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A Constrained Maximum Available Frequency Slots on Path Based Online Routing and Spectrum Allocation for Dynamic Traffic in Elastic Optical Networks

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Abstract—**Elastic optical networking is a potential candidate to support dynamic traffic with heterogeneous data rates and variable bandwidth requirements with the support of the optical orthogonal frequency division multiplexing technology (OOFDM). During the dynamic network operation, lightpath arrives and departs frequently and the network status updates accordingly. Fixed routing and alternate routing algorithms do not tune according to the current network status which are computed offline. Therefore, offline algorithms greedily use resources with an objective to compute shortest possible paths and results in high blocking probability during dynamic network operation. In this paper, adaptive routing algorithms are proposed for shortest path routing as well as alternate path routing which make routing decision based on the maximum idle frequency slots (FS) available on different paths. The proposed algorithms select an underutilized path between different choices with maximum idle FS and efficiently avoids utilizing a congested path. The proposed routing algorithms are compared with offline routing algorithms as well as an existing adaptive routing algorithm in different network scenarios. It has been shown that the proposed algorithms efficiently improve network performance in terms of FS utilization and blocking probability during dynamic network operation.**

Keywords-**Elastic optical networks, routing and spectrum allocation, blocking probability, continuity constraint, contiguity constraint**

I. INTRODUCTION

THE internet traffic has rapidly increased due to the real time online services including internet of things, cloud computing, and online gaming and video broadcastings with the development of wireless communication including 5G technology [1]–[3]. The collective impact of the short duration real time consumer traffic is projected to enhance up to 27% till 2021 [4]. This imposes new challenges of accommodating the zettabytes traffic with heterogeneous bandwidth requirements into the optical backbone networks with limited bandwidth. The bandwidth can be increased by installing many optical fibers which is not a feasible solution. Currently, the bandwidth of an optical fiber is divided into many channels with 50 GHz or 100 GHz fixed channel spectrums using the wavelength division multiplexing (WDM) technology [5], [6]. However, these channels support only fixed line rates and have low spectral utilization for dynamic traffic with heterogeneous bandwidth requirements. Therefore, the existing WDM based optical networks do not tune the spectral widths according to the consumer traffic with less bandwidth requirements and have reduced spectral utilization efficiency.

Recently, the concept of elastic optical networks (EON) has been introduced to overcome the limitations of WDM networks which has the capability to increase the spectral utilization efficiency. In EON, the bandwidth of an optical fiber is divided into fine graular optical slices (or slots) with narrow spectral widths equal to 6.25 GHz, 12.5 GHz, or 25 GHz [7], [8]. The spectral slots (also called frequency slots (FS)) are closely spaced and the spectrum can overlap each other without distortion using optical orthogonal frequency division multiplexing (O-OFDM). However, the transceiver requires coherent detection for fine tuning of modulated signals. This efficiently satisfies the traffic heterogenity with diverse bandwidth demands and data rates with bandwidth aggregation ability of EON for lightpath requests with high bandwidth requirements [9].

Routing and spectrum allocation (RSA) is one of the challenging issues in EON with multiple constraints called the spectrum continuity constraint and the spectrum contiguity constaint [10]–[12]. The spectrum continuity constraint is the same as the wavelength continuity constraint in WDM networks which avoids spectrum swapping with other spectrums and makes sure that the same spectrum is allocated on all links along a route. EON has the bandwidth aggregation ability and can assign multiple FS to a lightpath request. The spectrum contiguity constraint makes sure to assign contiguous FS which should be back-to-back with each other along a route [13]. The RSA problem can be classified into offline RSA and online RSA according to the static and dynamic network traffic process [14], [15]. In the static case, lightpaths with bandwidth demands are known aprior which are assumed to stay in the network for infinite duration of times. In the dynamic case, lightpaths arrive randomly to the network with variable and random bandwidth demands and stay in the network for finite and short duration of times [16].

An objective of the offline RSA is to minimize the numbers of network resources including FSs for establishing all lightpath requests in EON [17]–[19]. The alternate problem is to maximize the numbers of establishing lightpath requests for

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the given set of network resources. In EON, RSA problem is also called routing, modulation, and spectrum allocation (RMSA) which also selects the modulation format for the given set of connection requests with heterogeneous bandwidth requirements [20], [21]. The main objective of the online RSA problem is to minimize the network blocking probability which is an important parameter to measure the performance of dynamic networks [22].

