PERFORMANCE OF DYNAMIC COARSE GRANULAR ROUTING-BASED ELASTIC OPTICAL NETWORKS

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Abstract: In this paper, we study elastic optical networks utilizing multi-granular routing technique for provisioning dynamic lightpath services. We have developed a cost-effective coarse granular routing-based node architecture incorporating with an efficient dynamic control algorithm for coarse granular routing-based elastic optical network. The developed algorithm is capable of dealing effectively with the coarse granular routing restriction of the developed node architecture in the network to dynamically provide elastic lightpath services. Performance of our developed network solution is extensively and comprehensively investigated by using numerical simulations. It implies that our proposed network solution can be applied effectively to offer a persistent performance in different traffic load conditions. The obtained results also demonstrate that a trade-off exists between the network performance and the hardware reduction, through an intra-node parameter (called group routing granularity) and hence, selecting a proper group routing granularity is crucial in network design and optimization.

Keywords: Elastic optical network, spectrum selective switch, routing and spectrum assignment, network control algorithm.

I. INTRODUCTION

Recently, Internet traffic is growing explosively and endlessly due to the developments of new emerging high-performance and bandwidth-consuming services including real time IoT, 4k/ultra-HD video, e-Science, peer-to-peer applications and cloud or grid computing [1, 2]. In order to cope with such the Internet traffic explosion while still ensuring mobility and flexibility, the development of cost-effective and heterogeneous bandwidth-abundant flexible optical backbone networks are indispensable [3-7]. Nowadays, thank to advances in optical modulation and switching technologies, elastic optical networks (EONs) have been developed and practically realized as one of the most promising technologies for future Internet backbone networks. Elastic optical networks are capable of provisioning dynamic bandwidth-flexible end-to-end connection and offer service providers the flexibility to customize their infrastructure dynamically according to application requirements [8, 9]. Moreover, the introduction of elasticity and adaption into the optical domain enables spectrum- and energy-efficient transport of optical signals through bitrate-adaptive spectrum resource allocation using flexible grids and distance-adaptive spectrum allocation with modulation format optimization [10-13]. Key technologies of elastic optical networks are bandwidth-variable selective switches that can multiplex/demultiplex and selectively switch variable spectral bands, and bandwidth-variable/multi-flow transponders that can scale up to terahertz bandwidth [4, 10]. Different from that in conventional WDM networks, routing and spectrum allocation in elastic optical networks includes three sub-problems, namely routing, modulation and spectrum assignment (RMSA/RSA). However, there are still many technological issues and challenges that need to be overcome to realize and commercialize elastic optical networks due to the requirements of more complicated optical routing architectures and more sophisticated network planning and light-path provisioning schemes [14, 15].

On the other hand, most existing ROADM/OXC systems are developed with spectrum selective switches (SSSs), and to create a larger scale OXC, higher port count SSSs are required; some of the SSS ports also can be used to implement the optical add/drop function. The highest SSS port count commercially available at present is still limited and it seems unlikely that the SSS degree can be substantially enhanced cost-effectively in the near future [16-19]. Fortunately, spectrum selective switches will be cheaper and more reasonable with either smaller scale or coarser granular routing capability [20]. However, instead of switching spectrum slots individually like fine granular conventional spectrum selective switches, coarse granular spectrum selective switches are only capable of switching groups of continuous spectrum slots together. It implies that although coarser granular spectrum selective switches are simpler and as a result, more cost-effective but their routing capability is restricted more severely (less flexible). Incorporating multi-granular spectrum selective switches to create large-scale node architectures can help to exploit elastic optical networking and coarse granular switching for realizing cost-effective and bandwidth-flexible optical backbone networks.

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Furthermore, due to the group routing limitation caused by the use of coarse granular selective switches, network performance can be severely degraded, especially while provisioning light-path services dynamically [21, 22]. In short, there is a trade-off between the hardware scale/cost reduction and the network performance and flexibility. Therefore, effective network solutions that are able to deal efficiently with the trade-off indispensably needs to be developed.

On the other hand, in optical backbone networks, node degrees, which is defined as the adjacent node number of the node, are limited and pre-determined. During the network operation to meet traffic increments, these node degrees will not be varied but the number of parallel fibers which are established on links to adjacent nodes must be raised [23, 24]. This means that spectrum slots of a light-path that are originated from an incoming fiber and are to be routed to one of the adjacent nodes do not need to be delivered to all parallel fibers of the link to that corresponding adjacent node. This suggests that wisely setting a constraint on the intra-node routing capabilities, i.e., at a group of spectrum slots, on the express light-paths can help to attain a significant hardware reduction while still satisfying the routing flexibility at a certain level to ensure a slight network performance degradation.

