Congestion-Aware Dynamic RMCSA Algorithm for Spatially Multiplexed Elastic Optical Networks

Baljinder Singh Heera*, Yatindra Nath Singh, Anjali Sharma
Department of Electrical Engineering, Indian Institute of Technology Kanpur, 208016, India
Email: *baljinder.iitk@gmail.com

***Abstract*—We have proposed a dynamic Routing, Core, Modulation and Spectrum Assignment (RMCSA) algorithm for spatially multiplexed elastic optical networks with distance adaptive modulation formats. The algorithm finds an alternative candidate path based on the real-time traffic metric of the links. The algorithm reduces the connection-blocking probability by balancing the traffic load among network links. Extensive simulations are performed to validate the performance in terms of connection blocking and resource utilization efficiency. The results verify that the proposed algorithm performs significantly better than the benchmark K-shortest path routing and fragmentation-aware exact-fit spectrum allocation algorithms. The proposed algorithm with two alternative candidate paths outperforms the conventional K-shortest routing based RMCSA algorithm with four candidate paths.**

***Index Terms*—Congestion-aware, dynamic resource allocation, elastic optical network, space division multiplexing.**

I. Introduction

There has been an exponential rise in global internet traffic over the past decade. The proliferation of data-hungry applications like cloud computing, video conferencing, internet gaming, all kinds of sensing and automation using 5G services and the Internet of Things has led to many fold increase in the number of active internet users [1]. All of these Internet services offered to them are supported by different communication technologies with optical networks being the backbone. The capacity of single-mode optical fiber based networks has almost reached its nonlinear limit [2]. We need more capacity-efficient, cost-effective, energy-efficient, flexible and scalable networking solutions to serve the future capacity demands [3].

In Elastic Optical Networks (EONs), the channel bandwidth can be tailored using flexible spectrum allocation [4]. Also, higher-order modulation formats can be used to transmit multiple bits per symbol [5]. As a result, the EON can reduce the cost per bit by increasing spectral efficiency (bits/sec/Hz) [6]. For long-term capacity enhancement, we need to increase the available bandwidth. Many researchers have been investigating the deployment of multi-band transmission using S and L bands along with C band [7]. But dedicated Thulium Doped Fiber Amplifiers are required to optically amplify the spectrum in S-band. Multi-band transmission seems a promising technique to fulfil the capacity demands for near-future requirements. But the limitation is the development of the supporting equipment in a limited time frame.

Spatial multiplexing in EONs is another potential solution for the long haul as well as data-centre-based networks for capacity expansion in the future. Space Division Multiplexed-Elastic Optical Networks (SDM-EONs) enable parallel flexible transmission using spatial parameters viz. Multi-core Fibers (MCF), Few-mode fibers, and multiple fiber bundles, to name a few [8] [9]. The MCFs are limited by their crosstalk characteristics. The Crosstalk is caused by the power leakage from the adjacent cores in the core under consideration over a long-distance [10]. Depending on core coupling, MCFs can be classified as Strongly-coupled, weakly-coupled and uncoupled [11]. Uncoupled MCFs have two advantages: No crosstalk constraint and less space occupancy [12]. It can be fabricated within 125 μm cladding diameter of a single fiber. It is also break-resistant compared to MCFs with a large cladding diameter and more coupled cores. In the past few years, researchers have developed 4-core uncoupled MCFs for the long-haul and submarine optical networks [13].

Resource allocation in SDM-EON optical networks is an important area of research. An efficient RMCSA algorithm becomes more challenging due to added constraints viz spectrum continuity, spectrum contiguity, and core continuity [14]. Due to these constraints and the dynamic nature of traffic arrival and departure, the problem of fragmentation occurs. A drawback of fragmentation is that a connection request (CR) may get blocked even if required spectral resources are available but are fragmented [15]. A CR may also get blocked due to insufficient available spectral resources on the shortest path. However, not all the links of the shortest path may be the reason for blocking. The most central links, i.e., the links through which most of the traffic flows in the network, are the most likely reason for blocking [16]. Identifying such links and bypassing them to secure resources in alternative paths may be a better strategy to overcome the unnecessary blocking in the network. This is a better strategy as more alternate paths exist compared to node and link disjoint alternate paths. This paper proposes a congestion-aware RMCSA algorithm for resource allocation in a spatially multiplexed elastic optical network. The proposed algorithm can reduce connection blocking due to link congestion by balancing the load among the network links.

