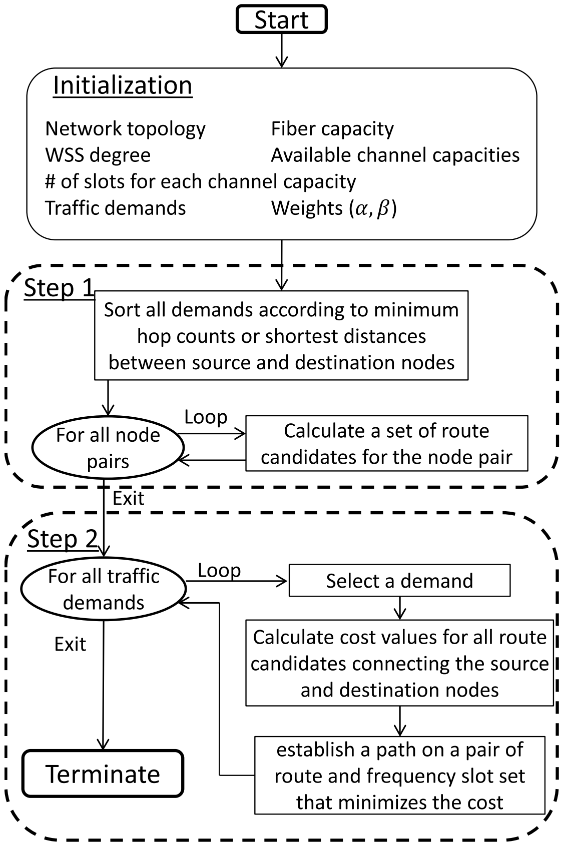


Fig. 9. Flow chart of proposed design algorithm.

colorless/directionless/contentionless (C/D/C) add/drop capability at nodes is assumed.

The wavelength conversion and the modulation format adaptation according to impairments, including distance, are not considered in this paper for simplicity; however, they can be easily incorporated into the algorithm. The proposed design algorithm is shown below (see also Fig. 6).

IV. Design Algorithm of Flexible Waveband Routing Networks

Step 1. Sort all path establishment requests of given traffic demands in descending order of minimum hop counts or shortest distances between source and destination nodes. The ordering in a set of requests with the same metric value is randomly determined. Calculate a set of route candidates for each node pair by the k-shortest path algorithm.

Step 2. In the order fixed in Step 1, select a path establishment request that has not been processed yet. Calculate the following cost function for all route candidates connecting the source and destination nodes for that request:

$$f(r, S) := d(r) + \alpha\,\mathrm{wss}_{\mathrm{new}}(r, S) + \beta\,\mathrm{fiber}_{\mathrm{new}}(r),$$

where r and S are a sequence of fibers, i.e., a route, and a contiguous slot set that can accommodate the demand; α and β are weights; $d(r)$ is hop count or distance of r; $\mathrm{wss}_{\mathrm{new}}(r, S)$ is the number of WSSs whose output ports are newly reserved on the route; and $\mathrm{fiber}_{\mathrm{new}}(r)$ is the number of additional fibers needed. Establish a path on route r and frequency slot set S that minimizes the cost function. Repeat this procedure until all requests are processed. If all paths are established, terminate.

The flow of the above algorithm is shown in Fig. 9.

Remark: In a network consisting of conventional OXC nodes, the accommodation of a path does not impose any restriction on the routing of other paths accommodated later. However, in the proposed flexible waveband network, the number of output fibers routed from an input fiber is bounded by parameter B. Thus a newly establish path may increase the number of selected output fibers for an input fiber at a node on the route. This reduces the flexibility in output fiber selection at the node. Parameter $\mathrm{wss}_{\mathrm{new}}(r, S)$ in Step 2 encourages the bundling of the path to an existing waveband to retain flexibility in terms of output fiber selection.

V. Numerical Experiments

This section evaluates the impact of flexible wavebands and the performance of the proposed design algorithm. Throughout this section, we assume that the available frequency range is the C-band (4400 GHz wide), which is divided into 352 frequency slots whose bandwidth is 12.5 GHz. Three channel capacities and modulation formats are set to 40 Gbps DP-QPSK/100 Gbps DP-QPSK/400 Gbps DP-16QAM [32]; these channels require 3/4/7 frequency slots, respectively.

