Shared Route Based Protection of Space Division Multiplexing Enabled Elastic Optical Networks

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***Abstract*- In the current work, to protect an elastic optical network based on space division multiplexing, we design a strategy, named as Shared Backup Route Protection for Multi Core network (SBRP-f-MCN), which is based on the shared backup mechanism and that generates the working and the secondary routes in a dynamic manner. The proposed SBRP-f-MCN strategy is compared to our previously designed Failure Independent Path Protecting-*p*-cycles for Multiple Core Network (FIPP-*p*-cycles-MCN) strategy and the existing Shared Route with assignment of Core and Spectrum (SR-w-a-CS) strategy. To compare the aforementioned strategies we consider realistic assumptions, topologies and parameters, and variations in the traffic load values. The obtained results make it evident that compared to both, the FIPP-*p*-cycles-MCN and the SR-w-a-CS strategies; the proposed SBRP-f-MCN strategy is able to provision complete protection against individual failures simultaneously incurring low overhead.**

Keywords— Elastic Optical Networks; Space Division Multiplexing; protection; RSA; RSCA.

1. Introduction

With the recent origination of multiple core fiber technology simultaneously with maturation of flexibility in assigning spectrum within elastic optical networks (EONs), there has been a growth in investigation of EONs which are based on space division multiplexing (SDM) technique [1]. SDM introduces a new dimension of 'space' and is realizable over a multiple core fiber (MCF), or a multiple mode fiber (MMF), or a few mode multiple core fiber (FMMCF). It is anticipated that SDM based EONs (SDM-b-EONs) will be able to (i) efficiently serve the next generation's applications and Internet which have been foreseen to handle traffic growth at a rate greater than the Petabit per second level [2], and (ii) provision much higher capacity and lower cost in comparison to the networks which resort to the use of conventional single mode fibers (SMFs) [3].

The basic issue to be resolved in EONs is that of routing and spectrum assignment (RSA) which requisites that both, spectrum-continuity and spectrum-contiguity constraints be satisfied over all links of candidate path [4]. Many studies exist in literature which has addressed the spectrum allocation issues in the EONs [5]. Further, with the use of SDM, for connection establishment, allocation of an individual or multiple core(s) is possible, and hence, SDM offers an extra freedom degree of 'space' that converts the basic RSA problem into routing, spectrum and core allocation (RSCA) problem which must additionally account for issues such as inter-core crosstalk or mode coupling [1]. Studies exist in literature which has addressed the RSCA issues in the EONs [6].

Further, an OTN's operation occurs in an unpredictable environment and hence, network protection is of immense significance especially for EONs which carry large traffic [7]. In addition, with the use of SDM in EONs, the amount of cores can be increased in view of larger network capacity which in turn will necessitate more protection. Amongst the many protection techniques, shared backup route protection (SBRP) method has been used extensively for protecting optical networks (both, fixed- and flexi-grid) owing to its efficient sharing of extra capacity and flexibility in providing service [8]. The SBRP technique utilizes a *1:N* scheme of protection wherein, the secondary (backup) routes are permitted to utilize similar slots (spectrum) under the condition that their corresponding primary (working) routes are disjoint in link [9].

To dynamically assign bandwidth in an EON, the authors in [1] have evaluated gains obtained by the extra dimension which is provided by SDM. In regard to the aforementioned, the authors have compared spectral and spatial super-channel assignment policies in a SDM-b-EON and have also investigated the modulation format's choice role on the blocking probability performance. In [9], the authors have investigated a static RSA strategy considering a survivable EON with SBRP. Initially, the authors have formulated the RSA/SBRP as an Integer Linear Programming (ILP) problem followed by the proposal of many heuristic methods. The efficiency of all the strategies is investigated considering various network cases and it is shown that the (i) proposed method outperforms the existing algorithms, and (ii) network topology and parameters significantly influence the obtained results.

