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PAPER

Assessment of Node- and Link- Level Blocking and Creating Cost-Effective Networks in the Era of Large Bandwidth Services

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SUMMARY Link-level and node-level blocking in photonic networks has been intensively investigated for several decades and the C/D/C approach to OXCs/ROADMs is often emphasized. However, this understanding will have to change in the future large traffic environment. We herein elucidate that exploiting node-level blocking can yield cost-effective large-capacity wavelength routing networks in the near future. We analyze the impact of link-level and node-level blocking in terms of traffic demand and assess the fiber utilization and the amount of hardware needed to develop OXCs/ROADMs, where the necessary number of link fibers and that of WSSs are used as metrics. We clarify that the careful introduction of node-level blocking is the more effective direction in creating future cost effective networks; compared to C/D/C OXCs/ROADMs, it offers a more than 70% reduction in the number of WSSs while the fiber increment is less than ~2%.

key words: *networks, photonic network, wavelength routing, optical cross-connect, reconfigurable optical add/drop multiplexer*

1. Introduction

Internet traffic is continuously increasing around the world at rates of 20–42% a year [1]. The explosion in traffic is propelling the introduction of higher-bitrate transmission systems including 100 Gbps and 400 Gbps, and also a steady increase in the number of optical fibers between optical nodes [2], [3]. Expanding the link capacity and node throughput is a perpetual goal. The importance of developing large-scale reconfigurable optical add-drop multiplexers (ROADMs) or optical cross-connects (OXCs) (in this paper, ROADMs and OXCs are used interchangeably) has accordingly been emphasized [2]–[6]. For example, when the capacity of current 8 fiber-degree OXCs is completely occupied, a traffic increase of 30% a year will need 50 ($= 8 \times 1.3^7$) fiber-degree OXCs in 7 years.

Optical networking technologies using wavelength routing, i.e. OXCs, are now mostly applied to core and metro-core networks. The network cost is taken to be the sum of link cost and node cost (operation cost is another factor, but lies out of the scope of this paper). The introduction of OXCs can enhance fiber-utilization efficiency without relying on costly optical-to-electrical (O/E) and electrical-to-optical (E/O) conversion, and the importance of colorless/directionless/contentionless (C/D/C) OXCs are often emphasized to attain the maximum fiber utilization, which can minimize link cost [7]. So far, the required OXC port count has been 8 or less in most networks, so the C/D/C attributes can be well utilized. Unfortunately, given the large traffic demands expected, the needed OXC port count will explode and OXC hardware will be increased nonlinearly as will be discussed later, while link cost is proportional to traffic demand. In metro networks, metro traffic is growing nearly twice as fast as core traffic [1], which is due to the development of data centers in metro areas and the advancement of content delivery networks. Metro networks can have lower link cost than core networks since the transmission distances between adjacent metro nodes are shorter. In this context, the OXCs applied to metro networks must be much more cost-effective than those used in core networks even if the OXCs entail a marginal increase in fiber number [8]. This is made possible by wisely introducing routing restrictions in OXCs. In other words, the dual requirements of large port-counts and high cost effectiveness of OXCs will drive pragmatic choices in the introduction of routing restrictions.

To date, link-level blocking caused by wavelength collision in WDM networks has been regarded as inevitable since wavelength converters or O/E/O can be very costly, and Wavelength and Route Assignment (WRA) algorithms have been adopted to minimize the blocking. This paper analyzes the import of link- and node-level blocking where non-blocking networks are used as a baseline; the goal is to elucidate the value of node-level blocking compared to link-level blocking. The authors believe that this is the first work to analyze the relations of both levels of blocking in detail on the same basis for different node architectures so far proposed, and that this will greatly help the proper understanding of the meaning of node-level blocking. Further, this work clarifies effective directions to take according to the application intended: it is shown that C/D/C nodes are effective only when the traffic volume is rather limited.

In the evaluations, the measures we use are fiber utilization (or inversely the necessary number of fibers), and the number of WSSs (Wavelength Selective Switches) needed (which dominates the switch cost of a node), since these measures are inherent and so better than using cost models

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that are affected by so many parameters including transmission distance, fiber facility conditions (conduit or tunnel and number of fibers in a cable), traffic volume and so on, which obscures the crucial point; routing performance of a node. On the other hand, the above measures make us perform network cost analyses using cost-parameter values that are specific and appropriate to each network condition.

This paper is organized as follows. In Sect. 2, we clarify the relations of link- and node-level blocking, network design strategies and the resultant link utilization (link cost), which provides the landscape of network blocking. Section 3 depicts different types of OXC nodes that introduce routing restrictions and compares their characteristics in detail. A newly developed path accommodation algorithm is explained. In Sect. 4, we analyze the necessary number of fibers and WSSs for various networks using the OXC architectures, and clarify the practical effectiveness of introducing node-level blocking. Sect. 5 provides discussions and Sect. 6 concludes this paper.

2. Implication of Link- and Node-Level Blocking

In wavelength routing optical path networks, blocking can occur in two parts of the network as depicted in Fig. 1: in a link fiber (link-level blocking) and within an OXC (node-level blocking). An OXC is composed of two major functional parts: express switch part and add/drop part. The express switch routes wavelength paths from input fibers to output fibers and the add/drop part is used for launching/terminating outgoing/incoming wavelength paths at a node.

To accommodate an optical path in a wavelength routing network that does not implement wavelength converters, the wavelength continuity constraint from source to destination node must be met, and wavelength collisions in a fiber must be avoided. The wavelength collision inherent in WDM networks, does not exist in electrical TDM (Time Division Multiplexed) networks, where each electrical digital path is identified by its time position in a TDM frame. The fiber utilization in wavelength routing networks without wavelength converters is always worse so more fibers are needed to accommodate a certain traffic volume (a certain optical path demand), which results in an increase in link cost. Using wavelength converters can resolve wavelength collisions and so reduce link cost, however, no practical converters exist and introducing a set of O/E and E/O devices for wavelength conversion remains an impractical solution due to its high cost. To minimize this impairment, various RWA (Routing and Wavelength Assignment) algorithms have been investigated over the years and implemented for the development of efficient wavelength routing optical path networks that employ OXCs.

Work to date has mostly considered link-level blocking, since as mentioned in Sect. 1, non-blocking nodes are possible when the OXC port count needed is small [9]. Along with the increase in the number of wavelengths accommodated in a fiber and in the number of inter-node fibers (OXC

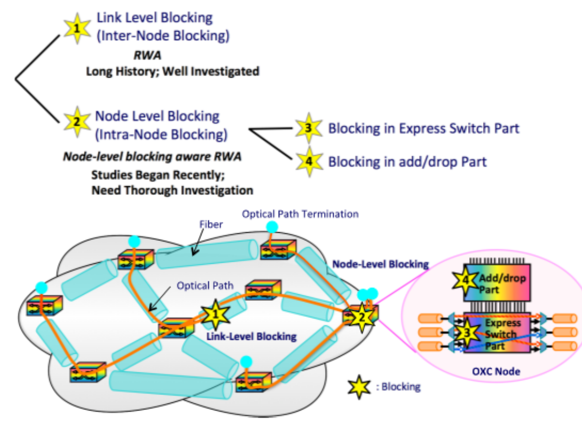


Fig. 1 Link-level and node-level blocking in optical path networks.

