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A Programmable ROADM System for SDM/WDM Networks

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Abstract: This paper proposed and evaluated a programmable ROADM system for MCF-based SDM/WDM networks. The proposed ROADM system employing both bypass connection and Route-and-Select wavelength switching enables adaptable virtual topology in optical networks by dynamically configuring bypass connection cores. The simulation results confirmed this ROADM system could provide acceptable performance with an around 10–20% reduction in the total cost including the number of ports and WSSs by comparing with a fully flexible SDM/WDM ROADM system, which cannot be implemented due to the required extremely high-port-count WSSs.

Keywords: optical network; multicore fibre; programmable ROADM; bypass connection

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1. Introduction

Optical networks, as the key Internet infrastructure in the information era, have served the explosive traffic growth successfully in the past decades. Innovations in digital signal processing (DSP) and high-order modulation signals have pushed the spectral efficiency in single-mode optical fibres (SMF) around 10 bits/s/Hz with a total capacity more than 40 Tbit/s per fibre [1]. However, the increased optical signal to noise ratio (OSNR) requirement for optical signals with advanced modulation formats reduces the transmission distance significantly. Mitigating optical nonlinearity helps improve the transmission distance but at the cost of a significant amount of computational power in the receiver. Furthermore, it has been becoming increasingly challenging to squeeze more capacity out of SMF-based wavelength-division multiplexing (WDM) technology.

Space-division multiplexing (SDM) can offer significantly higher capacity by bringing another dimension in optical networks [2]. Several technologies have been demonstrated to enable SDM in optical networks by using single-mode fibre bundles, multicore fibre (MCF), few-mode fibre, or orbital angular momentum multiplexing (OAM). Most of the efforts focus on link capacity improvement without considering the implementation of switching system in SDM networks. Among these technologies, few-mode fibre and OAM technologies present strong coupling between different spatial modes, prohibiting traditional WDM switching without cumbersome mode decoupling either by high-complex and power-hungry digital signal processing or advanced optical decoupling systems. Weakly-coupled MCFs provides a promising SDM solution with more matured fabrication and availability of relevant optical components [3,4]. Besides, MCF-based SDM networks provide full compatibility with current wide-deployed WDM systems. The latest research has demonstrated C+L band transmission of 19-core fibres for trans-oceanic communications [5]. In addition, a field-deployed MCF testbed has been installed in L'Aquila, Italy [6]. It is believed that MCF-based SDM networks provide a feasible solution for potential deployment in future optical networks.

Comparing the SMF, MCFs with a large number of cores incorporated with WDM technology could potentially increase the total capacities by 10 to 20 times. To manage the growing traffic in MCF-based SDM networks, switching strategies should be reconsidered to allow efficient network resource allocation and management. As the key switching element in optical networks, ROADM systems for SDM networks will also be at the heart of the switching solution. Traditional ROADM that conducts band switching in WDM-based optical networks poses a significant challenge for efficient scaling in MCF-based SDM networks [7]. Providing flexible spectrum switching for all fibre cores not only requires a large amount of cost; it may also introduce a significant amount of spectrum fragmentation [8]. Moreover, the implementation of ROADM with full-spectrum switching requires wavelength-selective switches (WSSs) with a considerable number of ports, which poses a limitation to further scaling up. Besides, spectrum flexibility in all fibre cores becomes unnecessary, providing the node degrees are far less than the core numbers. With a sufficient number of cores in one fibre, fibre cores should be treated as a type of switching entity compared to wavelength in the conventional WDW system. Therefore, the ROADM system for SDM-WDM networks providing both wavelength and fibre core switching granularity should be adopted to allow effective and efficient resource management.

