A novel large-scale OXC architecture and an experimental system that utilizes wavelength path switching and fiber selection

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Abstract: We propose a novel large-scale OXC architecture that utilizes WSSs for dynamic wavelength grouping and *1*x*n* switches for fiber selection. We also develop a network design algorithm that can make the best use of the routing capability of the proposed nodes. Numerical experiments on several topologies show that the architecture attains substantial hardware scale reduction. A prototype demonstrates good transmission performance and confirms the technical feasibility of the proposed OXC architecture.

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1. Introduction

The rapid growth of Internet traffic spurred by the penetration of broadband access is driving the introduction of photonic networks. To cope with the future expected traffic increase, driven by the advancement of video technologies including high-definition and ultra-high-definition TV (72 Gbps, uncompressed) [1] and future advanced services [2], the number of fibers connecting pairs of adjacent nodes need to be substantially increased. When we consider space switches, a 3-D micro-electro mechanical systems (MEMS) switch up to ~320x320 appears commercially feasible and a 512x512-port switch has been tested [3]. However, if we want to create, for example, a 48 fiber x 48 fiber wavelength cross-connect, where each fiber carries 96 λs, 96 48x48 optical space switches are required, this scale is not practical. Presently, most OXCs(/ROADMs) utilize wavelength selective switches (WSSs), however, the maximum available number of output ports is limited to 20+. To meet the future traffic demand, cost effective and scalable large-scale optical cross-connects (OXCs) are indispensable [4].

In existing communication networks, the practical node degree is limited [5] to, say, 8, where the determining factor is the physical network topology. Here node degree is defined as the number of adjacent nodes and not the number of input/outgoing fibers to/from a node. It will not be changed even if the number of parallel fibers increases on each link to accommodate increased traffic. In this situation, wavelength paths that are coming to a node from one of the input fibers and should be delivered to one of the adjacent nodes will not always be necessary to be distributed among all the parallel fibers on a link to the adjacent node. In other words, setting slight restrictions on fiber selections on a link so that those wavelength paths can be routed on one or a few fibers on the link without allowing each wavelength path to freely choose a fiber, is expected to yield an efficient solution.

In this paper, we propose a novel large-scale OXC node architecture that utilizes a two-stage routing mechanism; 1) WSSs for selective and dynamic wavelength grouping at the wavelength path level and 2) high-degree 1xn optical switches (SWs) for selecting fibers on a link between adjacent nodes. This architecture significantly reduces the WSS scale needed; up to 1/n (n: number of parallel fibers on a link to the adjacent node), as detailed herein. Recently, a 1x128 SW [6] or 4 arrayed 1x29 SW [7] were fabricated on a single PLC chip and allow effective realization of the proposed architecture. In order to evaluate our proposed OXC architecture, we developed an optical path network design algorithm. We also developed a prototype system that uses 12x8 Delivery and Coupling switches (DCSWs) [8]. The good performance of the OXC and its practicality are verified through numerical and transmission experiments. A preliminary investigation that introduced a node architecture, was detailed at an international conference [9].

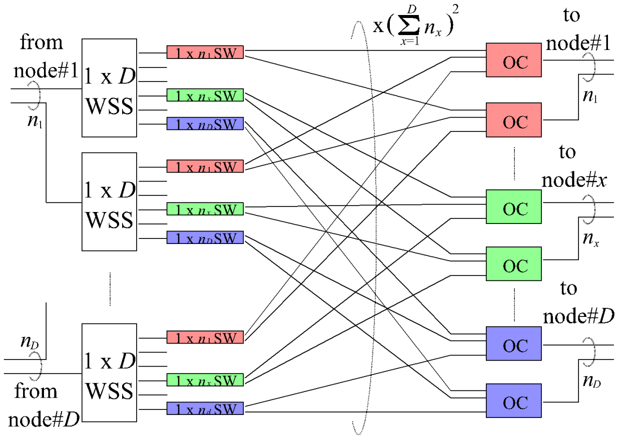


Fig.1. Proposed node architectures based on wavelength grouping and fiber selection.

