On routing, modulation format, space and spectrum allocation with protection in space division multiplexing-based elastic optical networks

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ABSTRACT
The required upgradation of the optical network capacity, which is constrained by the non-linear Shannon’s limit and the provisioning needed for the future diverse Internet traffic’s required capacity, can be resolved by the deployment of the Space Division Multiplexing (SDM)-based Elastic Optical Networks (EONs) (SDM-b-EONs). However, with an increase in the rates of transmissions, for countering the network failures, there will be a need for protection mechanisms, specifically those, which can protect the routes and also provision solutions which are end-to-end. In the current work, for an SDM-b-EON, we introduce the Routing, Modulation Format, Space and Spectrum Allocation with Protection-with-Protection (RMFSSA-w-P) algorithm which is independent of the failures in protecting the routes and also considers the modulation format adaptation. We conduct extensive simulations considering realistic networks and the obtained results demonstrate the superior performance of the RMFSSA-w-P algorithm than the existing strategies.

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1. Introduction

The ever-growing diverse traffic and its related bandwidth requests have rendered the optical networks (OTNs) limited by capacity (Agrell et al., 2016). With the introduction of elastic optical networks (EONs), the needs for large capacity and heterogeneous granularity in traffic of the next-generation OTNs can be satisfied (Iyer & Singh, 2019). However, owing to its use of only two multiplexing dimensions, (Winzer, 2012) has envisioned that the EONs will also result in a crunch of the fibre capacity. The aforementioned can be ameliorated by the adoption of the space division multiplexing (SDM) technology in which, many spaces (fibres, cores or modes) are utilized in parallel hence provisioning an increase in the spectral resources which can be utilized (Khodashenas et al., 2017). The SDM-based EONs (SDM-b-EONs) will be able to serve the next generation’s applications and Internet efficiently which have been anticipated to handle traffic growth at a rate greater than Petabit per second level (Winzer, 2014).
Network protection in the EONs assumes immense significance as such networks carry large amounts of traffic (Iyer, 2018) and as a consequence, become vulnerable to a massive loss in the data (Iyer & Singh, 2018a). Hence, various EON protection methods have been formulated of which, the $p$-cycle strategy is attractive since (i) it provisions prompt recovery times, (ii) in addition to reserving the secondary (backup) resources, it also pre-configures the secondary resources, (iii) it uses the surplus capacity to provision protection for the primary (working) paths and provides protection on both the on-cycle and the straddling (off-cycle) spans, and (v) mixes the gains achievable from the mesh networks with the speed of restoration obtained from the ring networks (Shen, Guo, & Bose, 2016; Walkowiak & Klinkowski, 2013). An extension of the $p$-cycle method is the Failure Independent Path Protecting $p$-cycles (FIPP-$p$-cycles) method which has been used extensively for the protection of the EONs (Iyer & Singh, 2018b; Muhammad, Zervas, Simeonidou, & Forchheimer, 2014; Proietti et al., 2015; Tode & Hirota, 2014). In addition to provisioning protection to the end-to-end primary routes comprising the end nodes over the $p$-cycle, FIPP-$p$-cycles do not limit the failures to only a link or a segment of the route which is an immediate neighbour of the end nodes. Also, the FIPP method is independent of the failures since the detection of the faults occurs only at the terminating node and hence there is no requirement to identify the location of the fault in dynamic time irrespective of the failure of a node or a span in addition to the occurrence point of the failure.