The online RSA problems are divided into the routing subproblem and the spectrum allocation subproblem. Fixed routing, alternate routing, and adaptive routing are used in the literature for routing subproblem [23]–[25]. Fixed routing computes only one shortest path between end pairs while alternate routing computes k numbers of paths between end pairs using Dijkstra's algorithm. These paths are computed offline which are then utilized for online network operation with dynamic traffic. Alternate routing has lowered network blocking probabilities compared to fixed routing as idle resources on other routes are utilized if not available on primary routes. However, it has higher blocking probabilities compared to adaptive routing in which routes are computed between end pairs during the online network operation with current network status [10]. For spectrum allocation subproblem, different heuristics are utilized including first-fit, random-fit, last-fit, most-used, least-used, and first-last-fit which are combined with routing subproblem during online network operation [26]–[28]. In this paper, an efficient adaptive routing algorithm is proposed which is combined with the first-fit spectrum allocation heuristic for dynamic traffic in EON with an objective to further reduce the amount of network blocking probabilities. The rest of the paper is organized as follows. Section II includes proposed adaptive routing algorithms for shortest path routing and k shortest paths routing. Section III discusses the performance of proposed algorithms for dynamic traffic in EON in different network scenarios. Finally, section IV concludes the paper.

II. RSA ALGORITHMS

Consider a network in Figure 1 with 6 bandwidth variable wavelength selective switch (BV-WSS) nodes and 7 optical links. Each link has two fiber, one for tramission of traffic in each direction. Let the bandwidth of each optical fiber is splitted into 8 spectrum FS, i.e., $\text{FS}_l = \{1, 2, \cdots, 8\}$. The FSs available on link $\{l_1, l_2, l_3, l_4, l_5, l_6, l_7\} = \{(4,5), (5,2), (2,3), (5,6), (6,3), (4,1), (1,2)\}$ are shown next to links in Figure 1. Let the availability of a FS is represented by 1 and the unavailability of a FS is represented by 0. Let a lightpath request originates at node 4 and terminates at node 3 with a bandwidth demand of 1 FS. There are three possible routes between the given s-d pair, i.e., $P_1^{4,3} = \{l_1, l_2, l_3\}$, $P_2^{4,3} = \{l_1, l_4, l_5\}$, and $P_3^{4,3} = \{l_6, l_7, l_3\}$. The availability of FSs on all paths can be found by taking the intersection of FSs available on all links along the path, which are given in Table I. Since FSs are available on all paths, the proposed algorithms will select a route based on maximum available FSs. The summation of FSs on $P_1^{4,3} = 2$, $P_2^{4,3} = 3$, and $P_3^{4,3} = 4$. Since, maximum FSs are available on $P_3^{4,3}$, this route will be selected based on maximum idle FS. This strategy utilizes all links on the selected route with maximum available FSs which in turn will improve the FSs utilization in networks and will reduce the amount of blocking probabilities.

TABLE I
PATH-LINK TABLE FOR THE GIVEN EXAMPLE

Slots on Link	$P_1^{4,3}$	$P_2^{4,3}$	$P_3^{4,3}$
FS_{l_1}	(10101101)	(10101101)	–
FS_{l_2}	(00001100)	–	–
FS_{l_3}	(10101101)	–	(10101101)
FS_{l_4}	–	(01111101)	–
FS_{l_5}	–	(11101011)	–
FS_{l_6}	–	–	(10111101)
FS_{l_7}	–	–	(00011101)
$\cap_{l \in P^{s,d}} \text{FS}_l$	(00001100)	(00101001)	(00011101)

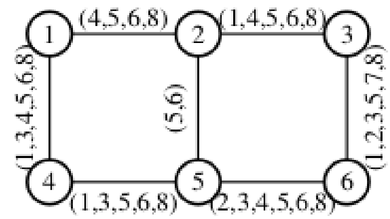

Fig. 1. A network with 6 nodes and 7 links

The fundamental reason for selecting a path with maximum idle FSs is that the probability of availability of contiguous idle FSs along the path is high compared to a path with minimum idle FSs. Let FS_t and FS_i along a path represent total number of narrow band FSs and idle FSs respectively. The probability of n numbers of contiguous FSs along a path can be derived which is equal to $\prod_{i=0}^{n-1} \left(\frac{\text{FS}_i - i}{\text{FS}_t - i}\right)$. For example, let $\text{FS}_t = 20$ and $\text{FS}_i = 16$. The probabilities of 2, 3, and 4 contiguous FSs are equal to 0.63, 0.31, and 0.12 respectively. Let FS_i becomes equal to 12. Therefore, the probabilities of availability of 2, 3, and 4 contiguous FSs along the path will reduce to 0.35, 0.07, and 0.01 respectively. The proposed algorithms are different from the existing CLIB-based routing algorithm in [10] which decides routing based on minimum available FS index on different routes. As demonstrated in Table I, route $P_2^{4,3}$ will be selected using the existing CLIB-based routing. Following algorithms will be used for routing and spectrum allocation in different networks using the proposed approach.