In this paper, a programmable SDM/WDM ROADM system is proposed and evaluated for MCF-based SDM/WDM networks, with an extension of our previous work [9]. The proposed ROADM system is featured with programmable node synthesization and dynamic bypass-fibre-core configuration. The bypass core configuration provides direct core-to-core connections from the source node to the destination node without any intermediate wavelength switching, which allows adaptable virtual typology in optical networks for different network traffic. At each node, the total number of fibre cores that require wavelength switching is reduced significantly with the fibre core bypass configuration so that a small-scale traditional WDM ROADM can be setup to provide wavelength switching capability. The proposed SDM/WDM ROADM system minimizes the required scale of WDM-ROADM at each node and reduces the required number of WSSs. The network simulation is carried out to validate the proposed SDM/WDM ROADM system. The simulation results indicate that the proposed SDM/WDM ROADM system provides similar performance as that of a baseline ROADM design, which provides WDM switching in all fibre cores. It is worth mentioning that the baseline SDM/WDM ROADM system is a fully flexible ROADM that treats each core as a single mode fibre. This baseline ROADM system cannot be implemented practically as it requires extremely high-port-count WSSs that is far beyond the current technologies. To evaluate the system cost, we choose the required quantities of WSSs and the total power quantity to reflect the cost. Our proposed SDM/WDM ROADM system requires less number of WSSs with 10–20 % reduction, which depends on the fibre core number and network scale. Most importantly, the port number per WSS in our proposed system is in the practical range. In the simulation network, the maximum port number of WSSs in a fully flexible ROADM scenario is 41 (assuming three degrees in the node, bidirectional transmission in the MCFs and 13 cores in each MCF). Moreover, the maximum total port count of practical WSSs is limited around 30 [10]. In addition, the SDM/WDM ROADM design is fully compatible with the current SMF-based optical networks and allows smooth migration to multidimensional optical networks. With the increase in core number in MCFs, the ratio of the saved hardware can be further increased for better hardware utilization.

The remainder of this paper unfolds as follows. The latest development of the SDM ROADM system is reviewed in Section 2. Section 3 presents the design of the programmable SDM/WDM ROADM. Simulation results to validate the proposed ROADM architecture are presented and discussed in Sections 4 and 5 concludes the paper.

2. Relevant Works

MCF-based SDM networks are designed to integrate with the traditional WDM technologies by adding another dimension. Multicore fibre is a typical approach to introduce multiple spatial paths into a fibre from an SDM fibre point of view [3]. The transmission distance and maximum cores number in MCFs are significantly limited by both cross talk and attenuation. Several compensating methods have been proposed. For example, crosstalk-aware spectrum defragmentation [11] was proposed to remedy the issue of spectrum fragmentation in the SDM optical network, and the EDFAs in switching nodes can compensate for the attenuation. In SDM/WDM networks, fully flexible spectrum switching would be a straightforward solution to use network resources efficiently [7,12]. The fully flexible ROADM will require WSSs, the key switching device in ROADMs, to provide switching ports more than the total fibre core numbers in all ingress fibres. Sato [13] explained how to create very large-scale ROADM, but the requirement of WSS port number is very high. With the increased core numbers offered by MCFs, WSSs with such high port counts become unpractical. Therefore, traffic aggregation emerged as an option to reduce switching complexity. Besides, the work in [14] confirmed that traffic aggregation in space and spatial can reduce the routing complexity and save a considerable amount of switching components.

One approach for traffic aggregation is to provide network resources as superchannel signals either in space or spectral [15]. Regarding space superchannel signals, several cores can be grouped together to perform core switching as shown in [16]. However, such coarse granularity in multiple core levels prohibits deployment in optical networks, which require flexibility in the channel level according to the client interface speed. By combining with spectra and cores, spatial superchannels can be set up over multiple cores [12]. Compared with the traditional spectral superchannel signals, the spatial superchannel signals require specially designed WSSs for switching operations. By taking account of the recent standardisation of 400GbE, the spatial superchannels over multiple cores will not be foreseen for any commercial deployment in a few years.

Another approach to handle SDM switching is to offer both core switching and wavelength switching in a collaborative approach. In 2017, we proposed the concept of core bypassing in [17], to reduce the scale of the ROADM for better hardware utilization. The followed work evaluated the design at the network level and further reduced the required port count of the WSSs in the ROADM by cascading two-level WSSs [9]. Jinno [18] recognized core bypassing as a key enabling technology for the massive SDM era. However, the work separates the whole network into a pure SDM network and a traditional WDM network. It is believed that integrating SDM and WDM networks with fibre core bypassing will achieve better switching performance. Therefore, several key enabling technologies are listed here to take full advantage of combined fibre core bypassing and traditional WDM in SDM/WDM networks.