In the SDM-b-EONs, larger network capacity is obtained which requires more amount of protection. (Tode & Hirota, 2014) have split the routing, spectrum, and space assignment (RSSA) problem into the routing and spectrum, and space assignment problems. For routing, the authors have introduced a pre-evaluation technique based on the k-shortest path algorithm. (Jinno et al., 2010) have used the k-shortest paths for evaluating the paths to find the solutions of the routing, modulation format and spectrum assignment (RMFSA) problem. To assign a spectrum, the authors have used the least initiating slot available in a spectrum. Furthermore, the MF is selected in terms of a function which depend on the route lengths such that a lesser spectrum is utilized. In our previous work (Iyer & Singh, 2018b) we proposed a FIPP $p$-cycle method to protect a SDM-b-EON. The obtained results revealed that the (i) proposed strategy is efficient in provisioning protection which is pre-configured, and (ii) considered network topology’s node degree significantly affects the blocking and the evaluated route’s length in the protected SDM-b-EON. The results also highlighted the immense potential that FIPP-$p$-cycles bears in view of protecting an SDM-b-EON. However, our study did not consider MFs in various investigations.

To the best of the author’s knowledge, except the study conducted by (Iyer & Singh, 2018b), thus far, no study has addressed the issue of protection in the SDM-b-EONs. In the current study, we introduce the routing, modulation format, space and spectrum allocation with protection (RMFSSA-w-P) algorithm which solves the RMFSSA problem simultaneously ensuring that the spectrum-continuity and the spectrum-contiguity constraints are satisfied (Iyer, 2017). RMFSSA-w-P makes a decision on the lightpaths’ establishment only in an FIPP $p$-cycle protected network which implies that the establishment of a light-path occurs only if there is a provision to protect the lightpath through an FIPP $p$-cycle which may have the on-cycle and the straddling links. Furthermore, RMFSSA-w-P uses a multi-graph representation of the spectrum and also adapts the modulation formats. Owing to the aforementioned, the results of extensive simulations considering two
realistic topologies demonstrated the superior performance of RMFSSA-w-P those that of the existing XT-a-p-w-DRP and SBR-w-a-CSMF strategies. Specifically, RMFSSA-w-P is shown to generate acceptable blocking performance in an SDM-b-EON despite the fact that it reserves the bandwidth to pre-provision the secondary routes. Also, RMFSSA-w-P is demonstrated to result in higher XTpFS values than those shown by the other two strategies since RMFSSA-w-P utilizes larger FSs amount for creating the secondary cycles.

Since the current study extensively uses many acronyms, for ease of readability, in Table 1, we list the various acronyms used in the current study and their corresponding description. Rest of the paper is structured as follows. Section 2 details the RMFSSA-w-P algorithm. Section 3 presents the simulation results. Finally, Section 4 concludes the study.

2. The RMFSSA-w-P algorithm

The RMFSSA-w-P algorithm guarantees a protection route for every lightpath, which is established, and also ensures protection against single failures. In RMFSSA-w-P, the availability of the spectrum is modelled in the form of multiple-graph (MG). In addition to considering protection, RMFSSA-w-P also utilizes different MFs which are chosen in accordance with the distance between the source and the destination since, with higher numbers of bits in every symbol, attenuation of the signal is more which results in incorrect signal decoding at the receiver (Iyer, 2017a). Also, the MFs with higher numbers of bits in every symbol have higher power consumption than those MFs which have lesser number of bits in every symbol; however, such MFs are more efficient owing to their power consumed in every bit ratio being higher (Iyer & Singh, 2017b). Following the studies conducted by (Iyer, 2018; Khodashenas et al., 2017; Perelló, Gené, Pagès, Lazaro, & Spadaro, 2016), the considered MFs in the current study along with their various parameters are detailed in Table 2.

