Multipath Routing in Elastic Optical Networks with Space-Division Multiplexing

Pedro M. Moura and Nelson L. S. da Fonseca

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Abstract

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Introduction

The wavelength-division multiplexing (WDM) technology has made bandwidth on the Internet link layer widely available, contributing to its scalability and rapid expansion. In WDM networks, the spectrum is divided into 50 GHz bands, associated with different wavelengths. Such a division imposes a coarse-grained bandwidth allocation scheme; however, this does not match the diversity of bandwidth requirements of all of the applications running on the Internet.

One of the main motivations for developing the (spectrum-sliced) elastic optical network (EON) technology was to obtain a fine-grained bandwidth allocation to overcome the coarse-grained bandwidth allocation problem in WDM. In EON, the spectrum is divided into narrow bands of 12.5 GHz each, called slots, which allows much greater flexibility in bandwidth allocation. Typically, spectrum allocation in these networks is carried out using (optical) orthogonal frequency-division multiplexing (OFDM).

Spatial multiplexing has also been introduced into EON technology in an attempt to cope with the ever increasing bandwidth demands, as well as an alternative for the limitations of transmission in a single core. This has greatly increased network capacity. One of the most common approaches to realize spatial multiplexing in these networks is the usage of multi-core fibers (MCF). In EONs with space-division multiplexing (EON-SDM) employing MCF, the spectrum can be allocated on different cores for a single lightpath, thus considerably increasing the flexibility of its allocation.

On the other hand, with MCF, the transmission in a core is subject to cross-talk interference from other cores, with the intensity depending on the distance between the cores and the transmissions carried in the interfering cores [1]. The intensity of the crosstalk on a slot can be such that it impairs the transmission in it. Therefore, the crosstalk on potentially allocable slots should be taken into consideration, as well as the impact of the establishment of a lightpath on the crosstalk on already allocated slots.

Inter-core crosstalk interference results from the optical power added to the power of a signal by adjacent links. It is the most relevant physical impairment in a multi-core fiber, and needs to be taken into consideration in slot allocation. If it is too intense, the slot should be considered unavailable, which can increase the fragmentation of the spectrum [2].

Moreover, the choice of modulation for the transmission along a lightpath should consider the crosstalk on the slots allocated to it. Establishing a lightpath requires the determination of the route, the slots to be allocated, and the modulation to be employed, and these choices are determined by the solution of the so-called routing, core, modulation level, and spectrum assignment (RCMLSA) problem. The slots allocated for a lightpath need to be continuous along the route and contiguous in the spectrum.

Moreover, the frequent allocation and de-allocation of slots by the establishment and tearing down of lightpaths may produce several small sets of unoccupied contiguous slots between allocated ones (fragments). The total bandwidth may even be sufficient or exceed the required one, but since the slots are not contiguous, they cannot be allocated to that lightpath. Fragmentation of the spectrum is one of the main reasons for the blocking (rejection) of requests for lightpath establishment, and it degrades the availability of network transport services [3].

Multipath routing provides an efficient way to deal with the fragmentation problem by splitting the requested bandwidth into (sub)flows with smaller bandwidth demands. These flows are then allocated on multiple paths with different spectra and potentially different routes. The splitting of a flow is usually carried out at the interface between layers 2 and 3 of the source node. Splitting should maintain the boundaries of layer 3 protocol data units (PDU) to avoid PDU assembly overhead. The ratio of PDUs to (sub)flows (splitting ratio) depends on the bandwidth available in each path. On the other hand, storage is needed to reorder PDUs at the destination as a consequence of dif-

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ferent end-to-end delays along different paths.

Multipath routing has been adopted in networks with different technologies; it is designed to allow the provision of bandwidth that is not available in a single path. In EON-SDM based on MCF, the spectra in different cores furnish flexibility in the allocation of slots for establishing a lightpath. However, a set of slots (in different cores) may not satisfy the contiguity constraint for a single path. Multipath routing can relax such constraints by employing multiple paths for the transmission of a single flow. Moreover, multipath routing capitalizes on the existing fragmentation of a spectrum to make possible the acceptance of incoming requests, thus decreasing fragmentation and increasing the acceptance ratio of lightpath requests.