1. The bypass cores should be integrated with the WDM system that consists of the residual cores with traditional ROADM switching. The integration allows the bypass core to serve as a part of optical links. Without the integration, bypass cores will impact network flexibility, especially when core numbers are low. The integration requires connecting bypass cores back to the ROADM system at the end of the bypass cores.
2. The bypass cores should be reconfigurable at each node. The configurability of bypass cores enables adaptability of networks to accommodate different network traffic and support the migration from SMF-based networks to MCF-based optical networks. Firstly, variations of network traffic during the life cycle of optical links require fibre cores to be reconfigured as either bypass cores or WDM cores to optimize network performance. The programmable bypass core configuration will provide compatibility to the current wide-deployed SMF-based networks.
3. Intelligent node management is required to handle the bypass core reconfiguration. For example, intelligent node power management is needed to optimize the optical power in the node. More advanced power management can be developed to support the dynamic network reconfiguration [19].

3. Design of Programmable SDM/WDM ROADM System

The proposed programmable SDM/WDM ROADM system creates two integrated networks over the MCF-based fibre networks. Generally, each core in MCFs is treated as a typical SMF with fan-in and fan-out devices for each MCF. Inside of each MCF, some fibre cores are configured as bypass cores and the residual fibre cores are configured as WDM fibre links. The number of bypass cores and WDM cores can be reconfigured by a centralized controller. Therefore, these two integrated networks can be optimized according to the traffic request. Bypass core links, combined with WDM cores, generate programmable virtual topologies in the MCF-based optical networks.

Figure 1 shows the concept of programmable bypass core configuration based on an exemplary SDM network. Nodes are interconnected with 7-core MCF links. Fibre cores in different MCF links that are directly connected without any wavelength switching in the intermediate nodes are defined as bypass cores. As shown in Figure 1, a bypass link is set up between node A to node F by connecting bypass cores directly to node C and node D. Similarly, other bypass links can be established between different nodes. As an example, to further illustrate, several cores in node C are configured as bypass cores, including node A to node E and node B to node D. The residual cores as shown in node D are used to achieve the Route-and-Select ROADM, such as the bypass link from node B bypassed node C and connected to RS ROADM in node D.

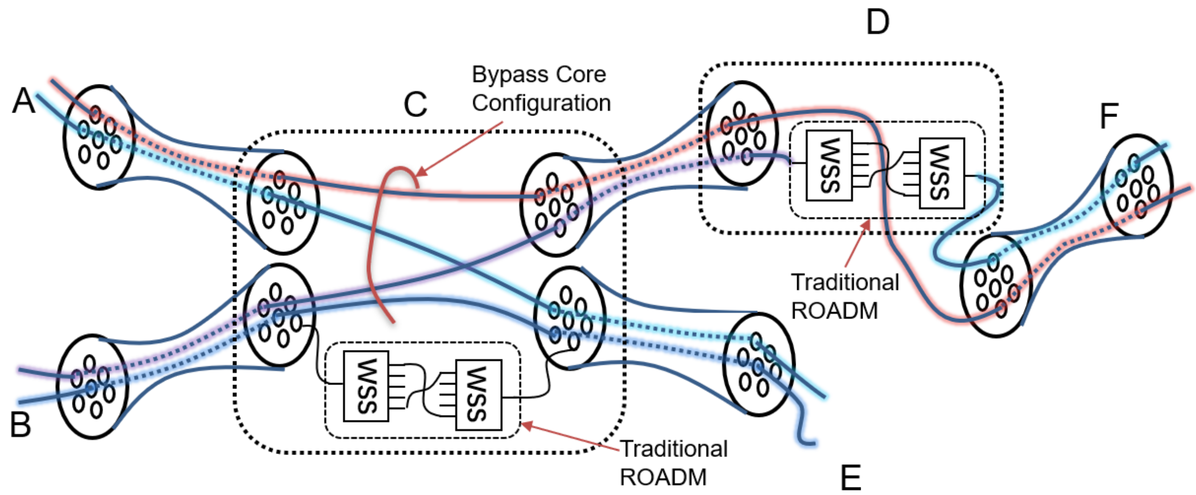

Figure 1. Concept of bypass-core configuration in an exemplary optical network with 7-core fibres. (**A**–**F**) are the node names. The color lines are the bypass links.