2.1. Notations

The following notations are used in the study:

Table 1. List of acronyms used in the study and their corresponding description.

| Acronym     | Description                                                                 |
|-------------|-----------------------------------------------------------------------------|
| BwBR        | Bandwidth Blocking Ratio                                                    |
| XT          | Crosstalk                                                                   |
| XTpFS       | Crosstalk per FS                                                           |
| DT          | Deutsche Telekom                                                           |
| EON         | Elastic Optical Network                                                     |
| FS          | Frequency Slot                                                             |
| FIPP-p-cycles | Failure Independent Path Protecting p-cycles                           |
| MG          | Multiple-Graph                                                             |
| OTN         | Optical Network                                                            |
| OXC         | Optical Cross Connect                                                      |
| RSSA        | Routing, Spectrum, and Space assignment                                     |
| RMFSA       | Routing, Modulation Format and Spectrum Assignment                         |
| RMFSSA-w-P  | Routing, Modulation Format, Space and Spectrum Allocation with Protection-with-Protection |
| SDM-b-EON   | Space Division Multiplexing (SDM)-based EON                                |
| SBR-w-a-CSMF | Shared Backup Route with the assignment of Core Spectrum and Modulation Format |
| TID         | Telefónica                                                                 |
| XT-a-p-w-DRP | XT aware provisioning with Dedicated Route Protection                       |
Table 2. The various modulation formats and their parameters.

| Modulation format | Transmission reach (km) | Bit-Rate (Gbps) | Maximum acceptable crosstalk (dB) |
|-------------------|-------------------------|-----------------|----------------------------------|
| 64-QAM            | 209                     | 200             | −32                              |
| 16-QAM            | 832                     | 150             | −24                              |
| QPSK              | 3311                    | 100             | −18                              |
| BPSK              | 6607                    | 50              | −16                              |

- $s$, $d$, $bw$ denotes the source node, the destination node, and the request for bandwidth in terms of frequency slots (FSs), respectively. Furthermore, $bw = 1, 2, \ldots, N$ where $N$ denotes the FS set amount between two nodes.
- $req(s, d, bw)Z$ denotes a request which initiates from the source node $s$ and terminates at the destination node $d$, and furthermore, demands a bandwidth $bw$ in terms of the FSs.
- $G = (V, E, Wi)Z$ represents an MG which is labelled and comprises $V$ node set, $E$ edge set, and $Wi$ edge weight set. Furthermore, in the MG $G$, $N$ slots within the link that connect two network nodes are represented by edges that connect two vertices of $G$.
- $mf = 1, 2, \ldots, MFZ$ denotes the utilized MFs. Furthermore, $bmf$ denotes requested bandwidth in terms of the FS which depends on the selected MF.
- $SP(G, req(s, d, bw))Z$ represents in MG $G$, the shortest route between the source node $s$ and the destination node $d$ which fulfils the demands for $bmf$ FSs.
- $E = (e_{u,v,n})Z$ represents a $n$ edge set where $e_{u,v,n}$ is $n^{th}$ edge which connects $u$ and $v$.
- $\mathcal{G}_{bmf}(n) = (V, E, Wi)Z$ represents a $n^{th}$ labelled MG in which $V = V$ represents node set, $E$ denotes edge set that connects $(u, v) \in V$, and $Wi$ denotes costs set linked to $E$. The edges within $E$ map to $bmf$ edges within MG $G$ initiating at the $n^{th}$ edge.
- $\rho = |\mathcal{G}_{bmf}(n)| = Cr \times (N - bmf + 1)Z$ represents the amount of the graphs obtained from MG.
- $\lambda = (G, Cr, bmf) = (\mathcal{G}_{bmf}(n))Z$ represents a function which generates all the $\rho$ graphs from MG $G$.
- $S_n$ represents $\mathcal{G}_{bmf}(n)$ string which ensures that the smallest and largest node that is ordered is denoted by the source node $s$ and the destination node $d$.
- $Wi(S_n)$ represents the route $(S_n)$ weight which implies aggregate weights of all edges within the string.
- $W_{is_d}$ denotes the shortest path weight between the source node $s$ and the destination node $d$.
- $Q_n$ represents $\mathcal{G}_{bmf}(n)$ string and ensures equal vertices and edges amount with a degree of ‘2’ for every vertex. Furthermore, $Q_{uv}$ represents a $p$-cycle set which contains $u$ and $v$ vertices in MG $G$.
- $\eta = (\mathcal{G}_{bmf}(n), S_n, req(s, d, bw))$ represents the least cycle between the source node $s$ and the destination node $d$ in $\mathcal{G}_{bmf}(n)$ for which $S_{Q_{uv}}$ occurs as a disjointed link to $S_n$.
- $\theta = (S_n, Q_{uv}, req(s, d, bw))$ represents the $p$-cycle which occurs in $Q_{uv}$ and for which $S_{Q_{uv}}$ occurs as a disjointed link to $S_n$ and which fulfils demands for $bw$ bandwidth.
- $Wi(Q_n)$ represents $Q_n$ $p$-cycle’s weight which implies aggregate weights of all edges within the string.
- $W_{is_d}$ represents the weight of that $p$-cycle which will provision protection to the route between the source node $s$ and the destination node $d$.  

