Large-Scale Optical Node Architecture Utilizing *M*x*M* Wavelength-Selective Switches Optimally Configured for Traffic Distribution

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***Abstract*—We propose a novel optical node architecture that fully utilizes *M*x*M* wavelength-selective switches (WSSs), where the subsystem modular architecture is adopted and the *M*x*M* WSS ports are optimally allocated to inter-node fibers and add/drop fibers in accordance with the traffic distribution. The proposed architecture can accommodate the maximum incoming(outgoing) fiber number of 60 in USNET and 50 in the pan-European network where fiber-utilization efficiency offset is less than 3% compared with the completely unrestricted node. The number of necessary *M*x*M* WSSs is reduced by up to 26% compared with the previously proposed scheme.**

Keywords—Photonic networking; Wavelength routing; Optical switching devices

I. INTRODUCTION

The optical node can cross-connect/add/drop wavelength-division-multiplexed signals without using costly optical-to-electrical and electrical-to-optical conversion. To accommodate the ever-increasing traffic cost-effectively, future optical nodes must support a large number of input/output fibers and transponders while offering high routing capability. According to Cisco's Internet traffic forecast, world traffic is increasing 22% a year, which yields 3 times more traffic in 6 years [1]. Therefore, in the future, we will need a network whose capacity is several times that of the current one. As a result, large-scale optical nodes will be needed soon [2-5]. Although the colorless, directionless, and contentionless (C/D/C) node can attain high routing performance, a large number of costly wavelength-selective switches (WSSs) in the optical-cross-connect (OXC) part and erbium-doped fiber amplifiers (EDFAs) in the add/drop parts are necessary when the node scale is large [6]. Moreover, complicated fiber interconnections within a node are needed.

To overcome these difficulties, we previously proposed a simple and cost-effective large-scale optical node architecture in which the OXC part adopts the subsystem-modular architecture and the add/drop part employs a transponder-bank structure where routing capability for signal adding/dropping was enhanced by OXC optimization [6]. In the OXC part, an *M*x*M* WSS can be utilized as a subsystem and multiple *M*x*M* WSSs connected with a limited number of fibers to create a single large-scale OXC. The use of *M*x*M* WSSs can simplify fiber interconnection inside the node [7-11]. Each *M*x*M* WSS allocates (*M*-2)/2 ports for inter-node connection, 2 ports for intra-node subsystem connection, and (*M*-2)/2 ports for add or drop connection. Hence, the maximum add or drop ratio can be 100%. As for the add/drop parts, multiple transponders are divided into banks and each bank is connected to a limited number of add/drop fibers. This scheme greatly reduces the number of necessary EDFAs since the splitter degrees needed for aggregation/distribution can be reduced even though it supports 40 incoming(outgoing) fibers in USNET. While the transponder bank structure does not offer complete directionless add/drop, the deficiency is well mitigated by utilizing the OXC routing function [6]. The subsystem modular architecture can suffer from intra-node blocking due to the limited interconnection between subsystems. The likelihood of blocking increases with the number of interconnected subsystems. Increasing subsystem port count, *i.e.* decreasing the number of interconnected subsystems, can reduce the blocking probability; however, the available port count of *M*x*M* WSSs will be strictly limited [7-11].

In this paper, we propose a large-scale optical-node architecture that makes the best use of limited-port-count *M*x*M* WSSs. The proposed scheme optimally allocates WSS ports to inter-node fibers and add/drop fibers according to the estimated traffic distribution. Since the number of inter-node fibers per *M*x*M* WSS is maximized, the probability of intra-node blocking is reduced. Compared with the previously proposed scheme, the maximum node scale can be increased to 60 from 40 in USNET network and to 50 from 30 in COST266 pan-European network. Furthermore, the optimum WSS-port allocation can substantially reduce the number of necessary WSSs, up to 26%. Such benefits can be enjoyed without any hardware alteration. The analysis herein can easily be extended to the elastic structure, assuming that the WSS can be made structure adaptive. In addition, our analysis is also applicable to space-division multiplexing systems [12,13]. However, we confine our analysis to conventional fixed grid systems because of the limited space.