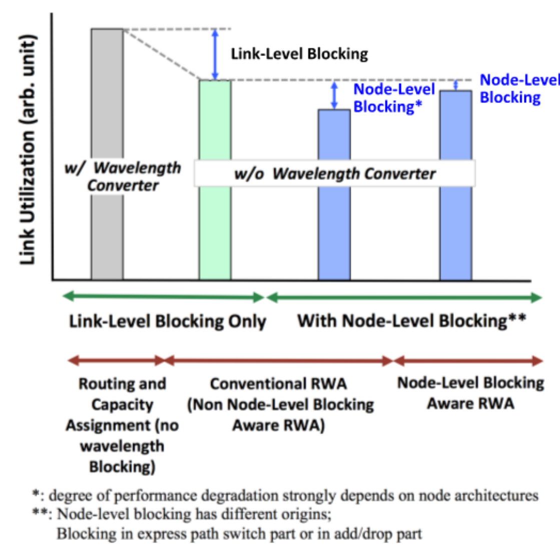


Fig. 2 Effect of link- and node-node blocking and RWA used on link utilization achievable.

port count), even when the OXC port count is less than 8, necessary hardware amount of the add/drop part can be a significant barrier to attaining non-blocking or C/D/C performance [10]–[12]. The introduction of blocking at the add/drop part (see Fig. 1) has been discussed so as to reduce the hardware amount. Various architectures that introduce blocking at the add/drop part (node-level blocking) have been discussed [10]–[14]. Node-level blocking further reduces link fiber utilization, however, it has been shown that if we develop appropriate RWA algorithms that are aware of this blocking, the fiber utilization offset can be made minimal [10]–[14]. The relationships among combinations of different blocking origins and RWA, and link utilization are schematically illustrated in Fig. 2; analytical evaluations are given in Sect. 4.

When we design the large scale OXCs demanded by future networks, required hardware amount for the express switch part can explode if we use existing architectures [15]; this is quantitatively analyzed in Sect. 3. Introducing some routing restrictions at the express switch part can substan-

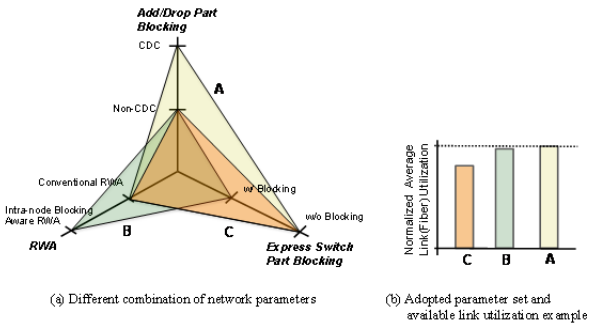


Fig. 3 Different node and network design conditions yield different link (fiber) utilization rates.

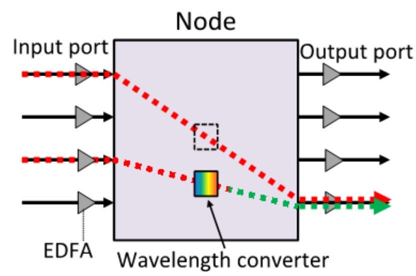


Fig. 4 Non-blocking-network node with wavelength conversion.

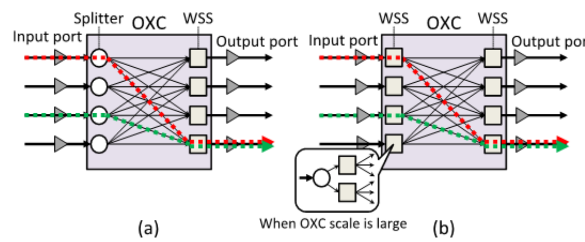


Fig. 5 Non-blocking OXC architecture; (a) broadcast-and-select, and (b) route-and-select.

tially curb switch hardware complexity [16]. As is discussed in Sect. 3, the recently proposed subsystem OXC architectures can greatly reduce hardware scale while the fiber utilization offset can be made marginal [17]–[19]. This is possible by developing the node-level blocking aware RWA algorithm, the complexity increase of which is shown to be marginal compared to the conventional approach that considers only link-level blocking [21]. Another important point to be noted is that the origin of blocking has little meaning from a practical viewpoint; the total performance is of prime importance. The important goal is thus total network optimization which involves the trade-off between necessary fiber resources (link cost) and node hardware scale (node cost). How a combination of node-level restriction (blocking at an add/drop part or an express switch part) and the RWA algorithm adopted will affect the available link utilization is schematically explained in Fig. 3; exact evaluations are given in Sect. 4.

In the next section, we assess network performance achieved by using different OXC nodes that allow internal blocking, and discuss attainable fiber utilization in reference to a network where neither link-level nor node-level blocking exists. In this paper, we highlight the performance and hardware requirements of the express switch part. This is because when a traffic demand matrix is given, the number of optical paths terminated at each node or that of transponders (which dominates add/drop cost) is common irrespective of the express switch architectures.

By analyzing the fiber utilization offset caused by link- and node-level blocking and assessing the degree of node hardware reduction, we will clarify the benefits of appropriately introducing blocking at express switches. Our analyses verify that this is the way to go for cost-effectively creating a bandwidth-abundant network that needs large port count OXCs.

3. Node Architectures

3.1 Non-Blocking-Network Node with Wavelength Conversion

Figure 4 schematically shows a non-blocking-network optical node with wavelength conversion. With this node, the input wavelength path can be routed to any output port fiber in a non-blocking manner and link-level blocking is also resolved by changing its wavelength to one that is vacant in the output port fiber. The network is free from link-level and node-level blocking and hence the link utilization can be maximized. This architecture, however, has not been adopted since cost effective wavelength converters are not available, or the possible link cost reduction gained with the link utilization improvement is insufficient to justify the node cost increment created by the wavelength converters. The performance of this node is used as a baseline to analyze the effect of each type of blocking.

3.2 Non-Blocking OXC Architecture

Figure 5(a) shows a typical so called non-blocking OXC architecture that utilizes multiple $1 \times M$ optical splitters and $M \times 1$ WSSs; they are connected in a broadcast-and-select manner. Optical signals can be routed without any internal blocking in OXC. This OXC does not use wavelength converters and hence link-level collision can occur in the network; the wavelength continuity requirement must be met. This architecture is hard to expand to form the large-scale OXCs expected in the future. When the OXC scale is large, the splitter degree becomes large, so the splitter loss becomes excessive. To resolve this problem, each splitter should be replaced with a WSS so as to form the route-and-select configuration as shown in Fig. 5(b). This architecture doubles the number of WSSs needed and also necessitates large port count WSSs. If the available port count of a WSS is smaller than the necessary OXC port count, WSS parallelization is required as shown in Fig. 5(b) insert, which further increases the number of WSSs needed and the node loss. Thus, the conventional non-blocking OXC architecture fails to support future traffic demands cost-effectively.

