Performance evaluation of large-scale multi-stage hetero-granular optical cross-connects

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Abstract: We proposed generalized large-scale two-stage-routing OXC architectures and evaluated the performance possible with the use of small-degree WSSs and simple optical devices; 1x*n* switches or WBSSs. Numerical evaluations verified that the new architectures reduce necessary hardware scale substantially at the cost of few additional fibers while their effectiveness increases with the traffic demand. The tradeoff between the link resource increase and the hardware scale reduction is also clarified.

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1. Introduction

Wavelength routing optical path networks employing Reconfigurable Optical Add/Drop Multiplexers (ROADMs) or Optical Cross-connects (OXCs) are being deployed widely throughout the world to cope with the rapid traffic expansion spurred by the penetration of broadband access services including ADSL and FTTH [1-3]. Further traffic explosion is expected in the near future with advances of video-centric broadband services such as IP-TV/VoD, which can offer high-/ultrahigh-definition video quality (up to 60-72 Gbps/channel) [4-5]. The future traffic explosion will force a substantial increase in the number of wavelength paths and that of fibers per link in future WDM networks [3, 6]. The development of cost-effective and large-scale ROADMs/OXCs is, therefore, becoming a critical issue [6, 7].

Most existing ROADM/OXC systems are developed on wavelength selective switches (WSSs), and to create a larger scale OXC, higher port count WSSs are required; some of the WSS ports also can be used to implement the optical add/drop function. The highest WSS port count commercially available at present is 20+ and it seems unlikely that WSS degree can be substantially enhanced cost-effectively in the near future. The conventional direct approach to increasing the port count is to cascade WSSs. This requires a considerable number of WSSs per input fiber and the optical loss is also increased. For example, if 1x9 WSSs (the most commonly utilized size at present) are applied, the two stage WSS cascading architecture provides 1x81 WSS, however, it requires ten 1x9 WSSs. Hence, to develop an 81x81 OXC with 1x9 (1x20) WSSs, the total number of necessary WSSs is 1620 (972), since the broadcast-and-select architecture can no longer be applied; instead, the route-and-select architecture needs to be utilized. Alternatives to wavelength selective switches include waveband selective switches (WBSS) and 1x*n* optical switches (1x*n* SW). Waveband selective switches have been developed recently and the world's first 1x5 and 1x10 WBSSs fabricated on a compact PLC (Planar Lightwave Circuit) chip have been demonstrated [8, 9]. WBSSs can selectively switch at the granularity level of wavebands (wavelength groups). 1x*n* optical switches are the simplest and very cost-effective device; the implementations of a 1x128 optical switch and 4 arrayed 1x29 switches on single PLC chips were developed in [10] and [11] respectively. However, 1x*n* switches can only switch all wavelength paths together from the input fiber to one of the output fibers. Even with this routing limitation, WBSSs and 1x*n* SWs are simpler and more cost-effective devices. Hence, new approaches that can exploit these optical switching technologies to enable cost-effective and scalable large-scale OXCs are of practical importance.

Up to now, to mitigate the hardware explosion caused by implementing add/drop functions, CD (Colorless/Directionless) ROADM architectures, which permit intra node blocking, have been actively discussed [12-16]. Similarly, wisely setting a restriction on the intra node routing capabilities on the express paths seems to be effective. In fact, node degree, which is the number of adjacent nodes, in existing communication networks is limited and to accommodate the increasing traffic, the number of parallel fibers installed on links will be increased, not node degree. In this context, wavelength paths that come from an input fiber and are to be delivered to one of the adjacent nodes do not always require to be distributed among all parallel fibers on the link to that adjacent node. Based on this understanding, our key idea is to set a restriction on output fiber selection on each link that contains multiple parallel fibers; the wavelength paths cannot be routed freely, and only one or a pre-determined very small number of output fibers on each link can be selected to deliver the optical paths. Regarding this approach, we have recently proposed simple OXC architectures that impose different levels of restriction on the intra-node routing capability. They utilize two-stage routing mechanisms; the first stage selects groups of wavelength paths to be delivered to the same adjacent node and the second stage selects output fibers on each link for the wavelength path groups. This two stage routing is implemented by combining WSSs with 1) 1x*n* switches [17] or 2) waveband selective switches [18].