The authors in [10] have split the RSCA problem into routing and SCA problem. The authors have introduced a *k*-shortest path (*k*-SP) pre-evaluation method for routing, and have also proposed SCA methods considering crosstalk awareness and prioritized area concept. In [11], the authors have extended an EON to include flexibility in 3 domains viz., time, frequency, and space. Considering various network topologies, the authors have investigated routing, spectrum, spatial mode, and modulation format assignment (RSSMFA) strategy. Specifically, authors have investigated a fragmentation-aware RSSMFA, and have focused on influence of constraints in formation of super-channels in a MIMO-based SDM system and their impact on network performance. The authors in [12] have formulated a RSCA problem for EONs using both, ILP and heuristic algorithms. The authors have aimed to optimally reduce the largest spectrum slices amount which is/are needed on any MCF core of a flexi-grid SDM network. The results show that the proposed method approximates closely with the optimal solution which is based on the ILP model.

In our previous study [13], we designed a FIPP-*p*-cycles for Multiple Core Network (FIPP-*p*-cycles-MCN) strategy which is independent of failure(s), and protects route(s). The results demonstrated that FIPP-*p*-cycles-MCN is efficient in provisioning of protection which is pre-configured, and that considered network topology's node degree significantly affects both, blocking and evaluated route's length in protected EON-b- SDM. To the best of the author's knowledge, except the study in [13], thus far, no other study has addressed the issue of protection in SDM-b-EONs.

In the current work, we propose the Shared Backup Route Protection for Multi Core network (SBRP-f-MCN) strategy which provisions shared protection in SDM-b-EONs. In view of decreasing Crosstalk per Slot (XTpSL), SBRP-f-MCN utilizes secondary routes such that they are provided with working routes. Further, SBRP-f-MCN uses a RSA algorithm whose basis is a multiple graph (MG) spectrum representation. The obtained results demonstrate that the SBRP-f-MCN strategy provisions effective protection without any substantial compromise on the blocking.

The rest of the paper is organized as follows. **Section 2** details the proposed SBRP-f-MCN protection strategy. In **Section 3**, initially, we detail the simulation assumptions followed by the presentation and discussion on the obtained simulation results. Finally, **Section 4** concludes the study.

2. SBRP-F-MCN Strategy

The proposed SBRP-f-MCN strategy solves the RSCA problem and hence, in addition to spectrum-continuity and spectrum-contiguity constraints which are addressed in RSA, SBRP-f-MCN also (i) considers the inter-core crosstalk (IC-XT) related to multiple core fiber, and (ii) ensures that during the routing process cores and links can be switched.

SBRP-f-MCN guarantees a protection route for every lightpath which is established and also ensures protection against single failures. In SBRP-f-MCN, the availability of spectrum within the network is modelled in the form of a MG which is allowed to have edges comprising of similar last (or end) vertices [13]. As shown in **Figure 1**, such a MG has vertices and edges which are representative of optical cross connect (OXC) and similar slot(s) set(s) in varied cores belonging to the link that connects OXCs, respectively. Also, in MG, *N* edges represent slot(s) number(s) within every network link's spectrum connect to the vertices, and further, irrespective of the core, a single slot is represented by every edge. Lastly, to utilize the shortest path (SP) routing algorithm within the proposed strategy, we ensure that the slot(s) availability is represented by tags on every edge wherein; a tag value of ' ∞ ' and '1' implies allocation of all slots, and availability for allocation of a minimum of single slot, respectively.

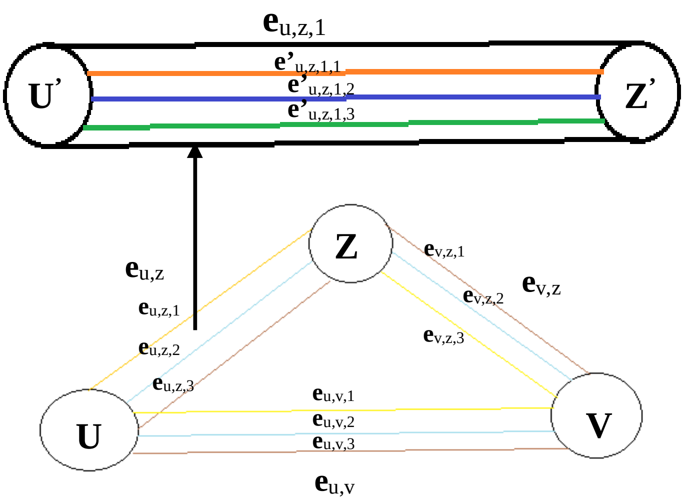

Figure 1. A Multiple Graph consisting of many edges

To detail SBRP-f-MCN, we use the following notations:

- s,d,bw denotes the source node, the destination node and the request for bandwidth in terms of slots, respectively. Further, $bw = 1,2,....N$ where N denotes the slots set amount between two nodes.
- $req(s,d,bw)$ denotes a request which initiates from the source node *s* and terminates at the destination node *d*, and further, demands a bandwidth of *bw* in terms of the slots.