Based on that, in order to exploit the advantages of EONs incorporating with coarse granular optical selective switching technology, we have introduced a novel coarse granular routing-based optical cross-connect architecture and successfully developed an efficient network control algorithm to cope with the coarse granular routing constraint effectively to provide light-path services dynamically in appropriate coarse granular routing-based elastic optical networks [25]. In this paper, we further investigate the performance of our developed dynamic coarse granular routing-based elastic optical network. We extensively simulate and evaluate the network performance in dynamically provisioning of lightpath services. Dependence of the network performance on major network parameters of the developed coarse granular routing-based elastic optical network including traffic load, traffic intensity and coarse granular routing parameter, called group routing granularity, is also verified. Numerical experiments are performed on a typical network topology and corresponding traditional elastic optical network under the same fiber configurations and network conditions is used for benchmarking.

II. DEVELOPED DYNAMIC LIGHTPATH PROVISIONING ELASTIC OPTICAL NETWORKS UTILIZING COARSE GRANULAR ROUTING

A. Coarse Granular Routing Elastic Optical Network

Based on an idea given in our preliminary evaluations of optical cross-connect architectures [17, 18] that utilize multi-granular optical path routing in WDM networks, we have successfully developed a novel coarse granular routing based- optical cross-connect architecture for elastic optical networks to provide dynamically lightpath services [25]. Figure 1 shows the developed coarse granular routing based-elastic optical cross-connect architecture. Different from traditional node architectures of optical cross-connects in conventional elastic optical networks that all employ finest granular spectrum selective switches (SSSs), our developed coarse granular routing node architecture is relied on both fine granular SSSs and coarse granular SSSs (denoted as C-SSSs) in order to exploit the advantage of coarse granular routing techniques for minimizing the overall hardware scale requirement.

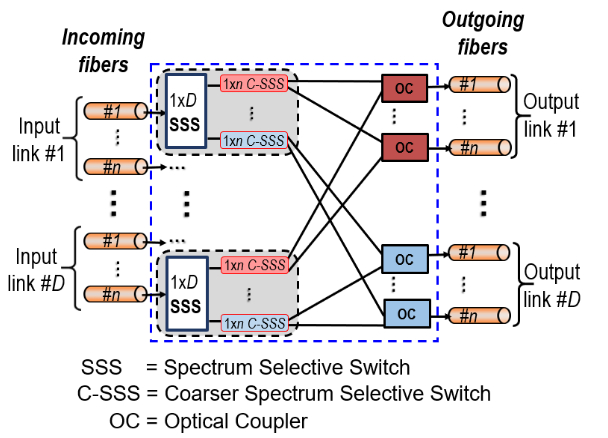

Fig. 1. Developed coarse granular routing elastic optical cross-connect architecture.

The developed coarse granular routing OXC architecture utilizes two-stage routing mechanism. At the first stage, the architecture first dynamically groups appropriate spectrum slots of lightpaths that request the same output links. Each spectrum slot group is, then, selectively routed to the requested outgoing fibers by the 2nd-stage devices. To realize the architecture, 1st-stage devices must be able to switch dynamically spectrum slots from each incoming fiber; this is possible with a fine spectrum selective switch. On the other hand, the 2nd-stage devices that need to be capable of routing flexibly groups of spectrum slots can be coarse granular SSSs. Note that C-SSSs are much simpler and more cost-effective optical switching devices than SSSs. At the output fiber side, optical coupling modules (OC) that can be a combination of a small degree SSS and/or small size couplers are utilized instead of single large port count optical couplers to minimize the loss.

In our developed node architecture, for each incoming fiber, the node architecture employs a fine granular SSS to route light-paths to output directions at spectrum slot level and several coarse granular SSSs to select the proper outgoing fiber out from the fibers of the output direction for each continuous spectrum slot group. As a result, the number of C-SSSs required for each incoming fiber is equal to the number of output directions of the node and C-SSS size depends on the number of fibers per link while the size of fine granular SSS is determined by the output direction number, that is the number of adjacent nodes of the current node. Due to the fact that the adjacent node number of nodes, depending on the network topology, is small, the required SSS size is minimized. Implementing with coarse granular SSS and small-size fine granular SSS will help to reduce significantly the necessary hardware scale of the node architecture.