The rest of the paper is organized as follows. Section II describes the network model and the problem statement. In section III, we discuss the proposed algorithm. In section IV, we describe network and performance parameters. The results of simulation experiments are explained in section V. Finally, we conclude our work in section VI.

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II. Network Model and Problem Statement

A. Network Model

SDM-EON network can be defined by a graph $G(N, L, C, SS)$ where N denotes the set of nodes in the network, L represents the set of links connecting the nodes, C denotes the total number of parallel fibers (or cores of MCF) in a single link, and SS is the set of available spectrum slots in each fiber core. A link in the network can be identified as $l(i, j)$ where i and j are the nodes connected by the link. The connectivity among the nodes via the links is expressed by an Adjacency matrix (A_{ij}), whose elements (d_{ij}) represent the distance (weights) of the links between the (i, j) node pairs. The spectrum slots in the cores of the links are allocated to CRs demanding services for some time units. A new connection request in the network is denoted as $r(s, d, b)$. Here s and d represent the source and destination nodes, and b represents the bandwidth requested in Gbps.

B. Problem Statement

The Routing, Modulation, Core and Spectrum Assignment (RMCSA) problem is crucial for efficient resource utilization in SDM-EON [14]. To reduce the complexity of the joint RMCSA problem, it is divided into small sub-problems, viz., route and modulation format selection and core and spectrum Allocation Problem. The conventional routing algorithms, namely, Dijkstra's shortest and K-shortest path algorithms, use greedy methods to find the route between the source and destination nodes. Their goal is to find the path with the shortest distance. After finding the shortest path, the appropriate modulation format is selected, and then in a core, the required number of spectrum slots are searched. The spectrum slots' search complies with spectrum continuity and contiguity constraints. In the K-shortest path algorithm, the next shortest path is considered if the resources are not available on the shortest path. All the K-shortest paths are searched until the required slots are found. The advantage of these greedy algorithms is that once the network topology is defined, the K-shortest paths between each source-destination pair can be pre-computed and stored. When a CR $r(s, d, b)$ arrives, the K-Shortest paths between the s and d can be directly fetched instead of running Dijkstra's algorithm for every CR.

But, the shortest path routing algorithm does not perform best in networks' resource utilization. In optical network topology, the central links lie more frequently in the shortest path of source-destination pairs, as evident by the Edge Betweenness Centrality [16]. As the load on the network increases, these links become congested before the peripheral links. In this scenario, if for two alternative shortest paths between a source and destination, a link is common, which is congested and leads to blocking, then the CR will get blocked on the alternative path also. Therefore, for uneven traffic load among the links, we need to balance the load due to the incoming traffic among the links to avoid any particular link becoming a bottleneck. In other words, we need to make all the links equally central using an appropriate routing algorithm.

TABLE I: **List of Notations and Symbols**

Notation	Description
	Network Parameters
$G(N, L, C, SS)$	Network topology.
Z	Set of all s and d pairs
BW_s	Bandwidth to a single spectrum slot
SOR_{ln}	Spectrum Occupancy Ratio of n^{th} link
SS_o	Total slots occupied on a link
SS_t	Total slots available on a link
	Performance Parameters
R_b	Total number of blocked CRs
R_a	Total number of accepted CRs
BW_b	Total BW requirement of the blocked CRs
BW_{tr}	Total BW required by all the CRs arrived
TH_r	holding time of a connection request r
H_p	Hops of a working path p
τ	Total observation time

III. Proposed Algorithm and Illustrative Example

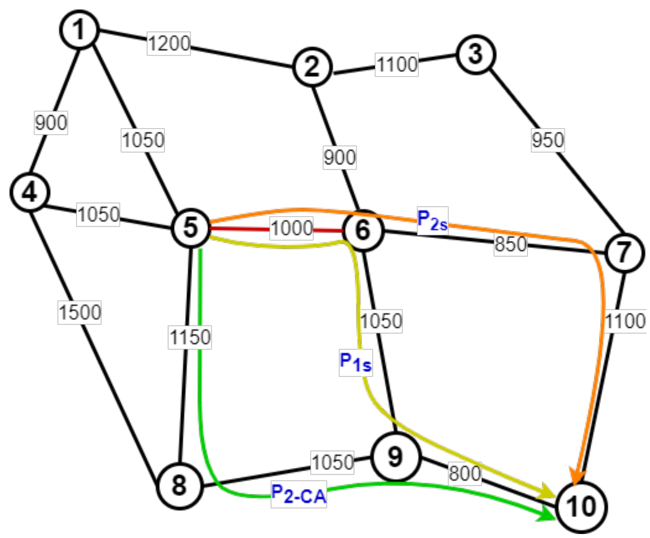


Fig. 1: Illustrative example.