The following sections will illustrate the detailed node structure including bypass connection and traditional WDM fibre links, programmable virtual topology, and hardware requirements.

3.1. Programmable ROADM Node Structure with Bypass Connection

The programmable ROADM node with bypass connection is shown in Figure 2. The node includes bypass configuration through core switching and WDM routing/selection based on Route-and-Select (RS) ROADM. To achieve the required configuration, all fibre cores are connected to a large-port-count fibre switch (LPFS) based on the architecture-in-demand (AoD) concept [20]. The WSSs and other components that are used for RS ROADM are also connected to the fibre switch to synthesize the RS ROADM, shown in Figure 2 separately on the top and the bottom two parts. A fixed degree ROADM can be used to replace the synthesized ROADM by connecting the ROADM as one subsystem for RS ROADM and the other subsystem for bypass connection. Figure 2 shows a 2-degree node which is a proposed node structure with four 13-core MCFs. Inside the node, the 13 cores in MCFs are regarded as 13 single mode fibres. Every core of fibre-in and fibre-out is connected to the AoD-based optical fibre Switch. The LPSF can reconfigure connections between different ports to achieve different selections of the proposed ROADM. As shown in Figure 2, the bypass connection part is on the top part of the node, which can directly connect every two cores of fibre-in and fibre-out. The other components are used to synthesise Route-and-Select ROADM for the residual fibre cores. Route-and-Select ROADM in the programmable node deploys 2-layer WSSs in the Figure 2. The first-layer WSSs demultiplex channels from every core of the input MCFs to select the destination cores in that node. WSSs in the second layer is used for multiplexing channels from different cores in the first-layer WSSs to the destination MCFs. The implementation of ROADM requires low port-count WSSs, which can bring the benefits of reducing hardware devices and saving the cost. Several functions are attached in the traditional Route ROADM part, it includes EDFAs, Couplers, Rx/Tx, and Functions/Subsytems. Based on the AoD concept, the RS ROADM can be reconfigured in terms of input fibre cores and the corresponding add/drop configurations.