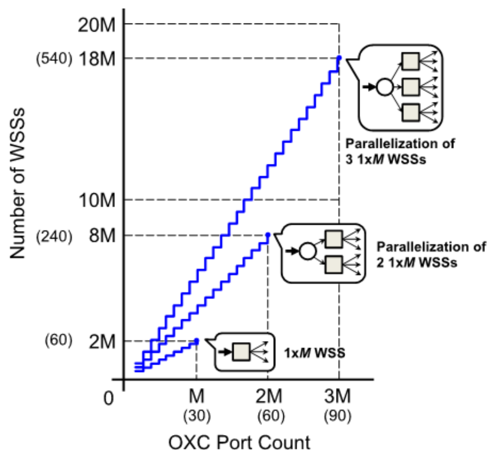


Fig. 6 Number of WSSs needed to form route-and-select OXC when using 1xM WSSs. Numbers in parentheses are for the case of M=30.

The maximum port count of the OXC is limited by the port count of the component WSS as shown in Fig. 6, where the route-and-select architecture is assumed. If we use one $1 \times M$ WSS per input/output fiber, the maximum OXC scale available is M. By parallelizing $1 \times M$ WSSs, we can realize an OXC that has port counts over M. Please note that in this architecture, the number of $1 \times M$ WSSs needed to attain an αM port OXC is $2\alpha^2 M$; the increase is proportional to the square of α (see Fig. 6). Furthermore, in practical operation environments, it is impossible to expand OXC scale from $M \times M$ to $2M \times 2M$ without disruption or interrupting existing services. Therefore, if the target future OXC scale is more than $M \times M$, we need to introduce the parallelized WSS configuration from the outset. With this configuration, service disruption free one by one input/output fiber addition is possible up to the maximum value (αM). Unfortunately, rather complicated intra-node interconnections between input and output side WSSs are needed at each input/output fiber increment timing. The larger the final expected OXC scale, the larger the number of WSSs needed (see Fig. 6). When, for example, needed OXC port count is 61 and 1×30 WSSs are used, a total of 540 WSSs are needed. Thus, the present non-blocking OXC architecture is not cost effective when developing scalable large port count OXCs.

3.3 Subsystem-Modular OXC Architecture

To resolve the scalability problem, we have proposed the subsystem-modular OXC architecture [17], [19] shown in Fig. 7. With this approach, a large-scale OXC is constructed by interconnecting multiple small-scale sub-OXCs. Each sub-OXC accommodates "inter-node fibers" and "intra-node fibers", where inter-node fibers connect adjacent nodes and intra-node fibers connect adjacent sub-OXCs in a node. To compensate the loss of traversing other sub-OXCs in a system, an EDFA should be inserted between adjacent sub-OXCs as shown in Fig. 7. When the number of inter-node fiber is N for each sub-OXC and s subsystems are used, the total number of inter-node fibers is sN. The OXC needs

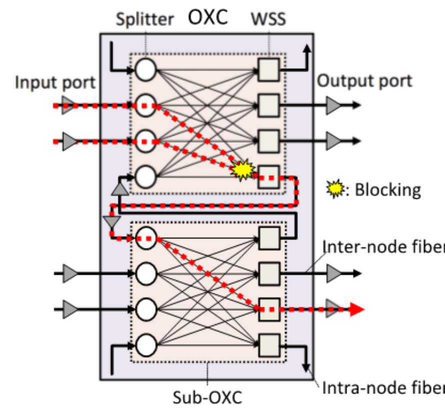


Fig. 7 Subsystem-modular OXC architecture.

$2sN + 2(s-1)$ EDFAs (for inter-node + intra-node fibers), whereas the conventional OXC with sN ports needs $2sN$ EDFAs. Thus, ratio of the EDFAs needed is $1 + (s-1)/sN$. When N is 7 (assuming 1×9 WSS for sub-OXC; 2 intra-node fibers), the ratio is smaller than 1.14 ($s = 5$). Indeed, the number of EDFAs needed for an OXC is dominated by those needed for the add/drop part as OXC scale is large [14]. As a result the increment in EDFA number (and also the penalties in optical signal-to-noise ratio, as explained below) in the express switch part for the subsystem modular OXC architecture is marginal.

One of the salient characteristics of the subsystem modular architecture is that since the port count of each sub-OXC can be small (usually less than 9), the splitter loss is small and hence the broadcast-and-select architecture is retained. Thanks to this architecture, the number of WSSs needed can be greatly reduced and high scalability attained; adding sub-OXCs can easily extend the total OXC port count without any service disruption and the scalability is not limited by the port count of the component WSS. For example, eight stages of 9×9 sub-OXC form a 56×56 OXC. Figure 8 compares necessary number of WSSs and necessary number of intra-node interconnection fibers, where the conventional non-blocking OXC takes the route-and-select configuration with 1×20 WSSs, while the subsystem-modular architecture uses smaller port count WSSs, 1×9 WSS, and hence each subsystem adopts the broadcast-and-select configuration. The great reductions achieved by the subsystem architecture are clearly shown in terms of necessary WSS port count (−55%), total number of WSSs (−79%), and intra-node interconnection fibers (−81%); simple OXC port count expansion is possible.

Furthermore, optical transmission characteristics including total optical node loss and number of WSS traversal for an optical path, have been confirmed to be much better or almost the same for a network with subsystem OXCs. This is due to use of the RWA (Routing and Wavelength Assignment) algorithm, which is aware of the node architecture [19]. Indeed, it has been confirmed that 90–80% of optical paths traverse a single subsystem in each node [21]. The RWA algorithm depicted below can limit the number of ex-

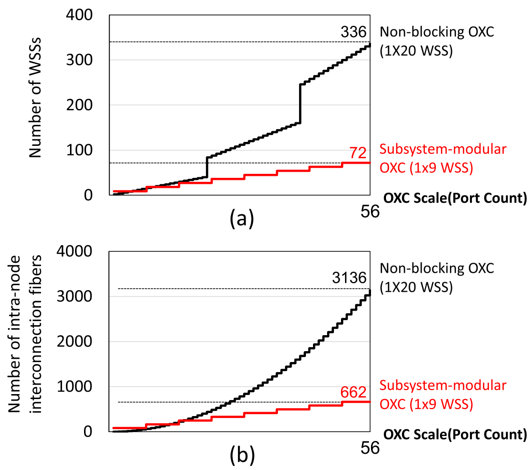


Fig. 8 Necessary number of (a) WSSs and (b) intra-node interconnection fibers.