In this paper, we propose a generalized architecture and analyze the performance of scalable large-scale OXCs that adopt the intra-node routing restriction on fiber selection for wavelength path groups of each input fiber. The proposed architecture can be regarded as replacing the large degree WSSs required in the conventional WSS-based architecture with smaller scale WSSs and 1x*n* switching devices that are simpler and more cost-effective than WSSs; this minimizes the necessary number of WSSs and as a result, significantly reduces total device cost. The 1x*n* switching devices can be WBSSs or 1x*n* optical switches, so the proposed architecture has two variants. We evaluate here the network performance of the OXC architecture variants in comparison with the conventional WSS-based architecture. The results prove that the proposed architectures can reduce system scale substantially at the cost of a few additional fibers. We also analyzed the tradeoff between the node routing flexibility and the attained hardware scale reduction. The optimal architecture depends on the relative cost of a 1x*n* optical switch and a WBSS to a WSS, and the additional fiber cost, however, the proposed architectures are a viable alternative for creating future large-scale optical node systems. A preliminary version of this work was presented at an international conference [19].

2. Generalized large-scale OXC architecture utilizing an intra-node routing restriction

After first step evaluations of OXC architectures [17, 18] that utilize multi-granular optical path routing, we developed and analyzed the generalized large-scale OXC architecture that employs two-stage routing (see Fig. 1). The architecture first dynamically groups wavelength paths (1st-stage) that request the same output links and then each group is selectively delivered to appropriate outgoing fibers by the 2nd-stage. The 1st-stage requires a wavelength level switching capability for each incoming fiber; this is possible with a WSS. The 2nd-stage devices, which switch wavelength path groups, can be 1x*n* optical switches or 1x*n* WBSSs that are much simpler and more cost-effective optical switching devices than a WSS. At the 2nd-stage, component wavelengths of each group are switched together while each group from an incoming fiber can be delivered to an outgoing fiber on the link (has *n* parallel fibers) and as a result, routing flexibility of the node relies on the number of wavelength groups (denoted as B) that are supported by the 2nd-stage devices as a whole. For example, if 1x*n* SWs are employed, all wavelengths (only one group (B=1)) delivered to one of the output ports of the 1st-stage WSS must be routed to the same outgoing fiber (this architecture is called WSS-1x*n* SW), however, for the architecture that utilizes 1x*n* WBSSs (so denoted as WSS-WBSS), those wavelengths are further divided into B groups (B>1) and each group can be delivered separately. Furthermore, the maximum number of selectable output fibers on each link for each wavelength group is determined by the number of 1x*n* SWs (or WBSSs) assigned for each link, k.

The proposed two-stage routing architectures can be regarded as replacing the second (or higher) stage WSSs in conventional WSS-cascaded OXC architecture with more cost-effective and technology-available switching devices like WBSSs or 1x*n* SWs, which simplify the architectures and make them cost-effectively realizable with present optical technologies. In fact, a simple prototype system of WSS-1x*n* SW that can support totally 48 input/output fibers (6 adjacent nodes with 8 fibers per link to each node) (k=1) and its good transmission characteristics, where the maximum power penalty at BER of 10^{-9} was only 0.08 dB after traversing four nodes, were demonstrated and verified in [17].

Moreover, at the output fiber side, unlike the previous studies [17, 18], optical coupling modules (small degree WSS combined with small size couplers) are utilized instead of single large port count optical couplers to minimize the loss. These output side modules are assumed for all the architectures discussed in this paper.