However, few papers have proposed solutions for multipath routing in EON-SDM [4–7]. This article introduces four novel multipath routing algorithms based on image processing techniques for the efficient identification of allocable slots for the establishment of a lightpath, which is the original aspect of our proposal. These techniques help to keep the computational complexity of RCMLSA algorithms low. The two image processing techniques employed are combined with different fitting policies in the definitions of the proposed algorithms. These algorithms take into consideration the crosstalk on allocable slots, as well as the crosstalk generated by the slots allocated to the existing lightpaths. Multiple paths are sought only when there is no single path with the bandwidth demanded, which decreases the computational overhead of the search for slots. The proposed algorithms employ adaptive modulation and always use the highest possible transmission rate, minimizing the number of slots allocated, and consequently leaving a larger number of slots available for future requests. Extensive simulations were conducted to assess the effectiveness of the proposed algorithms; the advantage of multipath routing has clearly been shown.

Multipath Routing in Optical Networks

Multipath routing has been extensively investigated for various different optical networking technologies. In [8], the establishment of lightpaths with supra wavelength demands and path protection in wavelength-division multiplexing (WDM) networks was investigated.

In [9], the authors present a comprehensive survey of multipath transmissions in IP-over-WDM networks. Both intradomain and interdomain routing protocols were discussed, with emphasis on challenges and requirements for interdomain routing. Various proposals were compared on the basis of criteria such as signaling overhead and scalability. The article concluded that multipath routing can realistically be implemented in IP networks, employing different approaches.

The seminal work in [10] proposed several online algorithms using different path selection policies for multipath routing in EON. Results showed significant reduction in bandwidth blocking ratio. Simulation showed that the algorithms could increase network throughput and reduce spectrum fragmentation.

In [11], a multipath algorithm employing the *k*-shortest path algorithm was designed to minimize the number of paths used and the number of guard-bands in EON networks, avoiding the exhaustion of transponder resources. If a lightpath cannot be accepted, a procedure for defragmentation of the spectrum without disrupting the transmissions is employed. The results indicated that blocking and spectrum fragmentation could be reduced considerably by this approach.

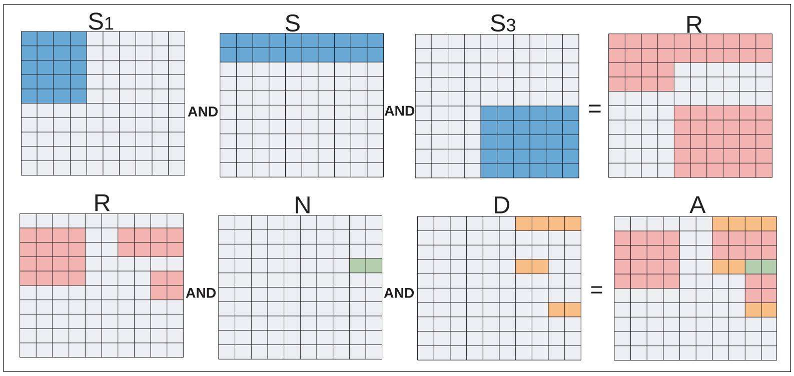

FIGURE 1. Optical spectrum representation matrices used by the RCMLSA algorithms.

Multipath routing has been employed not only to increase the availability of network transport services but also to furnish network protection based on redundancy. The work in [12] capitalized on multi-path routing with an adaptive number of working paths to provide disaster protection for inter-datacenter EONs leveraging cooperative storage.

Recently, multipath routing for EON-SDM has been considered. In [4], the authors introduced three heuristics to minimize the external fragmentation, which measures the degree of spreading gaps in spectra. The EON-SDM networks used in the evaluation employed 7-core MCFs.

In [5], the authors introduced the first proposal for protection in EON-SDM based on multipath routing and the use of p-cycle for 100 percent protection against single failures. Simulation results showed that the blocking produced by the multipath algorithm was less than that based on single-path routing.