Throughout this section, we adopt the following configurations in common. Regarding the parameter values of the proposed algorithm, the maximum number of route candidates in Step 1 is set to 100 and parameters α and β to 0.5 and 0.1, respectively. The values are selected empirically through experiments for several different configurations (i.e., topologies and traffic intensities), and the selected values give appropriate solutions for all situations. The number of hops is used for the first term of the cost function in Step 2 and the hop slug, i.e., the maximum number of hop increments caused by detouring, is set at 2 for all topologies. The traffic demand is a set of path establishment requests whose source and destination nodes are randomly selected according to a uniform distribution. The capacity of each path is also determined randomly where the probabilities for the three capacities are the same (i.e., 1/3 for each). The traffic intensity is characterized by the average number of optical paths between each node pair.

A. Performance Evaluation of Proposed Design Algorithm on Several Topologies

In this subsection, the impact of flexible wavebands is evaluated in terms of the number of WSSs and fibers

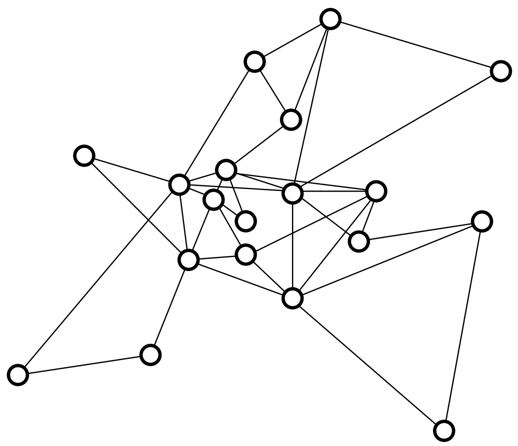


Fig. 10. Pan-European network.

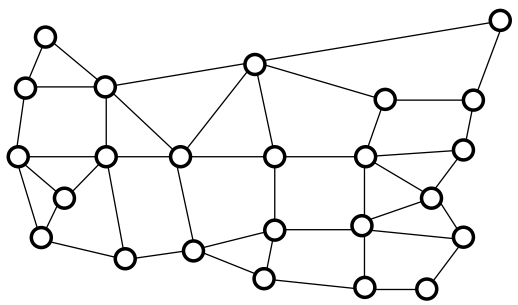


Fig. 11. USNET topology.

necessary in three real topologies, the pan-European network [31] (Fig. 10), the USNET topology [33] (Fig. 11), the Japan backbone network JPN12 [34,35] (Fig. 12), and a 7×7 regular mesh network. The pan-European network consists of 19 nodes and 37 links, while USNET consists of 24 nodes and 43 links. JPN12, which consists of 12 nodes and 17 links, is adopted to evaluate the performance of the proposed flexible wavebands in networks with a relatively small number of nodes. We also consider a 7×7 regular mesh network as an example of a large network; it consists of 49 nodes and 84 links.

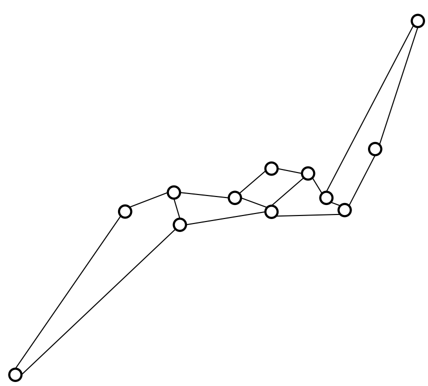


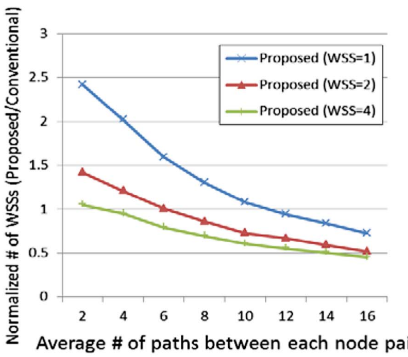
Fig. 12. JPN12 topology.