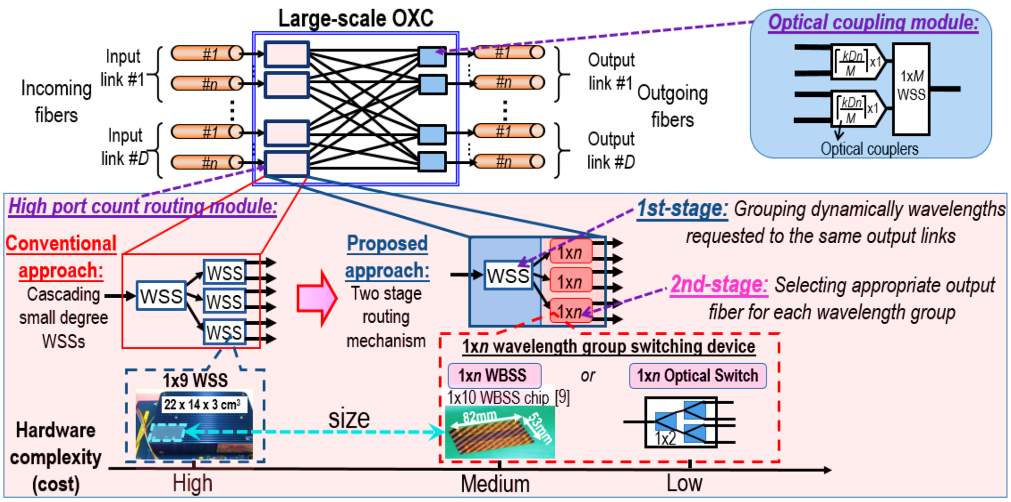


Fig. 1. Conventional WSS-based and Generalized two-stage routing OXC architectures

3. Node characteristics comparison

3.1. Node routing flexibility

Table 1 summarizes the main characteristics of the three OXC architectures compared: WSS-WBSS, WSS-1x*n* SW and conventional WSS-based OXCs. In terms of device cost, the WSS-1x*n* SW architecture is the most effective solution while the WSS-WBSS architecture is also expected to be much more cost-effective than conventional WSS-based OXCs.

Table 1. Feature comparison

	Compared OXC architectures		
	Conventional	***WSS-WBSS***	***WSS-1xn SW***
Switching components	Large port count WSSs (or cascaded small WSSs)	- Small WSSs - WBSSs	- Small WSSs - 1x*n* SWs
Switching mechanism	Wavelength selective switching	2-stage switching: + Grouping wavelengths destined to the same output fiber + Selecting the output link	
Routing flexibility	Highest	High ~ Fair (depends on B, k)	Lowest (depends on k)
Cost	Highest	Medium	Lowest

Unlike conventional WSS-based OXCs, which can selectively switch wavelength paths from any input fiber to any output fiber, both of our architectures slightly limit the node routing flexibility due to the use of coarser granular switching devices (WBSSs and 1x*n* SWs) for the selection of output fibers for wavelength paths. WBSSs route wavelength paths in groups and as a result, in the WSS-WBSS architecture, wavelength paths of a group from an input fiber cannot be routed to more than k different output fibers on each link. Hence, the routing flexibility of WSS-WBSS OXCs is determined by both k and the number of wavelength groups per fiber (B) supported by the WBSSs. The WSS-1xn SW architecture has an even more constrained routing capability because it uses 1xn optical switches instead of WBSSs; whole wavelength paths from one input fiber (B=1) can sent to no more than k different output fibers on each outgoing link. Therefore, utilizing larger numbers of wavelength groups per fiber (allowing finer granular routing) or applying more WBSSs per adjacent node (increasing k) can improve the node routing flexibility of WSS-WBSS OXCs while the only way to enhance the routing capability of WSS-1xn SW nodes is to increase k.