In [7], two energy-efficient multipath RSCA algorithms were proposed for SDM-EON. The first mitigates inter-core crosstalk, and the second prevents fragmentation within the cores. This multipath approach is used to maintain network survivability. The proposed algorithms are able to outperform p-cycles and shared path approaches in blocking probability and energy consumption.

In [13], a deep reinforcement learning framework for routing, modulation, and spectrum assignment (DeepRMSA) in EONs was proposed. It learns online RMSA policies by parameterizing the policies with deep neural networks that can sense complex states.

Multipath RCMLSA Algorithms

The solution for the RCMLSA problem consists of the selection of: a route, a set of cores and frequency slots in those cores, and a modulation level for the establishment of a lightpath. The selection of the cores and frequency slots must obey the contiguity constraint, which requires slots to be contiguous in the spectrum, and the continuity constraint, which establishes that the

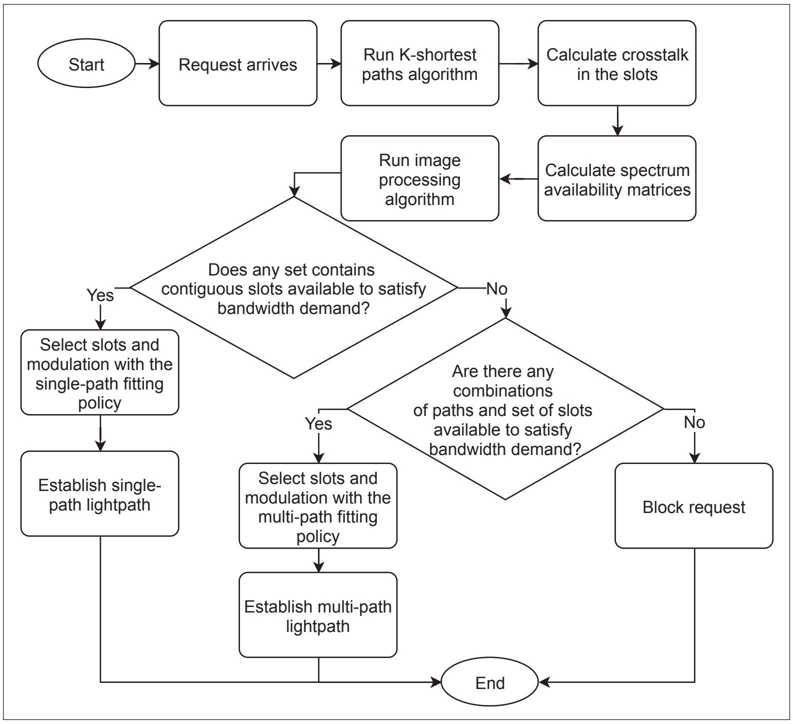

FIGURE 2. Description of the multipath RCMLSA algorithms.

same frequency slots should be allocated on the links along a lightpath. The algorithm must also consider the crosstalk generated between cores of a fiber in this type of network. This crosstalk is the interference from the transmission in one core to that in another core, which impacts the choice of the modulation level.

The dynamic nature of the establishment and tearing down of lightpaths can lead to the problem of spectrum fragmentation, which involves the existence of slots available for allocation spread in a non-contiguous fashion. The presence of fragments leads to inefficient usage of the spectrum and unnecessary blocking of requests.

Multipath routing divides the lightpaths into multiple parallel paths, with different sets of allocated slots, and a total bandwidth satisfying the requested bandwidth requirement. The proposed multipath RCMLSA algorithms mitigate spectrum fragmentation by allocating several fragments spread across the spectrum, thus promoting its efficient usage as well as reducing the blocking of requests.

In dynamic scenarios, RCMLSA algorithms must be executed in real time; thus, they need to have low computational complexity. To achieve this goal, the algorithms proposed represent the optical spectrum of the links as binary images with *cores* × *slots* dimensions. This representation allows the use of low computational complexity image processing techniques in the search for available slots.