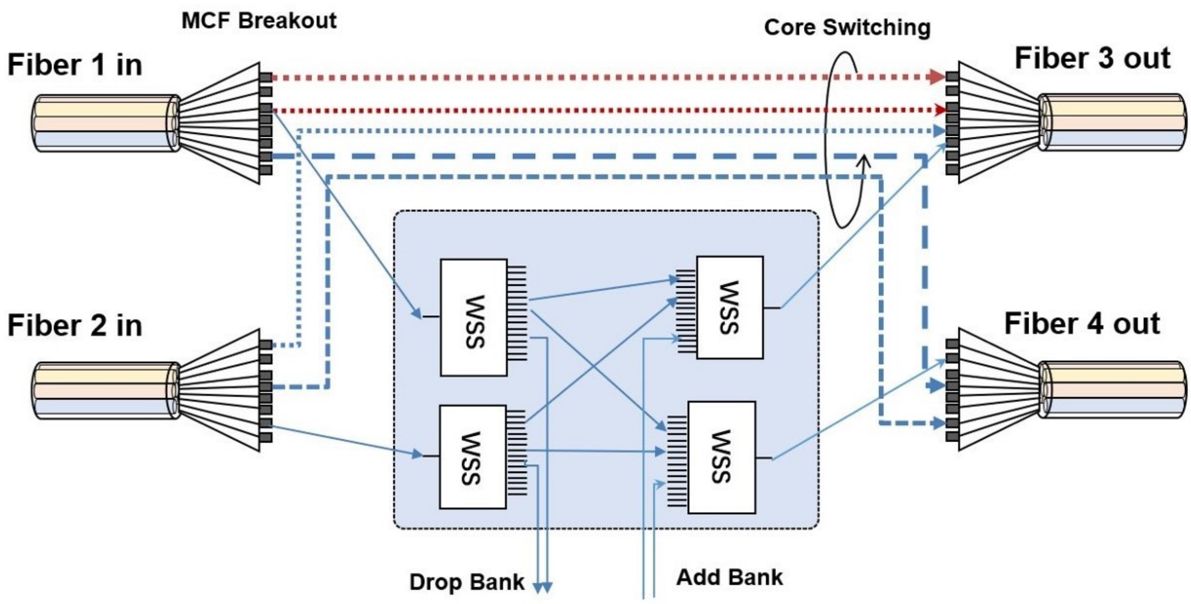

Figure 2. Detailed node structure including bypass connection and Route-and-Select ROADM.

3.2. Programmable Virtual topology

To demonstrate the promotion of optical network performance of core switch, 6-node topology optical network which is shown in Figure 3 has been used for analysis. There are four three-degree nodes and two two-degree nodes with 8 multicore fibres used in the whole network. The number of cores in every MCF was assumed as 13 and the fibre-core switch can select different numbers which can be controlled by a centralized controller. Due to there being only six nodes in this optical network, the pairs of transmitting and receiving nodes are including three types: neighbor pairs, one-hop pairs, and two-hop pairs. As mentioned above, the programmable ROADM can dynamically distribute the number of bypass connection cores and WDM RS cores, which can be seen as different virtual topologies. Three different topologies with different bypass connections are used to illustrate the virtual topology. The difference between these topologies is the number of bypass links and where to add them. One-hop core switch was proposed to explain the nondirect two-node whose shortest physical path needs two MCFs and goes through one internode, such as node 0 and node 2. Furthermore, two-hop core switch can be seen as the nondirect two-node whose shortest physical path needs three MCFs and goes through two internodes. Due to there being only six nodes in the proposed optical network, the maximum hop is two.

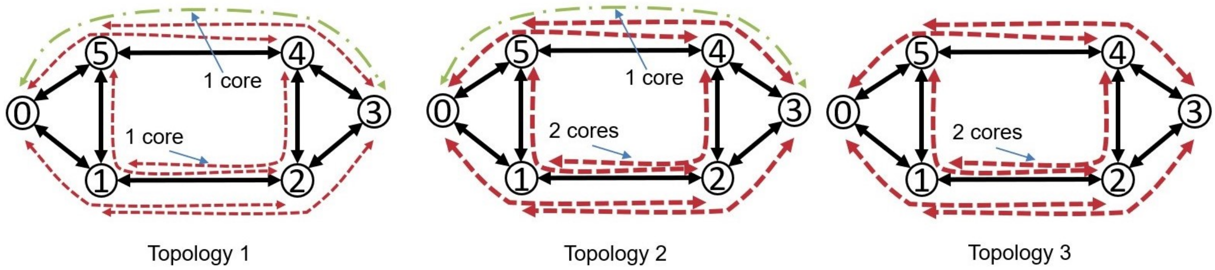

Figure 3. Three different Virtual topologies, named topology 1, 2, 3. The number of one-hop and two-hop bypass connection cores is separately for 1:1, 2:1, 2:0.

In Figure 3, the three different virtual topologies come from using different cores to set up the bypass connection. Topology 1 shows that one core is used for one-hop pair nodes with one core for two-hop pair node bypass connection, while topology 2 presents two cores that are used for one-hop pair-nodes and one core is used for two-hop pair nodes. As for topology 3, only two cores are used for one-hop pair nodes bypass connection.