- $G=(V,E,Wi)$ represents a MG which is labelled and which comprises of a V nodes set, an E edges set, and Wi edge weight set. Further, in G, the N slots within the link that connects two nodes of the network is represented by the edges that connect two vertices of G, which is mathematically represented as $|E| = N \cdot |V|$.
- $E=(e_{u,v,n})$ represents a n edges set where $e_{u,v,n}$ is the n^{th} edge which connects *u* and *v*. Further, $e'_{u,v,n,j}$ denotes that the core *j* has been selected for the utilization.
- $wi(e_{u,v,n})$ denotes the $e_{u,v,n}$ edge's weight. Further, $wi(e_{u,v,n})=1$ implies availability of the n^{th} slot within the link that connects the OXC *u* and *v*, whereas, $wi(e_{u,v,n})=\infty$ denotes the allocation of the slot.
- $Wi=\{wi(e_{u,v,n})\}$ represents the edge weights set.
- $\overline{G}_{n,bw}=\left(\overline{V},\overline{E},\overline{\overline{Wi}}\right)$ represents a n^{th} labelled MG in which $\overline{V}=V$ represents the nodes set, $\overline{E}$ denotes the edges set that connects $\{\overline{u},\overline{v}\}\in\overline{V}$, and $\overline{\overline{Wi}}$ denotes the costs set linked to $\overline{E}$. It must be noted that the edges within $\overline{E}$ map to the *k* edges within G initiating at the n^{th} edge.
- $\overline{e}_{u,v}\in\overline{E}$ represents the edge that connects $\overline{u}$ and $\overline{v}$. Further, $\left|\overline{e}_{u,v}\right| = bw$ and $\overline{e}_{\overline{u},\overline{v}}=\{e_{u,v,n}\}\in E$ denotes a string (or chain) in which the smallest and the largest edge that is ordered is denoted by $e_{u,v,n}$, and $e_{u,v,n+bw}$, respectively.
- $\overline{wi_n}\left(\overline{e}_{\overline{u},\overline{v}}\right)$ denotes the edge's (i.e., $\overline{e}_{\overline{u},\overline{v}}$) weight, and $\overline{\overline{Wi}}_n=\left\{\overline{wi_n}\left(\overline{e}_{\overline{u},\overline{v}}\right)\right\}$ denotes the edge weights set.
- S_n represents the MG $\overline{G}_n's$ string which ensures that the smallest and the largest node that is ordered is denoted by the source node (s) and the destination node (d).
- $Wi\left(\overline{S}_n\right): \sum_{\overline{e}_{\overline{u},\overline{v}}\in\left\{\overline{S}_n\right\}} \overline{e}_{\overline{u},\overline{v}}$ represents the route (i.e., $\overline{S}_n$) weight which implies the aggregate weights of all the edges within the string.
- $Wi_{S_{s,d}}$ denotes the SP's weight between source node (s) and destination node (d).
- $\overline{q}_{u,v,k}$ represents a backup route which contains the u and v vertices, and also the edges that correspond to the mapping of the MG $Gs\ \ bw$ edges. Also, $\overline{Q}_{u,v,k}=\overline{q}_{u,v,k}$ represents all the backup routes set which comprises of the u and v vertices, and also the edges that correspond to mapping of the MG $Gs\ \ bw$ edges.
- $\overline{Q}$ denotes the established and active backup route(s). Further, Q_n represents the $\overline{G}_n's$ string and also ensures that the smallest and the largest node that is ordered is denoted by the source node (s) and the destination node (d).
- $Wi\left(\overline{Q}_n\right): \sum_{\overline{e}_{\overline{u},\overline{v}}\in\left\{\overline{Q}_n\right\}} \overline{e}_{\overline{u},\overline{v}}$ represents the $\overline{Q}_n$ backup route's weight which implies the aggregate weights of all the edges within the string.
- $W_{Q_{s,d}}$ represents the weight of that backup route which will provision the protection to the route between the source node (s) and the destination node (d).