2.2. The RMFSSA-w-P algorithm working

RMFSSA-w-P models the availability of the spectrum in the form of an MG which is allowed to have the edges comprising similar last (or end) vertices. As shown in Figure 1(a), such an MG has vertices and edges which are representative of the optical cross-connect (OXC) and similar FS set in varied cores belonging to the link that connects the OXCs, respectively. Also, in the MG, \(N\) edges represent the FS numbers within every network link’s spectrum connect to the vertices, and furthermore, irrespective of the core, a single FS is represented by every edge.

On an edge, a tag indicates that the FS is available which occurs whenever such an FS is not utilized by any existing lightpath and furthermore, the crosstalk (XT) value on this FS is lesser than a pre-defined value of the threshold. Next, if there are \(Cr\) cores then, as shown in Figure 1(b), the MG is split into \(Cr\) MGs. Now, every obtained MG is further split onto many MGs (see Figure 1(c)) with every obtained MG having \(N - b_{mf} + 1\) edges. Finally, as shown in Figure 1(d), every obtained MG is converted into \(N - b_{mf} + 1\) MGs i.e. MGs in Figure 1(c) are converted into \(Cr \times (N - b_{mf} + 1)\) graphs shown in Figure 1 (d).

In the generated graphs, every edge is representative of the \(b_{mf}\) FS which ensures that spectrum contiguity is satisfied within the obtained solution. Also, in the graph of Figure 1 (d), a tag value of ‘1’ implies the availability of FS for assignment, whereas an ‘oo’ value indicates that at least one out of the available \(b_{mf}\) FSs is either assigned or has an unacceptable XT value over it. Finally, when all the graph edges have an ‘oo’ value, it indicates the corresponding \(b_{mf}\) FS group’s non-availability for assignment.

The working of RMFSSA-w-P is detailed by the pseudocode shown in Table 3.

1. In Line 1, RMFSSA-w-P ensures the transformation of MG into \(Cr \times (N - b_{mf} + 1)\) graphs.

| Table 3. Steps involved in the RMFSSA-w-P algorithm. |
| --- |
| 1. \(\lambda = (G, Cr, b_{mf}) = \{G_{n,bmf}\}_{mf \in MF} \) |
| 2. \((Wi(S_n), S_n) = SP(G_{n,bmf}, req(s, d, bw)) \forall n \in \rho \) |
| 3. \(Wi_{cr} = W(S_n) \forall W(S_n) \leq W(S_1) \) |
| 4. if \(Wi_{cr} = oo\) then |
| 5. blockreq(s, d, bw) |
| 6. else; |
| 7. if \(\exists \eta = (S_n, Q_{n,b}, req(s, d, bw))\) then |
| 8. establishreq(s, d, bw) as \(S_n\) and \(Q_n\) |
| 9. \(Wi_{\eta_{uv}} = oo \forall (u, v) \in P, \) |
| 10. else |
| 11. \(\lambda = (G, Cr, b_{mf}) \forall mf \in MF \) |
| 12. \((Wi(Q_n), Q_n) = \eta\{G_{n,bmf}, S_n, req(s, d, bw)\} \forall n \) |
| 13. \(Wi_{cr} = W(Q_n) \forall W(Q_n) \leq W(Q) \) |
| 14. if \(Wi_{cr} = oo\) then |
| 15. blockreq(s, d, bw); |
| 16. else; |
| 17. establishreq(s, d, bw) as \(S_n\) and \(Q_n\) |
| 18. \(Wi_{\eta_{uv}} = oo \forall (u, v) \in S, \) |
| 19. \(Wi_{\eta_{uv}} = oo \forall (u, v) \in Q, \) |
| 20. end if; |
| 21. end if; |
| 22. end if; |
Figure 1. Transformation of MG into graphs.
2. In Line 2, for $G_{n,bw}$ graphs, RMFSSA-w-P solves the shortest path algorithm and selects the route which demonstrates the least expense. Furthermore, if an infinite value of the shortest path weight occurs then it implies that, for request $bw$, it is impossible to evaluate a route under the constraint of spectrum contiguity.