Now we explain the proposed Congestion-aware first-fit routing, core, modulation, and spectrum assignment (CA-FF-RMCSA) algorithm using a test network of 10 nodes and 15 bidirectional links, shown in Fig. 1. According to the "Edge betweenness centrality" [16], the link $l(5, 6)$ will face large traffic if the shortest path routing is used. Let us assume a CR $r(5, 10, b)$ with source node $'5'$ and destination node $'10'$ arrives. If we use the 2-shortest path routing algorithm, the first shortest and the second shortest paths will be P_{1s} and P_{2s} with path lengths equal to 2850 Km and 2950 Km respectively. As we can see in Fig. 1, link $l(5, 6)$ is common in both paths. If a CR gets blocked on the path P_{1s}, there is a very high chance that it will get blocked on the path L_{2s} also. So, the idea of keeping more than one shortest paths ($K > 1$) to reduce connection blocking will not work in this case.

In contrast, the CA-FF-RMCSA algorithm at first finds resources in the shortest path P_{1s} itself. It chooses the value of Modulation format (M) against the length of the shortest path using Table II, and then computes the required number of spectrum slots (SS_r) using

$$SS_r = \left\lceil \frac{b}{BW_S * M} \right\rceil. \tag{1}$$

It uses the first-fit approach to select the core and to allocate the required spectrum slots (SS_r) inside the core. But, if the resources are not available in any of the cores in the shortest path, it uses the alternative path determined using the link congestion metric instead of the next shortest path as done conventionally. The congestion-aware shortest paths are also already stored in the memory. Now we describe the process of computing and storing the congestion-aware alternative paths. Suppose a shortest path between a $s-d$ pair spans n links say, $l_1, l_2, ..., l_n$. We set the weight of all these links as infinity one by one and compute the shortest path between the same $s-d$ pair n times using Dijkstra's algorithm. In this way we find alternative congestion-aware paths between a particular $s-d$ pair by omitting every link. These alternative paths are stored in the memory as $P_{2-CA}(s, d, l_n)$. Similarly, we compute congestion-aware alternative paths for every $s-d$ pair and store in the memory. Now we have shortest paths and congestion-aware alternative shortest paths stored in the memory for every $s-d$ pair.

Algorithm 1 To find a Congestion Aware-Alternative Path.

procedure CA-AP
Input: $G(N, L, C, SS)$, CR(s, d, SS_r), $P_{1s}(l_1, l_2, ...l_n)$
Output: P_{2-CA}
Fetch the links of the shortest path P_{1s}.
For every link, compute $SOR_{ln} = \frac{SS_o}{SS_t}$.
Sort the values of SOR_{ln}
Fetch the P_{2-CA} against highest congested link from the memory.
Return: P_{2-CA}.
end procedure

When a CR does not get required resources in shortest path, the congestion-aware alternative path is fetched from the memory using **Algorithm 1**. In the congestion-aware alternative path (P_{2-CA}) (see Fig. 1), the most congested link $l(5, 6)$ will not be there. Therefore, the availability of resources in the congestion-aware alternative path will be higher. The flowchart of the CA-FF-RMCSA algorithm is given in Fig. 2.