II. PROPOSED NODE ARCHITECTURE

Figure 1 shows our proposed node architecture in which the subsystem-modular OXC and the transponder-bank add/drop are combined in a complementary manner. Since a large-scale OXC is constructed by interconnecting multiple small-scale subsystems, a limited port count *M*x*M* WSS can be utilized as a subsystem. Each *M*x*M* WSS input(output) side accommodates *P* “inter-node fibers” (blue lines in Fig. 1), 2 “intra-node fibers” (red lines in Fig. 1), and *M*-*P*-2 “add(drop) fibers” (green lines in Fig. 1), where inter-node fibers link adjacent nodes, intra-node fibers bridge adjacent *M*x*M* WSSs within a node, and add/drop fibers connect the OXC part to the add/drop parts; *P* is flexibly determined in a node-by-node manner according to the network’s traffic distribution. Thus, overall performance of the node can be optimized by properly determining the *P* value depending on the traffic condition. At each intra-node fiber, an EDFA should be inserted to offset a subsystem loss though this is not shown in Fig. 1 for simplicity. The add/drop parts employ the transponder-bank architecture, where transponders are divided into groups. The dropped signals are distributed by a splitter and sent to *bK*/*NT* banks, where *b* is the number of fibers connected to each bank, *K* the number of transponders in the add/drop parts, *N* the number of input(output) inter-node fibers, and *T* the number of transponders in each bank. Next, each signal is delivered to an arbitrary receiver in the bank via a splitter, switch, and tunable filter. Note that the tunable filter may be omitted if a coherent receiver is used. The add signal is input to one of the add fibers via a switch and splitters. After that, the signal is switched by the *M*x*M* WSS to an arbitrary outgoing inter-node fiber. Here, routing flexibility and hardware requirements are controlled by parameter *b*; smaller *b* reduces EDFA number thanks to the decreased splitter loss, whereas larger *b* offers reduced blocking probability since the number of connectable banks for each add/drop fiber increases.

The point is how to allocate WSS ports for inter-node fibers and add/drop fibers. For example, if all the incoming signals are dropped at the node, drop fibers should equal the number of inter-node fibers. On the other hand, if the number of dropped signals is only a small portion of the incoming signals, the number of drop fibers per WSS can be reduced and hence the number of inter-node fibers per WSS can be increased. Considering such features, we can optimize the numbers of inter-node fibers and add/drop fibers to suit the traffic distribution. With using traffic distribution information (or future expected one), we calculate the maximum drop ratio at each node, where the drop ratio is defined as the ratio of the number of dropped signals to the maximum number of incoming signals. Similarly, the add ratio is defined as the ratio of the number of added signals to the maximum number of outgoing signals. With the estimated add ratio and drop ratio, we determine the minimum number of add/drop fibers needed that can accommodate all add and drop signals. In other words, the number of inter-node fibers per subsystem is maximized. This enhances the routing performance, since the increase of inter-node fibers per WSS reduces the necessary number of WSSs. Which in turn minimizes the blocking probability due to contention at intra-node fibers.

To maximize the fiber-utilization efficiency, we developed a route-and-wavelength assignment algorithm that makes the best use of our proposed node architecture. Figure 2 depicts the flowchart of the algorithm.

Step 1: Find routes and wavelengths that can connect a source transmitter and a destination receiver.

Step 2: Exclude route candidates if the additional hop count from the smallest one exceeds the prescribed limit.

Step 3: Select paths that use the minimum number of intra-node fibers.

Step 4: Select a pair of source and destination subsystems, that minimize the utilization of add fibers at source node and drop fibers at destination node.

Step 5: Assign a wavelength that offers the maximum number of route candidates.

