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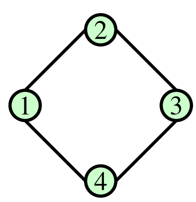

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Link Congestion Aware Proactive Routing for Dynamic Traffic in Elastic Optical Networks

Akhtar Nawaz Khan, [1] **Hassan Yousif Ahmed**, [2]
Medien Zeghid, [2,3] **Waqas A. Imtiaz**, [1] **and Zawar H. Khan** [1]

[1] Department of Electrical Engineering, University of Engineering and Technology, Peshawar, Jalozai Campus, Pakistan
[2] Electrical Engineering Department, College of Engineering at Wadi Aldwaseer, Prince Sattam Bin Abdulaziz University, Al Kharj, Riyadh, KSA
[3] Electronics and Micro-Electronics Laboratory (E. μ. E. L), Faculty of Sciences, University of Monastir, Monastir, Tunisia

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Abstract: Fixed alternate routing is a potential routing scheme for routing and spectrum allocation (RSA) in elastic optical networks (EON) which has less complexity and time consumption compared to adaptive routing scheme. However, adaptive routing scheme efficiently reduces the amount of network bandwidth blocking probabilities (BBPs) which uses traffic engineered paths and tunes according to the current network status. In this paper, an algorithm for routing is proposed for dynamic traffic in EON which works iteratively to arrange the pre-computed fixed alternate routes offline to incorporate link loading. During the offline process, the pre-computed routes are arranged with an objective to reduce link congestion and diverts lightpaths to the under-utilized links. The proposed scheme merges the properties of fixed alternate routing and adaptive routing and is utilized for dynamic traffic in EON. It has been shown through simulation results that the proposed scheme efficiently improves the performance of RSA in EON and reduces the amount of BBPs compared to the fixed alternate routing and an existing constrained-lower-indexed-block (CLIB) based adaptive routing algorithm. The proposed LCA greatly reduces congestion over all links during dynamic network operation and lowers congestion spikes over some links which occues in the existing alternate routing scheme in different network scenarios.

Index Terms: Bandwidth blocking probability, contiguity constraint, continuity constraint, elastic optical networks, link congestion, routing and spectrum allocation.

1. Introduction

Recent research on EON has received intensive attraction as it is becoming a promising technology [1], [2]. EON is utilizing an advanced modulation technique called optical orthogonal frequency division multiplexing (O-OFDM) [3], [4]. In EON, the bandwidth of an optical fiber is splitted into a large number of closely-spaced narrow spectrum slices (also called slots) which are assigned to lightpath requests based on the modulation formats and heterogeneous line rates [5]–[7]. In EON, modulation formats are also heterogeneous which are selected based on optical reach. A modulation format with high optical reach requires more spectrum slots compared to a modulation format with low optical reach for same request. Therefore, EON has a high spectrum efficiency compared to the wavelength division multiplexing (WDM) networks due to the fine granularity and rate adaptation with traffic demands with a goal to minimize the occupied spectrum slots (also called frequency slots (FS)).

In EON, the overlaping closely-spaced orthogonal frequency spectrums are multiplexed which requires coherent signal detection compared to WDM networks with reletively large frequency spacing between adjacent spectrums, i.e., 50 GHz or 100 GHz. Similarly, traditional WDM based algorithms with only the wavelength continuity constraints are not application for EON with heterogeneous spectrum allocation depending on the modulation format as well as the traffic demand. EON also considers the spectrum contiguity constraint along with the spectrum continuity which means that the allocated FS will be adjacent along the optical path [8]. In [9]–[11], the concepts, roles, and benefits of EON with random data rates are presented. Recently the machine learning technique has been adopted in [12] to extract useful information from the transmission traces in optical networks. However, its complexitiy will increase in EON due to the heterogeneous structure of traffic behaviour, resource allocaiton, modulation formats, and coding rates in EON. Similarly, software-defined network (SDN) solution is presented in [13] which is integrated with EON to enhance its performance with dynamic resources allocation in EON.

Compared to the routing and wavelength assignment (RWA) with uniform bandwidth spectrums, EON considers RSA for lightpath requests with variable bandwidth demands and associated variable spectrum widths [14]. Several algorithms have been proposed for RSA which are divided into static RSA and dynamic RSA [15]–[17]. In [18], a static optimization problem is modeled for RWA with burst switching. In [16], [17], RSA algorithm is proposed for static traffic which computes routes based on load balancing with the goal to reduce the maximum subcarrier index. In [19], an optimization problem is proposed which computes routes between source nodes and destination nodes (s-d) pairs in an offline phase. Typacally, static RSA problems use known traffic information with infinite service durations [20]. These models are designed to find optimal routes based on static traffic information with an objective to minimize network resources. These models are designed subject to the criteria to assign network resources to given set of lightpaths requests [15], [21]–[23]. In dynamic RSA problems, ligthpath requests with finite holding time and variable bandwidth demands arrives randomly and hold resources in the network till departure. The goal of the dynamic RSA problem is to reduce the probability of bandwidth blocking [24], [25] which can be divided into routing subproblem and spectrum allocation subproblem [26], [27]. A global optimizaiton method has been proposed in [28] called cross stratum optimization (CSO) which dynamically allocates resources according to the modulation format and bandwidth requirements in EON. However, CSO does not perform routing decision.