Table I summarizes the main characteristics of the developed coarse granular routing elastic optical network in comparison with conventional elastic optical network. The developed two-stage coarse granular routing-based architectures, that can be realizable with present optical switching technologies, replace expensive SSSs in higher stages of conventional SSS-based OXCs with simpler and more cost-efficient substitute 1xn switching devices, C-SSSs. In terms of device cost, our developed architecture integrating both SSSs and C-SSSs is more effective solution than conventional SSS-based OXCs.

TABLE I. NETWORK CHARACTERISTIC COMPARISON

	Comparative two network solutions	
	Conventional	***Coarse granular routing***
Switching components	Large port count SSSs (or cascaded small SSSs)	- Small SSSs - C-SSSs
Switching mechanism	Switching selectively each single spectrum slot	2-stage switching: + Grouping spectrum slots to the same output direction + Selecting the output fiber of each spectrum slot group
Routing flexibility	Highest	High ~ Low (depend on *the group routing granularity*)
Cost	Highest	Medium ~ Low (depend on *the group routing granularity*)

Suppose that the node which is connected to *D* adjacent nodes supports up to *n* fibers per link to each adjacent node. Therefore, each node has *N* incoming/outgoing fibers (where $N=nD$). In other words, the required size of SSS is 1x*D* to hold *D* output directions and the C-SSS scale should be 1x*n* to route a spectrum slot group to an appropriate fiber among *n* outgoing fibers of the link which the C-SSS is assigned. Based on that, for an input fiber, such an intra-node group routing node architecture will require only one 1x*D* fine granular SSS and up to *D* C-SSSs with the size of 1x*n*. Moreover, With the similar configuration, a traditional elastic optical node architecture will need an 1x*N* SSS per input fiber. For hardware complexity and scale comparison, we suppose that all SSSs and C-SSSs used are based on MEMS technology. The coarse granular routing architecture, hence, needs up to $DL(1+n/B)$ MEMS mirrors (denote *B* as the group routing granularity, the number of spectrum slots per group), expensive components of MEMS-based selective switches, for each incoming fiber. Using an SSS with the size of 1x*N*, the traditional architecture needs *nDL* MEMS mirrors where *L* is the number of spectrum slots supported by SSSs. Obviously, the coarse granular routing OXC architecture requires less hardware scale than the traditional one ($1+n/B << n$) and the hardware scale reduction relies on not only the size of node (*n*, number of fibers per link to each adjacent node) but also the group routing granularity (*B*) supported by C-SSSs.

However, despite of providing a significant hardware scale reduction, the developed coarse granular routing elastic optical network suffers from a constrained routing capability due to the use of coarse granular SSSs. The node routing flexibility depends on the spectrum slot group size (also called *group routing granularity*, denoted as *B*) of C-SSSs. Component spectrum slots of a group from an input fiber must be switched together. Implementing finer granular C-SSSs (smaller *B*) can help to improve the node routing flexibility but, the necessary node cost/hardware scale is also increased. Therefore, in order to exploit the coarse granular routing technique, development of a network control algorithm that can cope with the intra-node group routing constraint wisely and effectively is necessary.

B. Proposed Dynamic Lightpath Provisioning Control Algorithm for Coarse Granular Routing EONs

As mentioned above, the developed coarse granular routing elastic optical cross-connect suffers from an intra-node group routing restriction due to the implementation of coarser granular spectrum selective switching devices (i.e., C-SSSs) for choosing proper outgoing fibers in the second stage. In other words, its routing flexibility is constrainted and relies on the group routing granularity. That is because, unlike conventional fine granular spectrum selective switches, SSSs, that are able to delivery each spectrum slot freely and selectively from any incoming fibers to any outgoing fibers, C-SSSs only can switch spectrum slots in groups. Therefore, in our developed coarse granular routing node architecture, spectrum slot group from an input fiber can be divided into sub-groups to transfer to C-SSSs of different output directions (links) and the sub-groups are routed to only one output fiber on each link to an adjacent node. The two-stage coarse granular routing principle of the developed OXC architecture is illustrated in Figure 2.