2. Proposed node architecture

The routing philosophy of the proposed architecture is to select one of the adjacent nodes first and then one of the parallel fibers on the link. This simplified routing strategy reduces node complexity with virtually no drop in routing capability as shown in numerical experiments. For explanation simplicity, we assume in this section that the number of selectable fibers, k, is k=1 (each wavelength path group, which is created by a WSS at each input fiber and intended for one of the adjacent nodes, is accommodated in one fiber on the link). Let D be the physical degree of the node, and n_x be the number of parallel fibers on each link to an adjacent node x (x: 1, 2, …., D). Fig. 1 depicts the proposed node architecture; it consists of 1xD WSSs, 1xn_x SWs, and $\sum_{x=1}^{D} n_x$ x1 optical couplers (OCs). The necessary numbers of WSSs, 1xn_x SWs, and OCs are, respectively, $\sum_{x=1}^{D} n_x$, $D\sum_{x=1}^{D} n_x$ and $\sum_{x=1}^{D} n_x$. The OCs at the right hand side can be replaced by the 1x n_x SWs and WSSs at the left hand side in a symmetrical way to minimize loss. This mirrors the way in which a conventional OXC/ROADM that utilizes WSSs at input side and OCs at output side, the OCs can be replaced with WSSs (the so called route and select architecture) where the total number of WSSs is doubled while the power loss at OCs is reduced. Each WSS divides and routes incoming wavelengths into D groups according to the requested output adjacent nodes. Each group is routed by the 1x n_x SW to one of the output fibers that is connected to the requested adjacent node. Only one wavelength group is routed with each 1x n_x SW. The WSSs are used for grouping input wavelengths according to the next node, and SWs for fiber selection on each link. The total number input (or output) fibers of a node is $\sum_{x=1}^{D} n_x$, and hence the conventional WSS-based architecture requires $\sum_{x=1}^{D} n_x$ of 1x $\sum_{x=1}^{D} n_x$ WSSs. This architecture can reduce the necessary degree of the WSS, that is, $\sum_{x=1}^{D} n_x$ to D. Please note that a 1x $\sum_{x=1}^{D} n_x$ WSS can be realized by cascading multiple smaller degree WSSs. Our architecture can be regarded as replacing the 1x $\sum_{x=1}^{D} n_x$ WSS with a combination of 1xD WSS and 1xn_x SW, which simplifies the architecture and, as a result, significantly reduces optical loss and device cost, although there is a slight loss in routing capability.

An equivalent architecture to Fig. 1 is shown in Fig. 2. This architecture utilizes a $\sum_{x=1}^{D} n_x$ x n_x DCSW, which integrates $\sum_{x=1}^{D} n_x$ arrayed 1xn_x SWs and n_x arrayed $\sum_{x=1}^{D} n_x$ x1 OCs. The number of fibers that interconnect component optical devices is reduced to $D/\sum_{x=1}^{D} n_x$ (see Fig. 1 and Fig. 2), which eases fabrication.

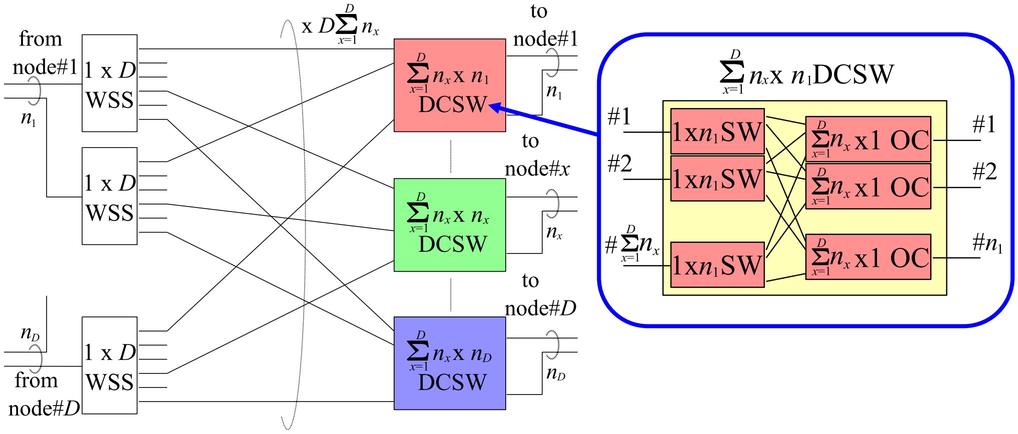


Fig. 2. Proposed node architectures based on Delivery and Coupling switches (DCSWs). Each DCSW corresponds to the same color parts in Fig. 1.

The number of selectable output fibers, k, can be increased. Fig. 3 shows the case for k=2. The degree of WSSs and the number of 1xn_x SWs increase with k. Increasing k enhances node routing capability, but also the hardware scale. The important task of network design is to attain the necessary node routing capability while keeping k to the minimum value possible.