A. Algorithm for shortest path routing and spectrum allocation (A_1)

Algorithm A_1 is considered for shortest path routing between s-d pairs which computes shortest routes between s-d pairs based on a constraint called maximum numbers of idle FSs. The flow chart of algorithm A_1 is given in Figure 2. Initially, k shortest paths between all (or selected) s-d pairs are computed using network topology information and Dijkstra's algorithm [29]. The algorithm A_1 selects only shortest paths among these pre-computed paths. If there are more than one

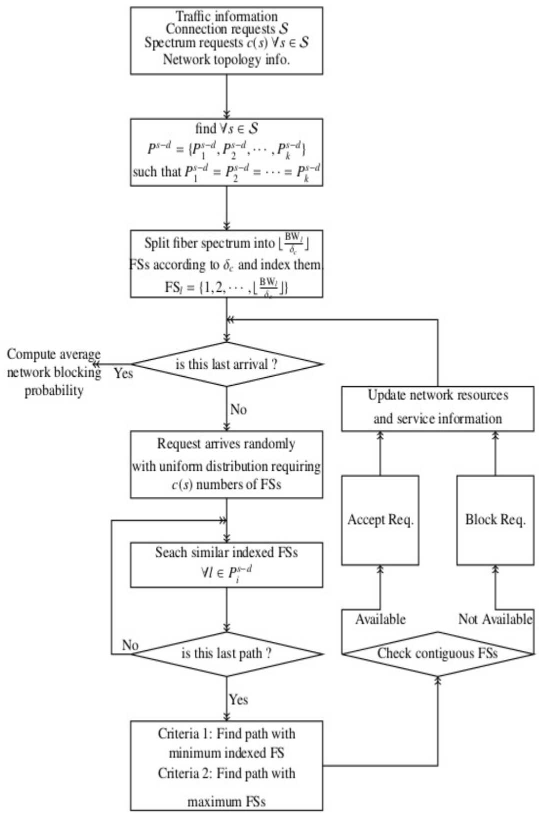

Fig. 2. Flow chart for the simulation to compute average network blocking probability using algorithm 1

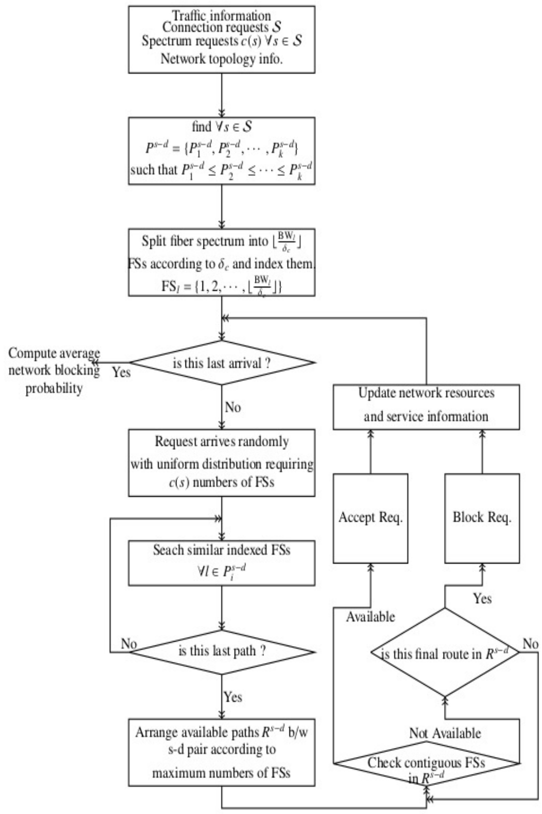

Fig. 3. Flow chart for the simulation to compute average network blocking probability using algorithm 2

shortest path with equal hop count, the algorithm selects all these paths in the initial round with equal hop count. Algorithm A_1 then search for similar indexed FSs on all links along a path ($\forall l \in p$) for all paths ($p \in P^{s,d}$) which satisfies the continuity constraint of similar frequency spectrum on all links along the path. Algorithm A_1 then selects routes between s-d pairs based on criteria 2, i.e., availability of maximum FSs on a route. Criteria 1 is included in Figure 2 for comparison which is based on CLIB-based routing in [10]. Finally, algorithm A_1 searches for contiguous FSs along selected routes. A request is accepted if contiguous FSs are available on the selected route with maximum FSs. Otherwise, it is blocked. The FSs will be assigned based on first-fit allocation. The algorithm A_1 selects only one route between s-d pairs based on maximum numbers of FSs before searching contiguous FSs along the same route using first-fit heuristic.