For benchmarking, we adopt the conventional nodes created by cascading 1×9 WSSs to realize fine granular routing, and our previous architecture [30] that imposes the bound of selectable fibers, denoted by k, for each physical link (it is thus denoted as "EACH" hereafter). A necessary WSS degree for the latter node will be the product of node degree and k, which will be 4 for $k = 1$ and 8 for $k = 2$ in regular mesh networks. The degree can be much more for higher physical degree nodes, such as Paris in the pan-European network, and larger k. Each data point is the ensemble average of 10 trials.

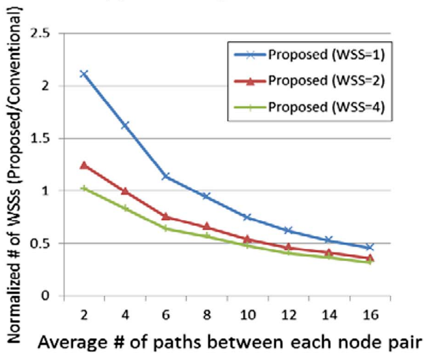
Figure 13 shows the variation in the normalized number of fibers needed for networks utilizing flexible wavebands relative to that needed with conventional fine granular wavelength routing. Namely, the horizontal line at the vertical axis value "1" shows the baseline achieved by conventional optical networks. Due to the routing capability reduction by flexible wavebanding, the normalized numbers of fibers achieved by the proposed and our previous [30] architectures will be lower than conventional for any case. Traffic intensity is represented by the average number of optical paths established between each node pair, which is common to all node pairs in a network. The average number of fibers on each link in the conventional networks ranges around 1 to 3, 1 to 5, 1 to 5, and 2.5 to 15, respectively, for the pan-European network, USNET, JPN12, and the 7×7 regular mesh network, depending on traffic intensity. The label "WSS $= B$" stands for WSS size, $1 \times B$. If $B = 1$, all the paths in an input fiber are routed together, i.e., fiber granular switching. For the previous work ("EACH") with $k = 1$, the derived ratio is not sufficiently close to 1, and up to 10% (pan-European), 20% (USNET), and 15% (JPN12) more fibers are needed even when we have sufficiently large traffic demand. Because some nodes located in the center of the network have high node degree (5 to 7) in the pan-European network, the total number of selectable outgoing fibers for each incoming fiber will reach 7 even when $k = 1$. This makes the performance of the previous method better for the pan-European network than USNET and JPN12; however, higher port count WSSs are necessary. On the other hand, the fiber increment for the proposed design using 1×4 WSSs (WSS $= 4$) is less than 5% when the average number of paths between each node pair is 8–16 in the pan-European network. The increment in USNET/JPN12 is less than 3% for all cases. A similar trend is observed in experiments on other topologies: for example, regular mesh networks of different sizes (see the next subsection).

Figure 14 shows the variation in the normalized number of necessary WSSs. Note that the conventional network uses 1×9 WSSs while the proposed network uses $1 \times B$ WSSs. The curve for $B = 9$ is almost the same as that for $B = 4$, so we omit the former. For both networks, the numbers of WSSs necessary are reduced substantially.

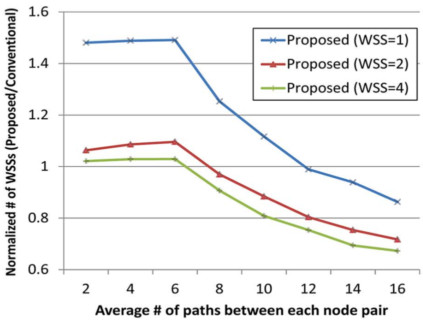
The 3%–5% fiber number increment for the WSS $= 4$ case implies that the amount of traffic that can be accommodated in a network will be 95%–97% compared with conventional networks utilizing huge OXCs. Considering the current traffic increase ratio of 1.3/year, the difference