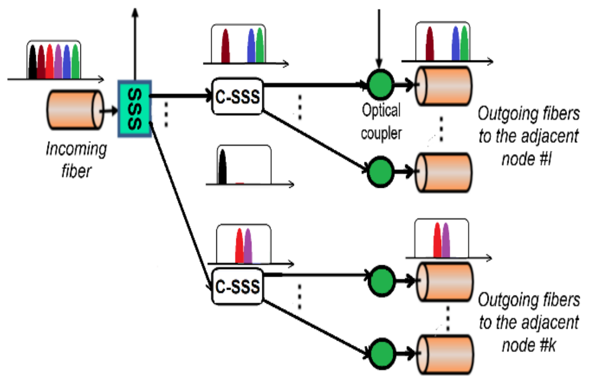

Fig. 2. Two-stage coarse granular routing principle.

Actually, we have proposed an effective network control algorithm that is capable of provisioning lightpath dynamically for coarse granular routing-based elastic optical networks [25]. Our proposed network control algorithm can deal with the group routing constraint caused by the deployment of C-SSSs to fully take the advantages of our developed node architecture. The developed algorithm is to setup and release light-paths dynamically in response to connection requests. To meet the spectrum slot group routing requirement of C-SSSs in nodes, spectrum slots of a light-path requested are assigned continuously and routed together within a same spectrum slot group which is switched to only one of output fiber on a link. This slot group must be established end-to-end while all other routing relaxations of traditional elastic optical networks have to be also satisfied. Thanks to the use of a fine granular SSS at the input of each node, spectrum slots of different light-paths in one slot group can be separated to move to different directions (links) to adjacent nodes.

In our algorithm, the traffic requests are served one-by-one, simultaneous light-paths ordered will be sorted in order of hop count between source-destination node pairs and longer hop count light-path request will be prioritized. To establish each light-path with x spectrum slots between a node pair (s, d), x is determined by the requested volume while s and d are source and destination nodes respectively, for a traffic request, with the network topology and current fiber configuration, we update the network states and build an auxiliary multi-layer light-path graph of the network (shown in Figure 3). The auxiliary graph includes GR layers, where GR is the number of spectrum slot groups of a fiber ($GR=L/B$). Each graph layer represents a multi-fiber network graph, a link may consist of multi-fibers, of a specific spectrum slot group index and at each node, the connections between incoming and outgoing fibers are updated to make sure that the group routing limitation is satisfied. Based on the auxiliary network graph, a multi-fiber shortest path algorithm, that is able to find the shortest route for each given source/destination node pair on the multi-fiber network graph, is then applied to find a shortest route on each layer. Finally, each traffic request is assigned by using the shortest route of all GR layers.

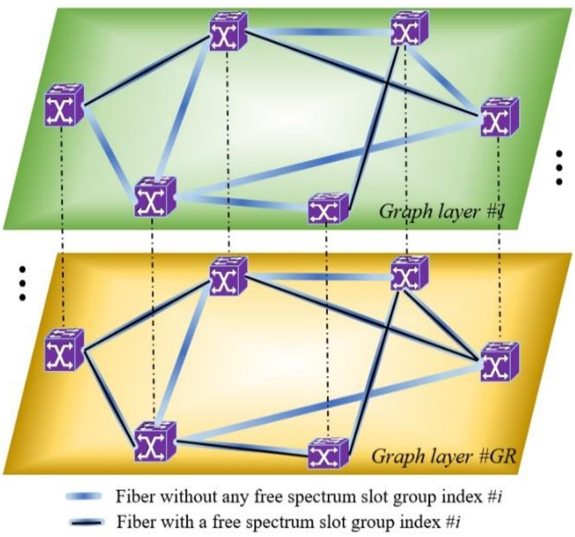

Fig. 3. Auxiliary multi-layer light-path graph of the network.

The proposed dynamic network control algorithm considering Coarse Granular Routing (CGR) constraint (denoted as CGR-aware-Control-Algorithm) is briefly summarized as followings.

CGR-aware-Control-Algorithm:

Input: ✓Network topology $G(V, E)$
✓Initial fiber configurations
✓Network parameters:
➢ L = Spectrum slot number per fiber
➢ GR = Number of spectrum group per fiber ($GR=L/B$)
✓Set of traffic requests (R(t, s, d, x)) where t is the arrival time, (s, d) is the ordering node pair and x is the requested bandwidth

1: **Repeat**
2: Scan requests at current time t, sort and send them to a *Waiting Queue*
3: **While** (*Waiting Queue* is not empty) **do**
If (R(t, s, d, x) is a *Setup Request*) **then**
4: Call ***Path-Setup***(t, s, d, x)
5: **Elseif** (R(t, s, d, x) is a *Release Request*) **then**
Call ***Path-Release***(t, s, d, x)
6: **Endif**
7: **Endwhile**
8: **Until** *Stop_Network_Operation*