IV. Network and Performance Parameters

We performed simulation experiments on two realistic network typologies namely USNET and German Network (Fig. 3). The USNET comprises 24 nodes and 43 bi-directional links with an average link length of 1002.3 Km. The German Network is comparatively smaller having 17 nodes and 26 links with an average link length of 170.4 Km. In our simulations, each link consists of a pair of MCF. Each fiber has 4 cores and each core has 320 spectrum slots, each of 12.5 GHz. We have considered dual polarization multiplexing, so the baud rate of each slot is taken to be 25 Gbaud. The

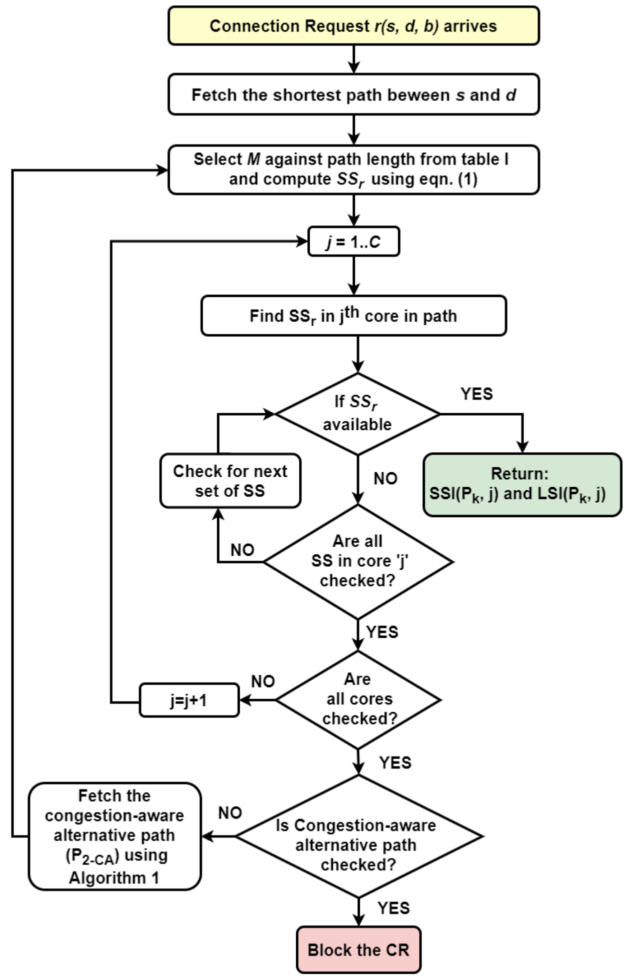
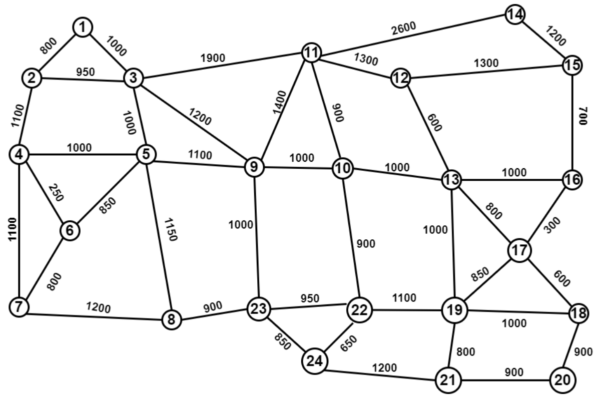


Fig. 2: Flowchart of CA-FF-RMCSA algorithm, SSI: Starting Slot Index, LSI: Last Slot Index.

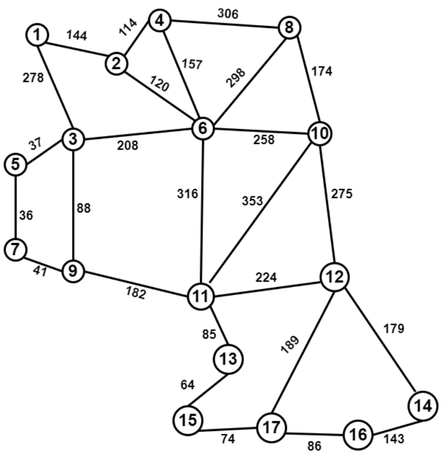
CRs arrive dynamically in the networks and follow a Poisson distribution with an average arrival rate λ, and the holding time is exponentially distributed with an average holding time $1/\mu$. The source (s) and destination (d) are chosen randomly with equal probability. A CR may ask for a data rate ranging from 25 Gbps to 150 Gbps with a granularity of 25 Gbps. The modulation format is chosen according to the path length (see Table II). Simulations are run for 10 iterations and results are recorded with a confidence interval of 99%. In each iteration, initial 10000 requests are not considered to allow the simulation to reach a steady state. Thereafter simulations are run up to 50,000 CRs.

