Wavelength-Selective CDC ROADM Designs Using Reduced-Sized Optical Cross-Connects

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***Abstract*— As optical transport networks become more configurable, the need for *reconfigurable optical add/drop multiplexers* (ROADMs) that are colorless, directionless, and contentionless (CDC) increases. Either of the two major classes of ROADM architectures, i.e., broadcast-and-select and wavelength-selective, can provide the CDC properties. With broadcast-and-select ROADMs, this is generally accomplished by employing more costly or complex configurations or adding adjunct equipment. In contrast, the wavelength-selective class of ROADMs, where the central component is an optical cross-connect (OXC), inherently provides the CDC properties. However, this architecture is limited by the achievable size (i.e., port count) of the OXC. We present alternative wavelength-selective ROADM designs that require smaller OXCs while providing equivalent functionality.**

***Index Terms*— Broadcast-and-select, colorless, contentionless, directionless, optical cross-connect, reconfigurable optical add/drop multiplexer, ROADM, wavelength-selective.**

I. Introduction

OPTICAL transport networks have historically been quasi-static, with connections (i.e., circuits) often remaining established for months or years, and with connection set-up typically requiring on-site manual involvement. Carriers have started to transition from this relatively rigid environment to a more configurable one, with connections established remotely through software control and with setup times on the order of a minute or less. Optical-layer configurability is highly desirable as it allows the carrier to rapidly deploy new capacity or redeploy existing capacity to respond to sudden surges or shifts in network demand, and efficiently respond to many types of network failures using the optical layer [1]-[3].

There are several requirements to enable a configurable transport layer. First, the network control and management system must support remote configurability operations. Second, the necessary equipment to establish a new connection, or reroute an existing one, must already be deployed in the network. Third, the network equipment, most notably the *reconfigurable optical add/drop multiplexers* (ROADMs), must possess the requisite flexibility to allow a connection to be remotely established, using any available wavelength.

There are three particular ROADM properties that carriers consider important in supporting a configurable transport layer; i.e., the *colorless*, *directionless*, and *contentionless* (CDC) properties [4]-[6]. *Colorless* indicates that any slot of the ROADM can accommodate a transponder of any wavelength. (A slot is the physical position on a ROADM shelf where the transponder circuit board is inserted.) This is especially beneficial when using tunable transponders as it allows a transponder to be tuned to a different wavelength without having to manually move the transponder to a different ROADM slot. *Directionless* refers to the ability of a transponder to access any of the network fibers that enter/exit a ROADM. Thus, a transponder that initially launches a connection on the eastbound fiber may later be re-purposed to launch a connection on the westbound fiber, without requiring any manual intervention. *Contentionless* indicates that a new connection cannot be blocked solely due to contention within the ROADM. For a ROADM that is *not* contentionless, the contention typically arises in the form of wavelength conflicts; e.g., a wavelength is available to be used on a network fiber, but is not available on the desired add/drop port of the ROADM. Various examples of ROADM contention are illustrated in [5], [7]. Contention can largely be avoided through the use of effective algorithms, especially if the traffic load is low to moderate; however, there still has been much effort to develop contentionless ROADMs. (While a ROADM that supports an add/drop percentage of less than 100% may not be considered truly contentionless, it is assumed here that 'contentionless' pertains to the elimination of wavelength contention.)

There are two chief ROADM architectures, both of which are capable of exhibiting the CDC properties; i.e., the broadcast-and-select (B&S) and the wavelength-selective (WS) architectures. Support for the CDC properties in the B&S architecture is typically achieved by deploying more costly configurations, by utilizing more complex equipment, or by adding ancillary equipment. For example, to achieve the directionless property, the add/drop ports are treated similar to network fibers [5]. In contrast to early non-directionless architectures where the add/drop ports were simple taps off of the network fibers, this essentially doubled the size and cost of the ROADM. To remove most, but not all, internal ROADM wavelength-contention scenarios, the add/drop traffic can be passed through an edge cross-connect (EXC) [5], [8] (the EXC can be used for other functions, such as transponder protection). Alternatively, fully contentionless operation can be attained through the use of M×N wavelength selective switches (WSSs) on the add/drop ports [9]. (Wavelength-selective *switches* should not be confused with the wavelength-selective *architecture*.) The M×N WSS is likely to be costly and may be limited with respect to the size of *M* and *N*. An alternative CDC architecture replaces the M×N WSS with an M×N multicast switch (MCS) [10], which is lower in cost but which has higher loss and requires greater receiver complexity. (The route-and-select (R&S) ROADM architecture is similar to the B&S architecture, and can be similarly architected as a CDC device.)