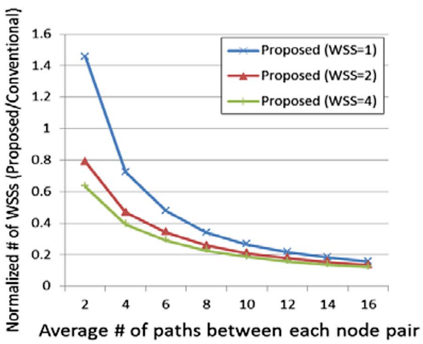
(a) Pan-European network



(b) USNET

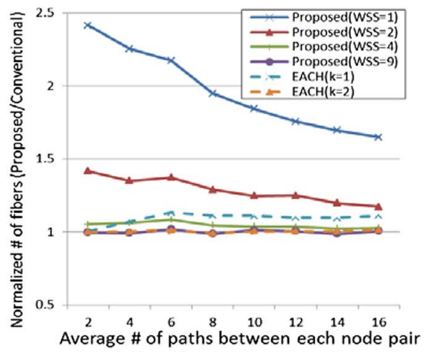


(c) JPN12

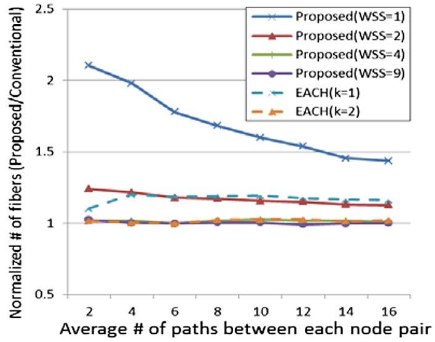


(d) 7x7 regular mesh

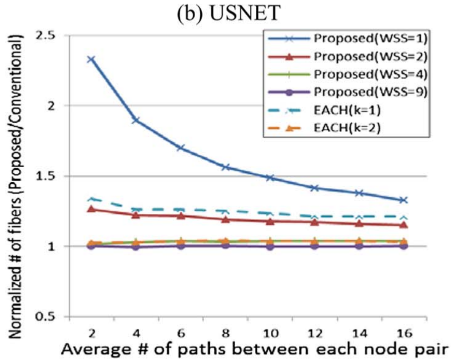
Fig. 13. Normalized number of WSSs.



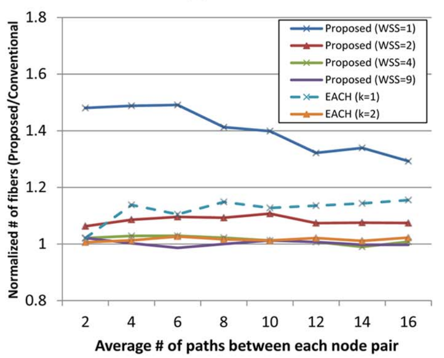
(a) Pan-European network



(b) USNET



(c) JPN12



(d) 7x7 regular mesh

Fig. 14. Normalized number of fibers.

corresponds to network expansion two months earlier while substantially reducing the hardware cost. Thus we can conclude that these results show that the proposed networks utilizing flexible wavebands can achieve almost equivalent routing performance, even though they greatly reduce the WSS degree requirement.

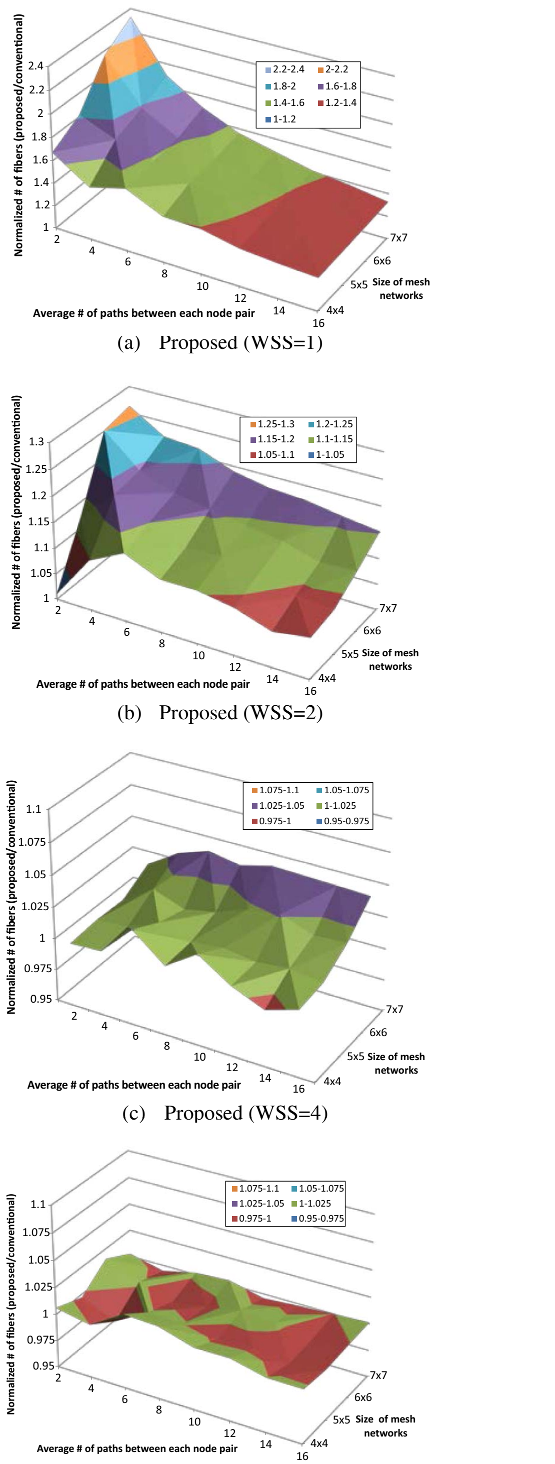
B. Analysis of Dependency on Network Size and Traffic Intensity

