Comparison of Wavelength-Selective Cross-Connect Architectures for Reconfigurable All-Optical Networks

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Abstract: The scalability, modularity and optical transport characteristics of various wavelength-selective cross-connect (WSXC) node architectures for reconfigurable all-optical networks are presented. In particular, these WSXC architectures are analyzed as the add-drop ratio and degree of the node are increased.

Keywords: optical switches, photonic cross-connect, wavelength division multiplexing

1. Introduction

High throughput and large add-drop capable wavelength-selective cross-connect (WSXC) nodes will be the basis of next-generation ultra-high-capacity optical networks [1]. With their ability to transparently switch wavelengths, WSXC's allow the realization of dynamically reconfigurable mesh networks, which provide end-to-end network-level failure protection and restoration. A WSXC node must be scalable from a degree 2 ROADM up to a degree 8 for complex mesh networks as well as providing modular growth capability for future in-service upgrades to higher degrees and add-drops without interrupting existing service. A typical node requires 20-30% add-drop including regeneration and wavelength-conversion while much higher add-drop ratios are also required for some nodes. In addition to providing network flexibility, a WSXC should also exhibit high optical performance for cascadability.

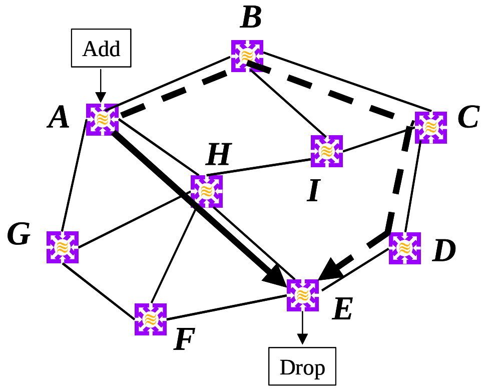

Figure 1: All-optical mesh network

Fig. 1 shows the schematic of a typical all-optical mesh network with nodes varying from degree 2 to 5. In this example, a signal is added to the network at the ingress node A and is dropped at the egress node E after traversing node H (solid line). Upon a fiber break or node H failure on this route, the signal is re-routed through nodes B, C and D (dashed line) using the same add-drop transponders. The following architectural requirements need to be provided at the WSXC node in order to achieve dynamic end-to-end mesh protection and restoration:

- The add-drop transponder has access to all N fibers (degrees) of the node for re-route purposes.
- The tunable transponder has colorless access to each of the N fibers since the original wavelength may not be available on the new route.

In addition to the above requirements, the WSXC architecture should also allow for flexible incremental growth as new fibers and add-drops are added.

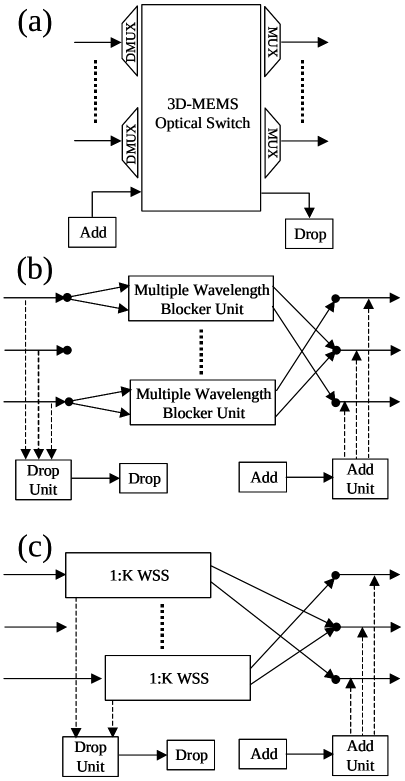

Figure 2: WSXC node architectures based on (a) 3-D MEMS WSPXC, (b) λ-blocker B&S, (c) WSS OXC

2. WSXC Architectures

WSXC architectures are based on 3 distinct technologies as summarized in Fig. 2:

3-D MEMS based WSPXC Architecture: The wavelength-selective photonic cross-connect (Fig. 2a) is realized by combining a set of wavelength-selective multiplexers and demultiplexers (D/MUX) with a large-scale 3-D micro-electro-mechanical systems (MEMS) optical switch [2]. The filters, which can either be integrated directly or added modularly to the core switch, simultaneously serve for both express wavelength switching and colorless add-drops while transponders are directly connected to the core switch.

λ-Blocker based B&S Architecture: The broadcast-and-select architecture (Fig. 2b) is based on passive optical splitters for broadcast/combine and liquid crystal (LC) or MEMS based wavelength blockers for selecting the desired wavelengths [3]. This architecture physically separates the express switching from the add-drop switching. Therefore, while each of the N fibers requires N-1 λ-blockers for express wavelengths, additional filtering and switching units are required for the add-drops.

1:K WSS based OXC Architecture: This optical cross-connect architecture is realized by employing LC or MEMS based 1:K wavelength-selective switches (with typical $K \leq 9$) [4,5], which distribute the incoming DWDM channels to any of the desired K outputs, and/or passive optical splitters. There are three WSS OXC types possible where each N fiber consists of (i) a splitter for broadcast/drop and a WSS for switch/add, (ii) a WSS for switch/drop and a coupler for combine/add (Fig. 2c), and (iii) two cascaded WSS's for drop, switch and add. In the remainder of the paper, we will mainly discuss type (i) due to its lower cost architecture. The WSS OXC architecture also requires additional units at the add-drop side.