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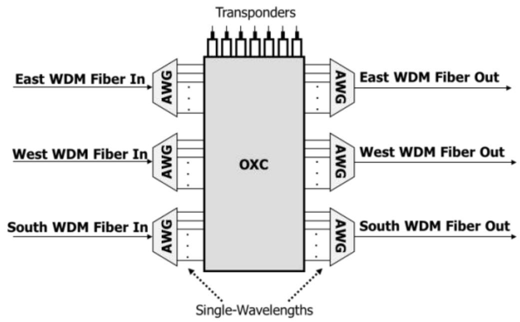

Fig. 1 A WS CDC ROADM. In the configuration shown, the OXC switches single-wavelength signals.

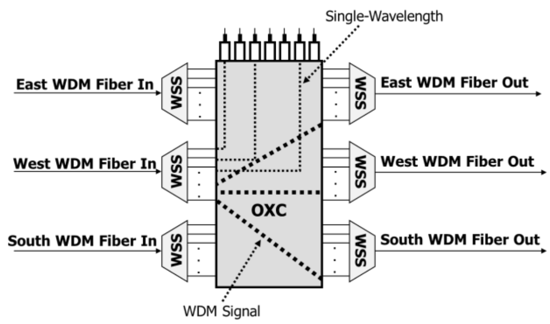

Fig. 2 WSSs are used for the mux/demux in this WS CDC ROADM. Potential connectivity from the West input fiber is shown. Thick dotted lines indicate a WDM signal; thin dotted lines carry a single wavelength.

In contrast to the B&S ROADM, the WS ROADM is inherently a CDC device. However, in current commercial offerings, the optical cross-connect (OXC) that is central to the WS architecture is limited in the supported number of ports. This excludes (or at least discourages) its use in many networks.

This paper proposes two WS ROADM designs that allow a reduced-sized OXC to be utilized. By judiciously architecting the ROADM, many of the configurations of a 'full-sized' OXC are not required. In many scenarios, this permits a smaller-sized OXC to be utilized. Such ROADM architectures potentially offer a more scalable, cost effective means of achieving the desired CDC properties.

The current canonical instantiation of the wavelength-selective architecture is presented in Section II. Sections III and IV probe WS designs that exhibit greater scalability by requiring an OXC of reduced size.

II. Wavelength-Selective ROADM Architecture

A typical WS ROADM architecture is illustrated in Fig. 1, for a degree-three node (i.e., three network fiber pairs). The central component of this architecture is an N×N OXC, with arrayed waveguide gratings (AWGs) on the network fibers performing the multiplexing/demultiplexing (mux/demux) function. The OXC can direct any wavelength from any input port to any output port. This provides the colorless property, as a transponder of any wavelength can be inserted in any of the OXC ports. Additionally, it provides the directionless property, as a transponder can transmit/receive to/from any network fiber. All OXC inputs/outputs carry a single wavelength; i.e., there are no WDM signals internal to the ROADM where wavelength conflicts can arise. Thus, this architecture is also contentionless.

One concern regarding the architecture of Fig. 1 is the reliability of the OXC. A failure of the switch matrix essentially brings down the node, such that any add/drop traffic at the node is lost. Thus, this ROADM does not exhibit the desirable property of *directional separability*, where a failure and the associated repair process affect traffic on just one network fiber pair [5]. To address this, vendors continue to work on improving OXC reliability, with the mean-time-between-failure (MTBF) currently on the order of tens-of-years (e.g., [11], [12]). Another option is to deploy redundant switch fabrics; however, this would increase the cost appreciably.