Typically, fixed routing, alternate routing, and adaptive routing algorithms are used for routing subproblem in EON netwoks. Fixed routing is the simplest routing strategy which precomputes single shortest paths between end pairs based on numbers of hops or actual distance between end pairs [29], [30]. However, alternate routing precomputes more than one shortest paths between end pairs. These routes will be assigned to dynamic lightpath requests. Alternate routing reduces amount of blocking probability compared to fixed routing as alternate routes will be utilized in case all resources occupied on first shortest paths [15]. However, both fixed routing and alternate routing will greedily use network resources with an objective to compute shortest paths. Adaptive routing computes routes between end pairs based on current network status [30]–[33]. Therefore, it reduces amount of blocking probability compared to alternate routing. However, it is more time consuming and complex than alternate routing which makes real time decisions to select routes based on current network status. The constrained lower indexed based routing is an adaptive routing in [30] which selects paths between end pairs from a list of all available routes for lightpath requests based on lower indexed frequency slot (FS).

Several heuristic approaches have been used for spectrum allocation in EON. An online unsupervised fuzzy clustering algorithm is used for resource allocation in [34] which takes into account physical impairements in EON. Similarly, first-fit, last-fit, random-fit, most-used, and least-used

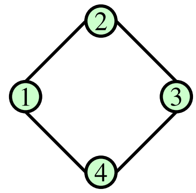

Fig. 1. Ring network with 4 nodes.

heuristics have been used for spectrum allocation in EON [19], [22], [26], [30]. Fragmentation is a major issue in EON which in large is related to the spectrum allocation techniques. A random spectrum allocation will result in higher fragmentation compared to first-fit (last-fit) policy for resource allocation as the later mostly utilizes the lower (upper) portion of link resources. Fragmentation on a link in EONs has been demonstrated with numerical examples in [35] which has been categorized as external fragmentation metric, entrophy-based fragmentation metric, and access blocking probability based fragmentation metric (ABPM). It has been reported that the external fragmentation ignores small fragments on a link and considers only largest available FS block. Similarly, entrophy-based fragmentation does not reflect accurate information in the inappropriate fragmented cases. Finally, the ABPM measures fragmentation comprehensively compared to the other two fragmentation metrics. In this work, we have adopted ABPM for estimating fragmentation in EONs.

We propose a routing scheme in this paper for dynamic traffic in EON. The proposed scheme works iteratively and arranges precomputed alternate routes based on the links utilization in the offline phase with an objective to balance link loading in terms of paths transiting network links. This reduces complexity and time consumption compared to adaptive routing while utilizing the traffic engineered paths between end pairs. We have investigated the performance of the proposed routing algorithm in different network scenario in terms of the bandwidth blocking probabilities. We have also investigated the performance of the proposed routing algorithm by considering other characteristics of the elastic optical networks including network fragmentation which is a major issue in EONs under dynamic network operation. The rest of the paper is organized as follows. Section II includes the proposed routing algorithm with a numerical example. The performance of the proposed scheme is given in Section III for dynamic arrival process with numerical results in different network scenarios. Finally, Section IV concludes the paper.

2. Link Congestion Aware (LCA) Based RSA Algorithm

Consider a ring network in Fig. 1 with 4 nodes and 8 directed fiber links for traffic flow in unidirection. Consider 4 source-destination (s-d) pairs s^{1-3}, s^{2-4}, s^{3-1}, and s^{4-2}. Assume there are two shortest paths between these s-d pairs such that s^{1-3}: [(1 − 2 − 3), (1 − 4 − 3)], s^{2-4}: [(2 − 3 − 4), (2 − 1 − 4)], s^{3-1}: [(3 − 2 − 1), (3 − 4 − 1)] and s^{4-2}: [(4 − 3 − 2), (4 − 1 − 2)]. LCA routing takes into account the network topology information and set of all possible (or selected) s-d pairs. It also utilizes the information about available shortest paths between s-d pairs based on Dijkstra algorithm [36]. The goal of LCA routing is to route lightpath requests between s-d pairs on traffic engineered routes with an objective to divert traffic from the congested links to the least congested links in a network. LCA routing considers the impact of link loading which may be defined as maximum numbers of routes between s-d pairs transiting through an optical fiber link.

Let k represents the numbers of shortest paths between s-d pairs. Consider k tables which are denoted by R_l^1, R_l^2, . . . , R_l^k, and are called link-route tables. In this specific example, $k = 2$ is considered. Routes between selected s-d pairs utilizing links on first and second shortest paths are given in Table 1 and Table 2 respectively. An entity equals to 1 in Table 1 and Table 2 shows that a route is transiting through an optical fiber link, otherwise it is equal to 0.

TABLE 1
R_l^1

Links	s^{1-3}	s^{2-4}	s^{3-1}	s^{4-2}
l_{1-2}	1	0	0	1
l_{2-3}	1	1	0	0
l_{3-4}	0	1	1	0
l_{4-1}	0	0	1	1
l_{2-1}	0	0	0	0
l_{3-2}	0	0	0	0
l_{4-3}	0	0	0	0
l_{1-4}	0	0	0	0

TABLE 2
R_l^2

Links	s^{1-3}	s^{2-4}	s^{3-1}	s^{4-2}
l_{1-2}	0	0	0	0
l_{2-3}	0	0	0	0
l_{3-4}	0	0	0	0
l_{4-1}	0	0	0	0
l_{2-1}	0	1	1	0
l_{3-2}	0	0	1	1
l_{4-3}	1	0	0	1
l_{1-4}	1	1	0	0

The new columns in the resultant link-route table will be iteratively added. The following algorithm is proposed which works iteratively to select a column. The newly added column will be a permanent column of the resultant link-route table in the next iteration.