Step 2 avoids the use of long detours that unduly consume the fiber bandwidth in the network. Step 3 minimizes the contention in intra-node fibers. In addition, the signal quality can be managed by excluding route candidates that necessitate an unacceptable number of intra-node fibers traversed. Steps 4 and 5 minimize the probability of wavelength contention at add/drop fibers. Through this process, we can effectively suppress the effects of the restriction imposed by the proposed node. Please note that the analytical complexity of designing a network that uses the subsystem-OXC architecture is not heavy as was analyzed in [14]. The simple Dijkstra’s algorithm can be applied, where each MxM WSS is regarded as a node.

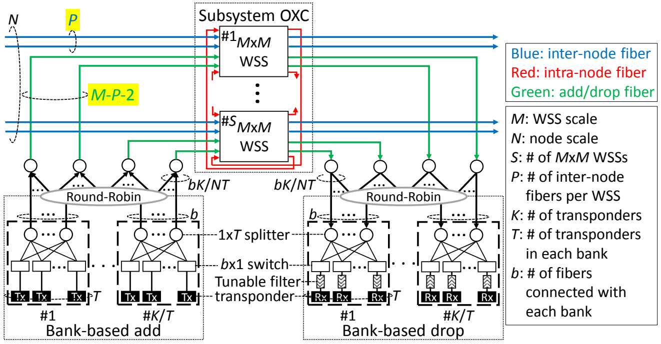


Fig. 1. Proposed optical node architecture, where *P* is optimized for each node.

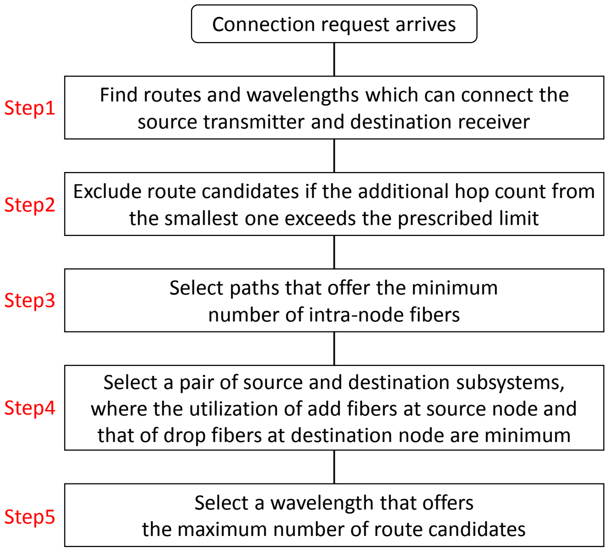


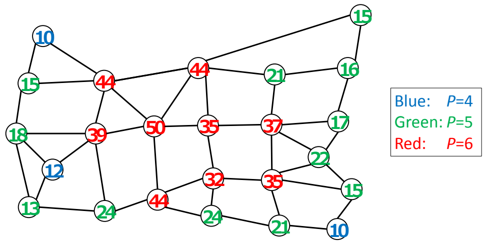
Fig. 2 Flowchart of the proposed route-and-wavelength assignment algorithm that is aware of the node restriction.