3.2. Node hardware scale

Let D be the node degree, which is the number of adjacent nodes, n be the number of parallel fibers on each link to an adjacent node (for simplicity, n is assumed to be the same for all links). Table 2 shows the switching component requirements of the proposed WSS-WBSS and WSS-1xn SW architectures in comparison with that of the conventional WSS-based OXC. At the input side, the conventional OXC requires Dn WSSs, (the required number is the same as the total number of input/output fibers), where the WSS degree is 1xDn. Both WSS-WBSS and WSS-1xn SW architectures utilize Dn WSSs, however, their WSS degree is only 1xkD, smaller than that of the conventional one (n>>k). In other words, the proposed architectures reduce WSS degree to k/n and as a result, the cost and/or the number of cascading WSSs required at the input side is greatly reduced. At the output side, all three compared architectures require Dn optical coupling modules but the size of these modules increases k times in the proposed WSS-WBSS and WSS-1xn architectures. By utilizing the combination of a 1xM WSS and small size optical couplers, the three architectures all require Dn 1xM WSSs and MDn optical couplers for the output side however, the optical coupler degree needed in conventional architecture is 1x$\left\lceil \frac{Dn}{M} \right\rceil$ while that required in WSS-WBSS or WSS-1xn SW is 1x$\left\lceil \frac{kDn}{M} \right\rceil$.

Table 2. Switching component requirement

			Compared OXC architectures		
			Conventional	***WSS-WBSS***	***WSS-1xn SW***
Input side routing device	WSS	*Degree*	1xDn	1xkD	1xkD
		Total #	Dn	Dn	Dn
	WBSS	*Degree*	-	1xn	-
		Total #	-	kD^2n	-
	1xn switch	*Degree*	-	-	1xn
		Total #	-	-	kD^2n
Output side optical couplers		*Degree*	1xDn	1xkDn	1xkDn
		Total #	Dn	Dn	Dn

Where D = Number of adjacent nodes
n = Number of fibers on each link
k = Number of 1xn substitute devices (WBSSs or switches) per link

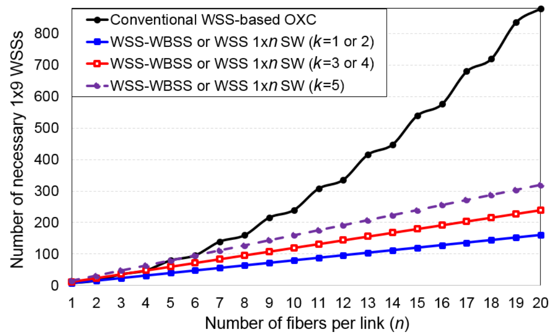
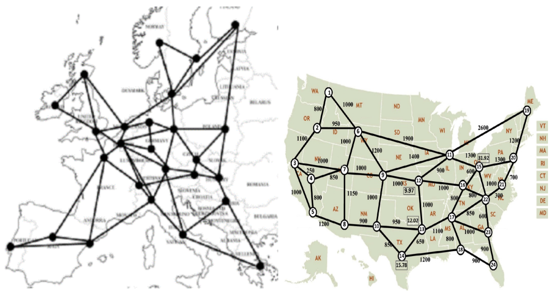


Fig. 2. Node scale comparison

Figure 2 shows the number of required 1x9 WSSs (most commonly utilized WSS degree at present) with respect to fiber number on each link, n, in the three compared OXC architectures with node degree of 4. It shows that both WSS-WBSS and WSS-1xn SW OXCs can substantially reduce the necessary WSS number, especially when n becomes large. Moreover, the hardware reduction depends on k; smaller k offers larger WSS number reductions. On the other hand, WSS-WBSS and WSS-1xn SW OXCs need additional components (WBSSs or 1xn switches). The WSS-WBSS architecture needs kD^2n WBSSs while the WSS-1xn SW requires the same number of 1xn optical switches. Hence, in the WSS-WBSS and WSS-1xn SW architectures, the number of selectable output fibers on each link, k, plays a key role in determining not only the WSS degree but also the number of additional components.