1) Find sets of all s-d pairs according to the number of hops which are found using shortest path routing using Dijkstra algorithm. For example, set of all s-d pairs with minimum hop count equal to 1, set of all s-d pairs with minimum hop count equal to 2, and so on.
2) Find traffic engineered routes starting with set of all s-d pairs with maximum hop count and ending with set of all s-d pairs with minimum hop count.
3) For an s-d pair i, select column i from the link-route tables R_l^j which is given by $R_l^{j(i)} = \{a_{l_1}^{j(i)}, a_{l_2}^{j(i)}, \ldots, a_{l_{|L|}}^{j(i)}\}$ such that $j \in \{1, 2, \ldots, k\}$ and $|L|$ represents numbers of fiber links. IN $R_l^{j(i)}$, $a_m^{j(i)} \in \{0, 1\} \forall m \in \{l_1, l_2, \ldots, l_{|L|}\}$ shows that a route is transiting through an optical fiber link l or not. For all routes $j \in \{1, 2, \ldots, k\}$, calculate weights of the selected column for an s-d pair i which represents the summation of all entities in column i of $R_l^{j(i)}$ tables, i.e.,

$$\forall j \in \{1, 2, \ldots, k\}, \;\; W^{j(i)} = \sum_{m \in \{l_1, l_2, \ldots, l_{|L|}\}} a_m^{j(i)}$$

Finally, find the minimum column weight to select an appropriate route R^i for an s-d pair i, i.e.,

$$\forall j \in \{1, 2, \ldots, k\}, R^i = \min\left(W^{j(i)}\right)$$

$$\forall j \in \{1, 2, \ldots, k\}, R^i = \min\left(\sum_{m \in \{l_1, l_2, \ldots, l_{|L|}\}} a_m^{j(i)}\right)$$

In the given example, if weight of $R_l^{2(i)}$ is the minimum one, then a route is selected for s-d pair i from R_l^2. Otherwise, a route for s-d pair i will be selected from R_l^1.
4) In case of a tie,
   a) Select a column i for s-d pair i which results in a minimum-maximum (min-max) entity value from the row summation in the resultant column of the link-route table. The min-max value can be found by finding maximum values in all j (such

TABLE 3
Resultant Table of All Link-Route Tables: First Iteration

Links	s^{1-3} $P^1 \mid P^2$	s^{2-4} $P^1 \mid P^2$	s^{3-1} $P^1 \mid P^2$	s^{4-2} $P^1 \mid P^2$	Sum of rows $\mathbf{P^1} \mid P^2$
l_{1-2}	1 | 0				**1** | 0
l_{2-3}	1 | 0				1 | 0
l_{3-4}	0 | 0				0 | 0
l_{4-1}	0 | 0				0 | 0
l_{2-1}	0 | 0				0 | 0
l_{1-4}	0 | 1				0 | 1
l_{4-3}	0 | 1				0 | 1
l_{3-2}	0 | 0				0 | 0

TABLE 4
Resultant Table of All Link-Route Tables: Second Iteration

Links	s^{1-3} $P^1 \mid P^2$	s^{2-4} $P^1 \mid P^2$	s^{3-1} $P^1 \mid P^2$	s^{4-2} $P^1 \mid P^2$	Sum of rows $P^1 \mid \mathbf{P^2}$
l_{1-2}	1 | •	0 | 0			1 | 1
l_{2-3}	1 | •	1 | 0			2 | 1
l_{3-4}	0 | •	1 | 0			1 | 0
l_{4-1}	0 | •	0 | 0			0 | 0
l_{2-1}	0 | •	0 | 1			0 | 1
l_{1-4}	0 | •	0 | 1			0 | 1
l_{4-3}	0 | •	0 | 0			0 | 0
l_{3-2}	0 | •	0 | 0			0 | 0

TABLE 5
Resultant Table of All Link-Route Tables: Third Iteration

Links	s^{1-3} $P^1 \mid P^2$	s^{2-4} $P^1 \mid P^2$	s^{3-1} $P^1 \mid P^2$	s^{4-2} $P^1 \mid P^2$	Sum of rows $P^1 \mid \mathbf{P^2}$
l_{1-2}	1 | •	• | 0	0 | 0		1 | 1
l_{2-3}	1 | •	• | 0	0 | 0		1 | 1
l_{3-4}	0 | •	• | 0	0 | 1		0 | 1
l_{4-1}	0 | •	• | 0	0 | 1		0 | 1
l_{2-1}	0 | •	• | 1	1 | 0		2 | 1
l_{1-4}	0 | •	• | 1	0 | 0		1 | 1
l_{4-3}	0 | •	• | 0	0 | 0		0 | 0
l_{3-2}	0 | •	• | 0	1 | 0		1 | 0

that $j \in \{1, 2, \ldots, k\}$) resultant columns of the link-route table. A minimum value among these maximum values will give min-max value. Let c^j represents resultant column of $R_l^j\ \forall\ j \in \{1, 2, \ldots, k\}$. Let $c^1 = (n_1, n_2, n_3, n_5)$ and $c^2 = (n_1, n_2, n_4, n_4)$ where $(n_1, n_2, \ldots, n_5)$ represents integer values such that $(n_1 < n_2, \ldots, < n_5)$. Therefore, $\max(c^1) = \max(n_1, n_2, n_3, n_5) = n_5$ and $\max(c^2) = \max(n_1, n_2, n_4, n_4) = n_4$. Finally, the min-max value is $\min(\max(c^1), \max(c^2)) = \min(n_5, n_4) = n_4$. Therefore, R_l^2 is selected which results in a min-max value in c^2 compared to R_l^1 with min-max value greater than R_l^2.

b) In case of a tie, select the column of an R_l^j, $\forall\ j \in (1, 2, \ldots, k)$ with min-max value appear first in the resultant column of the link-route table.