B. Algorithm for k shortest paths routing and spectrum allocation (A_2)

Algorithm A_2 is proposed for k shortest paths routing between s-d pairs which may not give same routes as obtained from using alternate routing between s-d pairs. The flow chart of algorithm A_2 is given in Figure 3. Initially, k shortest paths between all (or selected) s-d pairs are computed using network topology information and Dijkstra's algorithm. The proposed algorithm A_2 then search for similar indexed FSs on all links along a path ($l \in p$) for all paths ($p \in P^{s,d}$) which satisfies the continuity constraint of similar frequency spectrum on all links along the path, i.e., $\cap_{l \in p} \mathrm{FS}_l$, $\forall p \in P^{s,d}$. The proposed algorithm keeps the available paths with $\sum (\cap_{l \in p} \mathrm{FS}_l) \ge c(s)$ in decending order according to the maximum available FSs, i.e., $R^{s,d} = \{P_i^{s,d}, P_j^{s,d}, \cdots, P_k^{s,d}\}$ such that $\sum(\cap_{l \in P_i^{s,d}} \mathrm{FS}_l) \ge \sum(\cap_{l \in P_j^{s,d}} \mathrm{FS}_l) \ge \sum(\cap_{l \in P_k^{s,d}} \mathrm{FS}_l)$, where $c(s)$ are the required contiguous FS according to the bandwidth demand of each s-d pair s. The proposed algorithm A_2 then searches for the contiguous FSs on the ordered routes $R^{s,d}$ in an iterative manner until a route is found with with FS continuity and contiguity constraints. The proposed algorithm A_2 is different from the available CLIB-based algorithm which is given in Figure 4 for comparison with the proposed algorithm A_2. CLIB-based algorithm searches for the continuous and contiguous FS in the initial phase from a set of all available k-shortest routes and takes routing decision in the later phase based on the lower index of available FSs.

C. Spectrum allocation subproblem

In this work, first-fit heuristic is used for spectrum allocation which is integrated with the routing subproblem. A path is first selected from a set of available routes between end pairs using the proposed algorithms. It is then followed by spectrum

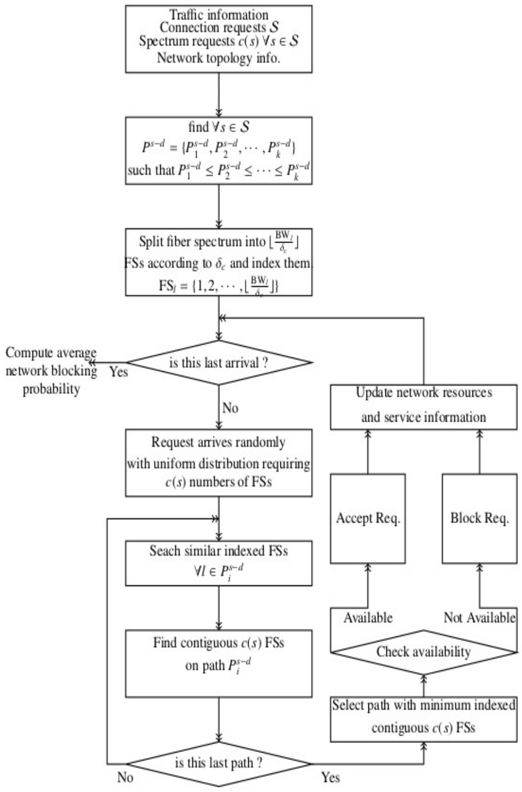

Fig. 4. Flow chart for the simulation to compute average network blocking probability using CLIB based RSA

allocation subproblem. The fiber sprectrum is divided into a number of FSs with equal bandwidth, i.e., 12.5GHz and are indexed. The first-fit heuristic computes all idle FSs along the selected path and allocates the lower indexed available contiguous FSs with higher priority.

III. Results and Discussion

The performances of the proposed algorithms have been investigated for dynamic traffic in different networks including

1) a randomly generated network with 14 BV-WSS nodes and 64 directed fiber links (net1),
2) a randomly generated network with 30 BV-WSS nodes and 140 directed fiber links (net2), and
3) a mesh network with 16 BV-WSS nodes and 48 directed fiber links (net3).

Each fiber has 160 narrow band FSs for transmission of traffic in one direction. The capacity of each FS is considered to be 12.5 GHz. One million lightpaths have been randomly generated according to a Poisson's distribution in Python [30]. The durations of all lightpaths are generated according to exponential distribution with a mean holding time equal to 1 unit. Lightpaths arrive to the network randomly with uniform distribution. Finally, the capacity of each lightpath is randomly selected with uniform distribution from the set $\{6.25\text{GHz}, 12.5\text{GHz}, 25\text{GHz}\}$. Each lightpath will take $\lceil \frac{c(s)}{\delta(s)} \rceil$ FSs where $c(s)$ is the demanded capacity and $\delta(s)$ is the capacity of one narrow band channel.