TABLE II: **Modulation formats against path length**

Modulation Format	M	Transmission Capacity (Gbps)	Path Length (Km)
DP-BPSK	1	25	8000
DP-QPSK	2	50	4000
DP-8QAM	3	75	2000
DP-16QAM	4	100	1000
DP-32QAM	5	125	500
DP-64QAM	6	150	250



(a)



(b)

Fig. 3: Network topologies with link length in Km: (a) USNET and (b) German Network

To analyze the connection-blocking performance of the algorithms, we have used Request Blocking Probability (RBP) and Bandwidth Blocking Probability (BBP) as the performance metrics. Further, to check the performance in terms of resource utilization efficiency, we computed Network Resource Utilization (NRU) for each algorithm.

$$RBP = \frac{R_b}{R_b + R_a} \tag{2}$$

$$BBP = \frac{BW_b}{BW_{tr}} \tag{3}$$

$$NRU = \frac{\sum_{r \in R_a} SS_r \times H_p \times TH_r}{SS \times L \times C \times \tau} \tag{4}$$

The list of symbols and notation is given in Table I.

V. Results and Discussion

A. Study of Benchmark Algorithms

At first, we compute the performance of the K-shortest path first fit routing, modulation, core, and spectrum assignment (KSP-FF-RMCSA) algorithm against the number of candidate paths (K). We performed simulation experiments on USNET

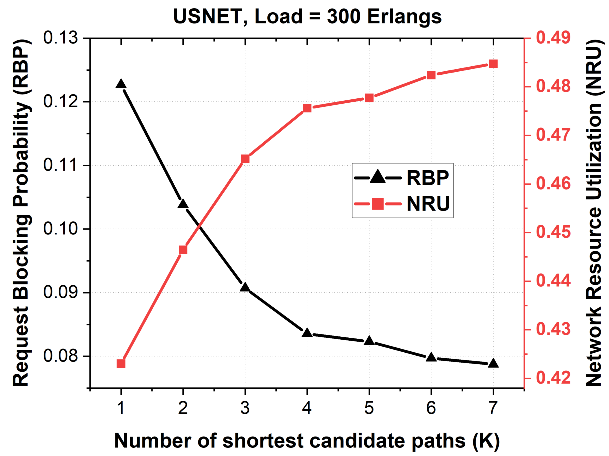


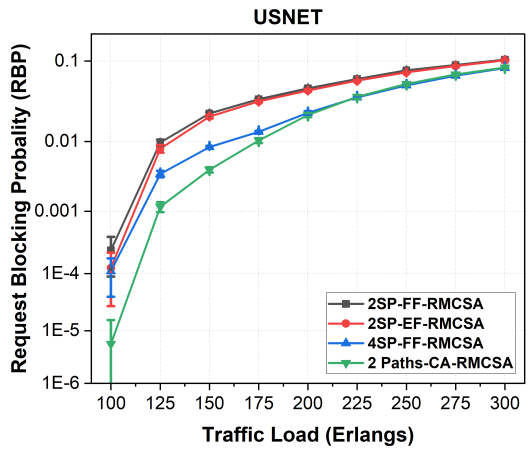
Fig. 4: Request Blocking Probability and Network Resource Utilization of KSP-FF-RMCSA algorithm against the Number of candidate paths (K)

network at a load of 300 Erlangs. We record the value of RBP and NRU by varying K from 1 up to 7. From the results (see Fig. 4), we found that RBP reduces as we increase the value of K. Also, the NRU increases as we increase the number of candidate paths. We can observe in these two plots, that as the number of available candidate paths increases, the algorithm is successfully able to find the paths with the required number of spectrum slots complying with continuity and contiguity constraints. It also results in an increase in NRU, as more CRs are being accommodated. From the results, we can see that the RBP and NRU performance increases almost linearly as we increase the value of K up to 4. For $K > 4$, both the RBP and NRU saturates. Therefore, using K up to 4 is effective. Beyond this, increasing K will increase the computational complexity without any significant performance gains. Therefore, to analyze and compare the results of the proposed 2 Paths CA-RMCSA algorithm, we took K=4 and K=2 in KSP-FF-RMCSA (4SP-FF-RMCSA and 2SP-FF-RMCSA) as benchmark algorithms.