A second limitation of the OXC-based ROADM is that it is not 'pay-as-you-grow'. The full-sized OXC must be deployed from the start, rather than increasing the element size as the network grows, thereby potentially incurring equipment costs sooner than necessary. Thus, the WS ROADM may be more desirable at nodes that are large and/or close to being fully built out.

A third drawback of the WS architecture is the limited available size of the OXC. Consider a degree-three node with 80 wavelengths per fiber (as may be found in a core network), and where up to 50% of the wavelengths on any fiber can add/drop at the node. This requires an OXC of size 360×360. A degree-eight node with 40 wavelengths per fiber and 40% add/drop (as may be present in a metro network) requires a 448×448 OXC. However, commercially available OXCs are typically no larger than 320×320; furthermore, this maximum size has not increased in several years. (While OXCs closer to 1000×1000 in size were architected in the 2000 time-frame, they were never deployed in volume.) This limits the usefulness of this particular architecture. While switch architectures composed of numerous smaller OXCs, e.g., the Clos architecture, can be used to achieve a larger, strictly non-blocking switch, this adds to the complexity, cost, size, and loss of the ROADM.

It is this OXC size limitation that we address here. The next two sections investigate variations of the WS ROADM that enable smaller-sized OXCs to be utilized.

III. Reduced-Size Wavelength-Selective Architecture Utilizing WSSs

One WS architecture that requires a smaller OXC is shown in Fig. 2. The key difference as compared to Fig. 1 is the mux/demux functionality is provided by 1×N WSSs as opposed to 1×N AWGs. A WSS is capable of directing *multiple* wavelengths from an input WDM signal to a single output port. (Most AWGs can direct just a single wavelength to an output port. Cyclic AWGs can direct a *small* number of *specific* wavelengths to an output port.) Thus, the WSSs can deliver WDM signals to the inputs of the OXC; most OXCs, e.g., those based on micro-electrical-mechanical system (MEMS) technology, are capable of switching a WDM signal.

This enables, for example, all of the wavelengths being routed from the west fiber to the east fiber to require just one input port and one output port on the OXC. This economy of ports can be implemented for any of the traffic that is being routed *through* the node.

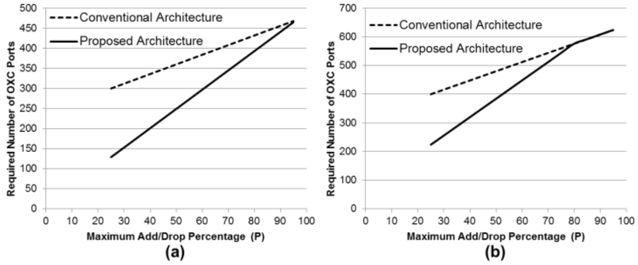

Fig. 3 Savings in port size provided by the proposed architecture for: (a) A typical core node, with degree 3 and 80 wavelengths per fiber; and (b) A typical metro junction-node, with degree 8 and 40 wavelengths per fiber.

For the add/drop traffic, it is assumed that there remains a one-to-one relationship between a transponder and an OXC port (i.e., the add/drop ports still carry a single wavelength as opposed to a WDM signal) so that no wavelength contention arises. Thus, this architecture remains fully CDC.

One potential advantage of the modified design is with respect to cascadability. The passband of a WSS is typically superior to that of an AWG, leading to the ability of an optical signal to pass all-optically through more ROADMs. Next, we quantify the benefits in size, loss, and cost.

A. Reduction in OXC Port Requirement

Let D be the degree of the node, let W be the number of wavelengths per fiber, and let P be the maximum add/drop ratio *per fiber*. (Commercial ROADMs often limit P to less than 100% [13].) Then, in the modified architecture of Fig. 2, an N×N OXC is required, where:

$$N = D \cdot min(D + W \cdot P, W) + D \cdot W \cdot P \qquad (1)$$

(If loopback, e.g., west fiber to west fiber, is not required then the $D + W \cdot P$ term can be replaced by $D - 1 + W \cdot P$.) This compares with:

$$N = D \cdot W + D \cdot W \cdot P \qquad (2)$$

in the conventional wavelength-selective architecture.