The previous section verified the effectiveness of the proposed flexible wavebands for different network topologies. The impact of the proposal can change with the average path length because there are more route candidates for longer paths in general, which makes path bundling easier. On the other hand, as the number of fibers in each link increases, the limitation on the number of selectable output fibers can become more severe. Typically, longer averaged path lengths and more traffic will be observed in larger networks. Thus we compared the performance of the wavebanding proposal for mesh network topologies with different sizes and different traffic intensities.

Figure 15 shows the results for different WSS sizes (1×1, 1×2, 1×4, and 1×9). For the highest port count WSSs, 1×9 WSSs, no degradation in routing performance is observed. On the other hand, networks with low port count WSSs, i.e., $1 \times 1/2$ WSSs, suffered from almost double the fiber number in the small traffic area. Finally, networks with 1×4 WSSs need up to 5% higher fiber number. The increment in a 7×7 network becomes more evident than in small networks, i.e., 4×4 and 5×5 networks. This elucidates that the impact of the increase of fibers on each link is more substantial than that of enhanced routing flexibility given by the increased number of route candidates.

Another notable point is that moderate WSS size (i.e., 1×4 WSSs) achieves, for each network size, almost a constant fiber number increment for different traffic intensities. Due to the rapid growth of Internet traffic, networks are generally required to periodically expand their capacity. This result shows that a WSS degree can be selected to fix the OXC node configuration and the configuration can be maintained throughout the following expansions.

The calculation time for mesh networks of different sizes is shown in Fig. 16. Throughout this time evaluation, 10 threads are running simultaneously on a processor (AMD Phenom II 1065T, 6 cores/2.9 GHz). The calculation time is almost proportional to the traffic intensity and increases with network size. The latter has greater impact than the former because increases in network size not only increase the number of paths in a network (to the power of two if the number of paths between node pairs are fixed), but also the number of route candidates that must be examined with each path establishment. However, even for the 7×7 mesh network, the design algorithm terminates within several hundred seconds, which will be short enough for green field network design.



(a) Proposed (WSS=1)

(b) Proposed (WSS=2)

(c) Proposed (WSS=4)

(d) Proposed (WSS=9)

Fig. 15. Variation in normalized fiber number subject to traffic intensity and size of networks.

C. Impact of Randomness in Ordering of Path Accommodation

Due to the computational difficulty caused by not only the wavelength continuity constraint in conventional optical networks but also the requirement of path bundling in proposed flexible waveband networks, we adopt a sequential-path-accommodation-based heuristic network design algorithm. The path accommodation scheme is applied in descending order of shortest distance/hop counts between source and destination nodes of given path setup demands. In the proposed flexible waveband networks, the number of selectable output fibers for each input fiber is bounded. This implies that more flexibility in selecting routes for each path is needed than in conventional optical networks. It may be better to accommodate shorter paths at first and then longer paths, which have more room in terms of route selection. Moreover, the impact of randomness in path

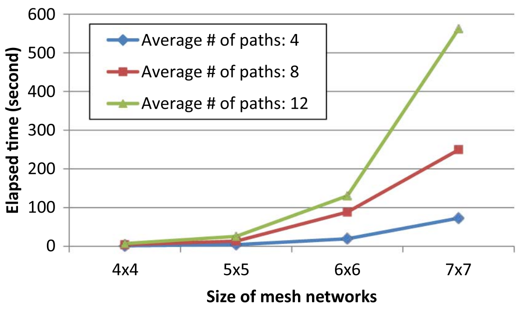


Fig. 16. Dependency of calculation time to network size.

accommodation ordering must be evaluated to verify the validity of the sequential path accommodation scheme.

