Colorless, Partially Directional, and Contentionless Architecture for High-Degree ROADMs

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Abstract: We design a new Colorless, partially Directional, and Contentionless (CpDC) architecture for high-degree ROADMs, in which a fixed interconnection pattern is developed to connect different nodal degrees and add/drop modules. Simulation results show the advantages of the proposed architecture to significantly reduce the cost, insertion loss, and volume.
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1. Introduction

With rapid growth of network traffic, more transmission capacities are required on network links, leading to multiple pairs of bi-directional fiber links incident to an optical network node. Thus, high-degree reconfigurable optical add/drop multiplexers (ROADMs) are required in future optical networks (today, we see ROADMs with a nodal degree of 16 deployed in some European networks). As an important component to realize efficient internal connection of a ROADM, a large wavelength-selective switch (WSS) is required with increase of ROADM nodal degree. Nonetheless, it is still quite challenging to fabricate large WSSs. Today, commercial WSSs are limited to 1×32 in size. Thus, it is important to consider how to use small WSSs to build high-degree ROADMs to support future high traffic demands. In the literature, there exist studies on design of a ROADM with small $1 \times K$ WSSs in the line side [1][2]. But to enable the contentionless feature of a ROADM [3-5], it is also important to reduce the size of a $M \times N$ WSS in the add/drop side, since it is more challenging and expensive to fabricate a $M \times N$ WSS. In this paper, we propose a novel Colorless, partially Directional, and Contentionless (CpDC) architecture based on small WSSs for high-degree ROADMs, in which an efficient interconnection pattern is developed to alleviate the disadvantage of non-full connection between different nodal degrees and add/drop modules subject to limited WSS size. We evaluate performance of the proposed architecture based on simulations and find that CpDC architecture is superior in aspects of cost, insertion loss, and volume compared to conventional CDC architecture.

2. CpDC ROADM Architecture

Fig. 1 shows the proposed CpDC ROADM architecture in comparison with the conventional CDC architecture. In this example, the ROADM has three directions (referred to as *directional degree*) and on each direction, there are four pairs of bi-directional fiber links (referred to as *fiber link degree*). In the line side, each bi-directional fiber link degree contains a pair of $1 \times K$ WSSs (also called a twin WSS; here for simplicity, we draw a single WSS to represent this twin WSS). In the add/drop side, there are multiple add/drop modules, and each module contains a pair of $M \times N$ WSSs (note that they also form a twin $M \times N$ WSS, and for simplicity we use a single $M \times N$ WSS to represent this twin WSS). In conventional CDC architecture, full fiber connectivity is configured between all the fiber link degrees and add/drop modules. As such, the size of a $1 \times K$ WSS in the line side should be $K = F \cdot (D - 1) + R$, where D is number of directions, F is number of fiber link degrees in each direction, and R is number of add/drop modules. In Fig. 1(a), K is 12 since $F = 4$, $D = 3$, and $R = 4$. Also, for a $M \times N$ WSS in an add/drop module, M equals $F \cdot D$ so that any fiber link degree in the line side can be connected to this module. In Fig. 1(a), M equals 12 since the total fiber link degrees is 12. Clearly, with increase of ROADM nodal degree, size of a $M \times N$ WSS will increase correspondingly, and it would be more difficult to fabricate an even larger-size $M \times N$ WSS. To overcome these difficulties, we propose a CpDC ROADM as shown in Fig. 1(b), in which full connectivity between all fiber link degrees and add/drop modules is not required. Rather, only at least one connection between each add/drop module and each directional degree is required. In Fig. 1(b), there are two connections between each add/drop module and each directional degree. Because of this partial directional configuration, sizes of line WSS and add/drop WSS can be largely reduced, which are 1×13 and $6 \times N$, respectively, much smaller than their corresponding sizes in the conventional CDC architecture. As a disadvantage, this simplified interconnection cannot ensure any channel added to an add/drop module to be directed to any fiber link degree, and vice versa. However, we find that, by properly configuring the connections (to be introduced in the next section) between the fiber link degrees and add/drop modules, the CpDC ROADM can perform similar to the conventional CDC ROADM, while the former shows a much lower cost, insertion loss, and volume.

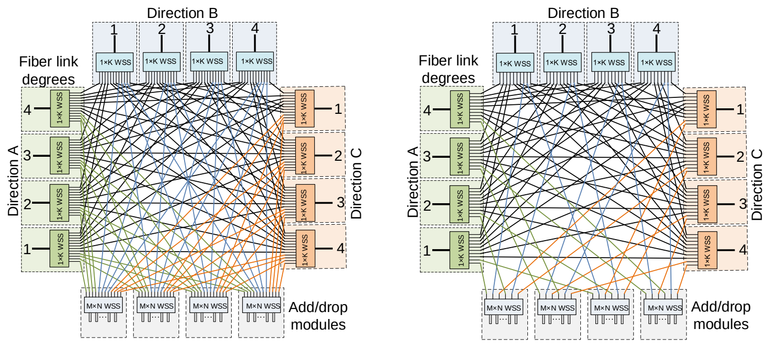


Fig. 1. Comparison between CDC and CpDC ROADM architectures.