Procedure *Path-Setup(s, d, x)*

Input: ✓Network topology G(V, E)
✓Updated fiber configurations
✓Connection request R(t, s, d, x)
Output: Provisioning status (*Established/Blocked*)

1: Create an auxiliary multi-layer graph with the availability of free bands of x-continuous spectrum slots in fibers and the intra-node routing restriction, G*={G^i where $i = 1, \dots, GR$}
2: **For** $i = 1$ **to** GR **do**
3: Find the shortest route of the node pair (s, d): $r^i(s, d)$ on the i^{th} graph layer
4: **Endfor**
5: $r^*(s, d) = \mathrm{Min}\{ r^i(s, d) \mid i=1,\dots, GR\}$
6: **If** ($r^*(s, d)$ *is found*) **then**
7: Establish the light-paths along the obtained route $r^*(s, d)$
8: Update the network state
9: Status:= *Established*
10: **Else**
11: Block the traffic request $R(t, s, d, x)$
12: Status:= *Blocked*
13: **Endif**
14 **Return** *Status*
End Procedure

Procedure *Path-Release(s, d, x)*

Input: ✓Network topology G(V, E)
✓Updated fiber configurations
✓Connection request $R(t, s, d, x)$
Output: Provisioning status (*Successful/Failed*)

1: **For** each node r_k along the route of $R(t, s, d, x)$ **do**
2: - Tear down the connection between the corresponding input and output fibers
3: - Check the associate link resources whether they can be released or not, if ok then release them
4: - Otherwise, **Return** *Failed*
5: - Inform the next node (if r_k is not the destination node)

Endfor
- Update the network state
Return *Successful*
End Procedure

III. PERFORMANCE EVALUATION AND DISCUSSIONS

In this section, we have evaluated the performance of the developed dynamic elastic optical network utilizing coarse granular routing and our proposed network control algorithm to provide lightpath services with respects to various network parameters including traffic load, group routing granularity. Numerical experiments are performed on a typical physical network topology named pan-European optical network (COST266) that consists of 26 nodes and 51 links (as illustrated in Figure 4). Table II briefly summarizes key characteristics of the experimental network.

Fig. 4. Experimental network topology - COST266

TABLE II. MAJOR PARAMETERS OF COST266 NETWORK

		COST network topology
Number of nodes		26
Node degree	*Min*	2
	Max	8
	Average	3.92
Number of Links		51
Number of shortest hops	*Min*	1
	Max	6
	Average	2.76

In our simulations, fibers are assumed to have a maximum capacity of 80 spectrum slots; each fiber is able to carry up to 80 spectrum slots and a slot bandwidth is supposed to be 12.5 GHz. For simplicity, we also suppose that only one (and low order) modulation format, like BPSK, is employed in overall network.

Moreover, traffic demands requested between each node pair are generated randomly following a uniform distribution. The traffic demands are represented as the average traffic bandwidths required between node pairs in the experimental network. In our numerical experiments, the traffic request arrival in the network is randomly generated and follows a Poisson process while connection holding time of the traffic demands follows a negative exponential distribution.

On the other hand, in our evaluation, traffic intensity is defined as the average bandwidth demand requested between each node pair and is supposed to be given in advance. We have tested with different traffic intensity values. Note that, the experimental network configuration, in terms of links and node resources are pre-determined and setup by using that offered by an efficient static network design algorithm that was proposed in [25]. The numbers of established fibers on links of the experimental network are estimated by using the static network design for an elastic optical network to accommodate the given traffic intensity. In our tested networks, spectrum conversion resource will not be deployed.

In order to evaluate the performance of the developed coarse granular routing elastic optical network with the capability of dynamic lightpath services provisioning and verify the impact of major network parameters, we have tested and measured the network performance in terms of connection blocking probability and accepted traffic volume when the investigated network parameters are varied. Here, the connection blocking probability is determined as the ratio of the blocked connection number to the total number of lightpath connections requested. The relative accepted traffic volume is calculated as the ratio of the traffic volume obtained by the developed network to that of corresponding conventional elastic optical networks under the same network configuration. The considered typical network parameters, in our numerical experiments, are traffic load, average traffic demand between node pairs and group routing granularity an important coarse granular routing elastic optical network that dramatically impacts the network flexibility.

