Latency-Crosstalk-Aware Resource Allocation Based on Multi-granular Node Deployment in SDM-EONs

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***Abstract*—In SDM-EONs, we first present a multi-granular node deployment scheme, and then implement a latency-crosstalk-aware resource allocation algorithm based on the multi-granular node to reduce transmission latency and crosstalk.**

Keywords—SDM-EONs, multi-granular node deployment scheme, latency-crosstalk-aware resource allocation.

I. Introduction

The combination of space division multiplexing (SDM) technology and elastic optical networks (EONs) has gained significant attention due to its potential for increasing the capacity of optical transmission systems [1-2]. In the realm of SDM optical networking, the development of multi-core fibers (MCFs) that contain several single-mode cores in the same fiber has emerged as the most extensively researched and promising advancement [3].

MCF-based SDM-EONs networks can offer obviously higher capacity by bringing space dimension in optical networks. However, this poses the challenge of high complexity and high cost of optical cross-connects (OXCs), which are hard to implement. To cope with this challenge, the most potential compensating method in the latest research is to offer both fine spectrum granularity switching and coarse fiber-core granularity switching in a collaborative way [4-7]. In [4-5], the authors proposed a hierarchical optical switching node with spacial cross-connect and wavelength cross-connect. In [6-7], the authors proposed a hardware-efficient optical switching node with fiber-core bypassing. Whereas, their proposed corresponding routing/core/spectrum assignment(RCSA) algorithms based on designed node architecture were challenging to guarantee the transmission quality of traffics since crosstalk was not considered [5][7]. Meanwhile, authors in [4-7] need help determining how many designed nodes to implement and where to deploy them at a network level.

In this paper, we propose a multi-granular node deployment scheme in SDM-EONs and then realize a latency-crosstalk-aware resource allocation algorithm based on multi-granular nodes. The specific work is as follows. For the multi-granular node that offers both fine spectral grooming by wavelength selective switches (WSSs) and coarse core-level switching by core-to-core bypassing connections, we first predesign the priority of cores in fibers, in order to establish non-adjacent core-to-core bypassing connections. WSSs take time to be switched and delay the lightpath setup time [8], while non-adjacent core-to-core bypassing connections directly bypass WSSs to realize the fast transmission channels that can carry a large number of traffics. However, the existence of core-to-core bypassing connections makes the switching flexibility of multi-granular nodes lower than that of route-and-select (RS) architecture nodes [9]. Therefore, in the case of sufficient hardware resources, mixing RS nodes and multi-granular nodes to form a network can enhance network performance. Thus, for SDM-EONs with hybrid node types, we propose a multi-granular node deployment scheme that can decide the location and the number of designed multi-granular nodes to deploy according to the number of available WSSs, traffic patterns, and network topologies. Furthermore, we propose a latency-crosstalk-aware RCSA algorithm based on multi-granular nodes. The algorithm selects a core combination containing more core-to-core bypassing connections for traffics to reduce transmission latency. If there are core combinations with the same number of core-to-core bypassing connections, a secondary core selection is used for traffics to choose the core combination with more spectral resource and less crosstalk. For the selected core combination, the best available spectrum block is chosen to carry traffics in joint consideration of crosstalk and spectrum fragmentation.

For dynamically arriving traffic requests, our numerical simulations consist of two parts. Firstly, given the hardware resource budget, we verify that the traffic blocking probability of the proposed multi-granular node deployment scheme is lower than that of the baseline under the condition of using the same RCSA algorithm. Secondly, we confirm that the proposed RCSA algorithm can reduce the transmission latency and crosstalk than that of baseline in the case of a network with the same node distribution.

II. Node Architecture And Node Deployment Scheme

A. Node Architecture

The right side of Fig. 1 shows the architecture of the multi-granular node, which can realize coarse granularity grooming

This work has been supported in part by NSFC project (62201088, 62271075, 62122015), Fund of SKL of IPOC (BUPT) (IPOC2021ZT04), and China mobile research institute.