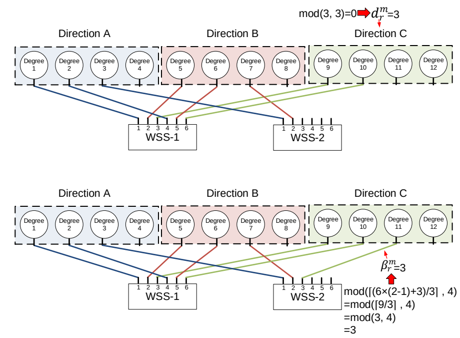


Fig. 2. Example of the interconnection pattern.

3. Interconnection Pattern between Fiber Link Degrees and Add/drop Modules

To ensure good performance of the CpDC ROADM, we develop an interconnection pattern to connect its fiber link degrees and add/drop modules. In this pattern, we connect each fiber link (degree) in a directional degree to a port on an add/drop module based on the following equations:

$$d_r^m = \begin{cases} D, if\ mod(m_r, D) = 0 \\ mod(m_r, D), otherwise \end{cases} \quad (1) \qquad \beta_r^m = \begin{cases} F, if\ mod(\lceil (M \times (r-1) + m_r)/D \rceil, F) = 0 \\ mod(\lceil (M \times (r-1) + m_r)/D \rceil, F), otherwise \end{cases} \quad (2)$$

Here, r is index of an add/drop module and m_r is index of a port on the r^{th} add/drop module. d_r^m is index of the directional degree that has a fiber link connected to the port m_r. β_r^m is index of a fiber link in directional degree d_r^m connected to the port m_r. D, F, and M have the same definitions as before. Fig. 2 shows an example of using the interconnection pattern to connect fiber link degrees and add/drop modules. Specifically, there are three directions, i.e., $D = 3$, and in each direction, there are four fiber links, i.e., $F = 4$. In each add/drop module, there are six ports, i.e., $M = 6$. Thus, port 3 on the second add/drop module (i.e., WSS-2) is connected to the third fiber link in direction C, i.e., Degree 11, since $d_r^m = 3$ and $\beta_r^m = 3$ when $r = 2$, $m = 3$, $D = 3$, $M = 6$, and $F = 4$.

4. Simulations and Performance Analyses

To evaluate the performance of the proposed CpDC architecture, we consider two test networks, i.e., a 14-node, 21-link NSFNET network and a 24-node, 43-link USNET network. We assume that each network link has four pairs of bi-directional fibers and number of wavelengths in each fiber is 80. A fixed number of add/drop modules is deployed in each CpDC ROADM. When evaluating the cost and insertion loss of a ROADM, we only consider the total cost and insertion loss of the WSSs contained in the ROADM since WSSs are the major components of a ROADM although there are other components such as short-reach fibers for internal connections (see Fig. 1), which are however negligible in cost and insertion loss. Total cost and insertion loss of a ROADM are defined as the sums of the costs and insertion losses of all the WSSs contained in the ROADM. In addition, we consider total volume of a ROADM and total number of short-reach fibers for the internal connections in a ROADM. Similarly, total volume of a ROADM is defined as the sum of the volumes of all the WSSs contained in the ROADM. Normalized costs, insertion losses, and volumes of different WSSs are given in Table I. Note that costs of $M \times N$ WSSs are not provided since they are not publicly available, and we are using some internal data from a company. We also assume that the lightpath demand between each node pair is uniformly distributed and dynamic, under which the arrival of lightpath requests follows a Poisson distribution and holding time of an established lightpath follows an exponential distribution. There are 15 and 8 Erlangs of lightpath load between each node pair in NSFNET and USNET, respectively. A total of 10^6 lightpath requests are simulated for the calculation of lightpath-blocking performance.

TABLE I Costs, Insertion Losses, and Volumes of Different Twin WSSs.