A. Blocking Probability

The blocking probability is an important indicator to determine the network ability to provide lightpath services dynamically and effectively. The smaller blocking probability is, the better network performance is achieved. As being demonstrated in our previous work [25], the developed network control algorithm that is capable of dealing efficiently with the node routing constraint caused by the use of coarse granular routing for the dynamic elastic optical network can help to overcome the intra-node group routing restriction and enhance the overall network performance to an acceptable level.

In this work, we have investigated the network efficiency with various average traffic demands requested between node pairs when the traffic load is changed. Figure 5 shows the obtained connection blocking probability with four different values, 100 Gbps, 125 Gbps, 150 Gbps and 175 Gbps, of the average traffic demands requested while the traffic load ranges from 800 to 1200 Erlang in order to clarify the typical range and trend of the blocking probability. The graphs demonstrated that the network performance is kept persistent with the various traffic demands. It means that our network solution can be applied for a wide range of network traffic applications. Moreover, the results also show that, for all network traffic demands, the network performance is degraded rapidly as the traffic load is increased. This is caused by the limitation of network resources in the established network configuration.

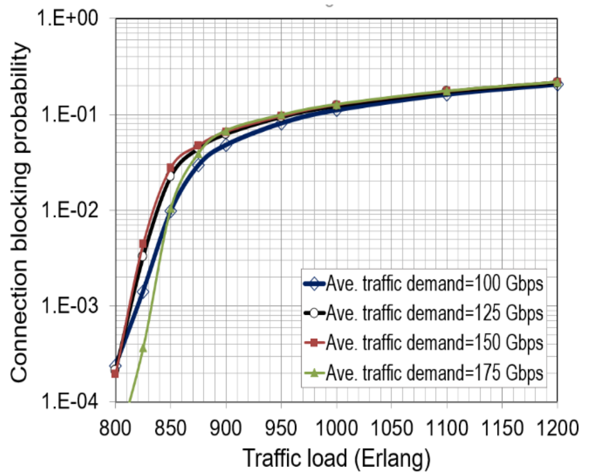

Fig. 5. Connection blocking probability versus traffic load with different values of the average traffic demands requested.

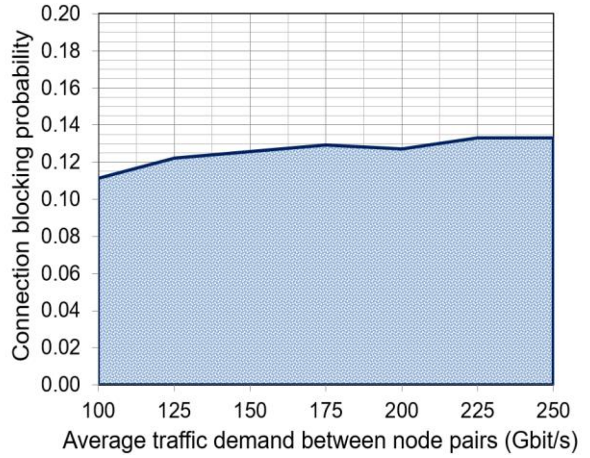

Fig. 6. Connection blocking probability versus average traffic demands between node pairs.

Furthermore, to clarify the performance of our developed solution and its applicability to various traffic intensities, we have simulated and estimated the connection blocking probability with different traffic demand values which range from 100 Gbps to 250 Gbps (equivalently, from 8 to 20 spectrum slots). In this simulation, the average mean hold time of the traffic demand requests is assumed as 1000 time-unit and the request arrival rate is set at 1.0. Figure 6 describes the attained connection blocking probability. It is verified that the blocking probability is slightly increased as the traffic intensity becomes greater. Again, this result implies that our developed network solution is able to implement effectively for all network traffic scenarios. Thanks to the consideration of course granular routing restriction wisely, our developed network performance doesn't rely much on the traffic intensity and the developed solution can be adapted properly with extremely heavy traffic conditions.

In addition, Figure 7 depicts the impact of the group routing granularity on the connection blocking probability of the developed elastic optical network utilizing our developed control algorithm when the average traffic demand requested between node pairs is set at 150 Gbps and the traffic load is changed from light to heavy. The group routing granularity, also known as the number of spectrum slots per group, is varied from 2 slots (the finest granularity is 1 slot and equivalent to the conventional elastic optical network) to 80 slots (the fiber capacity of 80 spectrum slots). The results show that the obtained network performance, in terms of the connection blocking probability, is enhanced with lighter traffic loads (smaller traffic arrival rates) and the network performance is significantly improved with finer group routing granularity (less value) thanks to the routing capability of the developed coarse granular routing elastic optical nodes with finer spectrum selective switches becomes more flexible and, of course, note that it is also much more costly. However, the performance gap tends to reduced rapidly as the traffic arrival rate becomes greater. It implies that our proposed network solution can effectively deal with the course granular routing limitation to offer a persistent performance in different traffic load conditions.