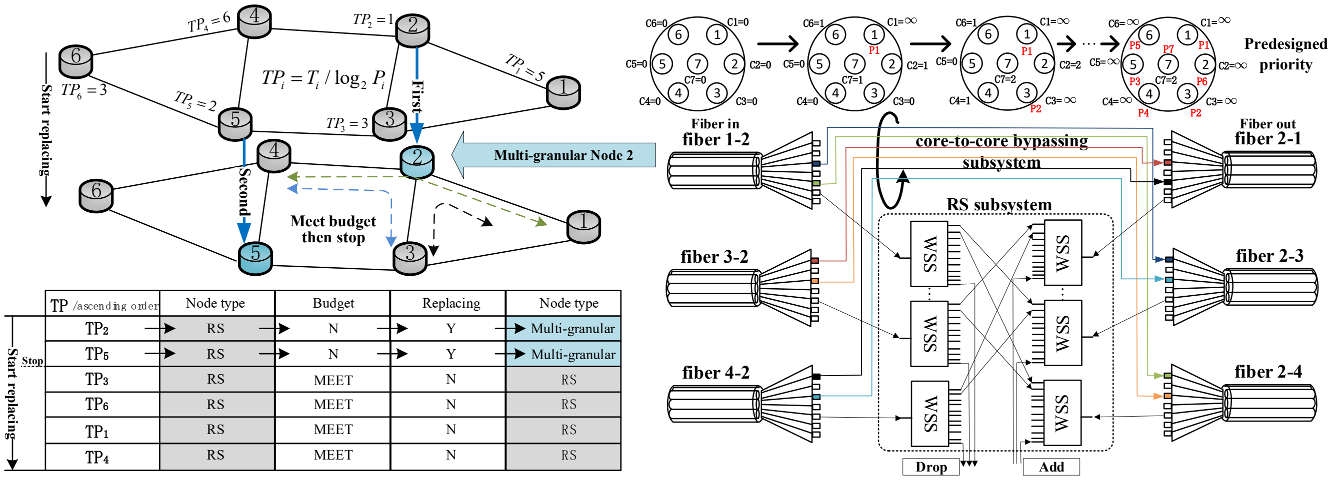


Fig. 1. Multi-granular node deployment scheme and node architecture.

up to a fiber-core level by core-to-core bypassing subsystem and spectral grooming by RS subsystem. Here, the core-to-core bypassing subsystem realizes only one core-to-core direct connection between every two adjacent fibers in the same color without any spectral grooming to form core-to-core bypassing connections, which can only bypass a maximum of one node. One node length of core-to-core bypassing connections can let more traffics bypass WSSs to achieve low transmission latency. When building the network, we set up the core-to-core bypassing connections according to the predesigned priority order of fiber cores. The purpose is to make bypassing connections as non-adjacent as possible and allow more traffics to pass through the bypassing connections while reducing crosstalk. The priority-setting steps are as follows. Firstly, set the cost function value C_i of each fiber core to 0. Secondly, randomly select a core with the smallest number of adjacent cores as the first priority P_1 and set its cost function to ∞, then add 1 to the cost function value of its adjacent cores. Thirdly, select the core with the lowest cost function and the closest distance to the core of the previous priority as the next priority. Finally, repeat the above steps until all cores are marked with priority. The RS subsystem follows the principle of conventional RS architecture. In the RS subsystem, the first-layer WSSs demultiplex channels from cores of the fiber-in to select the destination cores of fiber-out or drop in that node. WSSs in the second layer are applied for multiplexing channels from different cores in the first-layer WSSs and adding upload in that node to the destination cores of fiber-out.

B. *Node Deployment Scheme*

The left side of Fig. 1 shows the basic process of the node deployment scheme. We assume all nodes in the network are RS architecture nodes at the beginning and continuously replacing RS nodes with designed multi-granular nodes to meet the budget reflected in the available number of WSSs. Replacing a few large-ports RS nodes with multi-granular nodes may have the same ability to reduce the number of WSSs as replacing many small-ports RS nodes with multi-granular nodes. Due to the existence of core-to-core bypassing connections, multi-granular nodes sacrifice some switching flexibility, which can be seen as a reason for the more RS nodes being replaced by multi-granular nodes, the more network performance degradation will be. Hence, nodes with larger port counts and a greater number of WSSs are our top replacement targets. However, nodes with high ports and a high number of WSSs usually have more passing traffics, which means replacing these nodes will also degrade network performance.