In the first iteration, primary path P^1 from Table 1 and secondary path P^2 from Table 2 between s-d pair (1–3) result in equal amount of total sum of P^1 column and P^2 column. However, according to rule 4-b, column P^1 of link-route Table 3 is selected as the min-max entity value appears first in the P^1 column of the link-route table. In second, third, and fourth iterations given in Table 4, Table 5, and Table 6 respectively, paths P^2, P^2, and P^1 are selected respectively between s-d pairs (2-4), (3-1), and (4-2) due to min-max value according to 4-a.

Finally, the resultant columns will give primary routes between s-d pair in Table 7 according to LCA routing algorithm. These paths are s^{1-3}: $[l_{1-2} - l_{2-3}]$, s^{2-4}: $[l_{2-1} - l_{1-4}]$, s^{3-1}: $[l_{3-4} - l_{4-1}]$, and

TABLE 6
Resultant Table of All Link-Route Tables: Fourth Iteration

Links	s^{1-3} $P^1 \| P^2$	s^{2-4} $P^1 \| P^2$	s^{3-1} $P^1 \| P^2$	s^{4-2} $P^1 \| P^2$	Sum of rows $\mathbf{P^1} \| P^2$
l_{1-2}	1 | •	• | 0	• | 0	0 | 1	1 | 2
l_{2-3}	1 | •	• | 0	• | 0	0 | 0	1 | 1
l_{3-4}	0 | •	• | 0	• | 1	0 | 0	1 | 1
l_{4-1}	0 | •	• | 0	• | 1	0 | 1	1 | 2
l_{2-1}	0 | •	• | 1	• | 0	0 | 0	1 | 1
l_{1-4}	0 | •	• | 1	• | 0	0 | 0	1 | 1
l_{4-3}	0 | •	• | 0	• | 0	1 | 0	1 | 0
l_{3-2}	0 | •	• | 0	• | 0	1 | 0	1 | 0

TABLE 7
Resultant Table of All Link-Route Tables: Fifth Iteration

Links	s^{1-3} $P^1 \| P^2$	s^{2-4} $P^1 \| P^2$	s^{3-1} $P^1 \| P^2$	s^{4-2} $P^1 \| P^2$	Sum of rows $P^1 \| P^2$
l_{1-2}	1 | •	0 | •	0 | •	0 | •	1 | •
l_{2-3}	1 | •	0 | •	0 | •	0 | •	1 | •
l_{3-4}	0 | •	0 | •	1 | •	0 | •	1 | •
l_{4-1}	0 | •	0 | •	1 | •	0 | •	1 | •
l_{2-1}	0 | •	1 | •	0 | •	0 | •	1 | •
l_{1-4}	0 | •	1 | •	0 | •	0 | •	1 | •
l_{4-3}	0 | •	0 | •	0 | •	1 | •	1 | •
l_{3-2}	0 | •	0 | •	0 | •	1 | •	1 | •

s^{4-2}: $[l_{4-3} - l_{3-2}]$ which will become the primary paths and the resultant table will be updated accordingly as shown in Table 7. For alternate routes based on LCA algorithm, the other side columns will be added to the resultant table in the next iterations for all s-d pairs such that a route does not exist (columns with same entities) in the link-route table with primary paths. The links utilization can be found from the row summation in Table 7 for first shortest paths between s-d pairs. The links utilization obtained from the LCA routing in Table 7 is $[l_{1-2}, l_{2-3}, l_{3-4}, l_{4-1}, l_{2-1}, l_{1-4}, l_{4-3}, l_{3-2}] = [1, 1, 1, 1, 1, 1, 1, 1]$. However, the links utilization from the shortest path routing between s-d pairs using Dijkstra algorithm is $[l_{1-2}, l_{2-3}, l_{3-4}, l_{4-1}, l_{2-1}, l_{1-4}, l_{4-3}, l_{3-2}] = [1, 2, 1, 0, 1, 0, 1, 2]$. The summation of links utilization vectors in both routing schemes are equal to 8. However, LCA routing tries to equally utilize fiber links compare to the existing greedy algorithm which utilizes some links more often than the others.

Finally, for spectrum allocation, last-fit policy has been adopted [19], [37] which searches for free FSs on the available routes with the continuity and contiguity constraints. The contiguous free FSs with high indexes will be assigned to lightpaths for durations of requests.

3. Results and Discussion

The performance of the proposed LCA routing algorithm has been investigated for dynamic traffic in different networks including:

1) 14 bandwith variable wavelength selective switch (BV-WSS) based nodes network with 64 directed optical fiber links (net#1) in Fig. 2,
2) 30 BV-WSS based nodes randomly generated network with 140 directed optical fiber links (net#2) in Fig. 3, and
3) 4 by 4 mesh network with 16 BV-WSS based nodes and 48 directed optical fiber links (net#3) in Fig. 4.

The fiber link is used for transmission of traffic between neighbor nodes and the bandwidth spectrum of each fiber link is divided into 160 narrow channel FSs. The bandwidth of each FS is considered to be 12.5 GHz. In simulation phase, connection requests between end pairs are randomly generated according to a Poisson's process with connection mean arrival rate equals to

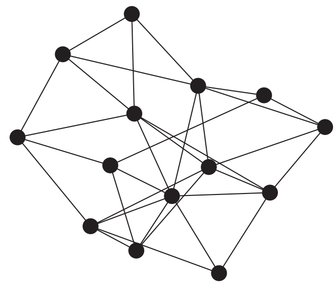

Fig. 2. (net#1) Network with $N = 14$ and $L = 64$.