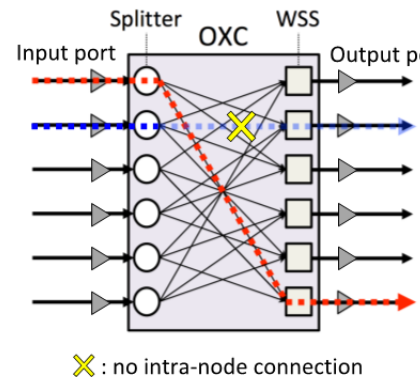


Fig. 9 OXC architecture with sparse intra-node connection.

cess subsystem traversals for an optical path from the source to destination to just a few, and the maximum and the average number of WSSs traversed by each path is significantly reduced, more than 50% [19], compared to conventional route-and-select architectures. As a result, the filtering impairment created by WSSs can be greatly mitigated and transmission performance can be substantially improved. Detailed investigations of these attributes are presented in [20], [21].

Node-level blocking can be marginalized by applying the restriction-aware RWA. The major procedure of the algorithm for static demand accommodation or traffic growth model uses the following steps, which are used in the evaluations presented in Sect. 4.

Step 1: All demands are accommodated one by one in descending order of the shortest hop count assuming non-blocking OXCs. If the demand cannot be accommodated, a new fiber is established between nodes to accommodate the demand.

Step 2: Based on Step 1, the number of needed sub-OXCs in each node can be estimated from the above derived number of inter-node fibers. Given the OXC scale as D, and the number of inter-node fibers in each sub-OXC as d, then $\lfloor D/d \rfloor$ sub-OXCs are necessary, where $\lfloor \cdot \rfloor$ denotes the ceiling function. For inter node connection, each sub-OXC is connected with sub-OXCs in the adjacent nodes in a Round-Robin manner to maximize the accessible sub-OXCs in the adjacent node, which can reduce the usage of intra-node fibers.

Step 3: All demands are accommodated one by one in descending order of the shortest hop count with the subsystem-modular OXCs. Each demand is accommodated with the same route as in a non-blocking OXC network. If there are multiple path candidates, we select the path that traverses the minimum number of intra-node fibers. If a demand cannot be accommodated, new fibers are established to accommodate the demand.

Estimating the numbers and configurations of necessary inter-node fibers and building Round-Robin sub-OXC connections with Step 1 and Step 2, would allow the demand to be accommodated with minimal use of intra-node fibers. Moreover, Step 3 minimizes the probability of intra-node contention. Indeed, it has been verified that the maximum intra-node fiber utilization can be less than 25% for different topology networks [21].

3.4 OXC Architecture with Sparse Intra-Node Connections

Another OXC architecture that introduces blocking by limiting input/output fiber connectivity is shown in Fig. 9 [22]. In this architecture, each splitter at the input side is connected to a limited number of WSSs at the output side. For example, the OXC has 6 input/output fiber ports while the component splitter or WSS is 1×3, and hence they are connected in a sparse manner. This scheme uses relatively small degree splitters and WSSs, and hence the broadcast-and-select configuration is retained; WSS parallelization is not required even if the target OXC port count is large. This OXC architecture is highly scalable and the port count of component WSS or splitter has no direct relationship to the OXC port count; there is virtually no limitation in terms of OXC expandability.

This OXC appears to suffer from node-level blocking since each input fiber port is not connected to all output ports. However, the impact of this limitation can be effectively minimized by applying the RWA algorithm that considers connection configurations of the splitter and WSS ports. The reason for the good performance stems from the difference between node degree (number of adjacent nodes) and OXC fiber degree (number of incoming and outgoing fiber pairs) [23]. When traffic is large and then there are multiple fibers on a link between nodes, the freedom of being able to choose one of many fibers to route an optical path in each link greatly alleviates the OXC routing performance needed. This freedom is further emphasized by the multiple routes possible between source and destination nodes. The routing restriction and the impact of node/fiber/WSS degrees are discussed in detail in [23].

Here, we develop a new optical path accommodation algorithm, and use it in evaluations of Sect. 4. Its key points are as follows

All optical path demands are accommodated one by one in descending order of the shortest hop count using OXCs that have sparse intra-node connections. A splitter-WSS interconnection is established as needed when demands are accommodated. If a demand cannot be accommodated, a new input/output fiber is added to accommodate the demand. If there are multiple route candidates for a path from the source to destination node, we select the route that offers the minimum cost as follows.

$$\text{Cost} = \sum_{i=1}^{h-1} p \cdot (d+1) \quad (1)$$

where i denotes the traversed OXC and h denotes the number of hops. p shows the existence of an intra node connection for traversing the OXC. If an intra-node connection between an input fiber and the destined output fiber already exists, $p = 0$. If not, $p = 1$. d denotes the number of established connections that traverse the input side splitter. Thus, this cost value is small when a splitter-WSS connection is already established or the splitter output ports are not fully utilized. With this algorithm, we can alleviate the effect of the restriction created by using small degree splitters and WSSs.

3.5 Comparisons of Different Node Architectures

Table 1 compares these four node architectures. Although using (A) non-blocking OXCs with wavelength conversion is free from blocking at the link- and node-level, they are quite expensive and have not been implemented so far. (B) Non-blocking OXCs without wavelength conversion are free from node-level blocking. However, in creating large port count OXC, large port counts and/or a large number of WSSs are necessary due to the obligatory route-and-select architecture and possible WSS parallelization; for small port count OXCs, say, up to 8×8 OXCs, broadcast-and-select architecture is used. In contrast, (C) subsystem-modular OXC and (D) OXC with sparse intra-node connections can be created at low cost, and hence their applicability will be high for large traffic demand situations in the future. Regarding link cost, blocking impairs link fiber utilization or increases the number of fibers to accommodate a certain traffic demand. Evaluations on how the link- and node-level blocking affect link cost (necessary number of fibers) are critical to determine overall network cost, which consists of node and link cost; this analysis is given in the next section. Another important point to be noted is node scalability. In the network, needed OXC port count will differ significantly among nodes and they increase year by year. The pay-as-you-grow capability and graceful port count expandability (future-proof) is desirable, especially for large port count OXCs. (C) and (D) match the criteria as highlighted in Table 1. Please note that this paper highlights the blocking characteristics in the express switch part as node-level blocking. Introducing blocking at the add/drop part can reduce the hardware of this part; this has been evaluated for different add/drop part configurations in combination with non-blocking express switch part [10]–[12] or blocking express switch part [13], [14], [24], [26].

Table 1 Comparison of node architectures.

	Link-level blocking	Node-level blocking	Node cost	OXC Scalability	OXC Expansion Process
(A) Non-blocking OXC w/ wavelength conversion (see **3.1**)	No	No	Very high	Limited by WSS port count	Port by port (complicated)
(B) Non-blocking OXC w/o wavelength conversion (see **3.2**)	Yes	No	High	Limited by WSS port count	Port by port (complicated)
(C) Subsystem-modular OXC (see **3.3**)	Yes	Yes	Low	**Virtually no limit**	Sub-OXC by Sub-OXC (simple)
(D) OXC with sparse intra-node connection (see **3.4**)	Yes	Yes	Low	**Virtually no limit**	Port by port (complicated but relaxed)

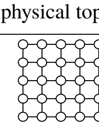
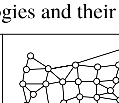
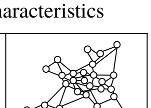
4. Numerical Experiments

4.1 Static Traffic Scenario

In order to clarify the effectiveness of employing node level blocking, we conduct network simulations of two traffic scenarios: static traffic model and traffic growth model. This section presents results on the static traffic model, where a traffic demand matrix is given and the number of fibers necessary to accommodate the traffic is analyzed. The assumed traffic intensity (average number of optical path demand between a node pair) is parameterized. This scenario is commonly used to evaluate generic network performance.