3. In Line 3, a route is chosen among all shortest paths such that it has a minimum value of weight.

4. In the event that the weight of all shortest paths is infinite (Line 4), it is implied that there occurs no route to satisfy the demand of $bw$ FSs under the constraint of spectrum contiguity. As a consequence, the demand is blocked (Line 5).

5. Else, a search is initiated (Line 7) to evaluate a $p$-cycle for provisioning protection to lightpath which is to be established.

6. In the event that the existing $p$-cycle is found, which can protect an active and a new demand, a lightpath establishment occurs (Line 8). Consequently, in $G$, the weight of corresponding edges is altered to infinity (Line 9). Else, the creation of a new a $p$-cycle for protecting the established lightpath has to be conducted (Line 12).

7. To generate a $p$-cycle, RMFSSA-w-P considers the shortest possible cycle which connects the source and destination nodes. However, in the event that a $p$-cycle cannot be created to protect lightpath, blocking of the demand occurs (Line 15). Else, lightpath and $p$-cycle are established to satisfy the request (Line 17). Consequently, in $G$, the weight of corresponding edges is altered to infinity (Line 18 and Line 19) which implies that spectrum FSs are assigned to the new lightpath which has been established.

It must be noted that in RMFSSA-w-P (i) a FIPP $p$-cycle provisions the protection to primary routes which are disjoint, and (ii) for an arrival of a demand, to establish the lightpath(s) which is random (dynamic), there occurs a search for a $p$-cycle that exists to provide protection to the possible lightpath. In the event when there exists no $p$-cycle for the protection of the possible lightpath, for the demand, there occurs a route search for the creation of a new $p$-cycle. However, if no such route is found for protection, then the lightpath is not established.

The complexity of RMFSSA-w-P can be analysed as follows: To transform the initial MG into $r$ graphs, a complexity of $MF \times O(\|E\| + \|V\|)$ is incurred. Furthermore, for the working route, the shortest path (Dijkstra’s) algorithm is implemented which requires its implementation for $MF \times C_r \times (N - bw)$ times. To generate the $p$-cycles, it is required to implement the Suurballe’s algorithm (Iyer & Singh, 2018b) which is also executed for a maximum of $MF \times C_r \times (N - bw)$ times. Therefore, the Dijkstra’s and the Suurballe’s algorithm incur a $O(\|E\| + \|V\| \log \|V\|)$ complexity and since $MF$, $C_r$, $N$, $bw$ are constant values, the complexity of the RMFSSA-w-P is also $O(\|E\| + \|V\| \log \|V\|)$.

3. Simulation results

For the simulations, following our previous study (Iyer & Singh, 2019), we use two realistic network topologies viz., Deutsche Telekom (DT) and Telefonica (TID) as shown in Figure 2, with their various dimensional values shown in Table 4.