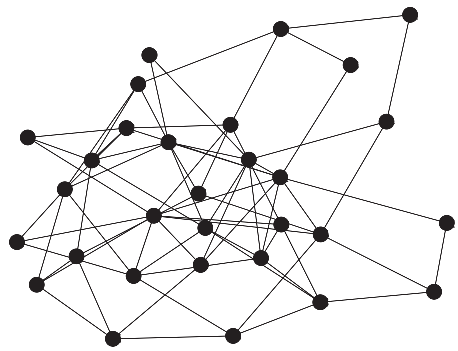

Fig. 3. (net#2) Network with $N = 30$ and $L = 140$.

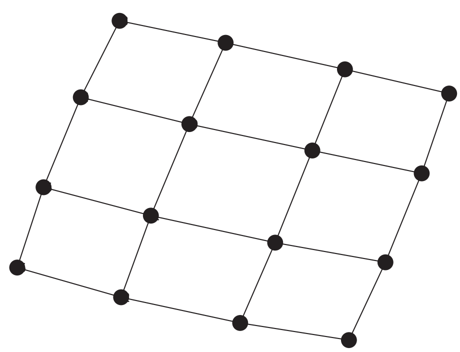

Fig. 4. (net#3) Network with $N = 16$ and $L = 48$.

λ. The connection requests randomly arrives to the network one by one with uniform distribution. The connection durations are generated according to exponential distribution with the mean service time μ equals to 1 unit. Similarly, the requested bandwidths between s-d pairs are randomly selcted from the set [6.25GHz, 12.5GHz, 25GHz] with uniform distribution. All simulation results have been obtained by generating 10^6 connection requests for accurate results [38]. Each point is obtained by taking an average value of 10 simulation results with 1 million connection requests during each simulation. Each point is an average of 10 different simulation results with standard deviation of the results at each point which is plotted in all figures to show the confidence interval and margin of errors of the reported work.

The performance of the LCA based routing is compared with the alternate routing [36] in terms of the link utilization in Figs. 5–7 for net#1, net#2, and net#3 respectively. The link utilization is defined as the number of lightpaths transiting through link l, i.e., P_l. The number of paths transiting some

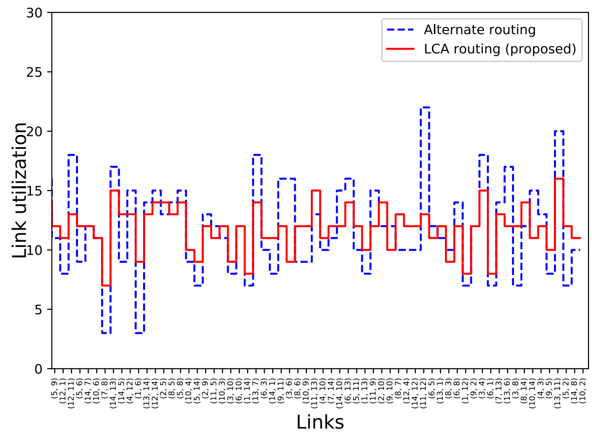

Fig. 5. Link utilization in net#1.

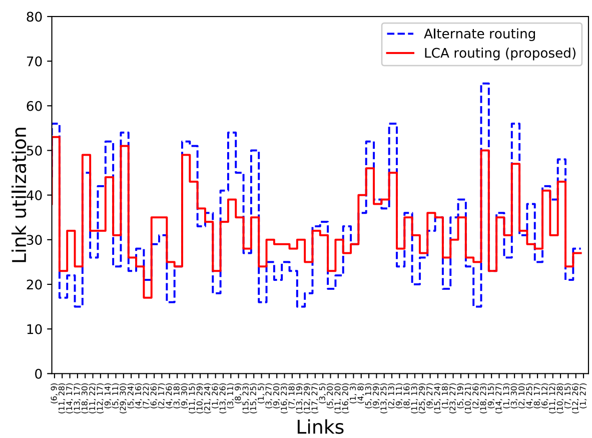

Fig. 6. Link utilization in net#2.

links are high in alternate routing scheme while in other links, few numbers of paths are transiting. Therefore, it leads to an inefficiently use FSs on high utilized links by keeping them busy all the time while under utilizing links and resources with few transiting paths. The proposed scheme tries to divert routes from the high utilized links to the under utilized links in all networks which are plotted in Figs. 5–7. The average numbers of paths transiting link *l* in both routing schemes remain similar as shown in Table 8 in all networks. However, the maximum numbers of paths transiting link *l* have been reduced by using the proposed LCA routing scheme from 22 to 16, 70 to 59, and 52 to 41 in net#1, net#2, and net#3 respectively. Similarly, the minimum numbers of paths transiting link *l* have been increased by using the proposed LCA routing scheme from 3 to 7, 11 to 17, and 11 to 16 in net#1, net#2, and net#3 respectively. This also reduces the standard deviation of paths transiting link *l* from 3.82 to 1.87, 12.63 to 8.32, and 9 to 6.23 in net#1, net#2, and net#3 respectively by using the proposed LCA routing scheme. The lower values of standard deviation in the proposed LCA routing scheme shows that network links have been treated near equally to the average link utilization compared to the alternate routing scheme. Therefore, the proposed LCA routing improves utilization of associated network resources compared to alternate routing. The first column in Table 8 shows the average number of paths transiting through a link in different networks. The values in different networks for the proposed LCA algorithm as well as the existing alternate routing algorithm remain same which shows that the space complexity of both algorithms

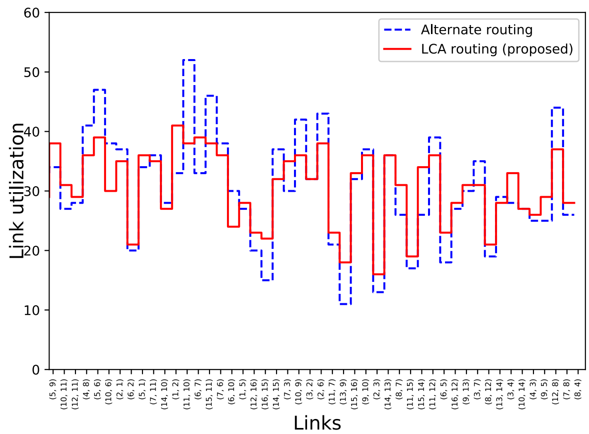

Fig. 7. Link utilization in net#3.