So, considering traffics and the number of WSSs ports in nodes, We first generate static requests based on a given traffic pattern that includes the distribution of source/destination nodes and the number of spectrum slots required for each request. Then use the proposed RCSA algorithm introduced in the next part for resource allocation and record the number of passing traffics per node. The replacement order of nodes is determined by TP_i, defined as Eq. (1)

$$TP_i = T_i / \log_2 P_i \tag{1}$$

Where T_i is the number of passing traffics in node i, and P_i denotes the sum of the port count of all WSSs in node i. We replace RS nodes with multi-granular nodes in the order of ascending TP value until the budget is met.

III. PROPOSED RCSA ALGORITHM

As shown in Fig.2, our proposed RCSA algorithm chooses a shorter path and more bypassing connections for traffics because WSSs take time to be switched and delay the lightpath setup time [8].

Suppose there are multiple core combinations after selection. In that case, we make a secondary core selection by choosing the core combination with more $RFCA$ costs to reduce crosstalk and spectrum fragmentation. $RFCA$ is defined by (2).

$$\begin{cases} RFCA = \dfrac{\sum_{q=1}^{|G_i|} \alpha \times \bar{R}FA + \beta \times \bar{C}A}{|G_i|} \\ RFA = \dfrac{|B_i^q|}{|FS^q| - b + 1} \\ CA = 1 - \dfrac{\sum_{j=1}^{|B_i^q|} \sum_{k=1}^{|adjacent|} sum\,(FS_{S_{ji}^{q}}^{qk} = 1)}{|B_i^q| \times b \times |adjacent|} \end{cases} \tag{2}$$

Where $|G_i|$ is the number of cores for the i_th core combination. b denotes spectrum slots required for the arriving traffic request. And an available spectrum block required for the arriving traffic holds b spectrum slots. $|B_i^q|$ denotes the number of available spectrum blocks on the q_th core of the i_th core combination. $|FS^q|$ is the total number

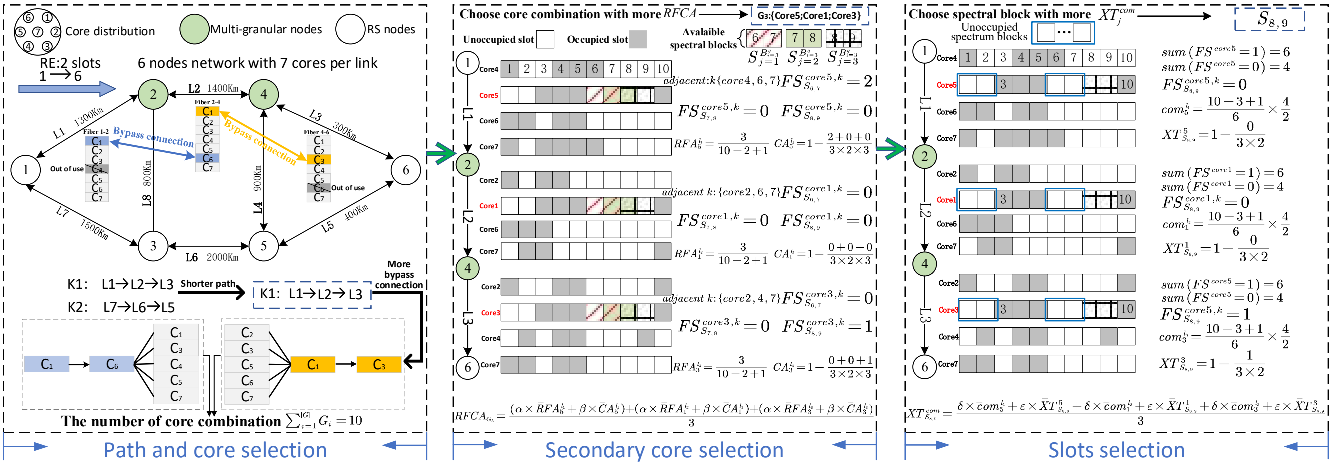


Fig. 2. RSCA algorithm process.

of slots on the q_th core of the i_th core combination. $S_j^{B_i^q}$ represents j_th available spectrum block in B_i^q. $|adjacent|$ denotes the number of adjacent cores of the q_th core. $FS_{S_j^{B_i^q}}^{qk}$ represents the spectrum slots on the k_th core that is adjacent to the q_th core, and these spectrum slots are in the same position as the spectrum slots in $S_j^{B_i^q}$. $FS = 1$ indicates that the spectrum slot is occupied. The RFA value is proportional to the number of available spectrum resources on the q_th core and the CA value is inversely proportional to the crosstalk of the available spectrum resources on the q_th fiber core. Both $\bar{R}F\bar{A}$ and $\bar{C}\bar{A}$ are normalized results. α and β are adjustable factors.