4. Network performance evaluation

Network performance of the three OXC architectures is compared with the following parameters. Tested physical network topologies are pan-European optical network (COST266) [20] and US nationwide network (USNET) [21] (see Fig. 3). Characteristics of those network topologies are summarized in Table 3. We call a matrix of average numbers of wavelength paths to be established between node pairs traffic demand. For each experiment, the number of wavelength paths to be established is set at the sum of components of the traffic demand, and then, source and destination nodes of each path are randomly selected according to a probability distribution that is proportional to the traffic demand. A fiber can accommodate 80 wavelengths; wavelength conversion is not considered. High port count WSSs are built with smaller degree 1xX WSSs. Wavelength group number per fiber, B, and number of selectable fibers/substitute devices on each link, k, are the intra-node parameters. Network design algorithm used for conventional network is that given in [22]. The network design algorithms applied for WSS-WBSS and WSS-1xn SW networks are respectively based on those of [18] and [17] with an additional re-optimization; the establishment of highly utilized wavelength groups is encouraged at first, then wavelength path routing and assignment is utilized only for grooming sparse traffic demands and finally, rerouting wavelength paths is applied to reduce the necessary network resources. All the obtained results are normalized against those of the corresponding conventional WSS-based OXC networks.



COST266 USNET

Fig. 3. Experimental physical network topologies

Table 3. Major parameters of COST266 and USNET networks

		Network topology	
		COST266	USNET
Number of nodes		26	24
Node degree	Min	2	2
	Max	8	5
	Ave	3.92	3.58
Number of Links		51	43
Number of shortest hops	Min	1	1
	Max	6	6
	Ave	2.76	2.99

4.1. Link resource and hardware scale requirements

The proposed WSS-WBSS and WSS-1x*n* SW OXC architectures utilize simpler and more cost-effective switches, WBSSs and 1x*n* optical switches, instead of WSSs, to reduce the necessary node scale/cost. However, their routing capability is somewhat restricted and as a result, more link resources are required to offset the routing limitation (or if the number of fibers are set equal, the maximum acceptable traffic volume is slightly decreased). Figure 4 depicts the relative number of necessary fibers in the pan-European optical network when the traffic demand ranges from 4 to 32, applied WSS degree is 1x9 (X=9, commonly available WSS degree at present), number of wavelength groups per fiber supported by WBSSs is 8 (B=8) and k=1. The total number of fibers needed by the appropriate conventional WSS-based OXC network is used as the benchmark (the relative number is equal to 1). It confirms that utilizing WSS-WBSS and WSS-1x*n* SW architectures requires more link resources (fiber count) due to their node routing restriction; the more flexible routing architecture requires fewer link resources. The WSS-1x*n* SW network needs about 13~17% more fibers while the WSS-WBSS network requires less than 4% fiber increment compared to the conventional network. Moreover, the relative fiber number is slightly fluctuated, especially in the small traffic demand area where the benchmark is small, due to the inefficiency of wavelength group switching in the second stage of the proposed architectures when the traffic demand is not sufficient enough to fill up the given capacity of wavelength groups.

Figure 5 describes the number of necessary WSSs in the same network. Both WSS-WBSS and WSS-1x*n* SW networks need fewer WSSs than the conventional network; their relative WSS numbers are less than 1. The relative WSS number of WSS-WBSS and WSS-1x*n* SW networks is reduced as the traffic demand increases or in other words, more hardware scale reduction (in terms of WSS number) is obtained with larger traffic demands; the target of our OXC architectures. Up to 68% (65%) reduction in the necessary WSS number can be attained at the cost of 2% (14%) fiber increment for the WSS-WBSS (WSS-1x*n* SW) network with the traffic demand of 32. The WSS-1x*n* SW network needs more fibers while offering a slightly smaller WSS number reduction than the WSS-WBSS network; this is offset by the fact that it requires only the simplest and most cost-effective substitute optical switching devices, 1x*n* optical switches, instead of WBSSs.