Considering the above observations, we determined the variation of results on a 5×5 regular mesh network. The averaged traffic intensity is set to two to eight paths between each node pair. This traffic range is selected because the randomness of path accommodation ordering is more evident for small traffic demand cases. We adopt four orders. The first one ("Random") makes path accommodation order purely random. The next one ("Longest first") picks up path demands in descending order of shortest hop count. The third one ("Longest first [node]") selects node pairs in descending order of distance; then all path demands between the selected node pairs are accommodated simultaneously. The last one ("Shortest first") selects path demands in ascending order of shortest hop counts.

Figure 17 shows the estimated variance in the total number of fibers normalized by the average fiber number for conventional optical networks. The result shows that the variance can be small, although the selectable output fiber number limitation is perceptible. Moreover, the variance decreases as the traffic intensity increases. In situations where broad bandwidth networks are requested and the flexible wavebanding proposal makes sense, the simple heuristic algorithm gives stable and sufficiently fewer fibers within a short computation time.

Figure 18 plots histograms, 100 trials for each accommodation order, in terms the number of fibers in a 5×5 mesh network both for the proposed and conventional networks. The derived number of fibers concentrates around the average for all cases; thus the sequential path accommodation heuristic is valid for the proposed flexible waveband

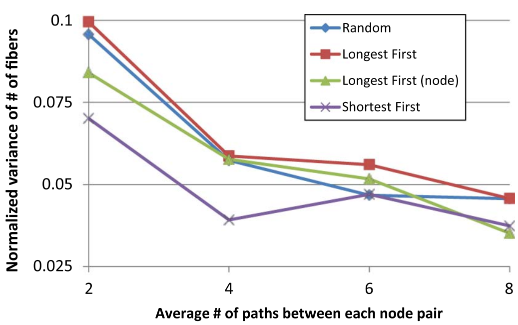


Fig. 17. Normalized variance of number of fibers.

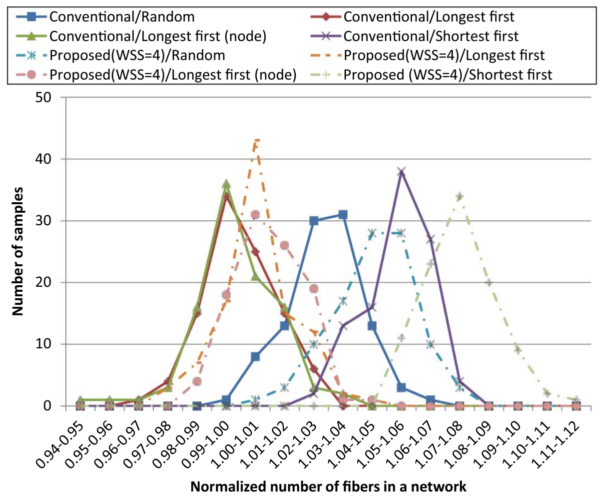


Fig. 18. Histograms of number of fibers in a network for 100 time trials.

networks. Among the four path accommodation orders, "Longest first" provides the best results both for the conventional and proposed networks. The computation time for each trial ends within several seconds; hence, random optimization with numerous parallel trials with the proposed algorithm will enhance the performance of the proposed networks. Further improvement would be possible, for example, by some meta-heuristic techniques such as tabu search and evolutionary computation, by using the above results of a random scheme as initial solutions; however, such improvement will be discussed elsewhere.

VI. Conclusion

We have proposed a coarse granular routing scheme for elastic optical networks. We also presented an OXC node architecture and a network design algorithm that yield cost-efficient networks based on the routing scheme. The proposed node uses WSSs as adaptive-bandwidth optical filters to bundle optical paths while matrix switches are responsible for the selection of output fibers. This two-stage routing mechanism reduces not only the number of WSSs but also WSS degree. Numerical experiments showed that the proposed design and routing algorithm offers almost the same routing capability even if small port count WSSs are utilized. We conclude that the architecture is a viable approach to realizing cost-effective elastic optical path networks.