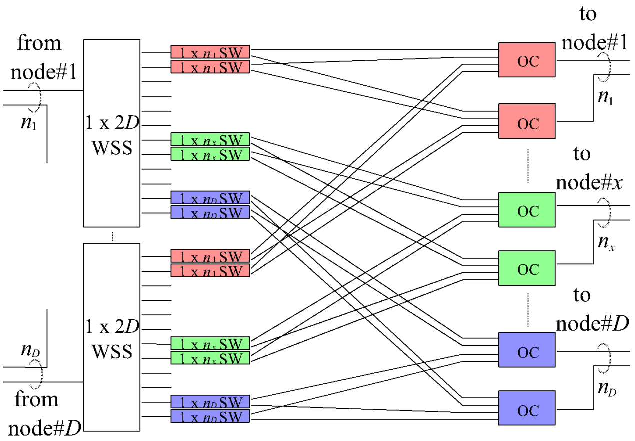
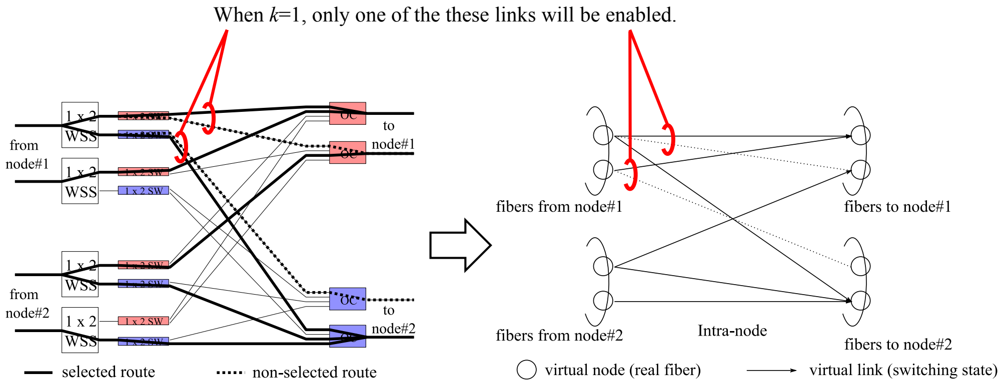


Fig. 3. Proposed architecture when the number of selectable parallel fibers k=2.

3. Network design algorithm

3.1 Virtual topology construction that considers switching states

We developed a design algorithm that considers the restriction on the routing capability of the proposed nodes. The goal of the network design algorithm is to minimize the number of required fibers. To handle the restriction on fiber selection, we create virtual topology graphs, in which fibers are translated into virtual nodes and switching states of nodes are translated into virtual links (intra-node links) as shown in Fig. 4. A virtual topology graph is defined for each wavelength index. Costs of links in the virtual topology are set at zero if there is no intra-(physical)node blocking (i.e. 1xn switch status) and the outgoing physical link fibers are available; costs of the virtual topology links that are not available are set at infinity. Costs of the virtual topology link that utilizes an additional new fiber is; $Cost_{SW} + Cost_{Fiber}$ ($Cost_{SW} < Cost_{Fiber}$). When the outgoing fiber is free and the virtual topology link to the outgoing fiber is not forbidden by the restriction, the cost of the virtual topology link is $Cost_{SW}$. Each wavelength path group, which is selected by a WSS at each input fiber and designated for one of the adjacent nodes, can be accommodated in the same fiber on the link. Therefore, we use the shortest path tree with the destination node as the root for routing and wavelength assignment on the virtual topology graphs. Because there are multiple pairs of a virtual source node and a virtual destination node, which indicate the same source/destination nodes on the real topology, source/destination node pairs of the demands on the real topology should be translated into node pairs on the virtual topologies. Inefficient combinations of virtual node pairs increase the minimum hop count and waste fiber resources. To solve this problem, we employ the source node sets corresponding to a combination of a destination node and the node adjacent to the destination node in order so as not to assign extra fiber resources.


When *k*=1, only one of the these links will be enabled.

(a) Routing at proposed node

(b) Construction of virtual topology

Fig. 4. A virtual topology graph.

3.2 Proposed network design algorithm

The structure of the proposed algorithm is summarized as follows.

<***Optical path network design algorithm considering dynamic wavelength grouping and fiber selection***>

Step 1

Search for the demand whose shortest hop count between the source and destination node pair is the largest among the given demands. Find a pair of route and wavelength index that minimizes the fiber increment by applying Dijkstra's algorithm on the virtual topology graphs. Update the link weight following switching states.

