Hardware-Efficient ROADM Design with Fiber-Core Bypassing for WDM/SDM Networks

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Abstract: A SDM/WDM ROADM is proposed with low port-count WSSs. Fiber-core bypassing reduces the number of and port-count of WSSs in the implementation. The design requires less hardware without compromising on network performance with the developed routing core and wavelength assignment algorithm.

OCIS codes: (060.4251) Networks, assignment and routing algorithms, (060.2360) Fiber optics links and subsystems

1. Introduction

Space division multiplexing (SDM) technologies provide promising solutions to further increasing fiber capacity in optical networks. SDM in optical networks can be implemented with multi-mode fibers (MMFs) [1] or multi-core fibers (MCFs) [2]. MCFs use commercial-available low-loss fan-in/fan-out devices to separate multiple spacial channels in SDM links, rather than the cumbersome spatial mode multiplexers and demultiplxers that are required in MMF-based SDM systems. MCF-based SDM networks also provide better compatibility with current wavelength division multiplexing (WDM) systems. MCF-based SDM technologies bring massive network bandwidth per fiber into optical networks but raise challenges for designs of Reconfigurable Optical Add/Drop Multiplexers (ROADMs) and the corresponding routing, and wavelength/core assignment (RCWA) algorithm.

The latest research in SDM/WDM ROADMs follows the current ROADM design and scaled up for SDM networks with extra-large port-count wavelength selective-switches (WSSs), which are hard to fabricate and also introduce huge insertion loss [3]. In addition, massive bandwidth resource in SDM networks requires spatially and spectrally flexible switching not only with a fine wavelength granularity but also a coarse granularity up to a fiber-core level. Previously, we explored a hardware-programmable WDM/SDM ROADM node focusing on flexible function synthesizing [4]. However, a practical ROADM network is still unavailable.

This paper proposes a hardware-efficient SDM/WDM ROADM network with pre-defined fiber-core bypassing and routing, core and wavelength assignment (RCWA) algorithm. The proposed SDM/WDM ROADMs consist of low port-count wavelength selective-switches (WSSs). The pre-assigned core-to-core connections greatly reduces the required number of WSS connections and the port-count of each WSS. Detailed simulations are carried out with different network topologies, assuming 7-core MCFs. The proposed RWCA algorithm with fiber-core bypassing reduces spectrum fragmentation and shows similar network performance to a ROADM network without fiber-core bypassing. Part of this work is present in a MSc thesis [5].

2. Design of Hardware-Efficient SDM/WDM ROADM with Fiber-core Bypassing

2.1 Fiber-core bypassing assignment The fiber-core bypassing assignment depends on core numbers, network topologies, and network traffic. In our simulations, we consider optical networks with 7-core fibers. The fiber-core bypassing in our simulation follows 2 principles: (a) there is only one core-to-core connection between any two adjacent fibers and (b)The bypass core will bypass a maximum of one node.

2.2 Architecture of WDM/SDM ROADM Figure 1 presents the proposed architecture of the hardware-efficient SDM/WDM ROADM. The assigned bypass cores are connected directlyin dashed line and marked with the same color. Cores that require wavelength switching are configured with multiple WSSs. The design deploys 4-layer WSSs: WSSs in the first layer are used for selecting the destination fibers; WSSs in the second layer select the cores of deatination fibers; the third-layer WSSs multiplex

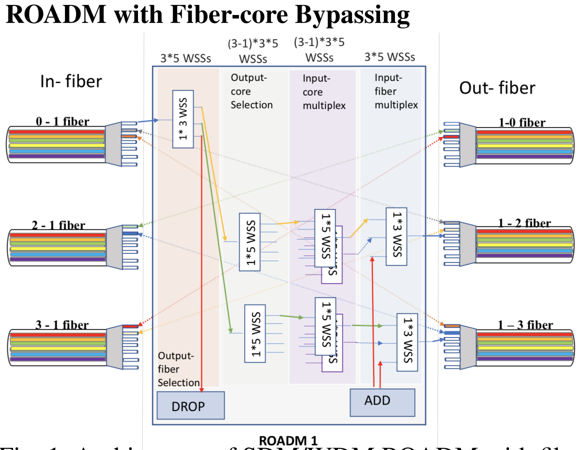


Fig. 1. Architecture of SDM/WDM ROADM with fiber-core bypassing.

channels from different cores of an input fiber; and the final-layer WSSs multiplex channels from different input fibers to a specific core. Each vacant input core has one first-layer WSS and two second-layer WSSs while each vacant core of a out-fiber has two third-layer WSSs and one final-layer WSS. In this design, the first and final layer WSSs require a port counts based on degrees of the ROADM. The second and third WSSs require a port count related to the number of cores that require wavelength switching. With core-to-core direct connections and the proposed ROADM architecture, the implementation of this ROADM only requires low port-count WSSs. In Section 4, we analysed the required number of WSSes and showed how this design reduce the required WSSs.