The steps involved in the SBRP-f-MCN strategy operation are detailed Table 1 which shows that the SBRP-f-MCN strategy comprises of the following steps:

1. In **Line 1**, strategy is able to establish all the edges set which are mapped onto $\overline{G}_{n,b}$.
2. In **Line 2**, for $\overline{G}_{n,b}$, strategy solves the SP algorithm and further, is able to provision the route and its corresponding weight. It must be noted that an infinite value of the SP's weight implies that, for a request *bw* with its allotting initiating with the n^{th} slot, it is impossible to evaluate a route under the constraint of spectrum contiguity.
3. In **Line 3**, a route is chosen amongst the *N-b+1* SPs such that it has minimum value of the weight.
4. In the event that the weight of all the SPs is infinite (specified in **Line 4**), it is implied that there occurs no route that is able to satisfy the demand of *bw* slots under the constraint of spectrum contiguity i.e., there is no available route. As a consequence, the demand is blocked (specified in **Line 5**).
5. Else, as specified in **Line 7**, a search is initiated to evaluate a route so as to provision protection to the lightpath which is to be established.
6. In the event that an existing route is found, the lightpath establishment occurs (specified in **Line 8**). Consequently, in the MG G, the corresponding edges' weight is altered to infinity (specified in **Line 9**) which implies that the spectrum slots are assigned to new lightpath which has been established. Else, as specified in **Line 11** and **Line 12**, creation of a new a route for protecting the established lightpath has to be conducted.
7. Lastly, in the event that no route can be established for protecting the lightpath, the demand is blocked (specified in **Line 15**). Else, there occurs the establishment of both, the working route and the secondary route (specified in **Line 17**) so as to satisfy the demand. Consequently, in G , the corresponding edges' weight is altered to infinity (specified in **Line 18** and **Line 19**) which implies that the spectrum slots are assigned to the new lightpath which has been established.

Table 1. Steps involved in the SBRP-f-MCN strategy

1.	$\forall n = 1......N - bw$
2.	$\{Wi(S_n), S_n\} = SP(\overline{G}_{n,k}, req(s,d,bw))$
3.	$Wi_{S_{s,d}} = Wi(S_n) \| \forall i\, Wi(S_n) \le Wi(S_i)$
4.	**if** $Wi_{S_{s,d}} = \infty$ **then**
5.	*block* $req(s,d,bw)$
6.	**else**;
7.	**if** $Q_n \ne \phi \quad \forall Q_n \in \overline{Q}$ **then**
8.	establish $req(s,d,bw)$ as S_n and Q_n
9.	$Wi(e'_{u,v,i}) = \infty \quad \forall\{u,v\} \in \overline{P}_i \quad n = n...i + bw - 1$
10.	**else**
11.	$\forall n = 1......N - bw$
12.	$\{Wi(Q_n), Q_n\} = SP(\overline{G}_{n,k}, req(s,d,bw))$
13.	$Wi_{Q_{s,d}} = Wi(Q_n) \| \forall i Wi(Q_n) \le Wi(Q_i)$
14.	**if** $Wi_{Q_{s,d}} = \infty$ **then**
15.	*block* $req(s,d,bw)$;
16.	**else**;
17.	establish $req(s,d,bw)$ as $\overline{S}_n$ and $\overline{Q}_n$
18.	$Wi(e'_{u,v,i}) = \infty \quad \forall\{u,v\} \in \overline{P}_i \quad n = n...i + bw - 1$
19.	$Wi(e'_{u,v,i}) = \infty \quad \forall\{u,v\} \in \overline{Q}_i \quad n = n....i + bw - 1$
20.	**end if**;
21.	**end if**;
22.	**end if**;

3. SBRP-f-MCN Strategy's Performance Evaluation

In this section, initially, we present the various simulation assumptions adopted in our study followed by presentation and discussion of the obtained simulation results.

3.1. Simulation Setup and Parameters

We evaluate SBRP-f-MCN's performance by comparing it with FIPP-*p*-*c*-MCN [13] and Shared Route with assignment of Core and Spectrum (SR-w-a-CS) [10]. FIPP-*p*-*c*-MCN decides on lightpaths' establishment only in a FIPP *p*-cycle protected network whereas, SR-w-a-CS addresses the working route independently which implies that it treats routing and CS issues separately by virtue of employment of pre-evaluated multiple paths. Further, in SR-w-a-CS the secondary route is also developed in the aforementioned similar manner; however, the secondary route resorts to the *1:N* scheme.