Step 2

Based on the selected node pair and its shortest route found in Step 1, create a set of demands that consist of the destination node and plural source nodes. The source nodes should satisfy; the shortest route that connects each source node of the set and the destination node contains the node that is one-hop before the destination node on the shortest route found in Step 1.

Step 3

Find the shortest path tree with the virtual destination node as the root of the tree by applying Dijkstra's algorithm on the virtual topologies and assign a pair of route and index of wavelength to the demand that has the shortest weight. Remove the demand from the demand set and update the link weight.

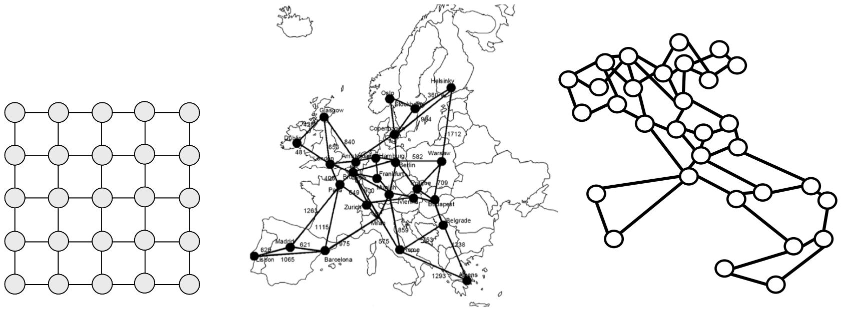
Step 4

Repeat Step 3 until either the demand set is empty or the capacity of the fiber as the virtual destination node is filled.

Step 5

Repeat Step 1 to Step 4 until all demands are accommodated.

The one-hop demands, whose shortest hop count between the source and destination node pair is one, do not transit any nodes. Therefore, such demands are assigned after finishing Step 4. The remaining one-hop demands are assigned after all demands whose shortest hop counts are two or more than two are assigned.



(a) 5x5 regular mesh network (b) COST266 (c) Italia network

Fig. 5. Experimental network topologies.

4. Numerical experiments

We compared the performance of networks with proposed switch architecture to those with conventional switches composed of large-scale WSSs. We use the following parameters: a 5x5 regular mesh network, the COST266 pan-European network model [10] with 26 nodes and 51 links, and the Italia network model [11] with 31 nodes and 49 links, see Fig. 5. Wavelength conversion was not considered, fiber capacity is 80 wavelengths, and randomly distributed traffic demands, represented as the average number of wavelength paths between each node pair. The necessary number of fibers was the average of 10 trials with different traffic distributions, and was normalized against that of the conventional networks. Figs. 6, 7 and 8 show normalized number of fibers for each network topology tested for different values of *k*. These figures show that the proposed networks need more fibers in the small traffic demand area, however, the fiber increment rapidly decreases as the demand becomes large. For a 5x5 regular mesh network, the increment is less than 10% when wavelength path demand is larger than 5 and *k*≥2. It reaches 0.4% when the demand is 28 and *k*≥3. For the COST266 network, it is less than 10% when the demand is larger than 10 and *k*≥2. It reaches 2.9% when the demand is 32 and *k*≥3. For the Italia network, it is less than 10% when the demand is larger than 7 and *k*≥2. It reaches 1.1% when the demand is 32 and *k*=4. Please note that this node architecture targets networks with large traffic demands.

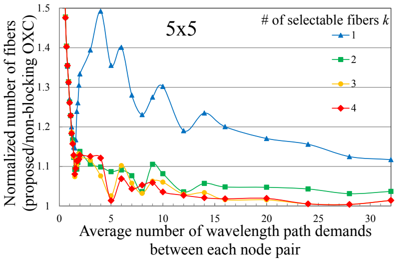


Fig. 6. Normalized number of fibers for 5x5 network.

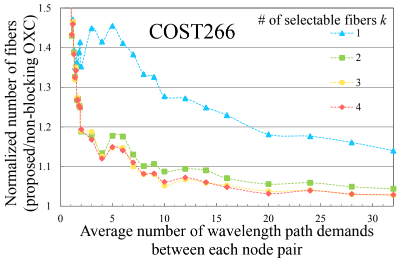


Fig. 7. Normalized number of fibers for COST266 network.

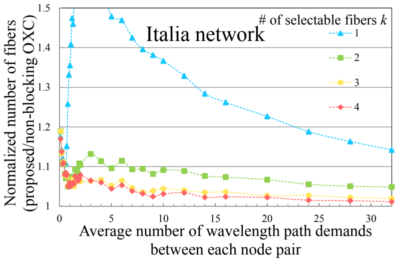


Fig. 8. Normalized number of fibers for Italia network.