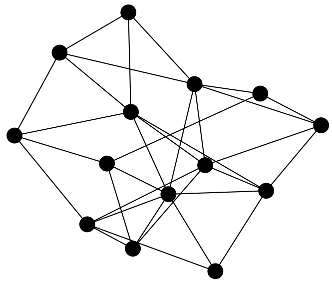

Fig. 5. (net1) Network topology with 14 switch nodes and 64 directed links

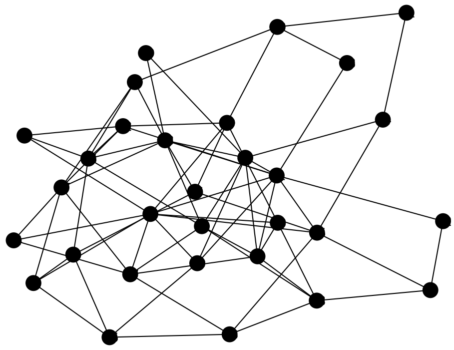

Fig. 6. (net2) Network with 30 switch nodes and 140 directed links

The performance of the algorithm A_1 with criteria 1 and criteria 2 has been investigated in terms of FS utilization which is defined as the number of times a FS is utilized

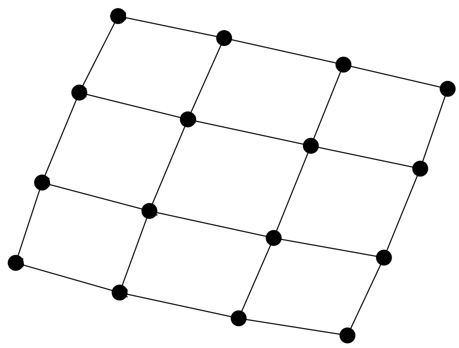

Fig. 7. (net3) Mesh network with 16 switch nodes and 48 directed links

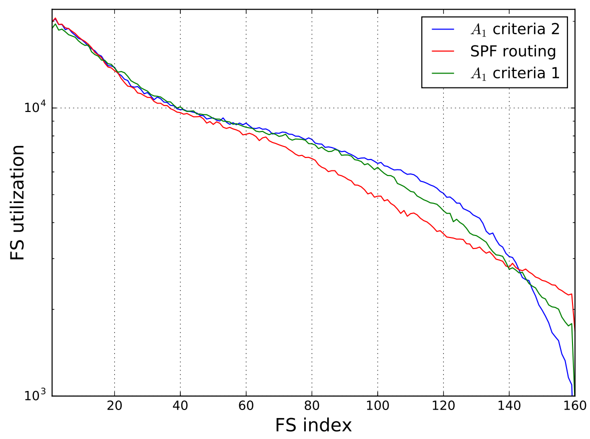

Fig. 8. FS utilization in net1 using algorithm A_1 for RSA for dynamic traffic

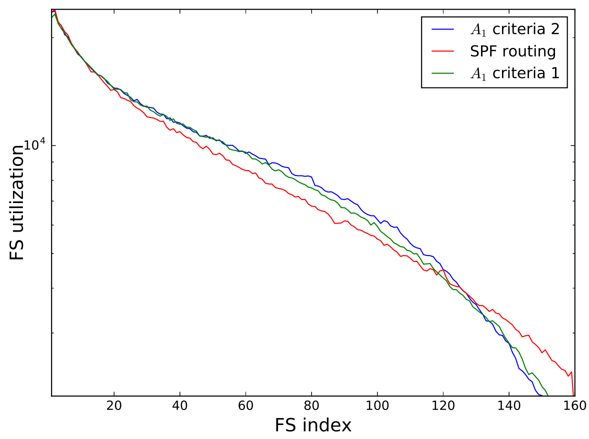

Fig. 9. FS utilization in net2 using algorithm A_1 for RSA for dynamic traffic

by a lightpath request during dynamic network operation. The performance of algorithm A_1 with both criterion are compared with SPF routing in Figures 8 - 10 for net1, net2, and net3 respectively. Since all RSA algorithms utilize first-fit heuristic for spectrum allocation which give preference to the lower indexed idle FS compared to the higher indexed idle FS. Therefore, the FS utilization of lower indexed FSs are higher in all networks compared to the higher indexed FSs in all RSA schemes. However, the average FS utilization of the proposed algorithm A_1 with criteria 2 is more compared to the RSA algorithm A_1 with criteria 1. Similarly, the FS utilization of algorithm A_1 with both criterion is greater than SPF based RSA scheme. The average FS utilization is given in Table II which shows that the proposed scheme efficiently utilize available set of resources. The selected paths based on maximum available idle FSs utilize idle resources efficiently compared to other schemes. In Figures 8 - 10, the higher indexed FSs in the proposed scheme have minimum FS utilizations compared to SPF routing scheme. However, it carries sufficient extra traffic load for an equivalent amount of the network blocking probability compared to the existing schemes which will further increase FS utilization of the proposed scheme. Therefore, the proposed scheme has a gain in terms of network blocking probability compared to the existing schemes. The performances of the proposed and existing RSA schemes have also been investigated in terms of network blocking probabilities for dynamic traffic in EON. It has been shown in Figures 11 - 13 that the proposed algorithm A_1 with criteria 2 has lower values of blocking probabilities compared to other schemes in all networks due to the efficient and higher utilization of available resources.