The simulation experiments were conducted under the assumption of 7 cores and the interval for confidence used was 96% level of confidence which was derived using the method of non-dependent replication. For every simulation, we generate 5,00000 demands and further, we ensured that all simulations in regard to the proposed strategy utilized a similar seeds set. Further, we adapted the average time of arrival and the average time for holding such that the traffic load (in Erlangs) which is desired could be simulated. We also assumed the division of spectrum into 320 slots with each slot being 12.5 GHz wide [4]. Lastly, we use the two realistic network topologies (i.e., DT, and TID) as detailed in [4].

3.2. Simulation Results and Discussions

To compare the strategies, we use the following metrics: (i) the Bandwidth Blocking Ratio (BwBR) defined as the ratio of bandwidth of the demands which are rejected and the aggregate bandwidth which is demanded, (ii) the mean working and secondary routes' hops amount, and (iii) the Crosstalk per Slot (XTpSL) defined as the ratio of existing (i.e., actual) index of XT and maximal value of index of XT. In our study, we (i) define XT ratio as the mean value amongst all the slots of spectrum as in [15], and (ii) do not consider the XTpSL in the case(s) when there has occurred a reservation of a slot however, that slot is not utilized. It must be noted that all the aforementioned metrics are plotted against variation of traffic load (in Erlang) for both the considered network topologies.

Figure 2 shows the variation of BwBR with traffic load for the TID topology. It can be observed from the figure that compared to both, the SBRP-f-MCN and the SR-w-a-CS strategies which begin to block the demands at approximately 85 Erlangs, the FIPP-p-c-MCN strategy starts the blocking of demands at 50 Erlangs. Further, at the traffic load of approximately 85 Erlangs, the SBRP-f-MCN strategy is seen to provide much lower blocking (BwBR = 0.00095) in comparison to the SR-w-a-CS strategy (BwBR = 0.01). Also, when the traffic load increases to a very high value of approximately 400 Erlangs, the SBRP-f-MCN strategy stills provides lesser blocking (BwBR = 0.10) when compared to the FIPP-p-c-MCN (BwBR = 0.13) and the SR-w-a-CS (BwBR = 0.24) strategies. With the aforementioned obtained results in regard to blocking, it can be deduced that in view of provisioning protection, in comparison to selecting the path and the core in different steps as conducted by the SR-w-a-CS strategy, it is beneficial to jointly select the path and the core as in the SBRP-f-MCN strategy. It can also be inferred that the SBRP-f-MCN strategy is able to generate acceptable blocking performance for a SDM-b-EON.

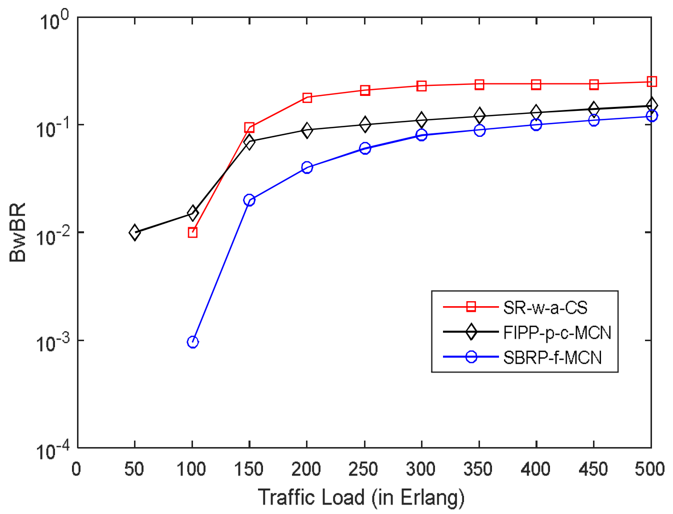

Figure 2. BwBP versus traffic load considering the TID topology

In **Figure 3**, for the TID topology, for a variation of the traffic load we show the mean working routes' hops amount which has a high value for small values of the traffic load since, with the spectrum being already assigned, under high traffic load there occurs a possibility to establish short routes only. It can be observed from the figure that till a load of approximately 100 Erlangs, the three considered strategies require the same hops amount for every working route; however, for high values of the traffic load, the SBRP-f-MCN and the SR-w-a-CS strategies demonstrate the lowest and highest hops amount which are assigned to every working route, respectively.