For every simulation, we generate 5,00,000 demands and ensure that all the simulations in regard to RMFSSA-w-P utilize similar seeds set. Furthermore, we adapt the average time
of arrival and the average time for holding such that the traffic load desired can be simulated. For evaluation, we assume a 19-core fibre amount (Khodashenas et al.), and the division of the spectrum into 320 FSs with each FS being 12.5 GHz wide (Iyer, 2017a). Finally, we consider eight different demand types with each demand having a bandwidth request which is stochastically chosen from the following values: 50, 100, 125, 150, 200, 500, 850 and 1000 Gbps.

We compare the performance of RMFSSA-w-P with the following two strategies: (i) XT aware provisioning with dedicated route protection (XT-a-p-w-DRP) detailed by (Tan et al., 2016); however, we enhance it to include the MF adaptation, and (ii) Shared Backup Route with the assignment of Core Spectrum and Modulation Format (SBR-w-a-CSMF) (Muhammad et al., 2014); however, we use its enhanced version as proposed by (Iyer & Singh, 2018b) which employs protection and adaptive MF, furthermore addresses the working route independently implying that SBR-w-a-CSMF treats the routing and core, and the spectrum issues separately by employing the pre-evaluated multiple paths. Besides, in SBR-w-a-CSMF the secondary route is also developed in the aforementioned similar manner; however, it resorts to the 1:N scheme.

For the performance comparison, we use the following metrics: (i) Bandwidth Blocking Ratio (BwBR): ratio of bandwidth of the demands which are rejected and the aggregate bandwidth which is demanded, and (ii) Crosstalk per FS (XTpFS): ratio of the existing index of XT and the maximal value of the index of XT. We define the XT ratio as the mean value among all the FS of the spectrum (Fujii, Hirota, Tode, & Murakami, 2014).

**Figure 2.** Network topologies used in the simulations (a) DT, and (b) TID.

**Table 4.** Various network topology(s) characteristics used in the simulations.

| Network topology | Location  | Number of nodes | Number of bidirectional links | Average length of the link (km) | Maximum length of the link (km) |
|------------------|-----------|-----------------|------------------------------|-------------------------------|-------------------------------|
| DT               | Germany   | 12              | 40                           | 243                           | 459                           |
| TID              | Spain     | 30              | 56                           | 148                           | 313                           |
In Figure 3(a), we show the variation of BwBP with the traffic load for the TID topology. It can be observed from the figure that XT-a-p-w-DRP and SBR-w-a-CSMF start to block the demands at loads of approximately 50 and 100 Erlangs, respectively.

Figure 3. BwBR versus traffic load for (a) TID, and (b) DT.

In Figure 3(a), we show the variation of BwBP with the traffic load for the TID topology. It can be observed from the figure that XT-a-p-w-DRP and SBR-w-a-CSMF start to block the demands at loads of approximately 50 and 100 Erlangs, respectively,
whereas RMFSSA-w-P initiates the blocking at a load of approximately 200 Erlangs for which, the BwBP difference between RMFSSA-w-P, and XT-a-p-w-DRP and SBR-w-a-CSMF is in the magnitude order of approximately ‘2’ and ‘1.5’, respectively. Also, XT-a-p-w-DRP demonstrates high BwBP since it does not share the secondary routes. On the other hand, RMFSSA-w-P shows low BwBP which demonstrates the benefits obtained by using the MG spectrum representation for generating the primary and

Figure 4. XTpFS versus traffic load for (a) TID, and (b) DT.
the secondary paths. Overall, RMFSSA-w-P generates acceptable blocking performance in an SDM-b-EON despite the fact that it reserves the bandwidth to pre-provision the secondary routes.