Figure 3(a) plots Eqns. 1 and 2 for a typical core network node, with D equal to 3, W equal to 80, and P ranging from 25% to 100%. Figure 3(b) is a plot for a typical metro network junction-node, with D equal to 8, W equal to 40, and with the same range of P. (For simplicity, it is assumed that OXCs can be arbitrarily sized.) As illustrated in the figure, the modified architecture can significantly reduce the required OXC size, especially for moderate P. For example, with D equal to 3, W equal to 80, and P equal to 50%, the required OXC size in the modified architecture is 249×249, as opposed to 360×360 in the conventional architecture, which represents a 30% decrease in port count. (In a typical backbone network with 2,500 km optical reach, almost all nodes have a P of 50% or less [5].) While the OXC size required in the proposed architecture is not 'small', the reduced size allows the OXC to be realized with current commercial offerings in many scenarios. Note that if $P \geq (1 - D/W)$, then no savings in OXC ports are realized; this can be seen in Fig. 3(b).

With regard to the mux/demux functionality, the required size of the WSS in the modified architecture is:

$$1 \times min(D + W \cdot P, W) \qquad (3)$$

The required size of the AWG in the conventional architecture is 1×W. Commercially available WSSs are limited to approximately 1×20. Equation 3 is likely to be larger than 1×20; thus, a WSS tree structure would be needed. The B&S architecture also typically requires that a WSS tree structure be used on the add/drop ports [14]. The impact of the tree structure is somewhat worse in the WS ROADM, as all traffic suffers the additional splitting loss, not just the add/drop traffic.

Note that if the maximum add/drop ratio is with respect to the *total* nodal wavelengths (rather than a *per fiber* ratio), then the N×N OXC in the modified architecture is required to be of size: $N = D \cdot min[D + D \cdot W \cdot P, W] + D \cdot W \cdot P$

Comparing this to Eqn. (2), which continues to hold for the conventional architecture, then a port savings is achieved as long as $D \cdot P < (1 - D/W)$.

B. Loss and Cost Comparisons

The nominal insertion loss of an AWG is on the order of 6 dB for core-network applications [15] and 5 dB for metro-network applications [16]; the loss of a WSS is roughly 6.5 dB [17]. Consider a core-network ROADM with 80 wavelengths per fiber. A tree of WSSs is likely required in the modified architecture, e.g., a two-way power splitter feeding two 1×22 WSSs (this supports 50% add/drop per fiber in a degree-three ROADM). In a metro network with 40 wavelengths per fiber, a WSS tree may not be necessary (depending on D and P).

If single-stage OXCs are utilized in both architectures, then the proposed architecture incurs greater loss. However, the motivation for using the modified ROADM architecture is to enable the use of a single-stage OXC in scenarios where it is not feasible with the conventional architecture. Thus, for the scenarios of interest, we assume that a three-stage strictly non-blocking Clos architecture is employed for the conventional architecture, where signals pass through three (smaller) OXCs. Assume that the worst-case OXC loss is ~3.5 dB [11], [18]. Assume degree-three for a core node and degree-eight for a metro node. Then the loss of the modified architecture (with a WSS tree used in the core node) is the same or better than the conventional WS architecture, as shown in Table 1.

Table 1 also shows the loss of B&S and R&S ROADMs, equipped with an edge XC to minimize contention, and with the number of add/drop ports equal to the number of network fibers; see [5] for figures of these architectures. In most scenarios, the through-path loss is lower as compared to the modified WS architecture, possibly improving cascadability; the add/drop loss is always higher.

Similar comparisons exist with respect to cost. The ports of a WSS are an order-of-magnitude more costly than the ports of an AWG, leading to a more costly mux/demux structure in the modified WS architecture. However, if an OXC based on the Clos architecture is required for the conventional WS ROADM, its overall cost is likely to be higher.