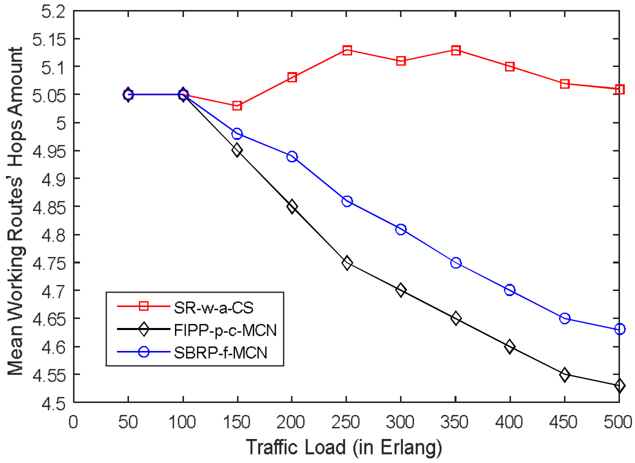

Figure 3. Mean working routes' hops amount versus traffic load considering the TID topology.

Figure 4 shows the mean secondary routes' hops amount with a variation in the traffic load for the TID topology. It can be seen from the figure that, irrespective of the traffic load, both, the SBRP-f-MCN and the SR-w-a-CS strategies generate approximately a constant hops amount which are assigned to every secondary route. Also, till approximately 150 Erlangs both the strategies are seen to require the same hops amount to be assigned; however, for loads greater than 150 Erlangs, the SBRP-f-MCN strategy starts to require lesser hops amount for assignment compared to the SR-w-a-CS strategy. Further, for all the traffic loads, compared to the SBRP-f-MCN and the SR-w-a-CS strategies, the FIPP-p-c-MCN strategy generates higher amount of secondary routes to be assigned owing to the cost which is incurred for creating the *p*-cycle.

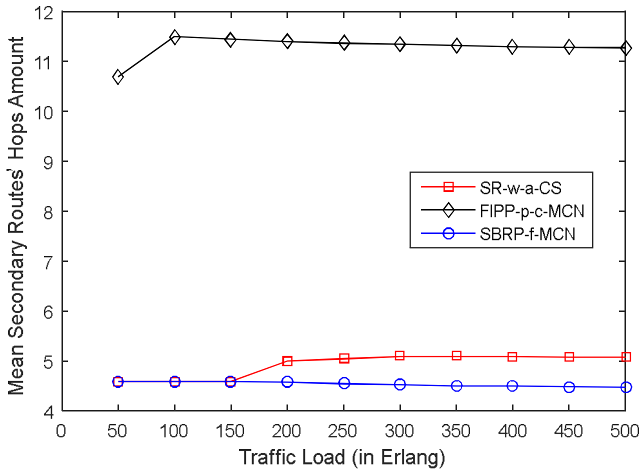

Figure 4. Mean secondary routes' hops amount versus traffic load considering the TID topology

Figure 5 shows the XTpSL values for the three considered strategies with a variation in the traffic load for the TID topology. For the SBRP-f-MCN and the FIPP-p-c-MCN strategies, the XTpSL initiates at the same value of 0.25, and increases till a value of 0.42 and 0.52, respectively. For a fixed traffic load value, the SR-w-a-CS strategy demonstrates much higher XTpSL compared to the SBRP-f-MCN and the FIPP-p-c-MCN strategies. For the SR-w-a-CS strategy, the XTpSL stars and ends at the values of 0.51 and 0.64, respectively. From the aforementioned results it can be inferred that (i) by resorting to use of the SBRP-f-MCN strategy, lesser amount of XT is generated owing to more uniform distribution of the connections, and (ii) the generated XT can be minimized by the interspersed core(s) utilization for both, the working and the secondary routes.

Overall, the results obtained for the TID topology suggest that the proposed SBRP-f-MCN strategy is able to demonstrate acceptable blocking performance with high utilization and low XTpSL generation.