The algorithms are composed of five steps:
- Search for the K shortest paths between the source and destination nodes.
- Identify continuous slots in the links along the paths given by the computation of a matrix of available slots.
- ;• Identify available contiguous slots via image processing techniques.
- Fit the requested bandwidth into the available set of contiguous and continuous slots along the shortest path.
- Allocate the requested bandwidth in multiple paths if there is no set of slots available for a single-path allocation.

The calculated K shortest paths do not need to be node or link disjoint; however, the multipath fitting policy must verify if the sets of slots are disjoint between the paths.

To identify the spectrum availability along a route, it is necessary to consider both the spectrum allocation of already established lightpaths and the slots that are inappropriate due to intense crosstalk. The upper part of Fig. 1 illustrates how to identify the contiguous spectrum along a path by verifying the spectrum availability in the links composing the route, which is represented by the occupancy matrix (in blue). Matrices S_1, S_2, and S_3 are the binary images representing the optical spectrum of the links. The resultant matrix R (in red) represents the continuous spectrum, identified by the computation of a logical AND operation between the S_i matrices. A second step identifies the slots in R that have acceptable levels of crosstalk and therefore are available for allocation. The bottom part of Fig. 1 shows how to identify frequency slots unavailable due to crosstalk. The first matrix is the occupancy matrix R, as calculated above. The second matrix is the noise matrix N (in green), which represents how the slots allocated to already established lightpaths interfere with each other. The third matrix D (in orange), called the disrupt matrix, represents how allocable slots would interfere with already established lightpaths.

Two image processing techniques were used to derive different RCMLSA algorithms: the Connected Component Labeling (CCL) algorithm and the Inscribed Rectangles Algorithm (IRA). The former employs a segmentation algorithm that searches for connected sets of pixels in an image. The latter searches for rectangles in connected sets. These algorithms differ in the shape of the portion of the spectrum that is searched. The CCL algorithm searches for sets of spectrum slots, regardless of their shape, which can increase the possibilities for spectrum allocation, whereas the IRA searches for rectangles inscribed in the available portions of the spectrum. The use of rectangles maintains a fixed pattern of allocation, providing easier identification of slots for allocation, since a rectangle is the final shape to be allocated and described by its height and width. The employment of image processing techniques is of paramount importance to keep the computational complexity of the RCMLSA algorithm low, since they have polynomial computational complexity [14].

With the available sets of slots selected, the RCMLSA algorithm must select one or more of them according to a fitting policy. Four fitting policies were experimented. For the CCL algorithm, traditional best-fit and random-fit policies were employed. The former allocates the lightpath in the set of slots that presents the bandwidth closest to the requested value, while the latter allocates the request in a random way, spreading the allocation throughout the spectrum, as this tends to reduce crosstalk. For the IRA, the minimal-blocking and minimal-crosstalk policies were employed. These policies use the width of the inscribed rectangles when choosing a set of frequency slots for a lightpath. The former is similar to the best-fit policy, but with rectangles classified by width first, prioritizing allocations in which the set of contiguous slots are in a single fiber core. Such an allocation minimizes the use of guard bands to separate the transmissions in multiple cores, prioritizing single-path allocation. The latter is similar to the random-fit policy, but the random allocation is changed to a weighted random approach, with the weights defined as the width of the rectangles selected by the IRA. This approach tries to mitigate the crosstalk while favoring allocations in the same core.

Since the CCL algorithm does not provide a fixed width for the sets of slots identified, it cannot employ the minimal-blocking and minimal-crosstalk policies. The best-fit and random-fit policies can be used together with the IRA, but experimental comparison suggests that the spectrum efficiency would be lower if these traditional policies were employed; thus, the combinations will not be used here.

Combining the image processing techniques and the fitting policies gave rise to four algorithms. The two based on the CCL algorithm are denominated Multi-Path Connected Component Labeling Best-Fit (MPCCLBF) and Multi-Path Connected Component Labeling Random-Fit (MPCCLRA); the other two are based on the IRA and denominated Multi-Path Inscribed Rectangles Algorithm Minimal-Blocking (MPIRAMB) and Multi-Path Inscribed Rectangles Algorithm Minimal-Crosstalk (MPIRAXT).