The tested physical topologies are (a) 5×5 regular mesh, (b) USNET, and (c) Pan-European (COST266), as shown in Table 2; some important topological parameters are given. In the simulation, the traffic demand is given and represented as the average number of optical path demands between each node pair. The assumed path demand geographical distribution is uniform and random. Twenty different random traffic patterns are tested for each traffic intensity and the results are averaged. We assume that a fiber can accommodate 80 wavelength paths and each optical path takes the shortest hop route. One WSS port or one splitter port is reserved for connection to the add/drop part of the OXC node irrespective of the node architecture tested.

Table 2 Tested physical topologies and their characteristics

			
Network topology	(a) 5x5 mesh	(b) USNET	(c) Pan-European (COST266)
# of nodes	25	24	26
# of links	40	43	51
Max. node degree	4	5	8
Average node degree	3.2	3.58	3.92
Max. # of shortest hops	8	6	6

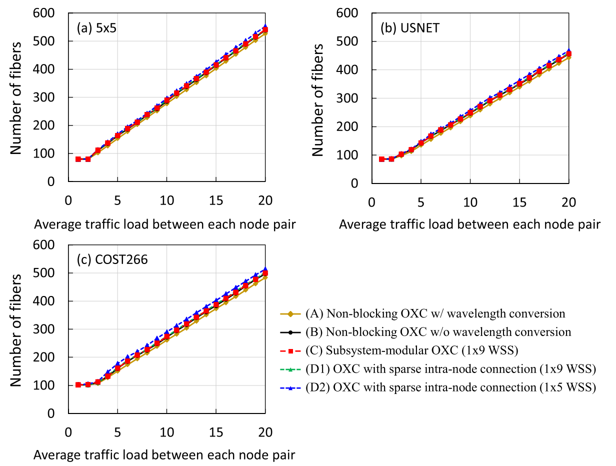


Fig. 10 Number of necessary fibers in a network in the static traffic scenario.

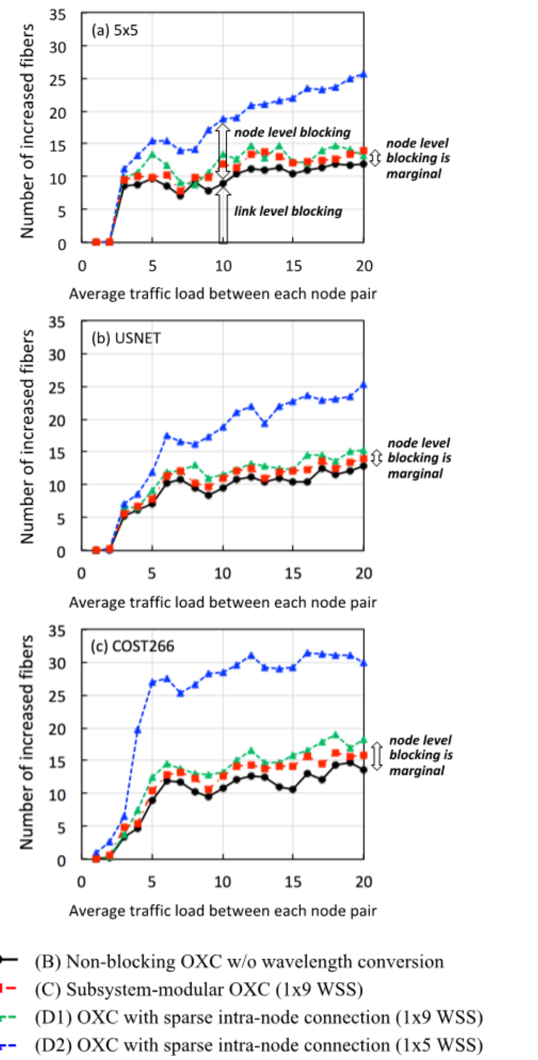


Fig. 11 Number of fiber increments from non-blocking OXC node with wavelength conversion in static traffic scenario.

Figure 10 shows the number of fibers needed for each topology network to accommodate the traffic demand represented as average traffic load (average path demand) between each node pair, for the OXC architectures in Table 1. We confirmed that the number of fibers increases linearly with the average traffic load, except for the very small traffic demand area where the traffic demand cannot fill single fiber capacity between nodes. The differences in the total number of fibers in terms of node architectures are small, and Fig. 11 highlights the number of fiber increments compared to the network with neither link-level nor node-level blocking (A). It is clear that link level blocking (B) is the major cause in the fiber number increment; this cannot be resolved without using wavelength convertors. With node level blocking, other than D2, the difference between (C) and (B), or (D1) and (B) is relatively very small compared to the link level blocking; a few additional fibers are needed, just 0.6% (=3/500) when total fiber number is around 500 (see Fig. 10, at the average optical path demand of 20). Regarding node level blocking, the fiber number is increased in the order of (C) subsystem-modular OXC using 1×9 WSSs, (D1) OXC with sparse intra-node connection using 1×9 WSSs, and (D2) OXC with sparse intra-node connection using 1×5 WSSs. From these results, it is clear that in wavelength routing optical path networks, link level blocking (wavelength collision in a link fiber) is the major origin of the increase in necessary fiber number except for (D2), in other words wisely introducing node level blocking and applying the node-restriction aware RWA keeps the additional fiber increment very small.

Regarding (D2) with 1×5 WSSs, the increase in the number of fibers is relatively higher than is true in other architectures that use larger port count (1×9) WSSs. This was suggested in Sect. 3.4 as related to node degree. Please note that with 1×5 WSS, one port is used for an add port and hence it works as 1×4 WSS for the express switch part. Indeed, Pan-European network suffers the largest increase compared to 5×5 regular mesh and USNET. This is because the Pan-European network has the largest maximum/average node degrees (the maximum is 8, see Table 2). The reason we examined such small port count WSSs is that this architecture minimizes WSS-oriented crosstalk due to its small port count and hence the number of node hops possible can be extended. Discussion of the transmission performance lies out of the scope of this paper, and will be published elsewhere.