Figure 6 shows the BwBR with a variation in the traffic load for the DT topology. It can be observed from the figure that the FIPP-p-c-MCN and the SR-w-a-CS strategies initiate the blocking of demands at 50 Erlangs whereas; SBRP-f-MCN strategy begins blocking the demands at approximately 85 Erlangs. Further, at the traffic load of approximately 85 Erlangs, the SBRP-f-MCN strategy is seen to provide much lower blocking (BwBR = 0.043) in comparison to the SR-w-a-CS strategy (BwBR = 0.32). Also, when the traffic load increases to a very high value of approximately 400 Erlangs, the SBRP-f-MCN strategy stills provides lesser blocking (BwBR = 0.16) when compared to the FIPP-p-c-MCN (BwBR = 0.18) and the SR-w-a-CS (BwBR = 0.56) strategies. Comparing the results of Fig. 6 for DT topology with those shown in Fig. 2 for the TID topology, it can be observed that owing to the DT topology's lower degree of node which results in constrictions, the BwBP increases at a much faster pace with the variation in traffic load.

In **Figure 7**, for the DT topology, for a variation of the traffic load we show the mean working routes' hops amount. It can be observed from the figure that till a load of approximately 100 Erlangs, the three considered strategies require the same hops amount for every working route. However, for high values of the traffic load, the SR-w-a-CS strategy starts to demonstrate very high hops amount which are assigned to every working route whereas; the SBRP-f-MCN strategy demands much lower mean hops amount for every working route.

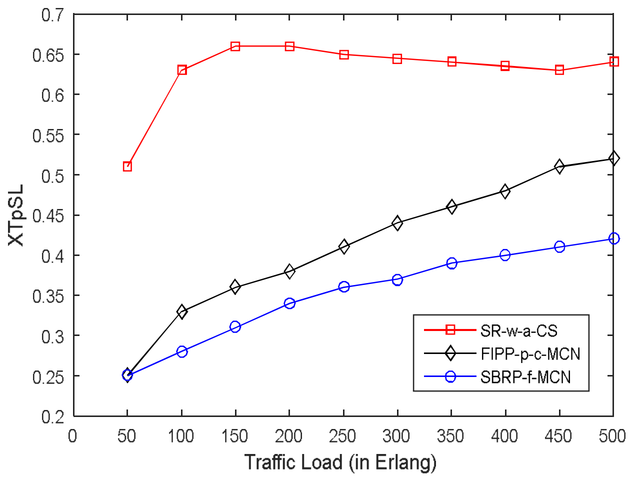

Figure 5. XTpSL versus traffic load considering the TID topology

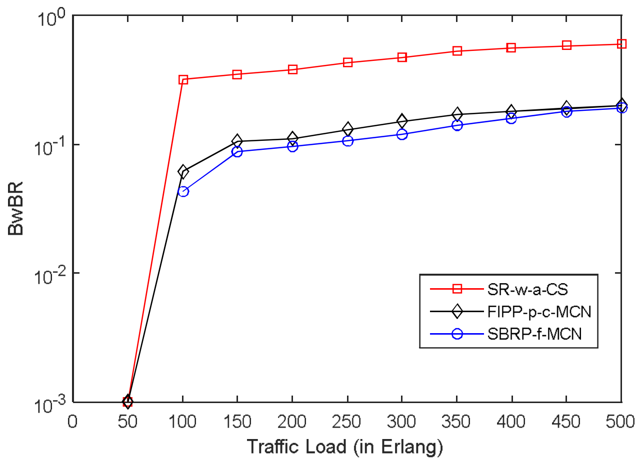

Figure 6. BwBP versus traffic load considering the DT topology

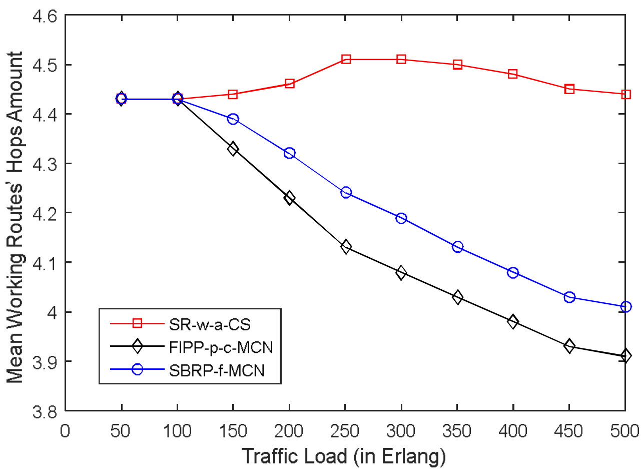

Figure 7. Mean working routes' hops amount versus traffic load considering the DT topology