Figure 3(b) shows the variation of BwBP with the traffic load for the DT topology. It can be observed that RMFSSA-w-P, XT-a-p-w-DRP and SBR-w-a-CSMF start to block the demands at loads of approximately 250, 100 and 150 Erlangs, respectively. Considering a high load of 300 Erlangs, its can be seen that the BwBP difference generated by RMFSSA-w-P and that by XT-a-p-w-DRP and SBR-w-a-CSMF is approximately in the magnitude order of approximately ‘1’ and ‘0.5’, respectively. Also, comparing the results of Figure 3(a) with those shown in Figure 3(b), it can be observed that owing to the DT topology’s lower degree of node which results in constrictions, for the highest load of 500 Erlangs, the difference between the BwBP generated by RMFSSA-w-P and SBR-w-a-CSMF is approximately a ‘0.15’ magnitude order.

Existing studies have shown that with the usage of multiple cores, inter-core XT is generated (Khodashenas et al., 2017; Perelló et al., 2016). Hence, in Figure 4 we plot the variation of XTpFS with the traffic load for the considered topologies.

Figure 4(a) shows the variation of XTpFS with load for the TID topology. It can be observed that when RMFSSA-w-P is used, it results in higher XTpFS values than those shown by the other two strategies since RMFSSA-w-P utilizes larger FSs amount for creating the secondary cycles. In Figure 4(b), we demonstrate the variation of XTpFS with the traffic load for the DT topology. It can be observed that SBR-w-a-CSMF generates the highest amount of XTpFS especially for the higher load values and RMFSSA-w-P closely follows the SBR-w-a-CSMF curve. Finally, in comparison to the TID topology, for the DT topology (i) XTpFS is substantially affected by the network capacity’s high usage, and (ii) values of the XTpFS are much higher.

4. Conclusion

In the current work, for an SDM-b-EON, we introduced the RMFSSA-w-P algorithm which solves the RMFSSA problem and simultaneously ensures that the spectrum-continuity and the spectrum-contiguity constraints are satisfied. RMFSSA-w-P establishes only those lightpaths, which are FIPP-p-cycles protected, and uses a multi-graph representation of the spectrum while adapting the modulation formats. Owing to the aforementioned, the results of extensive simulations considering two realistic topologies demonstrated the superior performance of RMFSSA-w-P than the existing XT-a-p-w-DRP and SBR-w-a-CSMF strategies. Specifically, RMFSSA-w-P generates acceptable blocking performance in an SDM-b-EON despite the fact that it reserves bandwidth to pre-provision the secondary routes. RMFSSA-w-P also results in higher XTpFS values than those shown by the other two strategies since it utilizes larger FS amount for creating the secondary cycles.

As a scope for future research, we will extend the RMFSSA-w-P algorithm by considering traffic grooming and spectrum overlapping.

Disclosure statement

No potential conflict of interest was reported by the author.
Notes on contributor

Sridhar Iyer received his B.E. degree in Electronics and Telecommunications Engineering from Mumbai University, India in 2005. He received his M.S. degree in Electrical and Communication Engineering from New Mexico State University, U.S.A. in 2008, and his Ph.D. degree from Delhi University, India in 2017. Currently Dr. Iyer is an Associate Professor in the Department of ECE, Jain College of Engineering, India. His research interests include the architectural, algorithmic, and performance aspects of the optical networks, with current emphasis on efficient design and resource optimization in the space division multiplexing enabled flexi-grid Elastic optical networks. Dr. Iyer has published over 60 peer-reviewed articles in the aforementioned areas.

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References

Agrell, E., Karlsson, M., Chraplyvy, A. R., Richardson, D. J., Krummrich, P. M., Winzer, P., … Gisin, N. (2016). Roadmap of optical communications. Journal of Optics, 18, 1–40.

Fujii, S., Hirota, Y., Tode, H., & Murakami, K. (2014). On-demand spectrum and core allocation for reducing crosstalk in multicore fibers in elastic optical networks. IEEE/OSA Journal of Optical Communications and Networking, 6, 1059–1071.

Iyer, S. (2017a). Effect of modulation format’s transmission reach on spectrum utilization in elastic optical networks. International Journal of Information Technology, 9, 335–344.