Then select the available spectrum blocks with higher XT_j^{com} costs to decrease crosstalk and spectrum fragmentation. XT_j^{com} is defined by (3).

$$\begin{cases} XT_j^{com} = \dfrac{\sum_{q=1}^{|C_i|} \delta \times \bar{X}\bar{T}_j + \varepsilon \times \bar{c}om}{|G_i|} \\ com = \dfrac{\max(FS^q=1) - \min(FS^q=1)+1}{sum\,(FS^q=1)} \times \dfrac{sum\,(FS^q=0)}{series\,(FS^q=0)} \\ XT_j = 1 - \dfrac{\sum_{k=1}^{|adjacent|} sum\,(FS_{S_j^{B_i^q}}^{qk}=1)}{b \times |adjacent|} \end{cases} \tag{3}$$

The calculation of com is performed after the arriving traffic request occupies the j_th spectrum block on q_th core. $\max(FS^q = 1)$ and $\min(FS^q = 1)$ represent the maximum and minimum position number of occupied spectrum slots on the q_th core. $sum(FS^q = 1)$ and $sum(FS^q = 0)$ denotes the number of occupied and unoccupied spectrum slots on the q_th cores. $series(FS^q = 0)$ denotes the number of consecutive unoccupied spectrum blocks. The com value is inversely proportional to the fragmentation of q_th core and the XT_j value is inversely proportional to the crosstalk of the j_th spectrum block on q_th core. Both $\bar{X}\bar{T}_j$ and $\bar{c}om$ are normalized results. δ and ε are adjustable factors.

IV. Numerical Simulation Results

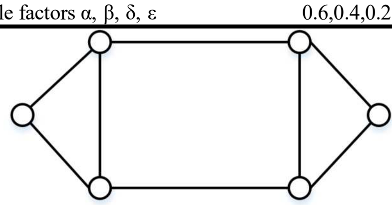
The simulations include two topologies of NSFNet[10] and n6s8[11], as shown in Fig.3. Parameter settings are shown in Table I. We assumed that the traffic pattern is uniform, which means requests' source/destination nodes are randomly selected among any node in the network, and the required spectrum slots of each traffic request are randomly generated between 2 and 6 slots. The arrival of traffics follows the Poisson process, and the departure time interval of traffics follows a negative exponential distribution.

To evaluate the performance of the proposed node deployment scheme, we conduct simulations in two topologies of n6s8 and NSFNet. The WSSs budget ranges from the required number of WSSs when all nodes are multi-granular to the required number of WSSs when all nodes are RS, which is 168 to 224 in n6s8 and 412 to 588 in NSFNet. A baseline nodes deployment scheme that randomly selects a RS node to replace is used to identify the improvement of the proposed node deployment scheme. Fig. 4(a) and Fig.4(b) show that the proposed node deployment scheme has lower traffic blocking probability than the baseline nodes deployment scheme in different network topologies, especially in few-node networks. Because the proposal comprehensively considers traffic patterns and nodes' physical structure characteristics. Such an approach can minimize the negative impact on network performance when deploying multi-granular nodes.

To evaluate the performance of the proposed RCSA strategy, we conduct simulations in NSFNet with a WSSs budget of 412 and 500. It is worth mentioning that before resource allocation, we use the proposed node deployment scheme to deploy multi-granular nodes and meet the budget.