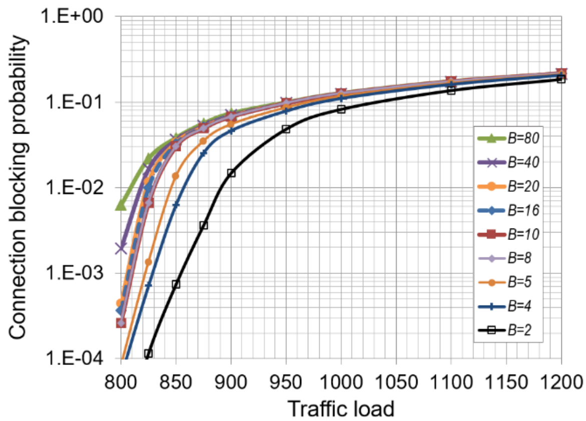

Fig. 7. Impact of the group routing granularity on connection blocking probability.

B. *Relative Accepted Traffic Volume*

In this part, in order to estimate the efficiency of our developed network solution, we evaluate and compare the traffic volume that can be provided by our network solution with that of an equivalent traditional elastic optical network employing conventional spectrum selective switch-based optical cross-connects with the same fiber configurations. The obtained experimental results of the traditional elastic optical network, then, are applied as the benchmark and the relative accepted traffic volume, the ratio of the attained result to that of the corresponding conventional network, is plotted. Hence, the relative accepted traffic volume of the traditional EON is 1.0.

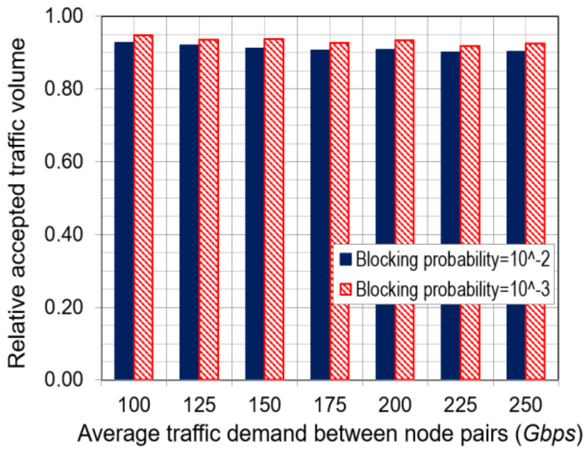

Fig. 8. Accepted traffic volume comparison with different connection blocking probability.

Firstly, we have investigated the impact of the average traffic demands between node pairs on the network performance in terms of accepted traffic volume. Actually, a trade-off exists between the accommodated traffic volume and the obtained hardware reduction. As being discussed in our previous work [25], comparing to the conventional elastic optical network, our network solution can achieve a significant hardware scale reduction thanks to exploiting the main advantage of coarse granular routing in elastic optical networks, says up to almost 49% total hardware scale can be saved, while the network performance suffers from a slight offset, i.e., only several percentages of the traffic volume is affected. Figure 8 describes the relative accepted traffic volume that can be accommodated by our solution when the blocking probabilities are 10^{-2} and 10^{-3} respectively when the average traffic demand requested between node pairs ranges from 100 Gbps to 250 Gbps. The obtained graphs show that our developed network solution is capable of dealing effectively with the coarse granular routing restriction and obtains a great performance, less than 10% performance offset in terms of traffic volume provisioning comparing to the equivalent conventional elastic optical network. The network performance also doesn't depend much on the traffic intensity, the average traffic demands requested between node pairs. The relative accepted traffic volume is marginally reduced as the traffic intensity becomes greater. This performance penalty caused by the coarse granular routing limitation in our developed network solution. Moreover, Figure 8 also demonstrates that the obtained performance is enhanced with smaller blocking probability.