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References

[1] 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 Commun. Mag.*, vol. 47, pp. 66–73, 2009.

[2] W. Zheng, Y. Jin, W. Sun, W. Guo, and W. Hu, "On the spectrum-efficiency of bandwidth-variable optical OFDM transport networks," in *Optical Fiber Communication Conf. (OFC)*, Mar. 2010, paper OWR5.

[3] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka, and A. Hirano, "Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network," *IEEE Commun. Mag.*, vol. 48, pp 138–145, 2010.

[4] K. Christodoulopoulos, I. Tomkos, and E. A. Varvarigos, "Routing and spectrum allocation in OFDM-based optical networks with elastic bandwidth allocation," in *Proc. Global Telecommunications Conf. (GLOBECOM)*, Dec. 2010.

[5] T. Takagi, H. Hasegawa, K. Sato, T. Tanaka, B. Kozicki, Y. Sone, and M. Jinno, "Algorithm for maximizing spectrum efficiency in elastic optical path networks that adapt distance adaptive modulation," in *European Conf. on Optical Communication (ECOC)*, Sept. 2010, paper We.8.D.5.

[6] M. D. Feuer and S. L. Woodward, "Advanced ROADM networks," in *Optical Fiber Communication Conf. and the Nat. Fiber Optic Engineers Conf. (OFC/NFOEC)*, Los Angeles, Mar. 2012, paper NW3F.3.

[7] 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 Conf. (OFC)*, Mar. 2015, paper Tu3A.7.

[8] M. Iwama, M. Takahashi, Y. Uchida, M. Kimura, R. Kawahara, S. Matsushita, and T. Mukaihara, "Low loss 1×93 wavelength selective switch using PLC-based spot size converter," in *European Conf. on Optical Communication (ECOC)*, Sept. 2015, pp. 1–3.

[9] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki, "Hierarchical optical path cross-connect systems for large scale WDM networks," in *Optical Fiber Communication Conf. (OFC)*, Feb. 1999, pp. 356–358.

[10] L. Noirie, C. Blaizot, and E. Dotaro, "Multi-granularity optical cross-connect," in *European Conf. on Optical Communication (ECOC)*, Oct. 2000, pp. 269–270.

[11] X. Cao, V. Anand, and C. Qiao, "Framework for waveband switching in multigranular optical networks: Part I–multigranular cross-connect architectures," *J. Opt. Netw.*, vol. 5, pp. 1043–1055, 2006.

[12] O. Moriwaki, K. Noguchi, H. Takahashi, T. Sakamoto, K. Ichi Sato, H. Hasegawa, M. Okuno, and Y. Ohmori, "Development of terabit-scale compact hierarchical optical cross-connect system using planar device integration," *J. Lightwave Technol.*, vol. 29, pp. 449–455, 2011.

[13] R. Izmailov, S. Ganguly, V. Kleptsyn, and A. Varsou, "Non-uniform waveband hierarchy in hybrid optical networks," in *Proc. IEEE INFOCOM*, San Francisco, Mar. 2003, vol. 2, pp. 1344–1354.

[14] 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 J. Sel. Areas Commun.*, vol. 26, pp. 22–31, 2008.

[15] O. Turkcu and S. Subramaniam, "Optimal waveband switching in optical ring networks," in *Proc. INFOCOM*, Mar. 2010.

[16] Z. Shen, H. Hasegawa, and K. Sato, "Effectiveness of wavelength/waveband conversion and its allowable cost bound for hierarchical optical path networks," *J. Opt. Commun. Netw.*, vol. 5, pp. 1262–1274, 2013.

[17] S. Chandrasekhar, C. R. Doerr, and L. L. Buhl, "Optical networking without guard bands using novel 8-skip-0 banding filters," *IEEE Photon. Technol. Lett.*, vol. 17, pp. 579–581, 2005.

[18] K. Ishii, H. Hasegawa, K. Sato, S. Kamei, H. Takahashi, and M. Okuno, "Monolithically integrated waveband selective switch using cyclic AWGs," in *European Conf. on Optical Communication (ECOC)*, 2008, paper Mo.4.C.5.