Figure 12 plots the ratio of total number of fibers in a network normalized by that needed in the equivalent network with neither link-level nor node-level blocking (A). The ratios decrease as the traffic load increases when the average traffic load between each node pair is more than around 6. The link level and node level blocking can be relaxed when traffic demand increases or the number of fibers in each link increases (note that the node degree does not change, only the fiber degree increases) since it enhances routing freedom between nodes: the increased flexibility in selecting link fiber, or number of alternative routes, relaxes the blocking. Thus, as traffic increases, routing restrictions at the link and node level tend to relax. The fiber increment in (C) and (D1)

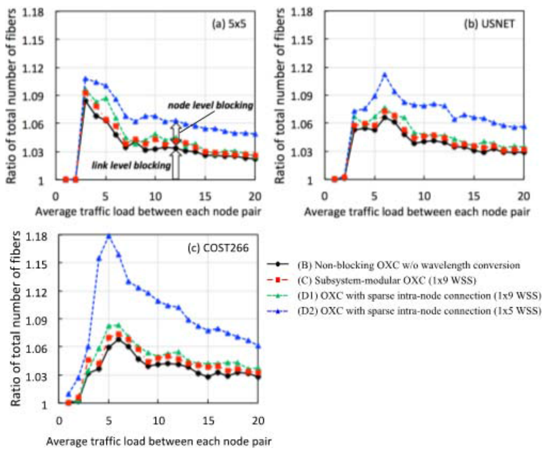


Fig. 12 Ratios of total number of fibers in a network normalized by that needed in a network with neither link-level nor node-level blocking in static traffic scenario.

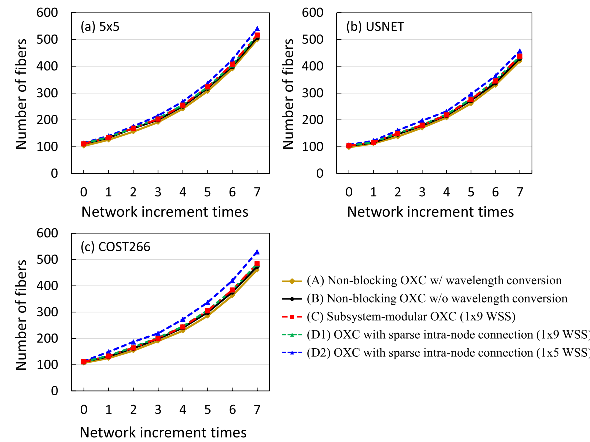


Fig. 13 Number of fibers in the traffic growth scenario.

compared with (B) is at most 1% and 2%, respectively. Thus node level blocking incurs only small cost while yielding a huge node cost reduction as discussed in the next sub-section.

4.2 Traffic Growth Scenario

We conduct here network simulations using a traffic growth scenario for the same physical network topologies in Table 2. This scenario increases traffic demand gradually; the increase rate at each stage (for example one year interval) is assumed to be 30% in view of current IP traffic growth. At each network design stage, the network is expanded (additional fibers are established and node scale is expanded to accommodate the expected 30% traffic increase by the next design timing), where existing optical paths in a network are kept intact. We set the initial average optical path demand between each node pair to 3, and traffic expansion is conducted seven times, which results in a path demand of around 19 ($= 3 \times 1.3^7$). The maximum number of wavelength channels per fiber is 80 and each optical path is accommodated using the shortest hop route. One of the WSS ports is used for connection from/to the add/drop part for all tested node architectures in the same way as in Sect. 4.1.

Figure 13 shows the number of fibers needed to accommodate the traffic demand at each stage. The number of fibers increases super-linearly with the stages. This is reasonable as the traffic load is increased exponentially. Figure 14 shows the increase in the number of fibers compared to the equivalent network with neither link-level nor node-level blocking (A). The additional number of fibers is less than 24 except for (D2); we note that the total number of fibers in a network is around 500. In particular, the Pan-European network needs more additional fibers, as in the static traffic scenario. It is also true that link level blocking (B) is the major cause of the fiber number increment.

Figure 15 plots the ratio of the total number of fibers in a network normalized by that needed in the equivalent network with neither link-level nor node-level blocking (A).

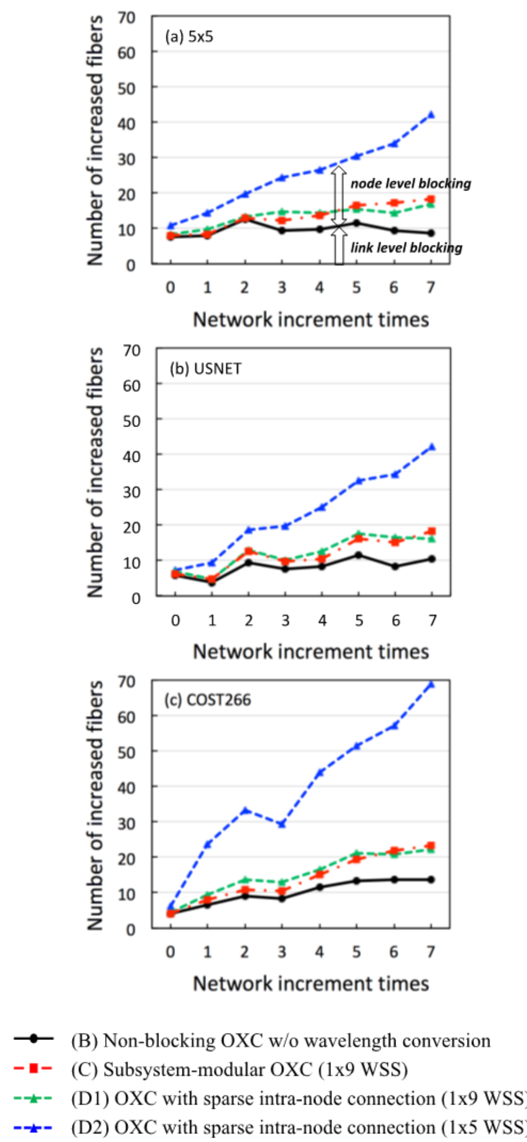


Fig. 14 Number of fiber increments from non-blocking OXC node with wavelength conversion in the traffic growth traffic scenario.

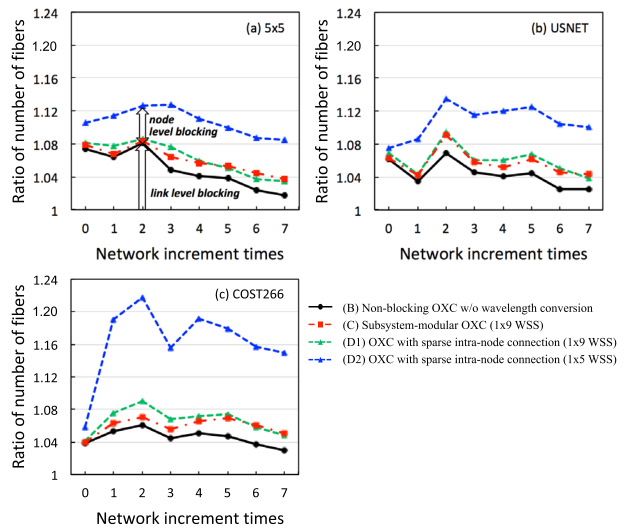


Fig. 15 Ratios of total number of fibers in a network normalized by that needed in a network with neither link-level nor node-level blocking in the traffic growth scenario.