When allocation of the slots is not possible in a single path, slots are allocated in multiple paths with allocated bandwidth supporting the requested one. In order to minimize the number of slots used for allocation, the proposed algorithms employ the least-hops policy, which chooses paths in increasing order of length and allocates all available slots in these paths, unless the bandwidth of the last one is larger than what must be allocated.

Figure 2 illustrates the RCMLSA. When used with specific image processing techniques and fitting policy, it will yield one of the four proposed algorithms. The algorithm is triggered by the arrival of a request for lightpath establishment. The first step identifies the k shortest paths. Then the crosstalk values on the slots are calculated. The availability matrices are calculated for the links along the chosen paths, considering slots occupied by previously allocated lightpaths and how they interfere with each other, not only how the already established slots interfere with the transmission on allocable slots, but also the impact of the allocation of slots on those already allocated. Since the availability matrices represent the allocable slots along the paths, the continuity requirement is satisfied. An image processing technique is then employed to find the sets of available contiguous slots. The possibility of allocation of one of these sets with a certain modulation level is then determined. If this is not possible, the algorithm attempts to combine several sets of slots in distinct paths to constitute a lightpath composed of multiple paths. If a set of slots is available that

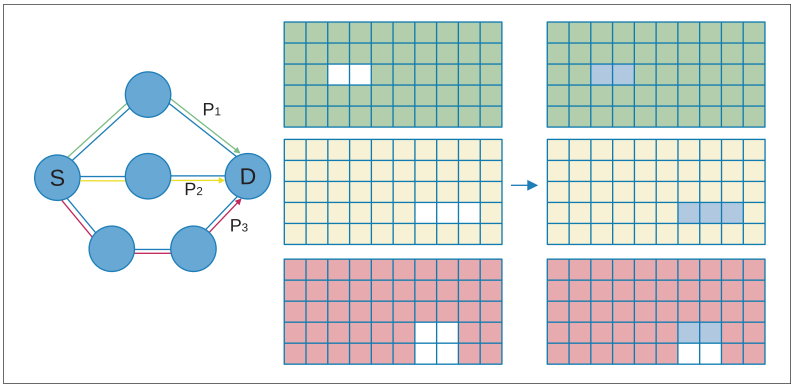

FIGURE 3. Description of the multipath fitting policy.

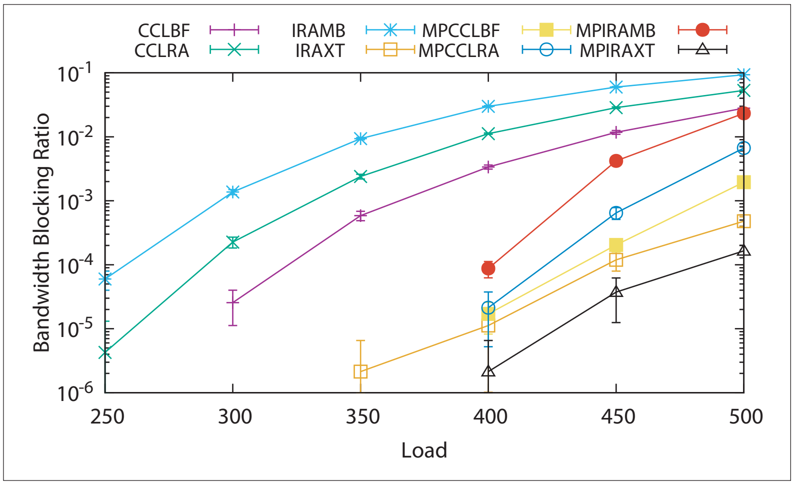

FIGURE 4. Bandwidth blocking ratio as function of the load for the NSF topology.

satisfies the requested bandwidth, a fitting policy is used to choose which slots will be allocated. If no combinations can satisfy the requested bandwidth, the request is blocked.