TABLE 8
Route-Link Utilization in Different Routing Schemes

Routing scheme	Avg. no. of P_l	Max. no. of P_l	Min. no. of P_l	std. dev. of P_l
14 node random network				
Alternate	11.81	22	3	3.82
LCA	11.81	16	7	1.87
30 node random network topology				
Alternate	32.57	70	11	12.63
LCA	32.57	59	17	8.32
4 by 4 mesh network				
Alternate	30.66	52	11	9.00
LCA	30.66	41	16	6.23

are equal. The proposed scheme requires an additional time for arranging the existing alternate routes which depends on the number of routes and network size. However, the existing alternate routing scheme as well as the proposed routing scheme compute routes offline. Therefore, the proposed LCA scheme will not require an overhead time during the dynamic network operation. The proposed LCA algorithm requires an equal time as alternate routing scheme during dynamic network operation.

The performance of the proposed LCA routing scheme has also been investigated for dynamic traffic in different elastic optical networks in terms of an average bandwidth blocking probability (BBP) which is an important performance parameter for dynamic traffic. An average BBP has been defined in [25] as the ratio of bandwidth demands of connections which could not be served during dynamic network operation due to unavailability of network resources to the total bandwidth of connection requests. The total bandwidth includes the bandwidth of the accepted connection requests as well as the bandwidth of the connection requests which are blocked during dynamic operation. The results obtained for net#1, net#2, and net#3 are plotted in Figs. 8 10 respectively. The results obtained from using LCA based routing are compared with alternate routing scheme as routes are computed in the offline phase in both routing schemes. However, alternate routing scheme does not consider any routing constraints. Therefore, it always tries to route traffic on shortest possible paths and greedily use some links more often than others. The associated resources on these links are highly utilized and have less chances to become idle most of the time. This leads to higher BBP in alternate routing compared to LCA based routing scheme as the later uses traffic engineered routes with the constraint to avoid link congestion. The results obtained from LCA based routing are also compared with the existing CLIB based routing scheme

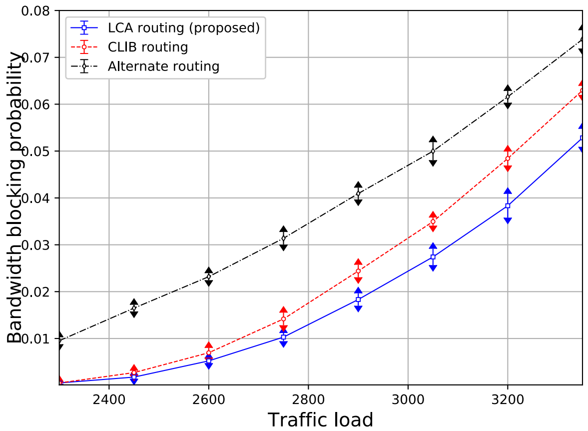

Fig. 8. Average network blocking probability vs. traffic load in net#1.

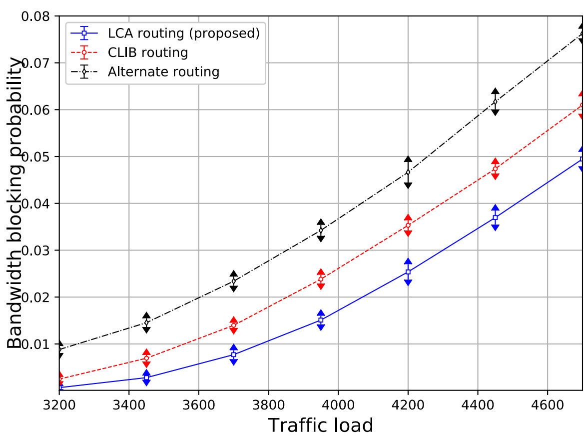

Fig. 9. Average network blocking probability vs. traffic load in net#2.

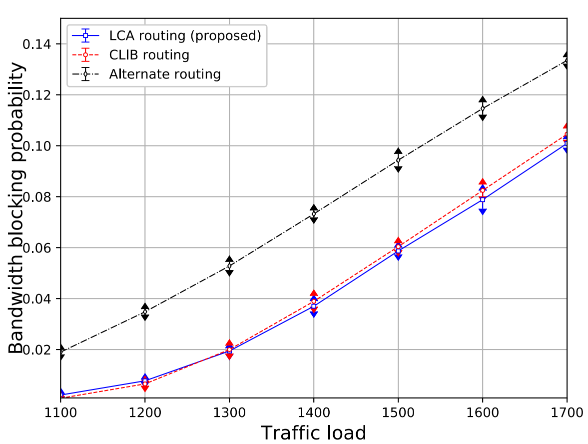

Fig. 10. Average network blocking probability vs. traffic load in net#3.