Iyer, S. (2017). A novel dedicated route protection scheme for survivability of link failure in elastic optical networks. International Journal of Advances in Telecommunications, Electrotechnics. Signals and Systems, 6, 120–127.

Iyer, S. (2018). Traffic grooming with survivability and power-efficiency in software defined elastic optical networks. Journal of Optics Springer, 47, 351–365.

Iyer, S., & Singh, S. P. (2017b). Investigation of cost, power and spectral efficiency in fixed- and flexi-grid networks. Journal of Communications and Information Networks. Springer, 2, 92–106.

Iyer, S., & Singh, S. P. (2018a). Comparison of cost, power consumption and spectrum utilization in protected fixed- and flexi-grid optical networks. The Institution of Electronics and Telecommunication Engineers (IETE) Journal of Research, 64, 611–619.

Iyer, S., & Singh, S. P. (2018b). A novel protection strategy for elastic optical networks based on space division multiplexing. In Proceedings of IEEE Signal Processing and Communications (SPCOM). 1–5.

Iyer, S., & Singh, S. P. (2019). Multiple-period planning of internet protocol-over-elastic optical networks. Journal of Information and Telecommunication. Taylor and Francis, 3, 39–56.

Jinno, M., Kozicki, B., Takara, H., Watanabe, A., Sone, Y., Tanaka, T., & Hirano, A. (2010). Distance-adaptive spectrum resource allocation in spectrum sliced elastic optical path network. IEEE Communications Magazine, 48, 138–145.

Khodashenas, P. S., Manuel Rivas-Moscoso, J., Siracusa, D., Pederzolli, F., Shariati, B., Klonidis, D., … Tomkos, I. (2017). Comparison of spectral and spatial superchannel allocation schemes for SDM networks. IEEE Journal of Lightwave Technology, 34, 2710–2716.

Muhammad, A., Zervas, G., Simeonidou, D., & Forchheimer, R. (2014). Routing, spectrum and core allocation in flexgrid sdm networks with multi-core fibers. In Proceedings of IEEE International Conference on Optical Network Design and Modeling (ONDM). 192–197.

Perelló, J., Gené, J. M., Pagès, A., Lazaro, J. A., & Spadaro, S. (2016). Flex-grid/SDM backbone network design with inter-core XT-limited transmission reach. IEEE/OSA Journal of Optical Communications and Networking, 8, 540–552.

Proietti, R., Liu, L., Scott, R., Guan, B., Qin, C., Su, T., … Yoo, S. (2015). 3d elastic optical networking in the temporal, spectral, and spatial domains. IEEE Communications Magazine, 53, 79–87.
Shen, G., Guo, H., & Bose, S. K. (2016). Survivable elastic optical networks: Survey and perspective. *Photonic Network Communication*. Springer, 1, 71–87.

Tan, Y., Zhu, R., Yang, H., Zhao, Y., Zhang, J., Liu, Z., … Zhou, Z. (2016). Crosstalk-aware provisioning strategy with dedicated path protection for elastic multi-core fiber networks. In *Proceedings of IEEE ICOCN*, 1–3.

Tode, H., & Hirota, Y. (2014). Routing, spectrum and core assignment for space division multiplexing elastic optical networks. In *Proceedings of IEEE 16th International Telecommunications Network Strategy and Planning Symposium (Networks)*. 1–7.

Walkowiak, K., & Klinkowski, M. (2013). Shared backup path protection in elastic optical networks: Modeling and optimization. In *Proceedings of IEEE 9th International Conference on Design of Reliable Communication Networks (DRCN)*. 187–194.

Winzer, P. J. (2012). Optical networking beyond WDM. *IEEE Photonics Journal*, 4, 647–651.

Winzer, P. J. (2014). Spatial multiplexing in fiber optics: The 10x scaling of metro/core capacities. *Bell Labs Technical Journal*, 19, 22–30.