3.3. Hardware Requirements in Different Topology

In ROADM systems, switching devices, such as WSSs, contribute to most parts of the cost. The cost depends on the number of WSSs as well as the total number of port count in WSSs. Based on the 6-node topology, the total system cost is estimated by calculating the required number and the total port count of WSSs. With the bypass connection, the required WSSs and total WSSs ports are reduced dramatically. To roughly get the hardware saving, the WSS number and total port number in different topologies should be calculated as shown in Table 1. Firstly, the number of cores used for bypass connection in three different virtual topologies has been calculated. After that, the WSS number and the total ports number are presented. As shown in Table 1, comparing with the fully flexible/basic topology, topology 1 could save 7.7% WSSs while the total port number saves 12.6%. Meanwhile, topology 2 and 3 save a little more than topology 1 which has been given the exact percentage in the table. Furthermore, as shown in the last column, the maximum port number in WSSs was calculated in each topology. Comparing with the other three proposed topologies, the fully flexible topology needs an unpractical large-scale WSSs. As mentioned above, the maximum total port count of practical WSSs is limited around 30 so that under the existing conditions, the fully flexible topology cannot be achieved. Besides, the cost of WSSs will be rapidly increased with the port number increasing. In practical networks with more nodes and large core number MCFs, more hardware can be saved based on the proposed SDM/WDM ROADM system.

Table 1. Comparison of hardware request between four topologies.

Topology	Bypass Core/WDM Core	WSS Number	Total Ports Number	Maximum Port Number
Fully flexible topo	0/104	416	10296	41
Topo 1	15/89	38−7.7%	9000−12.6%	33
Topo 2	27/77	360−13.5%	8028−22.1%	25
Topo 3	24/80	368−11.5%	8352−18.9%	25

4. Simulation Results

Simulation analysis was used to demonstrate that an optimal virtual topology with bypass connection can be found to replace the fully flexible topology in optical network and saving a lot of hardware devices. To assess the optical network performance, Blocking Probability is used to evaluate the performance, including bandwidth blocking probability and traffic blocking probability. Both blocking probabilities are simulated and analyzed. Bypass connection would reduce the wavelength switch in the node so that the bandwidth continuity request will be reduced. To begin with this simulation, the assumed configuration should be set. The number of cores in one multi-core fibre (MCF) is 13 and the supposed topology is a typical 6-node core optical network as mentioned above. Assuming the whole bandwidth in one core is 2 THz and every slot is 12.5 GHz, there are 160 slots in one core based on every traffic can be randomly generated from 12.5 GHz, 25 GHz, 37.5 GHz, 50 GHz, 100 GHz, and 200 GHz corresponding with 1, 2, 3, 4, 8, and 16 slots. In addition, bidirection has been considered in this simulation, and it appears that the 2 THz bandwidth is only for the unidirection in one core and the 4 THz assumed used to present bidirection bandwidth. Meanwhile, the cross talk and attenuation could not be considered as mentioned above there are several methods to compensate them. Furthermore, the distance between every two nodes is assumed 40 km so that EDFAs should not be used in the whole optical network.

To evaluate the performance of the proposed network with programmable ROADM combined fibre/core switch with WDM routing/selection node, the traffic blocking probability and bandwidth blocking probability of the same traffic request based on different topology should be given. The blocking probability can be seen as the ratio of the amount of rejected traffic and traffic bandwidth which cannot be transmitted network to the total amount of traffic and the traffic bandwidth in the whole optical network.

4.1. Traffic and Bandwidth Blocking Probability Results in 6-Node Topology

In this section, the traffic request of 6-node core optical network is the same and randomly generated with the ratios of direct-link pair nodes, one-hop pair nodes, and two-hop pair nodes are 1:1:1, 3:2:1, and 6:3:2; three scenarios are separately named traffic request 1, 2, and 3. Regarding every traffic request, four topologies can be simulated to deal with the data. Four topologies are including the basic fully flexible physical 6-node optical network topology and three different virtual topologies with bypass connection, including topology 1, topology 2, and topology 3 as mentioned above.