3. Hardware-efficient RCWA algorithm enabling traffic grooming

Based on the proposed SDM/WDM ROADM network architecture, a hardware-efficient RCWA algorithm (shown in Algorithm 1) is developed to reduce the average path length and wavelength fragmentation in a bypass network. When a traffic request arrives, all available paths will be arranged according to their status. Paths with shorter length, higher bypass status, and more continuous wavelength resources will have higher priority. The traffic request will be blocked, when no available path can be assigned. Once a path is selected, the wavelength for this traffic request is calculated according to the *Pack* algorithm [6].

Algorithm 1 Hardware-efficient RCWA Algorithm

procedure ROUTING AND WAVELENGTH ASSIGNMENT
$T_i \in$ traffic request list
B_i : bandwidth request of T_i
P_i : path list of T_i
$P_i^j \in P_i$: No.j path selection of T_i
$Path_i \in P_i$, is final path selection of T_i
L_i^j : path length of P_i^j;
$Bypass_i^j$: Bypass status of P_i^j;
bypass exists, $Bypass_i^j = 1$, else, $Bypass_i^j = 0$;
R_i^j :maximum continuous λ in P_i^j;
$resource_i^{available}$:
a list of continuous wavelength slots in $Path_i$.
S_i^j :$(L_i^j, Bypass_i^j, R_i^j)$, path status of P_i^j

Start:
T_i shows up and requires B_i
Path Selection:
$P_i^{available} = []$
$S_i^{available} = []$
for $P_i^j \in P_i$ **do**
if $R_i^j > B_i$ **then**
$P_i^{available} += P_i^j$
$S_i^{available} += S_i^j$
Sort sequence of $P_i^{available}$ according to $S_i^{available}$:
$S_i^{available}$ follows ascending rule : $(True, False, False)$
if $P_i^{available} == []$ **then**
T_i **fails**
$i{+}{+}$
go to start.
else: Path of T_i :$Path_i \leftarrow P_i^{available}[0]$
Wavelength Selection:
for $k \in resource_i^{available}$ **do**
if $k > B_i$ **then**
T_i **succeeds** and occupies k in $Path_i$
$i{+}{+}$
go to start.

4. Simulation setup and results

To evaluate the proposed SDM/WDM ROADM and the RCWA algorithm, we implement the SDM/WDM ROADM networks for the 4-node, 6-node, and 14-node topologies, as shown in Fig.2-4. The bypass core assignments are indicated partially in the figures. 160 WDM channels per core were considered. For comparison, we also implement a full-flexibility ROADM network without fiber core bypassing, called no_bypass core. The no-bypass network deploys ROADMs without any bypass-core connections.