The performance of the proposed algorithm A_2 has also been investigated for dynamic traffic in terms of FS utilization and compared with the existing alternate routing scheme and the adaptive CLIB based routing scheme in different elastic optical networks. The FS utilization obtained from different schemes are plotted in Figure 14, Figure 15, and Figure 16 for net1, net2, and net3 respectively. The average FS utilization is given in Table III. The proposed scheme efficiently utilizes available FS resources in different networks compared to

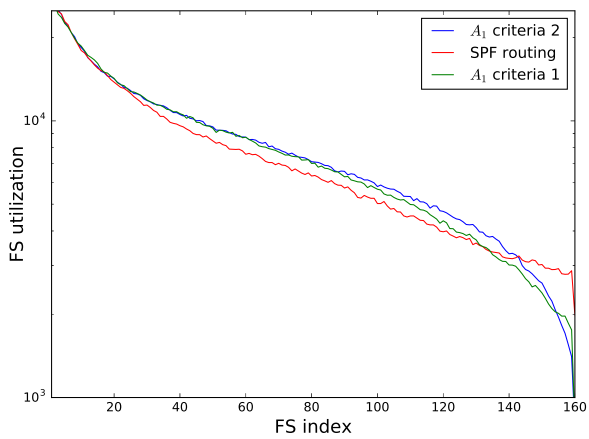

Fig. 10. FS utilization in net3 using algorithm A_1 for RSA for dynamic traffic

alternate routing scheme. The FS utilization of the proposed scheme is higher compared to CLIB based RSA scheme in all networks as both RSA schemes are considered to utilize different paths. Moreover, the proposed RSA scheme has higher FS utilization compared to alternate RSA scheme in all networks as the later always tries to use first shortest path. If

TABLE II
AVERAGE FS UTILIZATION IN DIFFERENT ELASTIC OPTICAL NETWORKS FOR DYANAMIC TRAFFIC USING SPF RSA, A_1 RSA WITH CRITERIA 1, AND A_1 RSA WITH CRITERIA 2

Routing scheme	Average FS utilization
net1: Network with 14 BV-WSS nodes and traffic load = 2700	
SPF RSA	7486
A_1 criteria 1 RSA	7885
A_1 criteria 2 RSA	8056
net2: Network with 30 BV-WSS nodes and traffic load = 3700	
SPF RSA	8088
A_1 criteria 1 RSA	8372
A_1 criteria 2 RSA	8501
net3: Network with 16 BV-WSS nodes and traffic load = 1200	
SPF RSA	7820
A_1 criteria 1 RSA	8180
A_1 criteria 2 RSA	8333

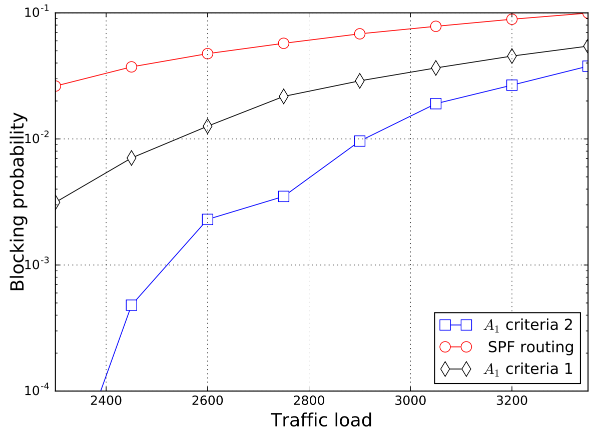

Fig. 11. Comparison of blocking probabilities obtained from algorithm A_1 with criteria 1 and criteria 2 and SPF based RSA scheme in net1