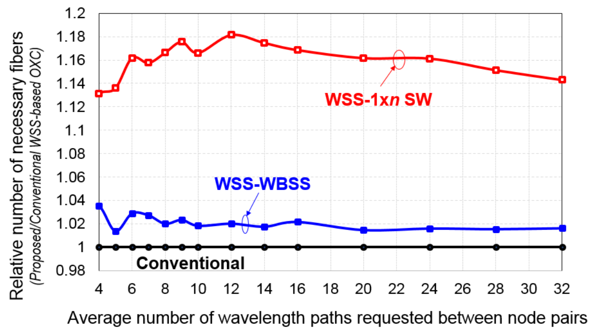


Fig. 4. Link resource requirement of COST266 network

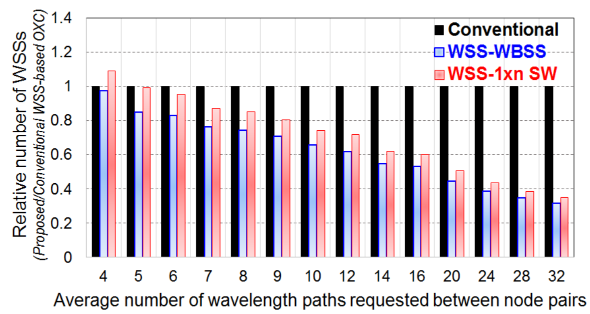


Fig. 5. WSS number reduction obtained for COST266 network

Similarly, the fiber increment and hardware scale reduction in terms of WSS number attained in US nationwide network are shown in Figures 6 and 7. It also demonstrates that the proposed architectures become more efficient with larger traffic volumes and utilizing the WSS-WBSS (or WSS-1x*n* SW) architecture can provide up to 67% (65%) hardware scale reduction, in terms of WSS number, at the cost of less than 2% (8%) fiber increment with the traffic demand of 32.

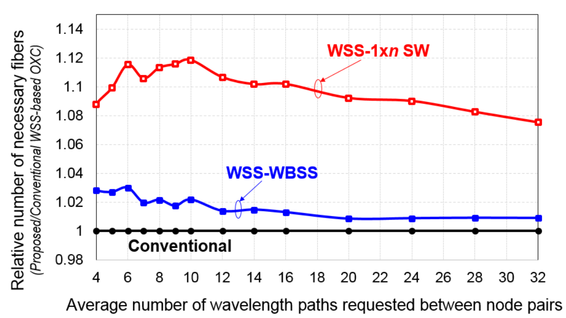


Fig. 6. Number of necessary fibers in USNET network

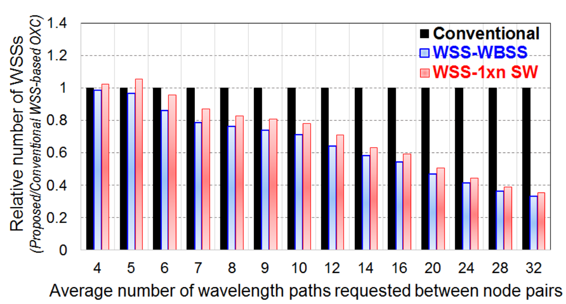


Fig. 7. Number of necessary switching devices in USNET network

4.2. Analysis on the switching configuration parameters

The node routing flexibility of the proposed architectures depends on the intra-node parameters, which are the number of wavelength groups per fiber, *B*, and the number of selectable output fibers per link, *k*. Please note that when *B*=80, the results correspond to a conventional WSS-based architecture, and when *B*=1, it is a WSS-1x*n* SW architecture. Applying WBSSs that can support a larger number of wavelength groups per fiber (*B*) in the WSS-WBSS architecture or using a greater number of substitute switching devices per link, *k*, for both WSS-WBSS and WSS-1x*n* SW architectures enhances the routing flexibility of the nodes and hence, reduces the required link resources, i.e. number of necessary fibers. However, WBSSs that support higher wavelength group numbers per fiber (larger *B*) may be more expensive and as a result, the required node cost is likely to increase. On the other hand, using a greater k will cause a substantial increase in the number of switching devices needed, especially 1xn SWs and WBSSs, and the node cost is consequently also increased. Therefore, a tradeoff exists between the node routing flexibility (link resource) and the node scale/cost (WSS and WBSS/1xn SW numbers) requirement.