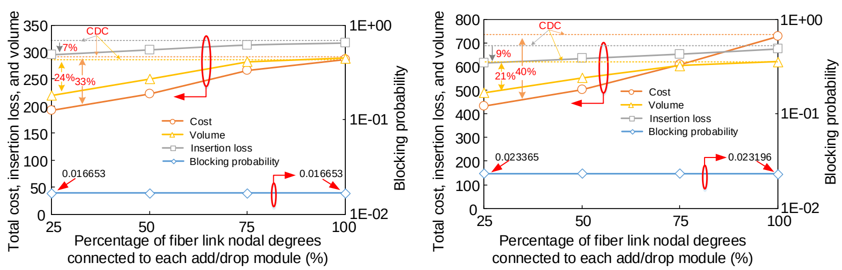
Size	**1× 9**	**1×16**	**1×20**	**1×24**	**1×32**	**1×40**	**4×24**	**8×24**	**12×24**	**16 ×24**	**20×24**
Cost	0.2	0.35	0.4	0.45	0.5	0.55	-	-	-	-	-
Loss	0.8	0.82	0.83	0.84	0.86	0.88	0.94	1	1.04	1.1	1.2
Volume	0.4	0.5	0.6	0.6	0.7	0.7	0.8	1	1.1	1.2	1.2

Based on the test networks, we evaluate the performance of different types of ROADMs from the perspectives of cost, insertion, volume, number of short-reach fibers for internal connection, and lightpath-blocking probability. Figs. 4(a) and (b) show the total cost, insertion loss, and volume of all the ROADMs in NSFNET and USNET, respectively. The numbers of the different types of WSSs required by the different types of ROADMs are shown in Table II, in which “N” and “U” correspond to NSFNET and USNET, respectively. For NSFNET, we see that the CpDC architecture can always reduce the total cost, insertion loss, and volume of the ROADMs compared to the

CDC architecture, which are up to 33%, 7%, and 24%, respectively. This is reasonable since the CpDC ROADM uses smaller WSSs, which have lower cost, insertion loss, and volume. Meanwhile, we find that the lightpath-blocking probabilities of the networks based on the CpDC ROADM keep almost constant when we increase the percentage of fiber link degrees connected to each add/drop module from x=25% to 50%, 75%, and 100% as shown in Fig. 4. Actually, a minor difference between x=25% and 100% does exist for a higher lightpath load. This means that the reduction of interconnection between fiber link degrees and add/drop modules (i.e., reduction of directionless capability) does not significantly affect the performance of the CpDC architectures in carrying lightpath traffic demand. This observation agrees with the results in [3], where we found that the directionless feature of a ROADM does not play a significant role in improving the lightpath-blocking performance.

For USNET, we have similar observation on the performance of CpDC architecture in comparison with CDC architecture, which include a lower total cost, a lower total insertion loss, and a smaller total volume of WSSs, which are up to 40%, 9%, and 21%, respectively. Also, a similar observation can made for the lightpath-blocking performance, i.e., the partial directionless feature of a CpDC ROADM does not significantly impact the network lightpath-blocking performance.

We also compare the total number of short-reach fibers for the internal connections in a ROADM. Fig. 5 shows the results for NSFNET and USNET, respectively. We see that, with an increasing percentage x of fiber link degrees connected to each add/drop module, total number of short-reach fibers used increases as well. This is reasonable since a larger x requires more ports in fiber link degrees connected to add/drop modules and thus increases the number of fibers. Also, we see that the CpDC architecture is efficient to save the total number of fibers used in ROADMs by up to 51% compared to CDC architecture, which can significantly reduce the volume of a ROADM.



(a) NSFNET (b) USNET

Fig. 4. Performance comparison for different ROADM architectures.

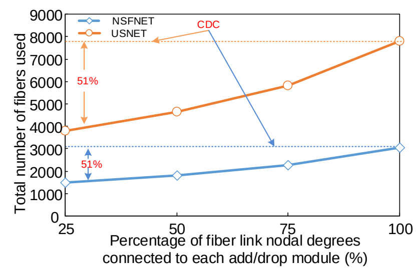


Fig. 5. Total number of short-reach fibers used in different ROADM architectures.

TABLE II Number of Different Twin WSSs Used in NSFNET and USNET Networks under Different Values of x.

x	Net	1×9	1×16	1×20	1×24	1×32	1×40	4×24	8×24	12×24	16 ×24	20×24
25%	**N**	16	120	32	0	0	0	168	0	0	0	0
	U	24	120	80	120	0	0	224	120	0	0	0
50%	**N**	16	120	32	0	0	0	16	152	0	0	0
	U	24	120	80	0	120	0	24	200	120	0	0
75%	**N**	0	16	120	32	0	0	0	16	152	0	0
	U	0	24	120	80	120	0	0	24	200	120	0
100% (CDC)	**N**	0	16	0	120	32	0	0	16	120	32	0
	U	0	24	0	120	80	120	0	24	120	80	120

5. Conclusion

To construct high-degree ROADMs using small WSSs, we proposed a new CpDC ROADM architecture and studied a fixed pattern to interconnect different fiber link degrees and add/drop modules. Simulation results show that the CpDC architecture can significantly reduce the total costs, insertion losses, and volumes of the ROADMs, while not affecting the lightpath-blocking performance, in comparison with the conventional CDC architecture.

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