III. SIMULATIONS

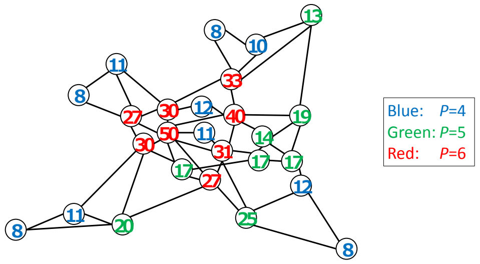
In order to verify the effectiveness of the proposed node architecture, we evaluate fiber-utilization efficiency under dynamic traffic scenarios. The tested topologies are USNET network and COST266 pan-European network, see Fig. 3 [15,16]. We assume that the maximum number of wavelength channels per fiber is 80 and the WSS scale, M, is 10. The number of transponders of each bank, T, is 64. The maximum node scale in the network and the number of fibers connected to each bank, b, are parameterized. First, we conduct tentative simulations assuming the full-C/D/C node and estimate the maximum add ratio and drop ratio for each node. The traffic demand is uniformly and randomly distributed between pairs of transmitters and receivers. Path-setup requests follow a Poisson process and the holding time of each connection has a negative exponential distribution. Based on the estimated add ratio and drop ratio, we determine the number of inter-node fibers per MxM WSS, P and that of add/drop fibers, 10-P-2 for each node. When the add ratio and drop ratio of a node is 0-33%, 33-60%, or 60-100%, we assign 6, 5, or 4 inter-node fibers per WSS, respectively. For example, Fig. 3 indicates the node scale, *i.e.* the number of inter-node input(output) fibers of a node, N, and the number of inter-node fibers per WSS, P, for each node when the maximum node scale is 50. We observe that N and P incline to be large when the node degree is large. Then, we calculate an accepted traffic load using the traffic pattern and analyzed the difference from the benchmark under the same traffic distribution.

Figure 4 shows an accepted traffic load at the blocking ratio of 10^{-3} as a function of the maximum node scale, where the results are normalized against the performance of the full-C/D/C node. As a reference, performance of the conventional subsystem-modular OXC is also shown [6]. We observe that the conventional architecture cannot attain node scale of 50 in UNSET or 40 in COST266 within 3% performance offset even with C/D/C add/drop capability. In contrast, the proposed scheme respectively can attain node scales of 60 and 50 with $b \geq 6$.

Figure 5 depicts the number of 10x10 WSSs necessary for the entire network. Thanks to the appropriate assignment of WSS ports, the proposed network can reduce the number of necessary WSSs by up to 26%. Figure 6 presents the number of necessary EDFAs for the entire network when b=6. The EDFAs are assumed to have a gain of 23 dB. Owing to the bank structure, the proposed add/drop configuration can reduce the number of EDFAs by up to 82% compared to the full-C/D/C node.

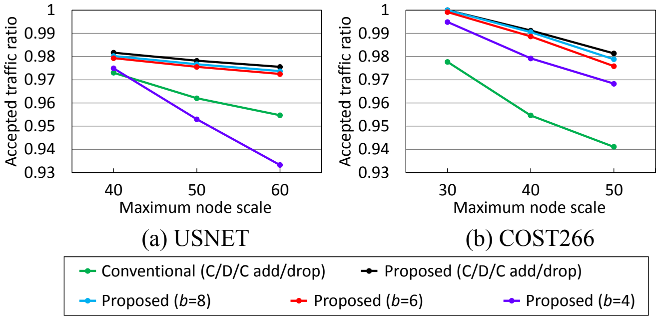


(a) USNET



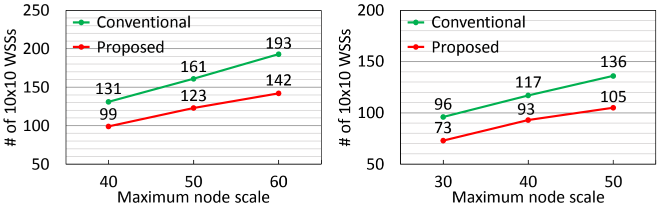
(b) COST266

Fig. 3. Physical network topologies and the node scale at each node when the maximum node scale is 50. (a) USNET network and (b) COST266 pan-European network.



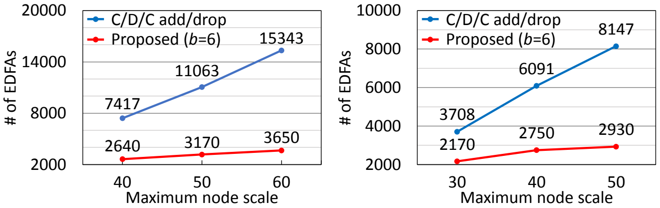
(a) USNET (b) COST266

Fig. 4. Normalized accepted traffic vs. maximum node scale at the blocking ratio of 10^{-3} in (a) USNET network and (b) COST266 pan-European network.