In order to verify the effect of the group routing granularity on the network performance in terms of the accepted traffic volume, we have simulated and evaluated the accommodated traffic volume of our network solution in comparison with that of corresponding conventional network with the following assumptions. The average traffic demand requested between node pairs is 150 Gbps. The average mean hold time is set at 1000 time-unit while the traffic arrival rate is varied. The connection blocking probability is assumed to be fixed at 10^{-3}. The group routing granularity is changed from 1 slot, the finest granularity, to 80 slots (whole fiber capacity), the coarsest granularity. The achieved results are summarized in Figure 9.

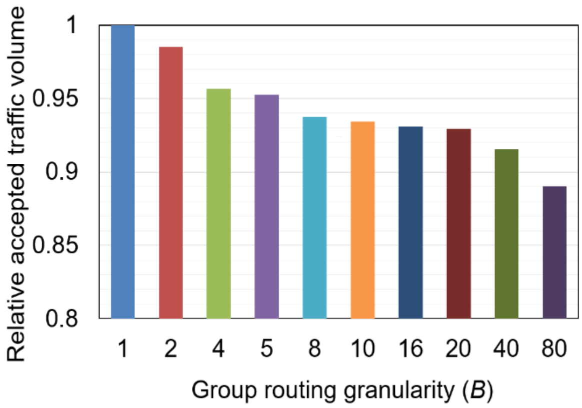

Fig. 9. Dependence of the accepted traffic volume on the group routing granularity.

The bar graphs demonstrate that the network performance strongly depends on the group routing granularity. The network performance significantly reduces when the larger group routing granularity is applied. The performance offset (in terms of the relative accepted traffic volume) becomes larger with small group routing granularity, says less than 10. The reason is that the routing flexibility of the network is more limited with larger group routing entity. However, note that in term of hardware cost, coarser granularity of spectrum selective switches offers dramatically more hardware reduction. Hence, there is a trade-off between the network performance, in terms of the accepted traffic volume, and the hardware reduction that can be attained by our network solution. Selecting a proper group routing granularity, then, is crucial in network design and optimization.

IV. CONCLUSIONS

We have investigated a cost-effective coarse granular routing-based elastic optical networks that utilizes multi-granular spectrum selective switches-based optical cross-connect architecture. The node architecture offers a substantial hardware-scale reduction however, it suffers from a coarse granular routing limitation. We have developed an efficient dynamic network control algorithm that can cope with the intra-node group routing constraint for provisioning dynamically light-paths to take the advantage of the developed network. Performance of our developed network solution is evaluated by numerical experiments. Numerical results demonstrated the efficiency of our developed network solution under various network conditions. This solution can be a viable approach for creating future cost-effective, bandwidth-abundant and flexible optical networks.

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HIỆU NĂNG MẠNG QUANG LƯỚI BƯỚC SÓNG LINH HOẠT ĐỘNG SỬ DỤNG KỸ THUẬT ĐỊNH TUYẾN THÔ CẤP PHÁT KẾT NỐI ĐỘNG

Tóm tắt: Trong bài báo này, chúng tôi đã nghiên cứu giải pháp mạng quang lưới bước sóng linh hoạt sử dụng các thiết bị chuyển mạch lựa chọn phổ tần đa mức để cung cấp các dịch vụ kết nối linh hoạt. Chúng tôi đã đề xuất một kiến trúc nút nối chéo quang hiệu quả về chi phí cùng với một thuật toán điều khiển mạng tương ứng cho các mạng quang lưới bước sóng linh hoạt. Thuật toán đề xuất có khả năng giải quyết tốt hạn chế về sự linh hoạt trong định tuyến của nút chuyển mạch được đề xuất nhằm hỗ trợ các dịch vụ kết nối phổ tần linh hoạt và hiệu quả. Hiệu năng của giải pháp mạng được phát triển của chúng tôi được khảo sát và đánh giá một cách toàn diện bằng cách sử dụng phương pháp mô phỏng số. Các kết quả cho thấy giải pháp mạng được đề xuất của chúng tôi có thể được áp dụng hiệu quả và mang lại hiệu suất ổn định trong các điều kiện mạng khác nhau. Ngoài ra, các kết quả thu được cũng chứng minh rằng có sự tồn tại của việc cân bằng giữa hiệu năng mạng và chi phí giá thành phần cứng và do đó, việc lựa chọn tham số mức định tuyến nhóm thích hợp đóng vai trò rất quan trọng trong thiết kế và tối ưu hóa mạng.

Từ khoá: Mạng quang lưới bước sóng linh hoạt, chuyển mạch lựa chọn phổ tần, định tuyến và gán phổ tần, thuật toán điều khiển mạng.

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