In Figure 4a,d, they show that the traffic blocking probability and bandwidth blocking probability of four topologies were based on traffic requests 1. The unit of the horizontal axis is Erlang, which is a unit of traffic load and equals the traffic arrival rate times traffic duration. Here we assume all traffic arrives at the same second and only lasts for 1 s [21]. Traffic request 1, which can be seen as a random traffic request, means that the probability of different traffic requests including direct-link pair-nodes, one-hop pair-nodes, and two-hop pair-nodes is equal or 1:1:1. It is obvious that the basic topology is the best one to deal with the data, but the other three topologies appear acceptable performance. Focusing on traffic blocking probability in Figure 4a, virtual topology 2 shows similar performance as the other two topologies while saving much more cost than others so that practically this cost-saving and similar performance topology can be used. As for Figure 4b,e, they show the simulation data on blocking probability based on four different topologies with traffic request 2, as well as Figure 4c,f show the results of four different topologies dealing with traffic request 3. Similar performance with less cost is what all researchers try to get, which can demonstrate that the bypass connection added in the programmable ROADM can improve the hardware efficiency and save hardware cost. To explain this benefit in detail, the wavelength fragmentation which can be reduced by adding the fibre-core switch should be considered as the reason. To illustrate the wavelength fragmentation, the RS ROADM part should be stated. An accepted traffic through RS WDM part needs allocating the same bandwidth in every passed core of MCFs which called bandwidth continuity so that fibre-core switch path does not have this limitation, which can reduce the wavelength fragmentation. As bandwidth blocking probability shown in Figure 4, it shows much better performance than traffic blocking probability, especially in traffic request 2 and 3. Topology 1 and 2 have almost the same bandwidth blocking probability as fully flexible topology in Figure 4e,f.