[19] A.-N. Patel, P.-N. Ji, J.-P. Jue, and T. Wang, "Hierarchical multi-granular switching in flexible grid WDM networks," in *Optical Fiber Communication Conf. and the Nat. Fiber Optic Engineers Conf. (OFC/NFOEC)*, Mar. 2012, paper OTh3B.6.

[20] H. Hasegawa, S. Subramaniam, and K. Sato, "Flexible waveband routing optical networks," in *IEEE Int. Conf. on Communications (ICC)*, June 2015, pp. 5198–5203.

[21] https://www.itu.int/rec/T-REC-G.694.1.

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

[23] T. Watanabe, T. Mizuno, Y. Hashizume, and T. Takahashi, "Silica-based PLC $1 \times N$ switch for all wavelength bands," in *Optical Fiber Communication Conf. (OFC)*, Mar. 2014, paper Th1I.5.

[24] T. Goh, M. Yasu, K. Hattori, A. Himeno, M. Okuno, and Y. Ohmori, "Low loss and high extinction ratio strictly nonblocking 16×16 thermooptic matrix switch on 6-in wafer using silica-based planar lightwave circuit technology," *J. Lightwave Technol.*, vol. 19, pp. 371–379, 2001.

[25] S. Sohma, T. Watanabe, N. Ooba, M. Itoh, T. Shibata, and H. Takahashi, "Silica-based PLC type 32×32 optical matrix switch," in *European Conf. on Optical Communication (ECOC)*, Sept. 2006, pp. 1–2.

[26] S. Han, T. J. Seok, N. Quack, B. W. Yoo, and M. C. Wu, "Monolithic 50×50 MEMS silicon photonic switches with microsecond response time," in *Optical Fiber Communication Conf. (OFC)*, Mar. 2014, paper M2K.2.

[27] S. Nakamura, S. Yanagimachi, H. Takeshita, A. Tajima, T. Katoh, T. Hino, and K. Fukuchi, "Compact and low-loss 8×8 silicon photonic switch module for transponder aggregators in CDC-ROADM application," in *Optical Fiber Communication Conf. (OFC)*, Mar. 2015, paper M2B.6.

[28] T. Ishikawa, H. Hasegawa, S. Subramaniam, and K. Sato, "A compact OXC node architecture that exploits dynamic path bundling and routing," in *Int. Conf. on Optical Network Design and Modeling (ONDM)*, May 2016.

[29] T. Ishikawa, M. Niwa, K. Ueda, Y. Mori, H. Hasegawa, S. Subramaniam, K. Sato, and O. Moriwaki, "Hardware scale analysis and prototype development of flexible waveband routing OXCs," in *Optoelectronics and Communications Conf./Int. Conf. on Photonics in Switching (OECC/PS)*, July 2016, paper TuA1-4.

[30] T. Ban, H. Hasegawa, K. Sato, T. Watanabe, and H. Takahashi, "A novel large-scale OXC architecture and an experimental system that utilizes wavelength path switching and fiber selection," *Opt. Express*, vol. 21, pp. 469–477, 2013.

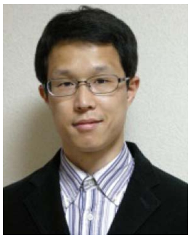
[31] J. Santos, J. Pedro, P. Monteiro, and J. Pires, "Scalable and cost-effective design of optical transport networks supporting heterogeneous Ethernet services," in *European Conf. and Exhibition on Optical Communications (ECOC)*, Sept. 2010, paper Th.10.F.7.

[32] O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Commun. Mag.*, vol. 50, pp. s12–s20, 2012.

[33] A. Nag and M. Tornatore, "Optical network design with mixed line rates," *Opt. Switching Netw.*, vol. 8, pp. 227–234, 2009.

[34] T. Sakano, Y. Tsukishima, H. Hasegawa, T. Tsuritani, Y. Hirota, S. Arakawa, and H. Tode, "A study on a photonic network model based on the regional characteristics of Japan," *IEICE Tech. Rep.*, vol. 113, pp. 1–6, 2013 (in Japanese).

[35] http://www.ieice.org/~pn/jpn/jpnm.html (in Japanese).



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