Regarding hardware scale, the average input/output fiber count of the largest node in COST266 is, at average traffic volume of 20, 50/50, which means that 50 1x50 WSSs or 150 1x20 WSSs are required for the conventional node. While with our architecture (at *k*=2) the average input/output fiber count is 55/52, and hence 55 1x20 WSSs and 52 1x*n* (*n*≤11) SWs are required. In the Italia network, the average input/output fiber count of the largest node is, at the average traffic volume of 20, 77/77, which means that 77 1x77 WSSs or 324 1x20 WSSs are required for the conventional node. While with our architecture (at *k*=2) the average input/output fiber count is 80/75, and hence 80 1x20 WSSs and 75 1x*n* (*n*≤28) SWs are required. The hardware requirement is thus significantly reduced.

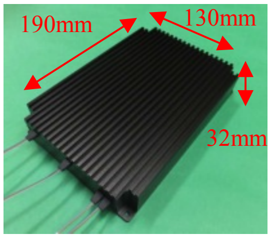


Fig. 9. 2 array 12x8 DCSW [12].

5. Transmission experiments

In this experiment, we assumed that each link had the same number of parallel fibers, that is, $n_x=n$. We developed a prototype system on the proposed architecture with D=6 and n=8. For the prototype, a 48x8 DCSW was constructed using four12x8 component DCSWs and eight 4x1 OCs. Fig. 9 shows a 2 array 12x8 DCSW [12] module with size of 19 x 13 x 3.2 cm. Fig. 10 shows the experimental setup used to evaluate the cascadability of the prototype system. Light from a distributed-feedback laser diode (DFB-LD) was modulated by a 9.953280-Gb/s, non-return-to-zero, and pseudorandom bit stream (PRBS) with word length of $2^{31}-1$. We measured the bit-error rate of the signal as it traversed up to four proposed nodes (loop-back configuration). Fig. 11 and Fig. 12 plot, respectively, bit-error rate and power penalty measurement. Good transmission characteristics were realized; the maximum power penalty at the bit-error rate of 10^{-9} was only 0.08 dB after traversing four nodes.

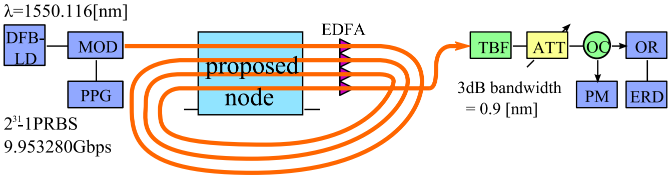


Fig. 10. Experimental setup. MOD: modulator, PPG: pulse pattern generator, EDFA: Erbium dope fiber amplifier, TBF: tunable band path filter, ATT: attenuator, OC: optical coupler, PM: power meter, OR: optical receiver, ERD: error detector.

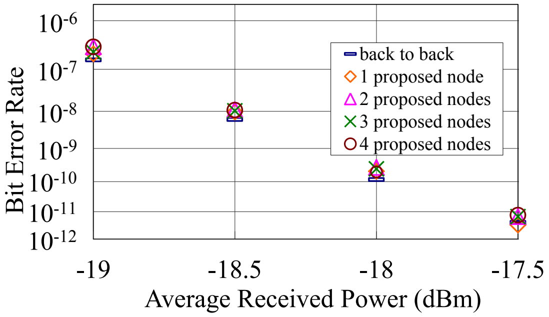


Fig. 11. Measured bit-error rate.

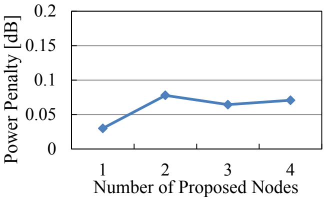


Fig. 12. Power penalty versus the number of the nodes traversed (BER=10^{-9}).

6. Conclusions

We proposed a novel large-scale OXC node architecture that consists of small-degree WSSs and 1xn SWs. We also proposed an optical path network design algorithm that can make the best use of the proposed architecture. Numerical experiments verified that it offers significant hardware scale reduction at the cost of a few additional fibers. We developed a prototype system and verified its technical feasibility through transmission experiments.

Acknowledgement

The authors would like to thank researchers of NEL for their valuable discussions. This work was partly supported by NICT λ-reach project and KAKENHI (23246072).