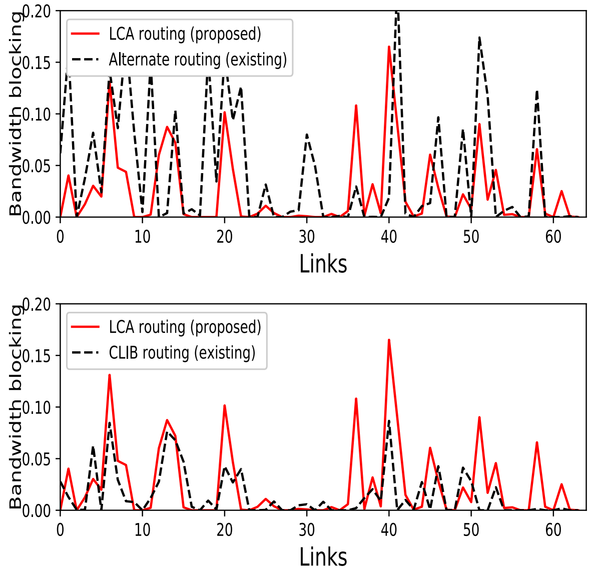

Fig. 11. BBPs observed by each link in net#1 considering network load = 2800.

for dynamic traffic which is an adaptive routing scheme [30]. The later selects set of all routes with free FSs and the routing decision is made based on the available lower indexed FS. This dynamically routes traffic between end pairs where the routes are not necessary to be shortest routes between s-d pairs. CLIB based routing scheme has lower BBP values compared to alternate routing scheme in all networks in Figs. 8–10 due to its dynamic nature. However, it has higher values of BBPs compared to the proposed LCA based routing scheme. Moreover, the proposed scheme computes LCA paths in the offline phase which are utilized for dynamic traffic in the online phase. However, CLIB based routing searches for lower indexed paths in the online phase which is more time consuming when it is utilized for dynamic networking compared to the proposed LCA based routing scheme.

Similarly, the most important performance of the proposed LCA scheme has been investigated in terms of the average link BBPs observed on all fiber link during dynamic network operation. The average link BBPs give a complete picture of the network using the proposed LCA routing scheme with an objective to minimize link congestions. The average link BBPs are simulated for networks in Figs. 2–4 which are respectively shown in Figs. 11– 13. It has been observed that the proposed LCA has reduced the congestion spikes on fiber links which were obtained using alternate routing scheme where the later greedily used shortest possible routes in all cases. Moreover, the existing CLIB based routing has approximately an equal congestion on network links compared to the proposed LCA routing scheme where the earlier use dynamic networking with an objective to utilize routes with lowered indexed FSs. However, both reduces link congestions compared to the alternate routing. The advantage of the proposed LCA routing scheme is that it utilizes the pre-computed routes for networking which will have minimum processing time during dynamic network operations compared to CLIB based routing which computes routes during the dynamic operation based on the current network state with paths having minimum indexed FSs.

Finally, we have investigated the impact of fragmentation using the proposed LCA algorithm which is compared with the existing alternate routing and CLIB based routing algorithms. EON considers the heterogeneous traffic as well as heterogenous bandwidth allocations. Therefore, it has a major issue in the form of fragmentation which is caused due to lightpath connections in EON requiring contiguous FSs along the paths. We have investigated the fragmentation issue in different network scenarios in this work by considering ABPM adopted from the work in [35] which

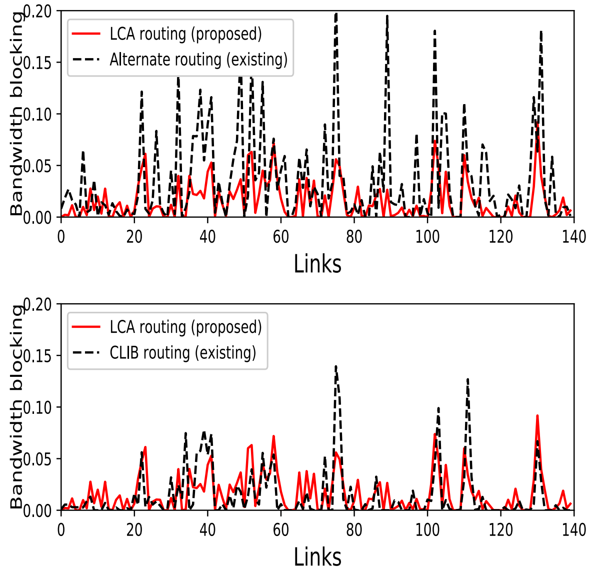

Fig. 12. BBPs observed by each link in net#2 considering network load = 3800.

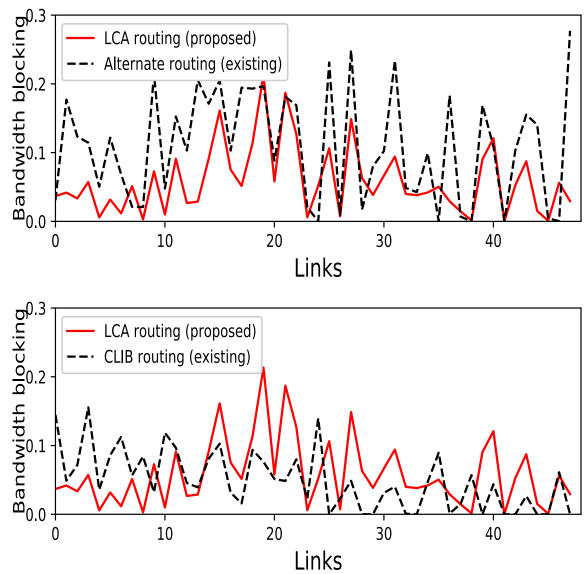

Fig. 13. BBP observed by each link in net#3 considering network load = 1200.

is mathematically expressed in 1.