(a) USNET (b) COST266

Fig. 5. Number of 10x10 WSSs vs. maximum node scale in (a) USNET network and (b) COST266 pan-European network.



(a) USNET (b) COST266

Fig. 6. Number of EDFAs vs. maximum node scale in (a) USNET network and (b) COST266 pan-European network.

IV. CONCLUSION

We proposed an *M*x*M* WSS based optical node architecture in which *M* WSS ports are optimally allocated to the inter-node fibers and the add/drop fibers in accordance with the traffic distribution. With the proposed scheme, we can attain node scale of 60 for the USNET network and 50 for the COST266 pan-European network at an efficiency offset less than 3%, while substantially reducing the numbers of WSSs and EDFAs needed.

ACKNOWLEDGMENT

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REFERENCES

[1] Cisco Systems, “Cisco Visual Networking Index (VNI) Complete Forecast for 2015 to 2020,” 2016.

[2] S. Woodward, “ROADM options in optical networks: flexible grid or not?” OFC/NFOEC, OTh3B.1, 2013.

[3] R. Egorov, “Next Generation ROADM architecture and design,” OFC/NFOEC, NW1J.3, 2013.

[4] G. Rizzelli, G. Maier, and A. Pattavina, ”WSS requirements in next-generation wavelength switched optical networks,” OFC, OTh4B.1, 2013.

[5] R. Younce, J. Larikova, and Y. Wang, “Engineering 400G for colorless-directionless-contentionless Architecture in Metro/Regional Networks,” J. Opt. Commun. Netw. 5(10), A267–A273 (2013).

[6] M. Niwa, Y. Mori, H. Hasegawa, and K. Sato, “Tipping point for the future scalable OXC -What size MxM WSS is needed?-,” OFC, W4B.5, 2016.

[7] N. K. Fontaine, R. Ryf, and T. Neilson, “NxM Wavelength Selective Crossconnect with Flexible Passbands,” OFC, PDP5B.2 2012.

[8] H. Uetsuka, M. Tachikura, H. Kawashima, K. Sorimoto, H. Tsuda, K. Sasaki, and Y. Yamashita, “5×5 Wavelength Cross-connect Switch with Densely Integrated MEMS Mirrors,” Photonics in Switching, PW2B.2, 2014.

[9] K. Yamaguchi et al., “M x N Wavelength Selective Switches Using Beam Splitting By Space Light Modulators,” Photonics Journal 8, No. 0600809, 2016.

[10] K. Suzuki and Y. Ikuma, “Spatial and Planar Optical Circuit,” OFC, Th3E.1, 2016

[11] L. Zong, H. Zhao, Z. Feng and S. Cao, “Demonstration of ultra-compact contentionless-ROADM based on flexible wavelength router,” ECOC, P.4.4, 2014.

[12] Marom, Dan M., et al. "Survey of Photonic Switching Architectures and Technologies in Support of Spatially and Spectrally Flexible Optical Networking," Journal of Optical Communications and Networking 9.1 (2017): 1-26.

[13] M. Jinno, Y. Mori, “Unified architecture of an integrated SDM-WSS employing a PLC-based spatial beam transformer array for various types of SDM fibers,” JOCN, Volume 9, Issue 2, 2017.

[14] K. Sato, H. Hasegawa and K. Sato, “Disruption free expansion of protected optical path networks that utilize subsystem modular OXC,” JOCN vol.8, No. 7, pp. 476-485 (2016).

[15] S. F. Gieselman, N. K. Singhal, and B. Mukherjee, “Minimum-cost virtual-topology adaptation for optical WDM mesh networks,” ICC, ON10-2, 2005.

[16] R. Inkret, A. Kuchar, and B. Mikac, Advanced Infrastructure for Photonic Networks—Extended Final Report Of Cost 266 Action. Brussels, Belgium: Cost, 2003, Ch.1.