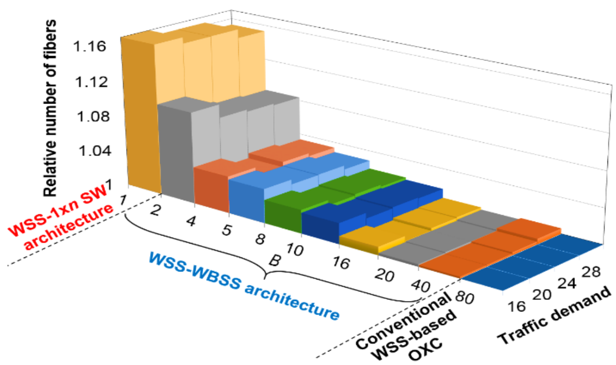


Fig. 8. Relative fiber number (*k*=1)

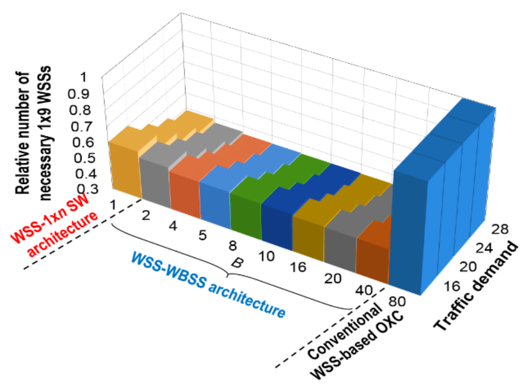


Fig. 9. Relative number of WSSs (*k*=1)

Figures 8 and 9 show the dependence of the fiber number and the 1x9 WSS number on parameter *B* with *k* of 1 for the COST266 network; four traffic values (16, 20, 24 and 28) are examined. The results demonstrate that the WSS-WBSS architecture ($40 \geq B \geq 2$) offers not only lower fiber number but also greater WSS number reduction than possible with the WSS-1x*n* SW architecture (*B*=1). The WSS-WBSS architecture provides a moderate solution between WSS-1x*n* SW and conventional WSS-based networks. The effectiveness of the WSS-WBSS network increases with *B*; fewer fibers (less link cost) are needed as *B* increases, and when *k* is 1, fiber increment ranges from 0.2% to 10.3% with *B* values from 40 and 2. The WSS-

WBSS network can attain more than 60% WSS reduction at the cost of less than 2% fiber increment when the traffic demand is greater than 20 and $B \geq 8$ is supported. The WSS-1xn SW network can also achieve a 60% WSS reduction, but it needs at least 14% more fibers.

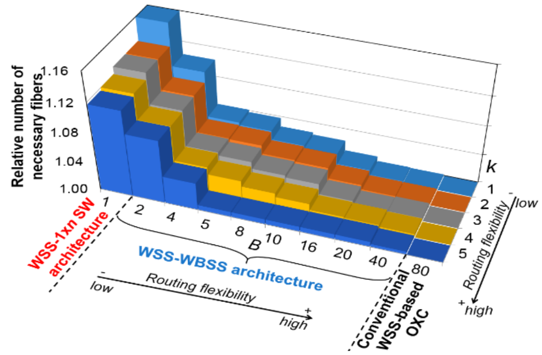
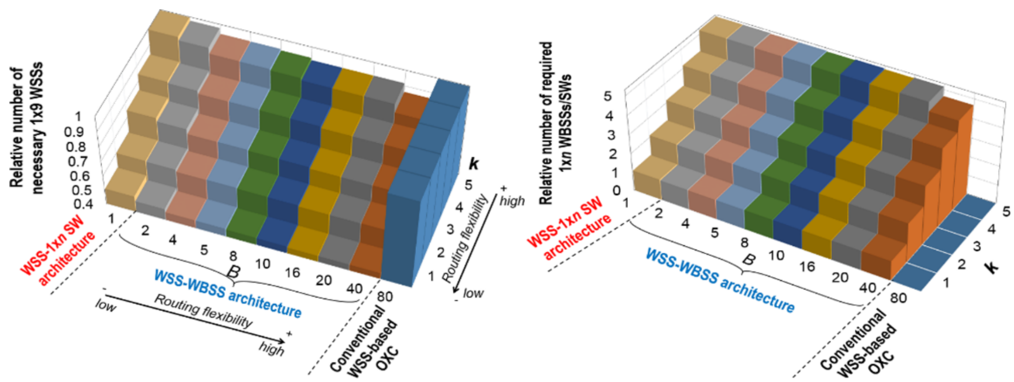