$$\mathrm{ABPM} = \frac{\sum_{\forall \mathrm{arrivals}} \left(1 - \frac{\sum_{\forall \text{available FS blocks}} \lfloor \frac{\text{block size}}{\text{demanded slots}} \rfloor}{\lfloor \frac{\text{FSs on path}}{\text{demanded slots}} \rfloor}\right)}{\text{number of arrivals}} \tag{1}$$

The values of ABPM are obtained for net#1, net#2, as well as net#3 which are plotted in Figs. 14–16 respectively. The alternate routing algorithm greedily allocates traffic on the shortest possible routes between end pairs. Therefore, it contributes in higher fragmentation as the value of average ABPMs are higher compared to the proposed LCA routing scheme in different network scenarios. The proposed LCA scheme tries to balance the link loading during the offline stage and

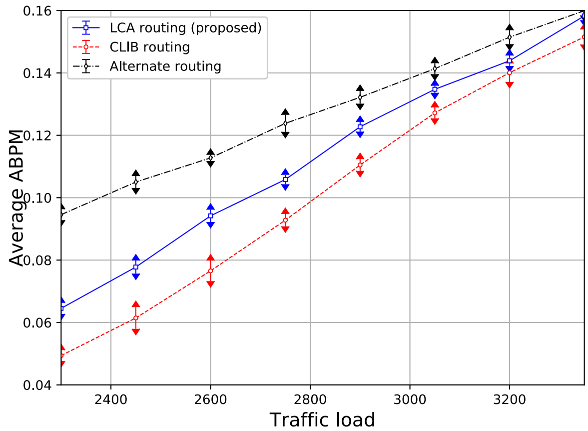

Fig. 14. Fragmentation in net#1.

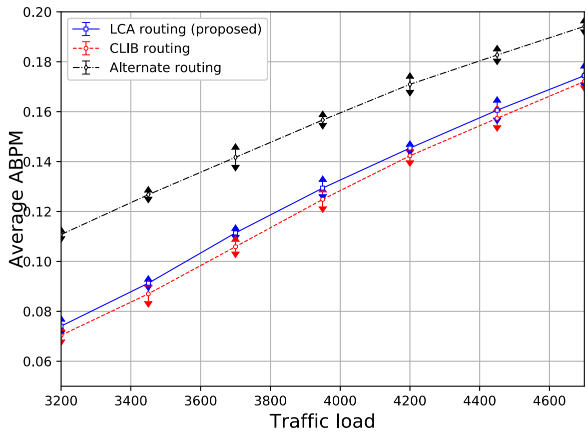

Fig. 15. Fragmentation in net#2.

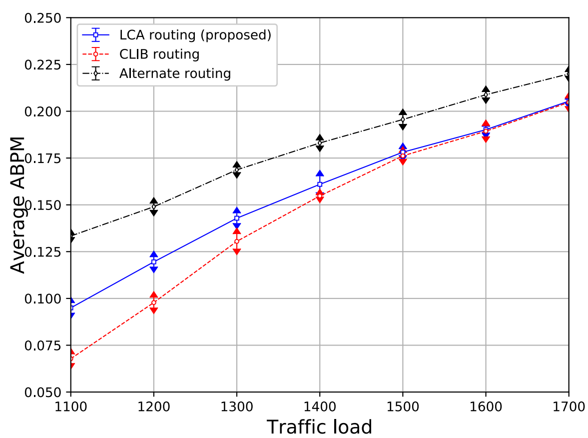

Fig. 16. Fragmentation in net#3.

signifiently reduces fragmentation during online network operation compared to alternate routing. Each point in Figs. 14–16 is obtained by taking an average value of ten simulation results with 1 million connection requests in each case. The existing dynamic routing algorithm, i.e., CLIB, selects a path between end pairs based on lower indexed FSs during the online network operation. However, it mostly utilizes lower portion of the spectrum as the algorithm selects a path between end pairs with the lower available FSs. Therefore, it contributes in minimum fragmentation for dynamic traffic.

4. Conclusion

In this work, LCA based routing scheme is proposed for dynamic traffic in EON which takes into account link congestion avoidance in the offline stage. The proposed scheme has been shown to outperform existing alternate routing scheme as well as CLIB based adaptive routing scheme for dynamic traffic in elastic optical networks. The proposed LCA based routing scheme has been shown to reduce the standard deviation of link utilization from the mean value in different networks in terms of the numbers of paths transitting an optical fiber link compared to alternate routing which has higher standard deviation from the mean value. Therefore, alternate routing greedily allocates some links more often than others. The proposed LCA based routing scheme diverts traffic from over-utilized links to under-utilized links. This efficiently improves resource utilization of networking components on all links. Therefore, it has been shown to efficiently reduce network BBPs compared to existing routing schemes in elastic optical networks. The proposed scheme has also been compared with the existing CLIB based adaptive routing which does not consider link congestion avoidance during online network operation. Therefore, the proposed scheme has lower BBPs in different networks compared to the existing CLIB based adaptive routing scheme. Similarly, the BBPs over all links in different networks were simulated using the proposed LCA model as well as the existing routing models. The proposed LCA scheme greatly improves link congestions for dynamic traffic compared to other routing schemes which is the main objective of the proposed model to divert traffic from the over congested links to improve network performance in dynamic network operation. Finally, the performance of the proposed LCA routing has been extended to investigate network fragmentation which is a challenging issue in EON. The proposed LCA outperformed the existing alternate routing scheme and resulted in lower fragmentation compared to the alternate routing as both schemes compute routing information in the offline phase. LCA has also been compared to the CLIB based routing which computes routing information in the online phase. CLIB based routing further reduces fragmentation at lower traffic. However, at higher traffic when network links become congested, both schemes resulted in equal amount of fragmentation in the network.

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