Figure 8 shows the mean secondary routes' hops amount with a variation in the traffic load for the DT topology. Similar to the case of the TID topology, it can be seen from Fig. 8 that, irrespective of the traffic load, both, the SBRP-f-MCN and the SR-w-a-CS strategies generate approximately a constant hops amount which are assigned to every secondary route. Also, for all the traffic loads, compared to the SBRP-f-MCN and the SR-w-a-CS strategies, the FIPP-p-c-MCN strategy generates higher amount of secondary routes to be assigned owing to the cost which is incurred for creating the *p*-cycle.

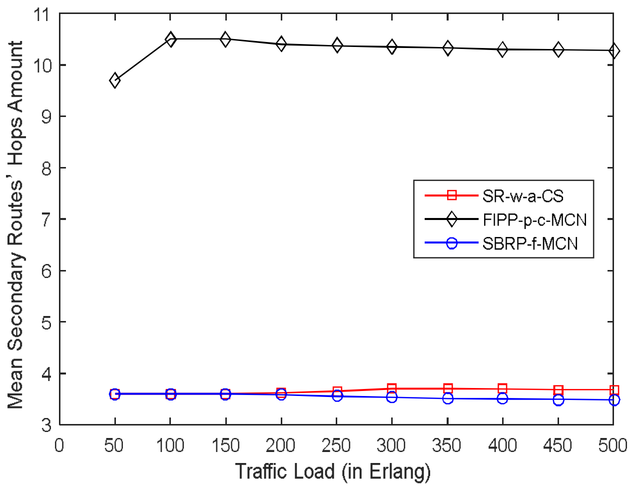

Figure 8. Mean secondary routes' hops amount versus traffic load considering the DT topology

Figure 9 shows the XTpSL values for the three considered strategies with a variation in the traffic load for the DT topology. Compared to the XTpSL results obtained for the TID topology (see fig. 5), for the DT topology, the generated XTpSL is much higher. For the SBRP-f-MCN, FIPP-p-c-MCN and the SR-w-a-CS strategies, the XTpSL initiates at 0.35, 0.4, and 0.61, and ends at 0.54, 0.62, and 0.74, respectively.

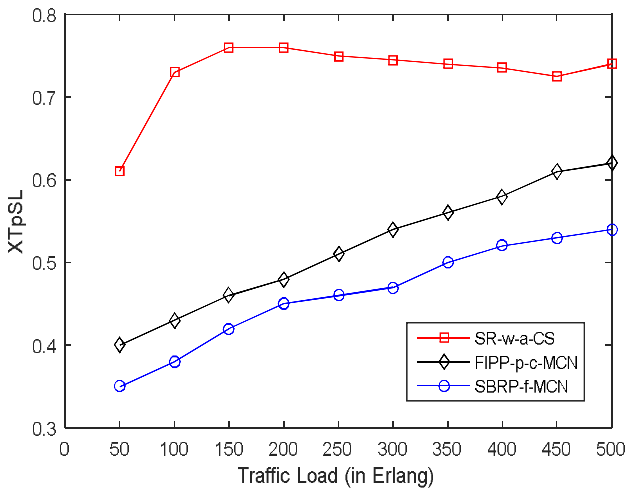

Figure 9. XTpSL versus traffic load considering the DT topology

4. Conclusion

In the current work, we proposed the SBRP-f-MCN strategy which dynamically generates working and secondary routes. To access SBRP-f-MCN's performance, we compared it with the FIPP-*p*-cycles-MCN and the SR-w-a-CS strategies, under the consideration of realistic assumptions, topologies and parameters, and variations in the traffic load values. The obtained results demonstrate that SBRP-f-MCN (i) provisions complete protection for individual failures simultaneously incurring low overhead, and (ii) demands an acceptable overhead for TID network (i.e., network with high node connectivity); however, for DT network, its performance is not attractive when compared to FIPP-*p*-cycles-MCN.

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