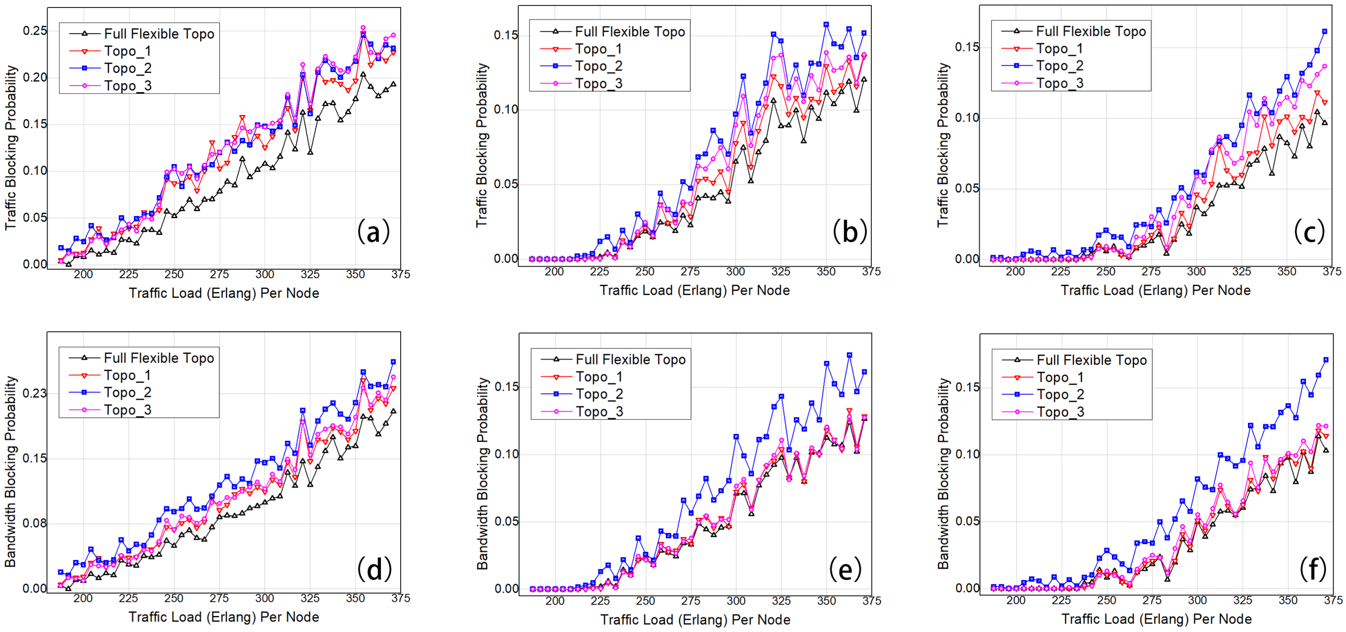

Figure 4. Traffic blocking probabilities and bandwidth blocking probabilities. The traffic request ratio between Neighbor pair-nodes:one-hop pair-nodes:two-hop pair-nodes is 1:1:1, 3:2:1, 6:3:2, respectively shown in (**a**,**d**), (**b**,**e**), (**c**,**f**) named traffic request 1, 2, 3. Three bypass connection topologies are corresponding with Figure 3 Topology 1, 2, 3.

4.2. Traffic and Bandwidth Blocking Probability Results in NSF Topology

The proposed SDM/WDM ROADM system is evaluated in the National Science Foundation (NSF) network. In the NSF network, 7-core MCFs are used for the simulation. As shown in Figure 5a, bypass links are set up based on numbers of neighbor nodes, to ensure direct connections are available between two neighbor nodes of the current node.

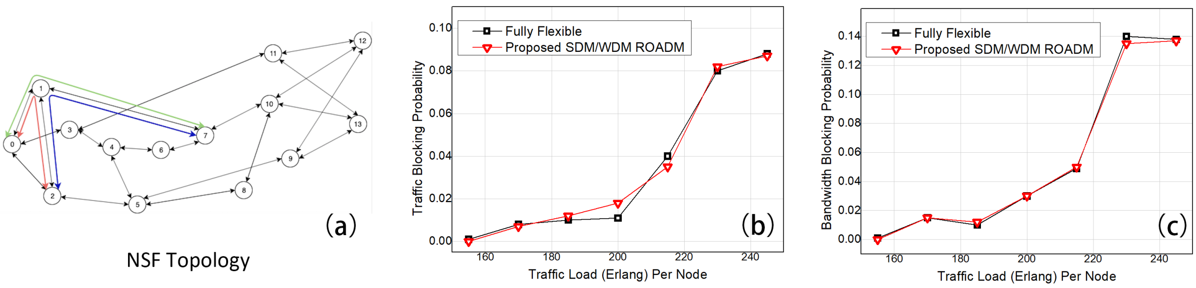

Figure 5. (**a**) NSF topology. (**b**) Traffic and (**c**) Bandwidth blocking probabilities in NSF topology.

Random traffic is used for the simulation. Heuristic routing wavelength/core assignment (RWCA) algorithm is used to evaluate the blocking probability.

Figure 5 shows the NSF topology and the results of blocking probability in NSF topology network by comparing between fully-flexible setup and the proposed setup with bypass configurations. In both traffic and bandwidth blocking probability as shown in Figure 5b,c, the proposed solution shows similar performance as the fully flexible setup.

The simulation results in Figures 4 and 5 suggest the proposed SDM/WDM ROADM system has an acceptable performance by comparing with the fully flexible topology in terms of traffic and bandwidth blocking probabilities. In addition, the proposed system reduces the total cost by roughly calculating the required quantity of WSSs and the total port number.

5. Conclusions

In this paper, a programmable SDM/WDM ROADM system is proposed for MCF-based multidimensional optical networks. The ROADM system introduces reconfigurable fibre-core bypass connections to generate different virtual topologies based on network traffic. The design reduced the required number and port count by using spectrum switching devices significantly by comparing with traditional ROADMs. The design takes account of the vast resources provided by the MCFs and provides a practical solution for wavelength switching. Our simulation analysis shows that the proposed SDM/WDM ROADM system provides acceptable performance as the fully flexible ROADM that treats all fibre cores as individual SMFs while saving considerable cost. The SDM/WDM ROADM design also allows dynamic reconfiguration based on network traffic and provides full compatibility with the current SMF-based networks. It is believed that the proposed SDM/WDM ROADM system provides a potential solution for future multidimensional optical networks.

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