TABLE I. PARAMETER SETTINGS

Parameter Name	Values
Number of cores per fiber	7
Number of spectrum slots per core	100(12.5GHz per slot)
Number of guard band slots	2
Modulation format	BPSK
Coupling coefficient	3.16×10^{-5}
Bend radius	4×10^{6}
Propagation constant	55mm
Core pitch	45μm
Crosstalk threshold	-32dB[12]
Adjustable factors α, β, δ, ε	0.6,0.4,0.2,0.8



(a) n6s8

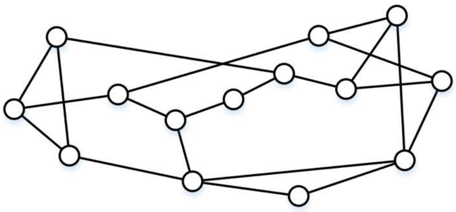
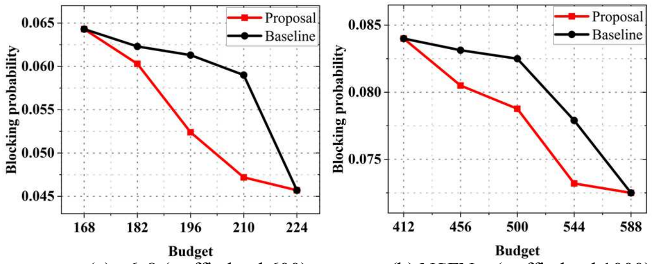
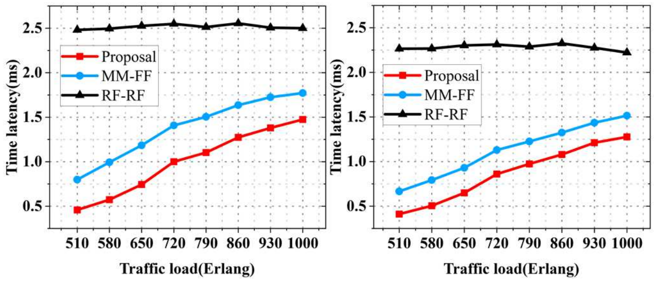


Fig. 3. Simulation topologies.



(a) n6s8 (traffic load 600) (b) NSFNet (traffic load 1000)

Fig. 4. Node deployment scheme in two topologies.



(a) WSSs budget of 412 (b) WSSs budget of 500

Fig. 5. Transmission latency.

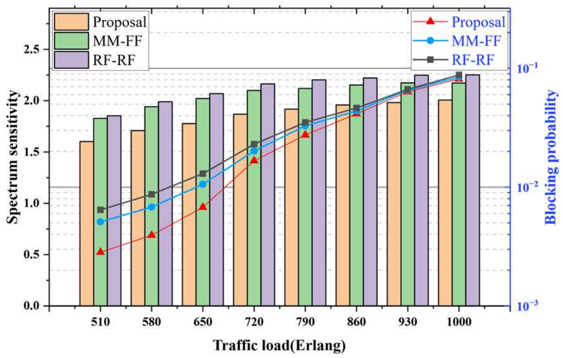


Fig. 6. Blocking probability and spectrum sensitivity with the WSSs budget of 412.

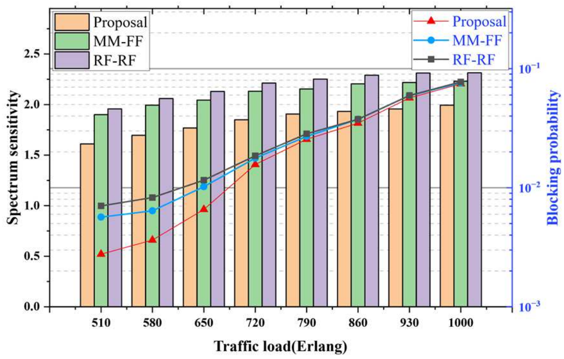


Fig. 7. Blocking probability and spectrum sensitivity with the WSSs budget of 500.

In this paper, the algorithm[7] that selects cores with more bypass connections and more spectrum resources in the shortest path, and places available spectrum blocks occupied by traffics with first-fit strategy, is used as a baseline(MM-FF). And the algorithm that randomly selects cores and available spectrum blocks in the shortest path for traffics, is used as an another baseline(RF-RF).

It can be seen from Fig.5 (a) and (b) that the proposed RSCA algorithm effectively decreases transmission latency in networks with different node distributions. Here, latency calculations are based on the assumption that 5 ms will be wasted when traffics pass through the optical switching devices(WSSs), and 5 ms will be saved by bypassing the optical switching devices instead. The reason is that in the MM-FF algorithm, the adjacent distribution of the core-to-core bypassing connections and the lack of consideration of crosstalk during resource allocation make the core-to-core bypassing connections unable to carry a large number of traffics. As to the RF-RF algorithm, it does not consider the existence of the core-to-core bypassing connections, resulting in high transmission latency.