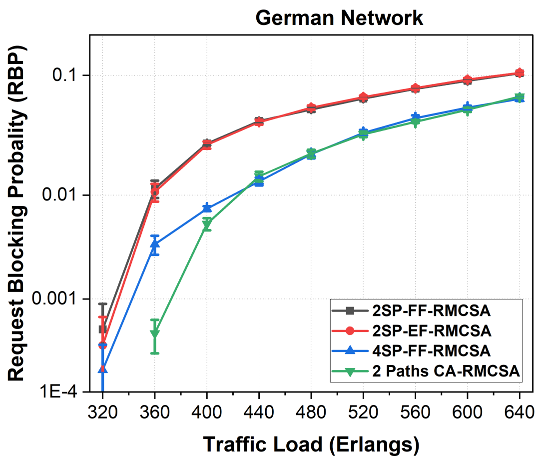
Then, among the most prevalent spectrum allocation techniques viz. random fit, first-fit, last-fit, and exact-fit, we found from the literature [17], [18] that the exact-fit spectrum allocation based RMCSA algorithm (KSP-EF-RMCSA) performs best in spectrum utilization at the cost of computational complexity. Exact-fit spectrum allocation is a fragmentation-aware technique that helps in the availability of more contiguous spectrum slots than the first-fit or last-fit technique by reducing the fragmentation level. So, we also took 2SP-EF-RMCSA as the benchmark algorithm.

B. Simulation Results

The RBP of the algorithms mentioned above for both the test networks is shown in Fig. 5. We can see that the 2SP-EF-RMCSA algorithm performs slightly better than the 2SP-FF-RMCSA algorithm, as stipulated earlier. It is because the



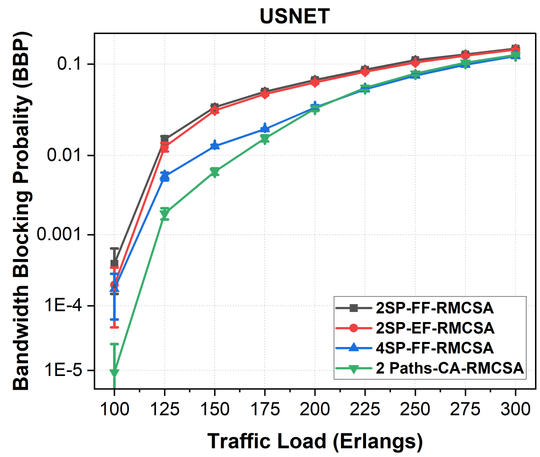
(a)



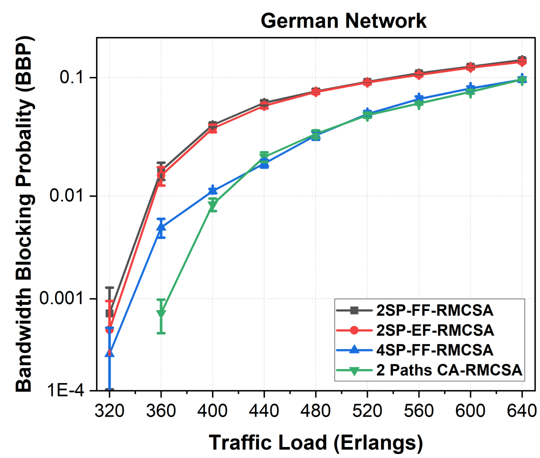
(b)

Fig. 5: Request Blocking Probability of (a) USNET and (b) German Network

exact fit algorithm helps to reduce the fragmentation and is capable of finding vacant contiguous slots more probably as compared to first-fit spectrum allocation. The 4SP-FF-RMCSA algorithm outperforms both 2SP-FF-RMCSA and 2SP-EF-RMCSA by a significant margin. This result points to the availability of more candidate paths with available SS_r complying with the continuity and contiguity constraints but with longer path lengths. Next, we computed the RBP performance of the proposed CA-FF-RMCSA algorithm and plotted it against the benchmark algorithms discussed above. It outperforms the 2SP-FF-RMCSA algorithm and 2SP-EF-RMCSA algorithms by a significant margin. The congestion-aware RMCSA algorithms with two candidate paths also perform better than the shortest-path RMCSA algorithm with four candidate paths for low traffic. For high traffic, both algorithms perform similarly. The results are consistent for both test networks. From these results, we may conclude that, if a CR gets blocked on the shortest candidate path, our proposed algorithm is able to find the alternative candidate path considering the link traffic metric, and the probability of accepting the CR is much higher than the alternative paths obtained from benchmark shortest path algorithms with the equal or higher number of candidate paths.