Fig. 10. Number of necessary fibers



(a) necessary number of WSSs

(b) necessary number of WBSSs/SWs

Fig. 11. Relative number of switching components

Figures 10 and 11 describe the impact of k on the fiber number and the node hardware scale (WSS and WBSS/ 1xn SW numbers) in the pan-European network (COST266), respectively; traffic demand is 20. The results demonstrate that the node hardware scale/cost requirement of our WSS-WBSS and WSS-1xn SW architectures is mainly dominated by parameter k. More hardware scale is required with a larger k, or in other words, the total node scale/cost of our proposed networks become greater if k is increased. Although parameter B greatly influences the node routing flexibility (required total fiber number), it is verified that it has only a small effect on the hardware scale requirement. Furthermore, using greater k also increases the number of intra-node interconnection fibers; node implementation becomes more complicated. It also results in higher optical combiner loss at the output fiber side. Hence, the intra-node parameters must be properly optimized to exploit the proposed architectures; when node cost dominates fiber cost, then k should be as small as possible to maximize the hardware reduction.

4.3. Impact of the WSS degree

WSS degree does not affect the routing capability of nodes but does play a key role in determining the number of necessary WSSs in the networks. Figure 12 depicts the impact of WSS degree on the number of WSSs needed by WSS-WBSS (k=1 and B=10) and WSS-1xn SW (k=2) networks relative to that of the conventional WSS-based OXC network with the traffic demands of 24 and 32, where WSS degree is changed. The WSS number reduction provided by WSS-WBSS and WSS-1xn SW networks decreases (the relative WSS number increases) as larger WSSs are employed. Unlike the conventional WSS-based OXC architecture, in which increasing the WSS degree can reduce the necessary number of switching elements, WSS-WBSS and WSS-1x*n* SW architectures need only limited degree WSSs; the maximum WSS degree is 1x*kD*, where *D* is the number of adjacent nodes ($D \leq 8$ for the COST266 network). As a result, utilizing very large WSS degree may not help to reduce the number of switching elements in the networks. However, of course, the hardware complexity is mitigated.

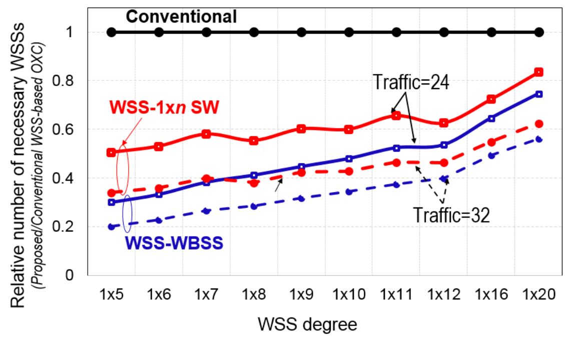


Fig. 12. Impact of WSS degree on the hardware scale reduction

5. Conclusion

We investigated the performance of novel large-scale OXC architectures that are based on combining small degree WSSs with simpler and more cost-effective switching devices; 1x*n* optical switches or WBSSs. The proposed OXC architectures offer a substantial hardware scale reduction at the cost of a few additional fibers and their effectiveness increases with the traffic demand. We also assessed the impact of intra-node parameters in networks utilizing the proposed OXC architectures and clarified the dependency of the link resource and the hardware scale requirements on the parameter values. It was verified that selecting the proper intra-node parameter values is very important in maximizing the effectiveness of the proposed architectures. Among the proposed architecture variants (with 1x*n* optical switches or WBSSs) and the conventional WSS-based architecture, which one is optimal depends on the relative cost of a 1x*n* switch and a WBSS to a WSS, and additional fiber cost, however, the proposed architectures will provide a viable solution for creating future large-scale optical node systems.

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