Figure 3 shows an example of how the multipath fitting policy allocates requests in multiple parallel paths. The graph on the left represents an EON-SDM with six nodes and seven links. The k-shortest paths between nodes S and D are shown as P_1 (in green), P_2 (in yellow), and P_3 (in red). The availability matrix for each spectrum is represented by the correspondent color of the path in the graph. Since several lightpaths have previously been established, few contiguous frequency slots are available for new lightpaths, and it is difficult to satisfy requests with bandwidth demand greater than four slots. If a new request with a demand of seven slots arrives, the multipath fitting policy tries to combine sets of slots from several paths to establish a multipath lightpath. If enough slots are available, the algorithm prioritizes the allocation of slots along the shortest paths. As illustrated on the right, P_1 and P_2 have fewer hops, so their slots are allocated first; P_3 is allocated last, as it has a larger number of hops. The bit rates of the lightpaths in a multipath transmission can be different.

Evaluation of the Proposed Algorithms

Simulations with the FlexGridSim[1] simulator were used to assess the performance of the proposed algorithms. Each replication simulated 100,000 request arrivals. Bandwidth demands of lightpath

[1] Available at http://www.lrc.ic.unicamp.br/flexgridsim/.

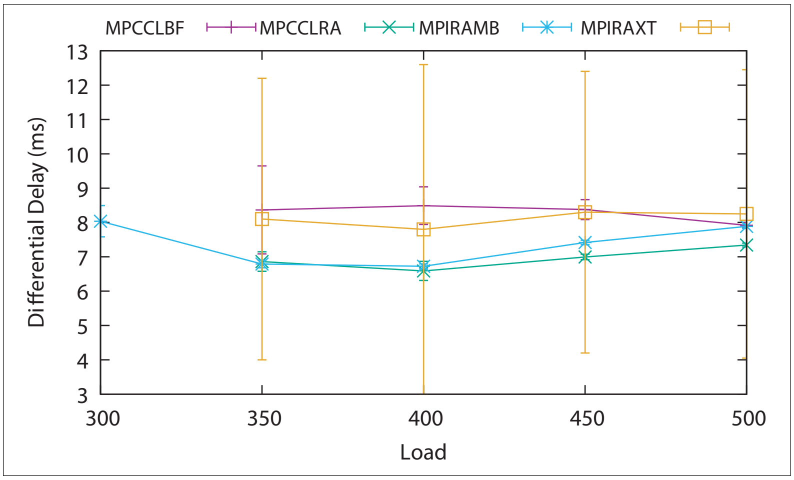

FIGURE 5. Differential delay as function of the load for the NSF topology.

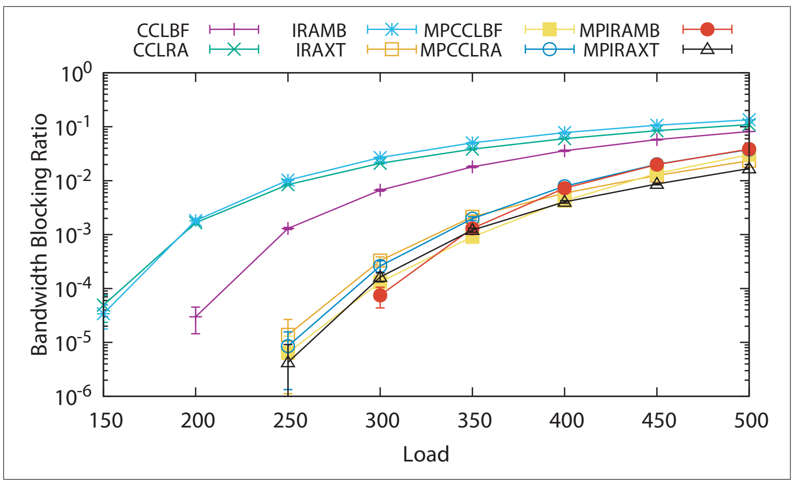

FIGURE 6. Bandwidth blocking ratio as function of the load for the USA topology.

requests were randomly selected from the discrete uniform distribution {40 Gb/s, 100 Gb/s, 400 Gb/s, 1 Tb/s}. The produced metric values of the two multipath algorithms were compared to their single-path counterparts using a 19-core [15] MCF architecture, and the impact of multipath allocation with the increased capacity of SDM elastic optical networks was evaluated. The parameter $k = 5$ was used in the k-shortest paths algorithm since no significant gains were observed with higher values.