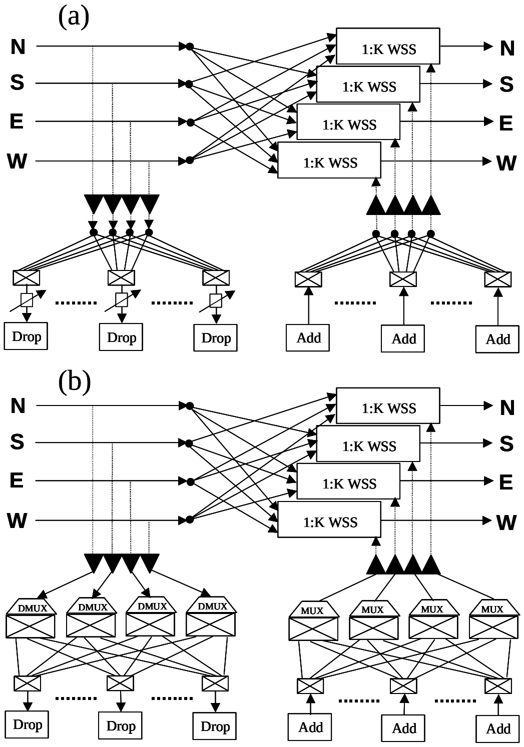

Figure 3: Add-drop configuration details of WSS OXC

The fundamental difference between the WSPXC and the other architectures is the nature of the add-drop. While the WSPXC requires only a patch-cord connection between the transponder and the core switch, the B&S and the WSS OXC architectures separate the express switching and filtering from the add-drop switching and filtering. Fig. 3 shows two possible configurations for a degree 4 WSXC node using WSS OXC's (same concepts for the B&S). The first add-drop requirement for a mesh network dictates that each transponder needs a 1xN switch. The colorless switching of the add-drop is achieved by using passive splitters and tunable filters at the receive end and a coupler on the transmit end in configuration A while 1:M D/MUX's with $M \times pMN$ optical switches at both add and drops are used for configuration B (where M and p are the number of λ's and the add-drop ratio, respectively, per N). For example, a degree 4 node with 40λ per fiber and a 25% add-drop ratio requires 40 tunable filters and eight 1:10 couplers for configuration A, and eight 40-channel D/MUX's and eight 40x40 switches for configuration B. Both configurations also require 80 1x4 switches at the transponders. Both the WSS OXC and B&S architectures may also require optical amplifiers to overcome excess losses. This then requires ASE-suppressing λ-blockers at the add for the B&S and WSS OXC type (ii) architectures.

Protection of the WSXC node is the second fundamental difference between the architectures. While the express node path is protected at the network level similarly to a fiber cut, the add-drop paths need to be protected locally. This requires duplicating the core optical switch in the WSPXC and adding 1×2 switches at each transponder. While the WSS OXC and B&S architectures do not need to duplicate their express switching elements, the $M \times pMN$ switches used in configuration B would also require protection for high λ's and add-drop ratios (this is ignored in this paper to simplify the comparison).

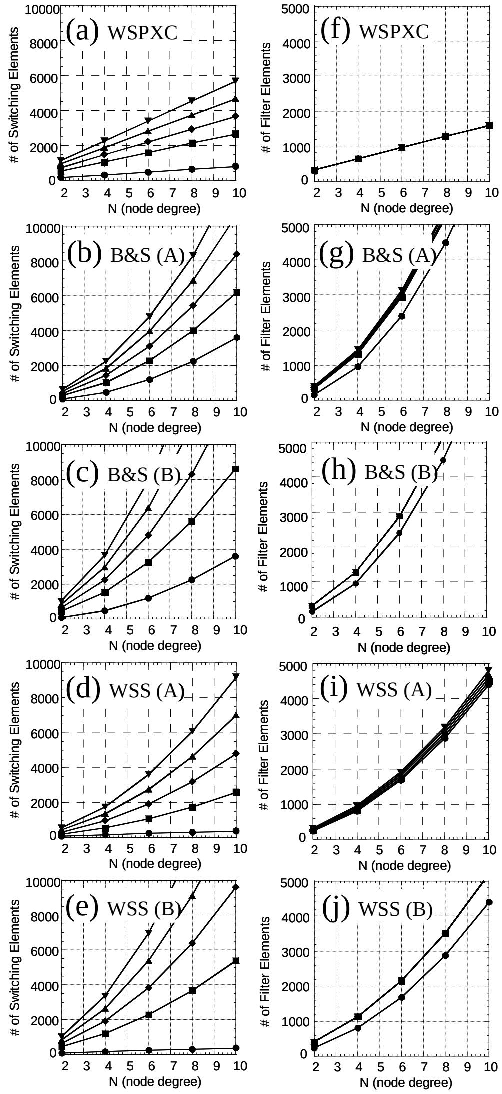

Figure 4: Scalability of switching (a-e) and filter (f-j) elements as a function of N and p (circle, square, diamond, upper & lower triangles – 0, 0.25, 0.5, 0.75 and 1 add-drop)