From Fig. 6 and Fig. 7, it can be seen that in networks with different node distributions, the proposed RSCA algorithm has lower traffic blocking probability and lower spectrum sensitivity than the two baseline algorithms. Here, the spectrum sensitivity is defined as the number of spectrum slots in a request affected by crosstalk divided by the number of spectrum slots occupied by a request, which is proportional to the crosstalk value. This is because the two baseline algorithms do not consider crosstalk when selecting cores and available spectrum blocks for traffics.

V. CONCLUSION

By establishing non-adjacent core-to-core bypassing connections in multi-granular nodes, we realized fast transmission channels that can carry a large number of traffics. According to the given hardware resources, we used the proposed node deployment scheme to deploy multi-granular nodes, which achieved the reduction of traffic blocking probability. And then we used the proposed RSCA algorithm based on the multi-granular node to allocate traffics. Simulation results found that such an approach improved transmission quality and reduced transmission latency.

ACKNOWLEDGMENT

This work has been supported in part by NSFC project (62201088, 62271075, 62122015), Fund of SKL of IPOC (BUPT) (IPOC2021ZT04), and China mobile research institute.

REFERENCES

[1] Yang H, Yao Q, Bao B, et al. Multi-associated parameters aggregation-based routing and resources allocation in multi-core elastic optical networks[J]. IEEE/ACM Transactions on Networking, 2022, 30(5): 2145-2157.

[2] Yao Q, Yang H, Bao B, et al. Core and spectrum allocation based on association rules mining in spectrally and spatially elastic optical networks[J]. IEEE Transactions on Communications, 2021, 69(8): 5299-5311.

[3] Wang Y, Mori Y, Hasegawa H. Resource Assignment based on Core-State Value Evaluation to Handle Crosstalk and Spectrum Fragments in SDM Elastic Optical Networks[C]//2020 Opto-Electronics and Communications Conference (OECC). IEEE, 2020: 1-3.

[4] Ishikawa T, Kodama T, Jinno M. Hierarchical SDM/WDM ROADM with any core access for spatial channel ring network[C]//2020 Opto-Electronics and Communications Conference (OECC). IEEE, 2020: 1-3.

[5] Jinno M, Asano Y, Azuma Y, et al. Technoeconomic analysis of spatial channel networks (SCNs): benefits from spatial bypass and spectral grooming[J]. Journal of Optical Communications and Networking, 2021, 13(2): A124-A134.

[6] Li Y, Yan S, Hua N, et al. Hardware Programmable SDM/WDM ROADM[C]//Optical Fiber Communication Conference. Optica Publishing Group, 2017: Th2A. 21.

[7] Liu L, Yan S, Maguire G Q, et al. Hardware-efficient ROADM design with fiber-core bypassing for WDM/SDM networks[C]//2020 Optical Fiber Communications Conference and Exhibition (OFC). IEEE, 2020: 1-3.

[8] Shakeri A, Wang X, Razo M, et al. Modeling the effect of wavelength selective switch latency on optical flow switching performance[J]. Journal of Optical Communications and Networking, 2018, 10(12): 924-935.

[9] Wang J, Chen S, Wu Q, et al. Solving the Static Resource-Allocation Problem in SDM-EONs via a Node-Type ILP Model[J]. Sensors, 2022, 22(24): 9710.

[10] Yao Q, Yang H, Bao B, et al. Snr re-verification-based routing, band, modulation, and spectrum assignment in hybrid c-c+ l optical networks[J]. Journal of Lightwave Technology, 2022, 40(11): 3456-3469.

[11] Ding S, Jiang Z, Bose S K, et al. Cost-minimized virtual elastic optical network provisioning with guaranteed QoS[J]. China Communications, 2021, 18(9): 148-166.

[12] Lei Y, Chen Q, Jiang Y, et al. Routing, Core, and Spectrum Allocation with Strict Crosstalk-Aware in Spatial Division Multiplexing Elastic Optical Networks[C]//Asia Communications and Photonics Conference. Optica Publishing Group, 2019: M4A. 209