Table 1. Nominal ROADM Loss (A/D = Add/Drop)

		Mod. WS	**Conv. WS**	**B&S w/ EXC**	**R&S w/ EXC**
Core	**Thru**	22.5 dB	22.5 dB	14.5 dB	13 dB
	A/D	13 dB	16.5 dB	27.5 dB	26 dB
Metro	**Thru**	16.5 dB	20.5 dB	18.5 dB	13 dB
	A/D	10 dB	15.5 dB	28.5 dB	23 dB

Table 2. Approximate Relative ROADM Cost

		OXC Size		Approximate ROADM Cost			
	P	**Mod. WS**	**Conv. WS**	**Mod. WS**	**Conv. WS**	**B&S w/ EXC**	**R&S w/ EXC**
Core	33.8%	171	321	X	1.5 X	1.05 X	1.2 X
	50%	249	360	Y	1.1 Y	1.04 Y	1.15 Y
	63.8%	315	393	Z	1.0 Z	1.03 Z	1.1 Z
Metro	2.5%	80	328	Q	2.2 Q	1.5 Q	2.9 Q
	20%	192	384	R	1.3 R	1.3 R	2.0 R
	40%	320	448	S	1.0 S	1.2 S	1.6 S

We assume that the port cost of a large OXC is *C*, the port cost of a small OXC (8×8 or smaller) is 0.2·*C*, the port cost of a WSS is 2·*C*, and the port cost of an AWG is 0.1·C. For a degree-three node in a core network, *P* from 33.8% to 63.8% represents the regime where the Clos architecture is required in the conventional WS architecture but a single OXC is sufficient in the modified WS architecture (assuming the current commercial size limit of 320×320). For a degree-eight metro node, that range is *P* from 2.5% to 40%. Table 2 compares the ROADM cost at these points (plus one intermediate point).

All costs are normalized to that of the modified WS architecture. The cost of the conventional WS architecture ranges from break-even to 50% higher in the core, and break-even to 120% higher in the metro. Perhaps more importantly, the difference in complexity is significant. The Clos architectures considered here require interconnecting roughly 200 OXCs.

The relative costs of B&S and R&S ROADMs, with edge cross-connects, are included in Table 2 as well. The proposed WS architecture provides cost benefits relative to these architectures in all considered scenarios.

IV. Reduced-Size Wavelength-Selective Design Utilizing AWGs

A second alternative WS ROADM does not represent a new architecture; rather, it takes advantage of an inherent limitation of the conventional architecture of Fig. 1, such that smaller OXCs can be used without affecting the functionality. AWGs are limited in the configurations that they can support, where only a specific wavelength can be directed from/to a particular input/output port. This implies that only certain OXC configurations are needed with regard to the through traffic.

As an example, assume that wavelength λ_1 is being routed from the west fiber to the east fiber. This wavelength can appear only on output port 1 of the west AWG and only on input port 1 of the east AWG. Thus, with regard to the west-to-east through traffic, only one OXC configuration could ever be required for this particular wavelength. It is assumed that full flexibility with respect to add/drop traffic is still required; i.e., if λ_1 is being dropped from the west fiber, then it is desirable to be able to direct it to any transponder. This ensures that support for the CDC properties remains.

Overall, any given OXC input port potentially needs to be connected to any of a set of OXC output ports, where the set is composed of D + D·W·P particular ports. With conventional wavelength-selective designs, the OXC provides connectivity from any input to any of the D·W + D·W·P output ports. Thus, the connectivity requirements for any given input port are reduced by D·(W-1) ports. This savings is independent of *P*. In the core-node example, with a *D* of 3 and a *W* of 80, each input port is connected to 237 fewer output ports. In the metro-node example, with a *D* of 8 and a *W* of 40, each input port is connected to 312 fewer output ports.

With less internal connectivity requirements, ideally the number of OXC ports can be increased. There should be little impact on cost, loss, or physical size (if anything, these factors should decrease). Of course, the OXC needs to be designed to take advantage of the lower connectivity requirement.

V. Conclusion

CDC ROADMs are desirable to support agile networks. The conventional WS ROADM architecture, while providing the CDC functionality, is limited in scalability. Two alternatives were presented that allow a reduced-size OXC to be employed. One was dependent on using WSSs rather than AWGs for the mux/demux function. The other used AWGs, but took advantage of the limited connectivity that is imposed by the AWGs. These architectures allow WS ROADMs to be viable CDC devices in a much larger range of networks.

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