The ratios are less than 10% except for (D2). The node level blocking, difference between (C) and (B), or (D1) and (B), is just a few %; smaller than with link level blocking, although the difference is slightly increased compared to the static traffic scenario.

Figure 16 depicts the number of necessary WSSs for the OXC architectures tested. (B) Non-blocking OXC without wavelength conversion (C/D/C OXC) requires a large number of WSSs even when using larger 1x20 WSSs due to its route-and-select configuration and WSS parallelization. In contrast, (C) subsystem-modular OXC and (D) OXC with sparse intra-node connection offer significant reductions in the number of WSSs even when using smaller port count WSSs (1×9 or 1×5). Since (C) implements its port count enhancement by adding a sub-OXC unit (not by adding individual WSSs), and 2 of the WSS ports are assigned for intra-node subsystem interconnection, the number of WSSs becomes larger than (D). With the traffic growth scenario, which matches the practical network operation condition, OXC (A) and (B) offer poor scalability as was discussed in Sect. 3, and (C) and (D) provide good scalability, in particular (C) offers the minimum operation complexity.

5. Discussions

In this paper, we examined link level blocking and node level blocking using different OXC architectures under common conditions, and the tradeoffs between node cost and link (fiber) cost were analyzed. The necessary number of WSSs and necessary number of fibers were used as metrics. The implication of node level blocking can be more clearly understood by comparison to the effect of link level blocking that has been a priori assumed to be inevitable. The link level blocking, which cannot be resolved without using wavelength convertors or the equivalent, is the major cause in the fiber number increment except for (D2). The

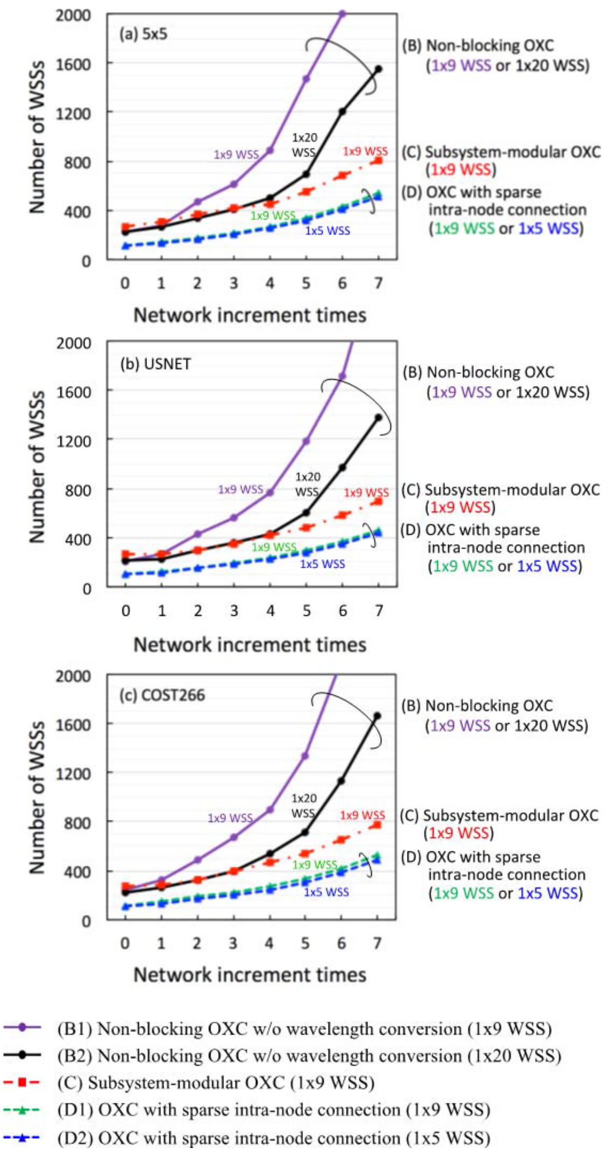


Fig. 16 Number of WSSs needed by the tested OXC architectures.

impact of node level blocking in the express switch can be thus subtle; the number of additional fiber increment is less than a few percent. Please note that we assume here a yearly traffic increase of 30%, so the 2–3% increment will, by the 7^{th} increment timing, hasten the installation of new fiber by about one month after 7 years. One more important point to be noted is that in practical network operation conditions for most carriers, the average fiber utilization in the network can not be kept so high, say less than 70%, in other words, fiber (transmission system) addition will be triggered with sufficient lead time ahead of the expected resource exhaustion, since demand prediction is not completely accurate. In practice, a few percent decrease in the ceiling on fiber utilization is hardly meaningful in most cases. On the other hand, expenditure does occur when expanding the node port counts and node hardware cost directly determines Capex, and thus the differences are important.

Regarding the node cost, the reduction achieved in (C) and (D) can be enormous: the proposal offers more than 70% reduction in the number of WSSs compared to the non-blocking OXCs. Furthermore, the necessary WSS port count can be reduced by more than 55% (1×9 WSS can be used instead of 1×20 or more).

This paper highlighted the express switch part since the add/drop part cost is basically common to all architectures since it is mostly determined by the number of transponders needed. Add/drop part configurations and the performances have been evaluated for specific add/drop configurations as mentioned in Sect. 3.5 [10]–[14], [24], [26].

6. Conclusions

To date, the common mind-set has been that the OXC express switch part should be non-blocking (C/D/C) as it can be realized with small port count, say 20×20, OXCs for networks with large transmission distances, like core and metro-core ones. However, when designing higher port count OXCs, and particularly for metro areas where transmission distances are relatively short, this assumption is not well supported. Link level blocking commonly exists, which cannot be resolved without using wavelength convertors. In this situation, the practical importance lies not in the origin of blocking but in the total performance available. The wise introduction of routing restrictions not only in the add/drop part, which has been discussed so far, but also in the express switch part, can dramatically reduce node cost, which results in total network cost reductions.

The analyses presented here showed that the subsystem OXC architecture offers several significant advantages; virtually no limit to port count expansion, hitless expansion, simple fiber interconnections among components, smaller WSS port counts, reduced number of WSS traversed by optical paths. All these benefits come with the cost of a marginal drop in fiber utilization. The effectiveness of the subsystem OXC architecture will be maximized when $M \times M$ WSSs become available; a single device can be used as a subsystem. Extensive research and development efforts [27]–[32] have recently demonstrated prototype fabrication and transmission experiments on 6×6 WSSs [33]; the results justify near-term commercial implementation.

We believe that the results presented in this paper clarify an important direction to proceed in developing large bandwidth and cost effective networks for the future, particularly in metro areas, where the C/D/C approach has less appeal.