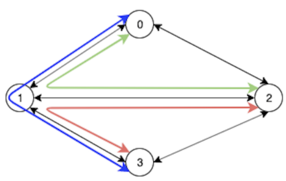


Fig. 2. 4-node topology

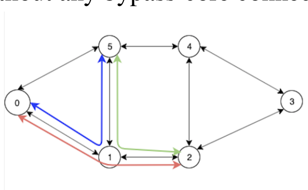


Fig. 3. 6-node topology

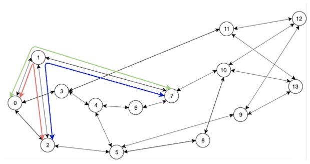
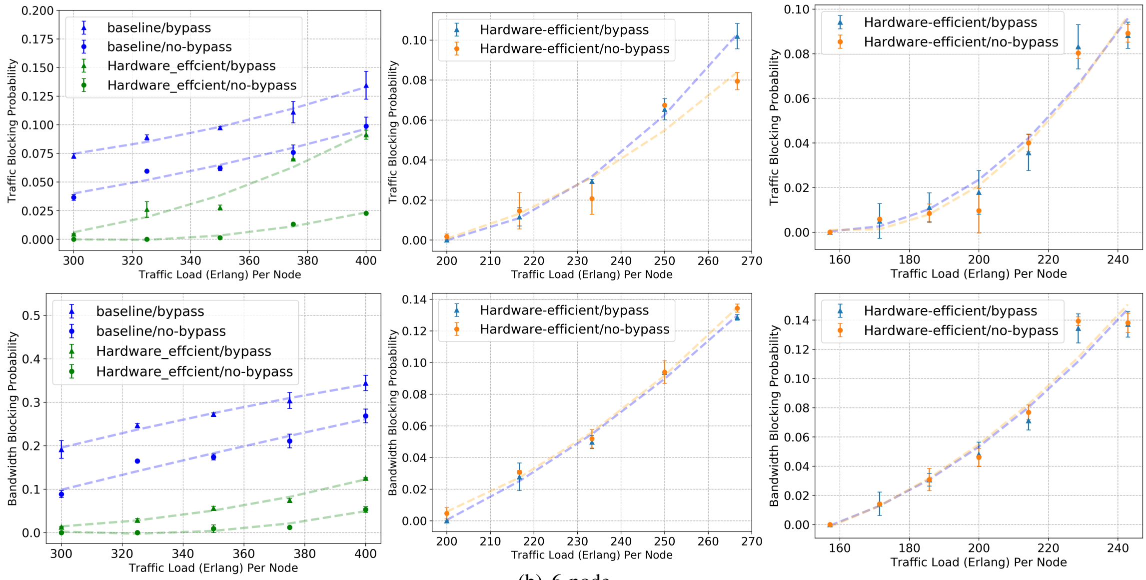


Fig. 4. 14-node topology

In the 4-node topology, a baseline RCWA algorithm (DR scheme[7]) is used to identify the improvement of the hardware-efficient RCWA algorithm. Results of this baseline and hardware-efficient RCWA algorithm in both bypass and no-bypass networks are shown in Figure 5(a). The hardware-efficient RCWA algorithm reduces traffic blocking probability by 6% in a bypass network and 8% in a no-bypass network as compared with the baseline RCWA algorithm. The bandwidth blocking probability of the hardware-efficient algorithm in bypass and no-bypass networks are 22.5% lower than with the baseline RCWA algorithm. However, there is a blocking probability difference between bypass and no-bypass networks in the 4-node topology. This difference comes from the longer average path length caused by bypass connections. When a network has more indirectly connected node pairs, bypass connections have less of an impact on the average path length and blocking probability. The hardware-efficient algorithm was also tested in 6-node and 14-node topologies and these results are shown in

Figure 5(b) and Figure 5(c). In both these topologies, the blocking probability difference between bypass and no-bypass networks disappeared. The introduced bypass-cores don't affect the network blocking probabilities. The node architecture and the designed RCWA algorithm achieved efficiently traffic grooming and avoided wavelength spectrum fragmentation.



(a) 4-node (b) 6-node (c) 14-node

Fig. 5. Traffic (upper) and bandwidth (lower) blocking probabilities in bypass and no-bypass networks

Bypass connections are used to reduce the number of active WSSs as well as reduce the path calculation time because bypass connections limit the potential path selection for traffic requests.As shown in Table 1, the *Ratio of Bypass core* indicates the number of bypass cores among all cores; the *Ratio of deployed WSSs* is the ratio of deployed WSSs in bypass and no_bypass network; and the *Time ratio* indicates calculation time difference between bypass network and no-bypass network, which equals to calculation time in bypass network divided by time in no-bypass network.

Table 1. Number of saved WSSs and calculation time ratio in different topologies

Topology	Ratio of Bypass core $Core_{bypass}/Core_{total}$	Ratio of deployed WSSs $Num_{bypass}/Num_{no\_bypass}$	Calculation Time Ratio t_{bypass}/t_{no_bypass}
4-node	32/70	384/504	0.33
6-node	56/112	624/840	0.05
14-node	170/294	1604/2408	0.00125

5. Conclusion

We proposed a novel hardware-efficient SDM/WDM ROADM network. A RCWA algorithm was developed for this proposed ROADM network. The design used only low port-count WSSs and can be deployed in MCF-based networks with a large number of cores. By placing fiber bypass cores, the required number of key hardware WSSs is greatly reduced. The simulation indicated fiber bypassing cores reduce spectrum fragmentation. The design also reduces the complexity of computing the RCWA for different traffic requests.

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