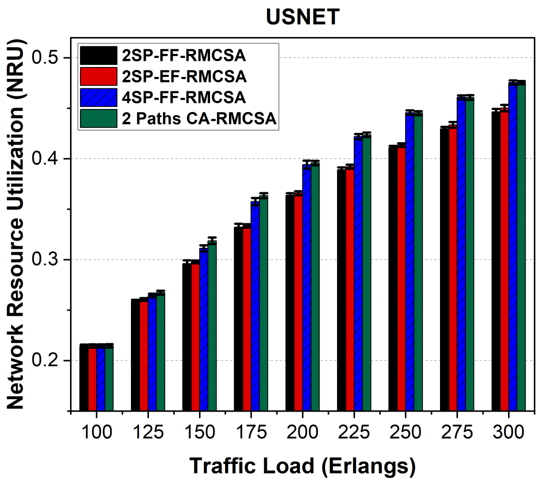
(a)



(b)

Fig. 6: Bandwidth Blocking Probability of (a) USNET and (b) German Network

Next, we compute the bandwidth-blocking performance of these algorithms under the same traffic conditions. We are considering this performance parameter because the algorithms tend to block higher bandwidth requests more than smaller bandwidth requests. Thus RBP does not capture the complete essence of blocking performance. The results are shown in Fig. 6. We can see that the proposed congestion-aware RMCSA algorithm performs better than the benchmark algorithms. It performs significantly better than the benchmark algorithms with two candidate paths. It also outperforms the 4SP-FF-RMCSA algorithm at lower load values. At higher load values, the 2 Paths-CA-RMCSA algorithm performs similarly to the 4SP-FF-RMCSA algorithm. So, we may conclude that the proposed CA-FF-RMCSA algorithm performs better than the benchmark algorithms for the dynamic traffic scenario, where the CRs demand heterogeneous data rates.



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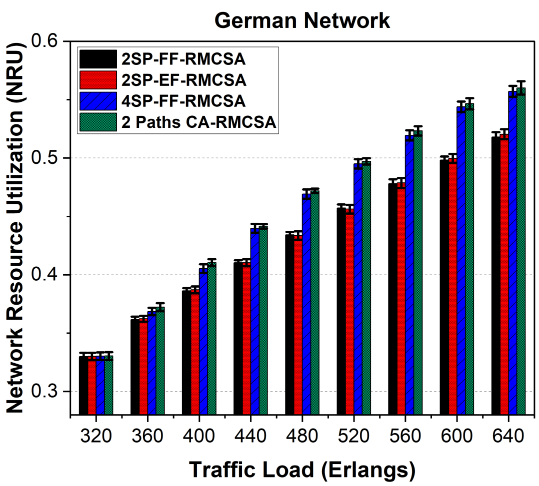

(b)

Fig. 7: Network Resource Utilization of (a) USNET and (b) German Network against the traffic load values

Finally, we compute the resource utilization efficiency of the proposed algorithm. It is desirable for an algorithm to utilize the available network bandwidth as much as possible by providing the resources for arriving CRs. Ideally, the NRU should increase as the value of the load increases. But due to variable traffic load among the links of the networks, some links may remain underutilized even at higher load values. In contrast, the other central links may face congestion and block future CRs. The NRU performance for both the test networks is shown in Fig. 7(a) and Fig. 7(b). We can see that the NRU of the proposed algorithm is significantly higher than the benchmark algorithms with two candidate paths. It is also slightly higher than the K-SP RMCSA algorithm with 4 candidate paths. Therefore, from the results, we conclude that the proposed algorithm can utilize the available network resources more efficiently by balancing the traffic load among the links of an optical network.

VI. Conclusion

We have proposed a dynamic-routing-based congestion-aware RMCSA algorithm for SDM-EON. It computes alternative candidate paths based on the spectrum occupancy status of network links. Extensive simulations are performed on two realistic network typologies using dynamic traffic scenarios with heterogeneous bandwidth demands. The proposed algorithm is tested on a spatially multiplexed elastic optical network. The proposed algorithm performs significantly better than the benchmark K-shortest path routing algorithm with first-fit and exact-fit spectrum allocation in connection blocking probability and resource utilization efficiency.

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