Acknowledgments

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References

[1] Cisco Visual Networking Index (VNI): Forecast and Methodology 2014–2019, and 2016–2021, White paper.
[2] P. Pagnan and M. Schiano, "A λ switched photonic network for the new transport backbone of Telecom Italia," Photonics in Switching, IEEE Technical Digest (CD) (Institute of Electrical and Electronics Engineers, 2009), paper ThII2-1, 2009.
[3] G. Rizzelli, G. Maier, and A. Pattavina, "WSS requirements in next-generation wavelength switched optical networks," Optical Fiber Communication Conference, OSA Technical Digest (CD) (Optical Society of America, 2013), paper OTh4B.1, 2013.
[4] K. Sato and H. Hasegawa, "Optical networking technologies that will create future bandwidth abundant networks," J. Opt. Commun. Netw., vol.5, no.2, pp.A81–A93, 2009.
[5] R. Egorov, "Next generation ROADM architecture and design," Optical Fiber Communication Conference, OSA Technical Digest (CD) (Optical Society of America, 2013), paper NW1J.3, 2013.
[6] S. Woodward, "ROADM options in optical networks: Flexible grid or not?" Optical Fiber Communication Conference, OSA Technical Digest (CD) (Optical Society of America, 2013), paper OTh3B.1, 2013.
[7] G.A. Wellbrock and T.J. Xia, "True value of flexible networks," Optical Fiber Communication Conference, OSA Technical Digest (CD) (Optical Society of America, 2015), paper, M3A.1, 2015.
[8] K. Sato, "Optical networking and node technologies for creating cost effective bandwidth abundant networks," OECC/PS 2016 (The 21st OptoElectronics and Communications Conference/International Conference on Photonics in Switching 2016), ThA1-2, Niigata, Japan, July 2016.
[9] R. Jensen, A. Lord, and N. Parsons, "Colourless, directionless, contentionless ROADM architecture using low-loss optical matrix switches," ECOC 2010, Mo.2.D.2, Torino, Sept. 2010.
[10] M.D. Feuer and S.L. Woodward, "Advanced ROADM networks," OFC/NFOEC 2012, NW3F.3, Los Angeles, March 2012.
[11] I. Kim, P. Palacharla1, X. Wang, D. Bihon, M.D. Feuer, and S.L. Woodward, "Performance of colorless, non-directional ROADMs with modular client-side fiber cross-connects," OFC/NFOEC 2012, NM3F.7, Los Angeles, March 2012.
[12] T. Zami, "Contention simulation within dynamic, colorless and unidirectional/multidirectional optical cross-connects," ECOC 2011, We.8.K.4, Geneva, Sept. 2011.
[13] H. Ishida, H. Hasegawa, and K. Sato, "An efficient add/drop architecture for large-scale subsystem-modular OXC," 15th International Conference on Transparent Optical Networks, ICTON 2013, We.A1.5, Cartagena, Spain, June 2013.
[14] H. Ishida, H. Hasegawa, and K. Sato, "Hardware scale and performance evaluation of a compact subsystem modular optical cross connect that adopts tailored Add/Drop architecture," J. Opt. Commun. Netw., vol.7, no.6, pp.586–596, June 2015.
[15] K. Sato, "Prospects and development of large capacity future optical transport node," 15th International Conference on Transparent Optical Networks, ICTON 2013, Tu.A1.1, Cartagena, Spain, June 2013.
[16] K. Sato, "Implication of inter-node and intra-node contention in creating large throughput photonic networks," IEEE Optical Network Design and Modeling conference, ONDM 2014, pp.144–149, Stockholm, May 2014.
[17] Y. Iwai, H. Hasegawa, and K. Sato, "Large-scale photonic node architecture that utilizes interconnected small scale optical cross-connect sub-systems," ECOC 2012, We.3.D.3, Amsterdam, Sept. 2012.
[18] K. Sato, "How to create large scale OXCs/ROADMs for future networks," ICTON 2014, We.B1.4, Graz, July 2014.
[19] Y. Tanaka, H. Hasegawa, and K. Sato, "Criteria for selecting subsystem configuration in creating large-scale OXCs," J. Opt. Commun. Netw., vol.7, no.10, pp.1009–1017, Sept. 2015.
[20] Y. Tanaka, H. Hasegawa, and K. Sato, "Performance analysis of large-scale OXC that enables dynamic modular growth," Opt. Express, vol.23, no.5, pp.5994–6006, 2015.
[21] K. Sato, H. Hasegawa, and K. Sato, "Disruption-free expansion of protected optical path networks that utilize subsystem modular OXC nodes," J. Opt. Commun. Netw., vol.8, no.7, pp.476–485, July 2016.

[22] K. Sato, Y. Mori, H. Hasegawa, and K. Sato, "Algorithm for raising OXC port count to meet traffic growth at minimum-cost," IEEE/OSA J. Opt. Commun. Netw., vol.9, no.2, pp.A263–A270, 2017.
[23] K. Sato, "Impact of node/fiber/WSS degrees in creating cost effective OXCs," 18th International Conference on Transparent Optical Networks ICTON 2016, Th.B1.6, Trento, Italy, July 2016.
[24] H. Ishida, H. Hasegawa, and K. Sato, "Highly scalable subsystem modular OXC nodes that host tailored add/drop mechanism," OFC 2015, Th2A.47, Los Angeles, March 2015.
[25] M. Niwa Y. Mori, H. Hasegawa, and K. Sato, "Tipping point for the future scalable OXC: What size MxM WSS is needed?," IEEE/OSA J. Opt. Commun. Netw., vol.9, no.1, pp.A18–A25, 2017.
[26] M. Niwa, Y. Mori, H. Hasegawa, and K. Sato, "MxM WSS based ROADM architecture with topology-insensitive routing performance," ECOC 2016, W.4.P1.SC4.7, Dusseldorf, Sept. 2016.
[27] K. Yamaguchi, M. Nakajima, J. Yamaguchi, T. Hashimoto, Y. Ikuma, and K. Suzuki, "MxN wavelength selective switches using beam splitting by space light modulator," OECC, PWe.08, Shanghai, 2015.
[28] N. Nemoto, Y. Ikuma, K. Suzuki, O. Moriwaki, T. Watanabe, M. Itoh, and T. Takahashi, "8×8 wavelength cross connect with add/drop ports integrated in spatial and planar optical circuit," ECOC, Tu.3.5.1, Valencia, 2015.
[29] N.K. Fontaine, R. Ryf, and D.T. Neilson, "N×M wavelength selective crossconnect with flexible passbands," OFC 12, paper PDP5B.2, 2012.
[30] L. Zong, H. Zhao, Z. Feng, and S. Cao, "Demonstration of ultra-compact contentionless-ROADM based on flexible wavelength router," ECOC 2014, paper P.4.4, 2014.
[31] 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 2014, paper PW2B.2, San Diego, July 2014.
[32] K. Suzuki, K. Seno, and Y. Ikuma, "Application of waveguide/free-space optics hybrid to ROADM device," J. Lightwave. Technol., vol.35, no.4, pp.596–606, 2017.
[33] R. Hashimoto, S. Yamaoka, Y. Mori, H. Hasegawa, K.-I. Sato, K. Yamaguchi, K. Seno, and K. Suzuki, "First demonstration of subsystem-modular optical cross-connect using single-module 6×6 wavelength-selective switch (invited)," IEEE/OSA J. Lightw. Technol., vol.36, no.7, pp.1435–1442, April 2018.

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