The National Science Foundation (NSF) and United States of America (USA) topologies were used in the simulations [14]. The NSF topology has 16 nodes and 25 links, whereas the USA topology has 24 nodes and 43 links and greater node connectivity. The links were composed of 19 core MCFs, with each core divided into 240 slots of 12.5 GHz. Requests were dynamically generated by randomly selecting source and destination pairs. Crosstalk from coupled fiber cores was estimated and considered during the RCMLSA allocation. Slots with high crosstalk from coupled cores as well as allocations that would interfere with already established lightpaths were considered to be unavailable.

The two performance metrics shown in this article are the bandwidth blocking ratio (BBR) and differential delay. The BBR is the ratio between the actual bandwidth provided and the requested one, while the differential delay is the delay introduced due to discrepancy in delay values along the paths of a multipath solution, which requires a buffer at the destination to reorder the packets. If, on one hand, multipath routing reduces blocking, on the other, it introduces overhead quantified by the differential delay. The mean value of these performance metrics are shown in the graphics, as well as confidence intervals with a 95 percent confidence level. The first fit fitting policy was employed in the decisions on slot allocation, although the use of this policy led to algorithms that underperform those shown in this section.

Figure 4 compares the BBR produced by the proposed multipath algorithms with that of their single-path counterparts for the NSF topology. All multipath algorithms produce lower BBR values than do their single-path algorithm counterparts. The multipath algorithms produce BBR values up to one order of magnitude lower than their single-path algorithms under loads of 400 Erlangs. Under loads of 500 Erlangs, the difference reached 46 percent. The effectiveness of the multipath algorithms in reducing blocking is due to capitalizing on existing fragments to compose a lightpath. When the multipath algorithms are compared, the MPIRAXT achieves the lowest blocking probabilities of all proposed algorithms, being one order of magnitude lower than those produced by the MPCCLBF. The MPIRAXT produced these lower BBR values due to its ability to limit allocations to fewer cores, which not only reduces crosstalk between established lightpaths, but also prevents spectrum fragmentation.

Figure 5 shows the differential delay resulting from the multipath allocations made by the proposed algorithms as a function of the load. MPCCLBF and MPCCLRA produced differential delay values of approximately 2 ms less than did MPIRAXT and MPIRAMB for loads of 350–400 Erlangs. Under loads over 450 Erlangs, MPCCLBF, MPCCLRA, and MPIRAMB produced differential delay values near 8 ms, and MPIRAXT produced values near 9 ms. Although the average values were similar for all algorithms, MPIRAXT produced differential delay values with greater confidence interval due to the highly saturated spectrum in which the multipath allocations were made, as this increased the number of parallel paths. While MPCCLBF, MPCCLRA, and MPIRAMB mostly established lightpaths composed of one or two parallel paths, the MPIRAXT algorithm established most of its multipath lightpaths with three or more parallel paths.

Figure 6 shows the BBR produced for the USA topology. Since this topology has long links, the modulation formats employed imply lower transmission rates and consequently an increase in the duration of lightpaths. Due to the high node degree and large number of parallel paths, all multipath algorithms produced similar BBR values. The algorithm producing the lowest BBR values was the MPIRAMB, which was the algorithm resulting in the least blocking.

For the USA topology, MPIRAXT produced up to 200 percent greater differential delay values than did the other proposed algorithms. The greater availability of parallel paths in the USA topology influenced the delay, which was between 1 and 4.5 ms, due to a greater probability of using shorter paths when compared to the NSF topology.

Conclusion

In EON-SDM, slots in different cores can be jointly allocated to form a lightpath, even if not all of them are on the same path. Multipath routing is an effective tool for combining fragments spread throughout the spectrum to establish a connection using multiple paths. Such multipath routing is crucial for coping with the spectrum fragmentation problem.

This article has introduced four multipath routing algorithms for EON-SDM. The proposed algorithms employ image processing techniques to identify potentially allocable slots, thus helping to keep the computational complexity of RCMLSA algorithms low. Simulation results indicate that the proposed multipath algorithms reduce the blocking of requests in EON-SDM. Bandwidth blocking ratio values up to one order of magnitude lower than for single-path algorithms were produced by the multipath algorithm, but the differential delay values were acceptable for all the simulated scenarios.