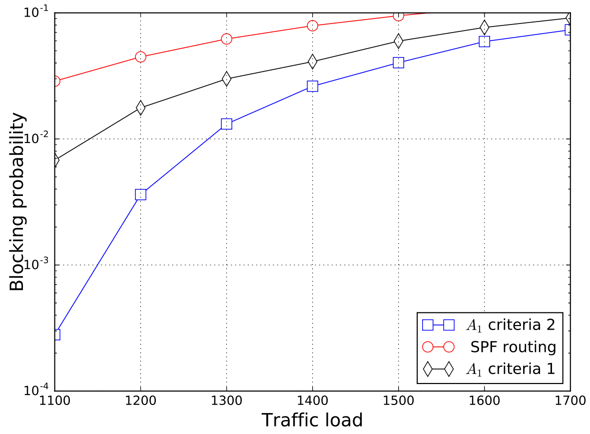

Fig. 13. Comparison of blocking probabilities obtained from algorithm A_1 with criteria 1 and criteria 2 and SPF based RSA scheme in net3

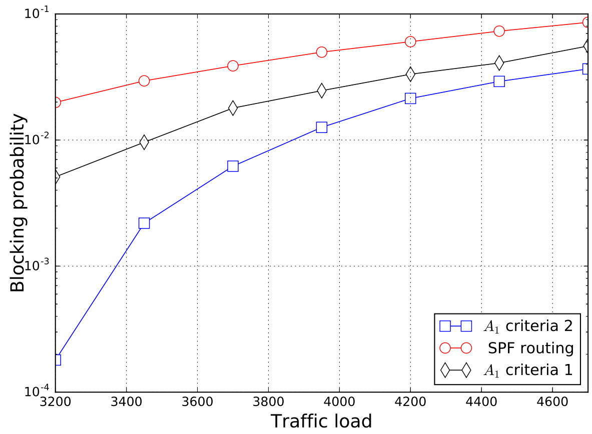

Fig. 12. Comparison of blocking probabilities obtained from algorithm A_1 with criteria 1 and criteria 2 and SPF based RSA scheme in net2

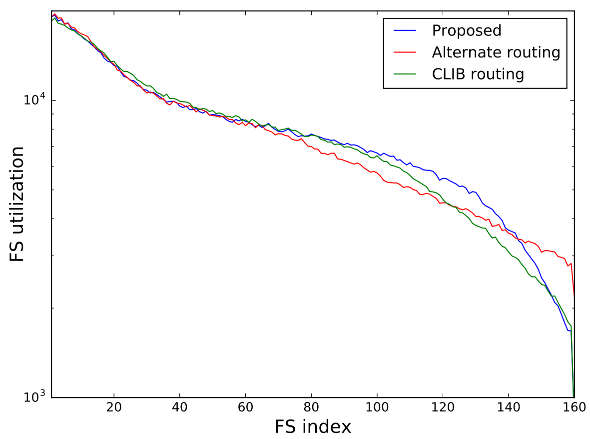

Fig. 14. FS utilization in net1 using algorithm A_2 for RSA for dynamic traffic

resources are not available on first shortest path, then it utilizes second shortest path. However, routes are greedily selected and the availability of idle FSs reduces on alternate routes. Therefore, FS utilization also reduces in alternate RSA scheme which is less than CLIB based RSA and the proposed RSA schemes in all networks. Finally, the performance of different RSA schemes have been investigated for dynamic traffic in terms of average network blocking probabilities which are plotted in Figures 17 - 19. Due to an efficient FS utilization as given in Table III, the proposed RSA scheme has minimum amount of blocking probabilities compared to the existing alternate routing scheme and the adaptive CLIB based routing scheme in different networks.

IV. Conclusions

In this paper, different adaptive routing algorithms have been proposed for dynamic traffic in EON with mixed line rates which make routing decisions based on maximum idle FSs on path during online network operations. The probability of availability of similar indexed contiguous FSs is more on a route with maximum idle FSs compared to other routes with minimum idle FSs. Therefore, the proposed adaptive algorithms efficiently route dynamic traffic in EON and reduces the average network blocking probability as well as increases the FS utilization compared to fixed routing, alternate routing, and existing adaptive routing algorithms.

TABLE III
Average FS utilization in alterante RSA, CLIB based RSA, and the proposed RSA scheme in different elastic optical networks for dynamic traffic

Routing scheme	Average FS utilization
net1: Network with 14 BV-WSS nodes and traffic load = 2800	
Alternate RSA	7810
CLIB based RSA	7922
A_2 based RSA	8056
net2: Network with 30 BV-WSS nodes and traffic load = 3800	
Alternate RSA	8331
CLIB based RSA	8396
A_2 based RSA	8515
net3: Network with 16 BV-WSS nodes and traffic load = 1400	
Alternate RSA	7756
CLIB based RSA	7992
A_2 based RSA	8079