3. Scalability

Fig. 4 shows the scalability of the three architectures (assuming MEMS based switching and waveguide based filtering elements for consistency) as a function of node degree N and add-drop ratio p. The two add-drop configurations discussed in the preceding section for the B&S and WSS OXC architectures are also considered. From the number of switching elements required (Fig. 4a-e), only the WSPXC architecture has a linear relationship with N for all add-drop ratios. While the WSS OXC has a linear relationship only for no add-drops, both the B&S and the WSS OXC exhibit a quadratic increase in switching elements with increasing add-drops. This is due to the $1\times N$ switches (for pMN add-drops) as well as the 2N $M\times pMN$ optical switches for configuration B. A similar trend is observed for the number of filter elements (Fig. 4f-j). While the WSPXC filter element scales linearly with N and independently of add-drop ratio, the filter element increases quadratically for the two other architectures (due to the express switch) with a linear contribution from the add-drop filters. These plots clearly show that the WSPXC is the most scalable as the node degree and add-drop ratios increase for a WSXC.

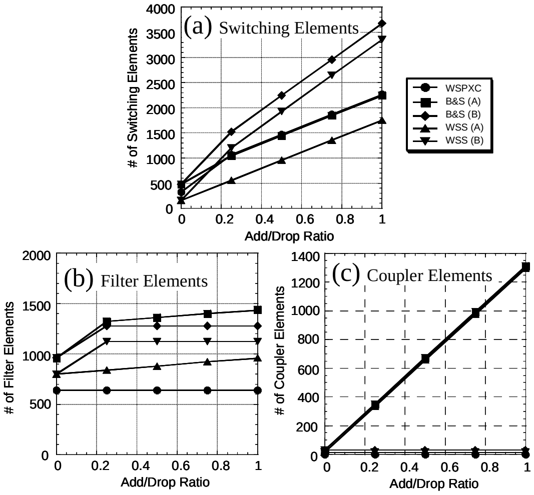

Figure 5: Comparison of number of (a) switching, (b) filtering, and (c) coupling elements for N=4 degree nodes

Fig. 5 compares the number of elements required for a degree 4 node as a function of add-drop ratio. The WSS OXC (configuration A) with couplers on the add-drop shows the lowest switching element count; however, it suffers from a high coupling element number that results in much higher express and add-drop losses. While both the WSPXC and the WSS OXC (configuration B) architectures have comparable switching elements at less than 20% add-drop ratios, the WSPXC requires much fewer elements beyond 20%. Furthermore, the WSPXC requires the least number of filter elements and no coupler elements for all add-drop ratios.

4. Optical transport characteristics

It is imperative that WSXC nodes introduce low optical impairments (such as loss, dispersion, channel bandwidth narrowing) in order to increase node cascadability and total transmission distance. High optical loss not only increases the node cost due to extra amplification, but it results in S/N degradation as well as more frequent regenerators and/or other error compensating techniques. Fig. 6 compares the three WSXC architectures for express and add losses. Regardless of N, the WSPXC has a low and constant loss while the other architectures' losses increase with N due to the use of splitters. The WSS OXC type (iii) with two cascaded WSS's achieves constant express loss (not shown) comparable with WSPXC while the add-drop configuration B loss is fairly constant as well.

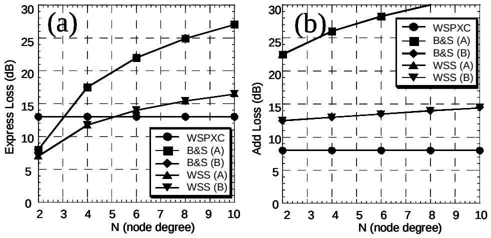

Figure 6: Comparison of express and add (25% ratio) losses

5. Modular growth

The modularity of the WSXC node at both the express (increase in N) and the add-drop (increase in p) layers for future expansion also need to be evaluated for cost savings at installation. For the WSPXC, both the D/MUX's and transponders can be added modularly as the node grows without impacting the existing service when a sufficiently large core switch is provided at installation. On the other hand, as the express layers of the B&S and WSS OXC (types i & ii) depend on splitters, there is limited modularity before optical loss has a significant impact (Fig. 6). Alternatively, WSS OXC type (iii) (with two cascaded WSS's) has an express layer expansion as efficient as the WSPXC. For the WSS OXC and B&S architectures, the add-drop layer expansion for configuration A (Fig. 3) is limited by the splitters while configuration B requires a prior knowledge of expected N and p for determining the fixed $1\times N$ and $M\times pMN$ switches at installation.

6. Conclusion

A comparison of various WSXC node architectures was presented. The importance of the add-drop configuration on the scalability and flexibility of the WSXC architecture was determined. Based on loss and flexibility, WSS OXC's are most suitable for nodes less than degree 3 and low add-drop ratios while the modular WSPXC's are most suitable for these nodes with high add-drop ratios and high degree nodes of all add-drop ratios.

7. References

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