A comprehensive comparison between the proposed spectrum allocation scheme and those based on a graph-coloring approach should be carried out in the future, as well as a study of the use of the proposed algorithms in conjunction with defragmentation mechanisms.

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References

[1] J. Perelló *et al.*, "Flex-Grid/SDM Backbone Network Design With Inter-Core Xt-Limited Transmission Reach," *IEEE J. Opt. Commun. Net.*, vol. 8, Aug. 2016, pp. 540–52.

[2] Y. Yin *et al.*, "Spectral and Spatial 2d Fragmentation-Aware Routing and Spectrum Assignment Algorithms in Elastic Optical Networks (Invited)," *J. Opt. Commun. Net.*, vol. 5, Oct. 2013, pp. A100–A106.

[3] P. M. Moura, N. L. S. da Fonseca, and R. A. Scaraficci, "Fragmentation Aware Routing and Spectrum Assignment Algorithm," *IEEE ICC*, June 2014, pp. 1137–42.

[4] F. Yousefi and A. Rahbar, "Novel Fragmentation-Aware Algorithms for Multipath Routing and Spectrum Assignment in Elastic Optical Networks-Space Division Multiplexing (EON-SDM)," *Opt. Fiber Tech.*, Nov. 2018.

[5] H. M. N. S. Oliveira and N. L. S. da Fonseca, "Multipath Routing, Spectrum and Core Allocation in Protected SDM Elastic Optical Networks," *IEEE GLOBECOM*, 2019.

[6] H. M. N. S. Oliveira and N. L. S. da Fonseca, "P-Cycle Protected Multipath Routing, Spectrum and Core Allocation in SDM Elastic Optical Networks," *IEEE ICC 2019*, 2019.

[7] S. Paira *et al.*, "On Energy Efficient Survivable Multipath Based Approaches in Space Division Multiplexing Elastic Optical Network: Crosstalk-Aware and Fragmentation-Aware," *IEEE Access*, vol. 8, 2020, pp. 47,344–56.

[8] X. Chen *et al.*, "A Multipath Routing Mechanism in Optical Networks with Extremely High Bandwidth Requests," *IEEE GLOBECOM*, Nov 2009.

[9] J. Domzal *et al.*, "A Survey on Methods to Provide Multipath Transmission in Wired Packet Networks," *Comp. Net.*, vol. 77, Feb. 2015.

[10] Z. Zhu *et al.*, "Dynamic Service Provisioning in Elastic Optical Networks with Hybrid Single-/Multi-Path Routing," *IEEE J. Lightwave Tech.*, vol. 31, no. 1, 2013, pp. 15–22.

[11] Ujjwal, J. Thangaraj, and R. Kumar, "Multi-Path Provisioning in Elastic Optical Network with Dynamic On-Request Optimal Defragmentation Strategy," *Opt. Switch. Net.*, vol. 41, 2021, p. 100,607.

[12] P. Lu *et al.*, "Highly Efficient Data Migration and Backup for Big Data Applications in Elastic Optical Inter-Data-Center Networks," *IEEE Network*, vol. 29, no. 5, Sept./Oct. 2015, pp. 36–42.

[13] X. Chen *et al.*, "Deeprmsa: A Deep Reinforcement Learning Framework for Routing, Modulation and Spectrum Assignment in Elastic Optical Networks," *J. Lightwave Tech.*, vol. 37, no. 16, 2019, pp. 4155–63.

[14] P. M. Moura and N. L. Da Fonseca, "Routing, Core, Modulation Level, and Spectrum Assignment Based on Image Processing Algorithms," *IEEE J. Opt. Commun. Net.*, vol. 10, no. 12, 2018, pp. 947–58.

[15] J. S. *et al.*, "19-Core MCF Transmission System Using EDFA with Shared Core Pumping Coupled via Free-Space Optics," *Opt. Express*, vol. 22, Jan 2014, pp. 90–95.

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