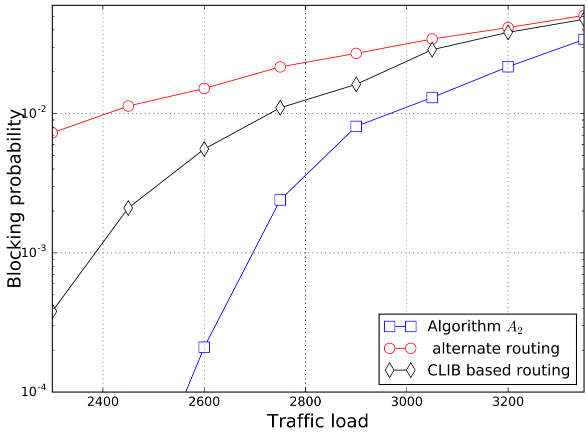

Fig. 17. Comparison of blocking probabilities obtained from RSA algorithm A_2, alternate routing, and CLIB based RSA in net1

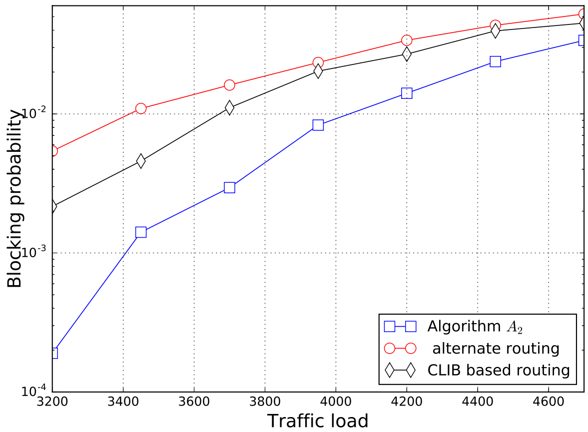

Fig. 18. Comparison of blocking probabilities obtained from RSA algorithm A_2, alternate routing, and CLIB based RSA in net2

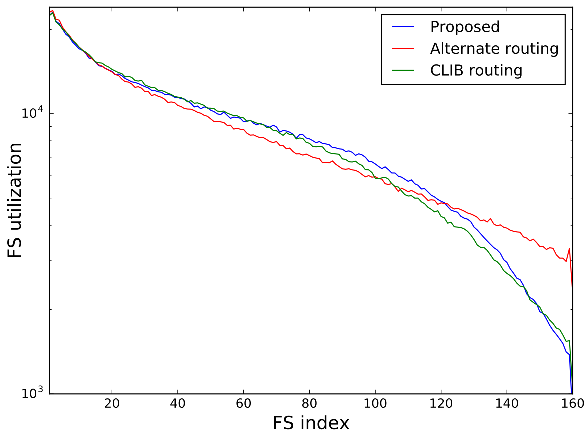

Fig. 15. FS utilization in net2 using algorithm A_2 for RSA for dynamic traffic

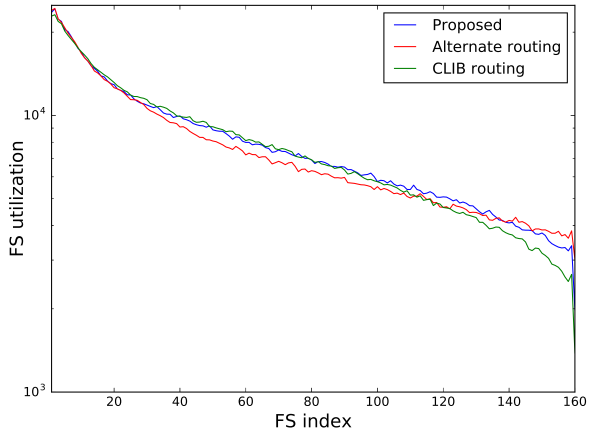

Fig. 16. FS utilization in net3 using algorithm A_2 for RSA for dynamic traffic

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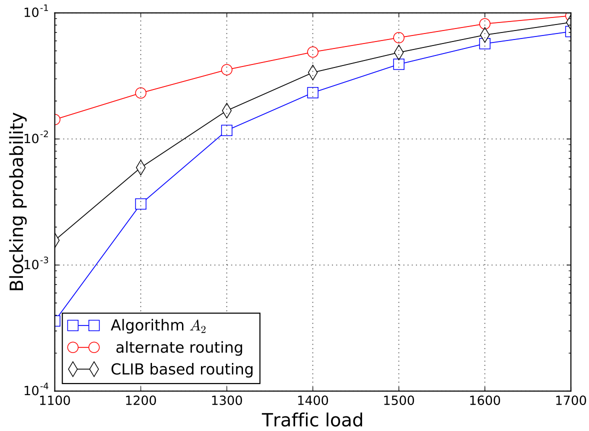

Fig. 19. Comparison of blocking probabilities obtained from RSA algorithm A_2, alternate routing, and CLIB based RSA in net3

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